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NATIONAL AEROSPACE
LEADERSHIP INITIATIVE
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Final Report for Period May 15, 2005 to June 30, 2008

THE NATIONAL AEROSPACE LEADERSHIP INITIATIVE-Phase I

Grant Number FA9550-05-1-0345

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14. ABSTRACT

The first phase of the multi-phase National Aerospace Leadership Initiative (NALI) has been completed. Four major tasks were initiated and carried out under NALI Phase I. In Task I, the foundation for the National Center for Aerospace Leadership has been established and important outreach and educational programs were conducted. Significant accomplishments in gas turbine engine modeling and in factory simulation and modeling has been made in Task II. Task III resulted in the formation of a world-class Laser Applications Laboratory that, combined with modeling and simulation, is key to transitioning next generation manufacturing technologies to small-medium size U.S. aerospace manufacturers. In Task IV, the basis for development of advanced visualization and decision support tool prototypes to improve total supply chain enterprise effectiveness has been established. The efforts were carried out by the NALI Consortium member companies: Connecticut Center for Advanced Technology (CCAT), Avetec Inc., and Concurrent Technologies Corp. (CTC)

15. SUBJECT TERMS

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Executive Summary

The National Aerospace Leadership Initiative (NALI) was created to respond to the critical needs of the United States aerospace small-to-medium size manufacturers (SMM) and the manufacturing supply chain. It is focused primarily on needs of the United States Air Force (USAF) advanced propulsion and power systems. The NALI aim is to assure the effectiveness of an innovative and highly-competitive domestic aerospace manufacturing supplier base to meet the current and future requirements of the Department of Defense and the U.S. national economy. Initially funded by the U.S. Congress in 2005, the NALI Phase I program is administered by the Air Force Office of Scientific Research. This initiative supports maintaining U.S. leadership in aerospace applied research and development, fortifies the U.S.-based manufacturing supply chain, and helps to reinforce the U.S. aerospace original equipment manufacturers' technology and production market share as well as the underlying supply base. Summarily, the NALI Mission is to:

- Strengthen the U.S. aerospace manufacturers and manufacturing supply chain - solve problems and enhance capabilities
- Accelerate technology transition from research to application
- Assure a workforce capable of technology implementation

The NALI program is being executed in multiple, overlapping phases. Four NALI phases have been awarded to date and this document constitutes the Final Report for NALI Phase I. Timelines for the existing four phases are follows:

NALI I	May 15, 2005 – June 30, 2008 (complete with this report)
NALI II	June 1, 2006 – May 31, 2009
NALI III	April 1, 2007 – March 31, 2012
NALI IV	June 6, 2008 – June 14, 2013

Implementation of the NALI program is through the NALI Consortium of three not-for-profit organizations in partnership with the U.S. Air Force. The three consortium members are:

Connecticut Center for Advanced Technology (CCAT), headquartered in East Hartford, CT
Avetec, Inc. headquartered in Springfield, OH, and
Concurrent Technologies Corporation (CTC), headquartered in Johnstown, PA.

To achieve its mission, the NALI Consortium works closely with the U.S. research and development community, OEM and prime contractors; and most importantly, small to medium size aerospace manufacturers to enhance and accelerate the transition of leading edge technologies. Additionally, the NALI Consortium works closely with the Air Force Research Laboratory (AFRL) and with the Office of Science, Technology, and Engineering (SAF/AQR) at HQ USAF.

Each of the current four NALI Phases incorporates four main tasks:

- Task I - Establish the National Center for Aerospace Leadership
- Task II - Application of Modeling and Simulation to Accelerate Technology Transition and Assure the Effectiveness of an Integrated Supply Chain.
- Task III - Transition Next Generation Manufacturing Technologies
- Task IV - Address Total Supply Chain Enterprise Effectiveness

Task I – Establish the National Center for Aerospace Leadership (NCAL)

Within this task, the primary objective is to create and sustain a national center dedicated to strengthening U.S. aerospace manufacturing to meet USAF and national needs. The center is to be established in East Hartford, Connecticut at the Connecticut Center for Advanced for Technology. The location is appropriate as the Northeast United States has a long rich aerospace manufacturing and service presence. The NCAL's focus is to be a value added resource to the U.S. aerospace manufacturing supply chain network and help enhance regional and national aerospace competitiveness and capabilities. The NCAL strives to foster innovation and collaboration to rapidly meet the ever changing demands of the DoD and commercial aerospace for new systems and life cycle sustainment. It will be a focal point for a knowledge network that identifies, creates, and transitions strategic technologies. The NCAL will nurture the development of a workforce capable of employing those technologies. Elevating the visibility, capability, and relevance of aerospace manufacturing locally, regionally, and nationally are key outcomes. The NCAL intends to promote the value and importance of manufacturing as a career choice and as an economic force to compete globally. Highlights of the NCAL development in Phase I are:

- Established the NCAL leadership team that has facilitated both technical and management collaboration with the Air Force, industry and academia.
    - Hired a full-time NCAL Director in May 2007 with nearly 40 years aerospace experience
    - Created a development plan for becoming a credible, value added focal point for multi-regional and national leadership
    - Formed collaborative relationship with AFRL
    - Added weapons systems sustainment and life cycle management elements to the initiative
    - Engaged USAF senior management and technical leaders in shaping the initiative's projects and outcomes
    - Connected with relevant aerospace and industrial organizations to establish coordination and cooperation
- Increased SMM and manufacturing supply chain companies' awareness of global progress being made in critical technologies, including modeling and simulation, supply chain effectiveness and laser based manufacturing processing.

  - Hosted a conference on "Innovation: The Future of Machining" at CCAT facility in March 2007 with representation from key Air Force stakeholders including OEMs, supply chain, machine vendors, educators, and Consortium staff
  - Partnered with the national SBIR Program by holding two events in 2007 under the theme of "The Future of Manufacturing is Innovation"
  - Established the Symposium for Aerospace Laser Applications (SALA) as an international event
  - Established annual NALI Review and technical workshops to communicate and demonstrate specific initiative achievements

- Executed educational programs to enhance student interest in the future of the aerospace industry and opportunities to work for the Air Force, including:
  - LaunchQuest™ Program on a national level, the STEM (Science, Technology, Engineering, and Math) Curriculum, collaboration with Project *Lead the Way*, and Gear-Up
  - The *Wright Scholars Program* at the Wright-Patterson AFB Research Center where internships have been bestowed from Avetec to fifteen Springfield, Ohio high school students
  - The *Talented Tenth Program*, a partnership between Avetec and Central State University (Wilberforce, OH) that inspired low-achieving but high potential inner-city Springfield, OH middle school students in STEM careers. As of 2008, Central State University has sustained the program without further financial support from Avetec
  - Expanded the Wright-Patterson Air Force Base/DoD STARBASE Program to involve 200 additional fifth grade students from Springfield, OH City Schools and their teachers in STEM learning

Task II - Application of Modeling and Simulation (M&S) to Accelerate Technology Transition and Assure the Effectiveness of an Integrated Supply Chain

This task builds and utilizes a distributed network of expertise and capabilities to solve critical problems and increase supply chain capabilities, which focuses on the application of Modeling and Simulation for advanced gas turbine engine performance as well as manufacturing, machining optimization, and sustainment processes. Activities specific to sustainment, legacy systems and reverse engineering are strengthened both in engine performance prediction and analysis as well as manufacturing process optimization. Highlights include:

- Demonstrated and validated M&S capabilities for manufacturing companies as follows:
  - Established a "Game Changer" method to widely disseminate the benefits of physics-based machining modeling

- Created a Beta version of the CAM software interface to Third Wave Systems Production Module environment. A Beta Test Program for this concept is currently underway

- Completed implementation of the Modeling and Simulation Laboratory with more than fifty software tools for product and manufacturing process design and optimization as well as develop materials to distribute these tools for SMM and Air Force use

- Enhanced an Excel spreadsheet database with an interface to Google Earth to map locations of supply chain companies capable of sorting by company capabilities

- Developed a unique interface between Value Stream Mapping software (eVSM) and a Discrete Event Factory Modeling Environment to dramatically reduce the amount of time it takes to build a working factory model (from days to minutes) in order to support Lean Manufacturing "what if" analysis activity

- Installed a web-based CNC program Interactive Learning Environment to introduce students to the concepts of NC Programming and how they are executed by CNC machines. This technology is accessible via the http://www.usnali.org website

- Developed and demonstrated significant advances in gas turbine engine performance modeling and simulation to solve the following problems related to aircraft propulsion systems:
    - Thermal Management - Collaborated with a large aircraft manufacturer to understand the structure and underlying thermal physics of an existing MATLAB-based thermal management code in order to streamline this model to make it more generalized for users and to develop generic physics-based models for engine components and other necessary components.

    - Developed and applied Computational Fluid Dynamics (CFD) code for jet engine turbo machinery through a university, government and industry collaboration. CFD tools were applied in full annulus simulations of aircraft jet engines, and elements of the research were published at the International Gas Turbine Institute Turbo Expo (conference) in Montreal in May, 2007

    - Devised and validated CFD code for operation of a micro-channel heat exchanger. The work was published at the 2008 AIAA Annual Meeting and Exposition in Reno, NV, in January, 2007 and commercialization efforts are being carried out by a small business government contractor

    - Modeled gas turbine combustor flow field using Large Eddy Simulation (LES) techniques. Compared simulation results to experimental data for both reacting and non-reacting flows, and results were published at the 2008 AIAA Annual Meeting and Exposition at Reno, NV, in January, 2007

- Constructed detailed, non-proprietary turbine engine models that can be used by the Air Force, government contractors, educators, and researchers as a medium for the development of new turbine engine, control, and health management technologies

- Investigated prognostic algorithms on novel computing architectures

- Initiated time and cost saving activities with OC-ALC with the development of a virtual engine test cell

- Developed a laboratory and framework for virtual testing and prototyping turbine engine health management systems.

Task III - Transition Next Generation Manufacturing Technologies

In Phase I, this task advances the knowledge and application of state of the art and next generation laser technologies. (Future Phases address technologies other than lasers.) Targeted areas of concentration include laser drilling (of new and used components) for turbine airfoils and larger sized components (e.g., combustor, augmenter, and nozzle applications), taking into consideration substrate material properties and both ceramic-based thermal barrier coatings (TBC's) and "special" coatings, especially in the areas of material property impact to sensing, measurement and breakthrough detection. Establishment of CCAT's NCAL Laser Applications Laboratory that includes next generation laser drilling workstations implemented as a flexible system to support new developing applications was a major objective of this task and was completed. Opportunities for qualification and implementation of precision laser machining and welding applications for Air Force needs were identified and tested under this task. Highlights include:

- Established world-class Laser Applications Laboratory with a highly skilled, experienced staff.
- Initiated the grand challenge of producing "designer" shaped cooling holes for military gas turbine engine airfoils directly from 3D files by solving software, machine tool motion and metallurgical issues to demonstrate next generation laser precision machining.
- Developed laser part marking processes and optimization to maximize "readability" and durability while minimizing material damage, for application to meet the DoD's Unique Identifier (UID) initiative.
- Increased education in the area of laser technology through the support of university level courses, thesis research, senior capstone projects, and internships as well as hosting professional society meetings and workshops
- Demonstrated the use of a laser-generated, crack-like feature for more consistent, timely, and cost effective sample generation and materials property (and component) validation.

Task IV - Total Supply Chain Enterprise Effectiveness

The competitiveness and effectiveness of U.S. aerospace industry are closely linked to the extended enterprise of a network of small to medium manufacturers in a supply chain. Fundamentals are understanding and monitoring the material, money and information flows. In Phase I information flow in the supply chain was addressed. This task focuses on overall supply chain enterprise effectiveness and brings into use advanced IT and web-based capabilities that improve responsiveness to war fighter needs. Advances in supply chain planning, management and execution were identified and a tool designed within this task. The tool was designed for use by USAF Purchasing and Supply Chain Management Commodity Councils. Highlights include:

- Developed and applied methods and tools which will enable the Consortium to work at the total supply chain enterprise level
    - Engaged various Air Force and DoD organizations to determine the feasibility to pilot use of visibility tools. These include the Air Force's Global Logistics Support Center, Oklahoma City Air Logistics Center, and the Defense Supply Center, Richmond (DSCR).
    - Completed the development of the framework for V*isualization Support Tool* that will provide total asset visibility of the supply chain from war fighter to manufacturer that can be synchronized with emerging Air Force systems. The Consortium has discussed and demonstrated this application at the Air Force Transformation Office in the Pentagon and the Purchasing Supply Chain Management office at Wright Patterson Air Force Base. Both agencies indicated an interest in this application.
    - Continued development effort for a web-enabled framework for an *Advanced Decision Support Tool*.

Bottom Line: In Phase I of the National Aerospace Leadership Initiative excellent progress has been made in the development of the program to meet its stated objectives. Much of this first Phase was focused on organizing and creating the capabilities needed to deliver on the tasks. Many accomplishments have been made and a solid foundation of management and technical skills are in place. The NALI, through the efforts of the Connecticut Center for Advanced Technology, Avetec and Concurrent Technologies Corporation is well on the way to establishing a national capability to strengthen our U.S. aerospace manufacturing supply chain network to compete in the global market place and contribute to national security.

THE NATIONAL AEROSPACE LEADERSHIP INITIATIVE – PHASE I

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1. Introduction

The National Aerospace Leadership Initiative (NALI) was created to respond to the critical needs of the United States aerospace small-to-medium size manufacturers (SMM) and manufacturing supply chain. It is focused primarily on needs of the United States Air Force (USAF) advanced propulsion and power systems. The NALI aim is to assure the effectiveness of an innovative and highly-competitive domestic aerospace manufacturing supplier base that can meet the current and future requirements of the Department of Defense and the U.S. national economy. Initially funded by the U.S. Congress in 2005, the NALI Phase I program is administered by the Air Force Office of Scientific Research. This initiative supports maintaining U.S. leadership in aerospace applied research and development, fortifies the U.S.-based manufacturing supply chain, and helps to reinforce the U.S. aerospace original equipment manufacturers' technology and production market share as well as the underlying supply base. Summarily, the comprehensive NALI Mission is to:

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Task I – Establish the National Center for Aerospace Leadership (NCAL)

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Task II - Application of Modeling and Simulation (M&S) to Accelerate Technology Transition and Assure the Effectiveness of an Integrated Supply Chain

The complexity of work interactions within manufacturers' firms, the components and systems' design and the external network of firms involved, makes modeling and simulation an important set of tools to enhance the U.S. aerospace industry productivity,. This task builds and utilizes a distributed network of expertise and capabilities to solve critical problems and increase supply chain capabilities, which focuses on the application of Modeling and Simulation for advanced gas turbine engine performance as well as manufacturing, machining optimization, and sustainment processes. Activities specific to sustainment, legacy systems and reverse engineering are strengthened both in engine performance prediction and analysis as well as manufacturing process optimization.

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Task IV - Total Supply Chain Enterprise Effectiveness

This task focuses on overall supply chain enterprise effectiveness and seeks to bring into use advanced IT and web-based capabilities that improve responsiveness to war fighter needs. Advances in supply chain planning, management and execution were identified and implemented within this task.

The subsequent sections of this Final Report provide detailed summaries of the NALI Phase I accomplishments for each of the four major tasks.

2. Summary of Accomplishments

2.1. Task I - Establish the National Center for Aerospace Leadership (NCAL)

In Phase I, this first task built the initial capabilities of a national center dedicated to leading the effort to enhance U.S. aerospace manufacturing competitiveness and supply chain effectiveness for a strong national economy and national security base. It focused on finding focused methods for strengthening connections between Air Force and commercial small to medium manufacturers' needs, as well as building CCAT/NCAL organizational capabilities. Emphasis was on executing specific, initial activities which can serve to integrate multiple resources for strengthening aerospace manufacturing, and to excite and encourage young people to become part of the aerospace's workforce of the future. Engaging the range of education and training infrastructures from K-12, to community colleges, and to four year and advanced degree institutions were pursued.

Given the evolving global security and economic threats to our Nation, it is imperative that the United States maintain its world leadership in advanced propulsion and power systems, as well as preserve an innovative and highly competitive domestic aerospace manufacturing supplier base to meet the Department of Defense's and the nation's current and future industrial needs. This initiative is used to support U.S. leadership in aerospace research and development, fortify the U.S.-based manufacturing supply chain, and buttress our aerospace original equipment manufacturers' technology, and production market share. The National Center for Aerospace Leadership is created to help do these things.

<u>National Center for Aerospace Leadership</u>

It is essential to the defense and economic security of the nation, that the United States:

- maintain world leadership in advanced propulsion and power systems.
- preserve an innovative, diverse and highly competitive domestic manufacturing supplier base responsive to Department of Defense's needs.
- ensure a workforce capable of innovation and using advanced technology.

To be successful we must be aware of significant challenges facing the U.S. aerospace industry and the DoD's technology base. Most notable among these are: (1) eroding U.S. leadership in research and development; (2) weakening of the U.S.-based supply chain in the face of global competition; (3) declining original equipment manufacturer (OEM) leadership in both manufacturing technology and market share, (4) the declining numbers of individuals in the U.S. studying science, technology, engineering and mathematics (STEM) subjects; so important to maintaining a workforce to keep the U.S. in such an important market, as well as (5) making manufacturing a career choice young people find attractive.

It is the purpose of the NCAL to create a focused response to these challenges through the formation of a multi-regional effort that enlists leaders in industry, academia and government that will do both regional and national good.

Objectives:

Create a credible National Center to assist the transformation of the domestic aerospace industry to meet current and future global markets and the U.S. national security requirements.

- Strengthen the effectiveness of OEM led distributed product development and manufacturing teams to produce best in world advanced military power and propulsion systems
- Proactively enable an innovative, diverse and highly competitive domestic supplier base to provide the OEM's viable alternatives to the growing trend of global, "outsourcing"
- Develop, support and maintain a domestic workforce that is world class in cost, capability and performance
- Assist government programs like the Small Business Innovation and Research (SBIR) program to encourage technology transition to Air Force benefit.

Approach:

- Utilize Connecticut based engineering & manufacturing capabilities and DoD focused systems, critical to national defense, as platforms for execution in partnership with the national supplier base.
    - Advanced propulsion platforms and applications
    - Advanced fuel cells for distributed power, cogeneration, portable and transportation applications
    - Strengthen capability of 2nd and 3rd tier suppliers to meet OEM requirements for higher levels of product integration and associated engineering support
- Enable more effective geographically distributed capabilities among diverse teams by incorporating intelligent tools into existing engineering and business processes.
    - Improve cost and risk management consequences resulting from increased engineering and subsystem content throughout the supply chain
    - Enhance total enterprise productivity
    - Increase competitive advantage through the adoption of transformational technology for both OEM's and tiered supply chain
- Enable and validate intelligent computational modeling and simulation capabilities that:
    - Span dimensional and time scales controlling system performance
    - Enable root cause based control of key processes, including fabrication, service and repair in a global environment
- Integrate continuous and adaptive workforce education tools to attain and upgrade skills for improved effectiveness
    - Knowledge capture and utilization tools
    - Adaptive tools for life long learning

- Phased development of program structure and content
  - Define program structure (focus, stakeholders and roles, program management)
  - Conduct workshops to clarify stakeholder needs and desired outcomes
  - Define intelligent tools requirements and implementation paths
  - Engage other National Centers of Excellence to insure program success

Program Execution

The National Center for Aerospace Leadership, NCAL, provides the focal point for a nationally executed program.

While Connecticut based, the effective creation and insertion of CCAT/NCAL into the national technology infrastructure requires working closely with other regions that share our concerns and possess well established centers of excellence that have demonstrated effectiveness and links to industry, government and academia. Specific regions include:

Ohio

- Like Connecticut, Ohio is prominent in the engineering and supply chain supporting our nations advanced power systems and propulsion needs. Avetec provides an exceptional partner in advanced competitive sciences and educational outreach.
- The Air Force Research Labs, Wright Patterson Air Force Base System Program Management offices, and the Air Force Institute of Technology provide a key role in establishing mission, system, education and supply chain effectiveness requirements.
- Ohio's leading universities possess engineering/technology excellence that is key to the creation of new materials and processes as well as foundational root cause understanding that enables effective modeling and simulation of processes and systems performance. Organizations like the Ohio Aerospace Institution, provides national potential partners.

Pennsylvania

- Through the Concurrent Technologies Corporation, CCAT's NCAL will have the opportunity to partner with a well established organization that is addressing the need for a "National Enterprise" view to supply chain and logistics issues.
- CTC provides:
  - Existing connectivity to address the logistics needs of advanced military power and propulsion, including those of the Army and Navy.
  - Provide an avenue for tech transfer to address additional DoD systems requirements.
  - Unique capabilities in transitioning technology, with excellence in manufacturing/ advanced processing, rapid product realization, environmental/sustainability issues and fuel cell testing/evaluation.
  - Information technology capability as it relates to total enterprise, including education/training that can be enhanced via application of intelligent tools.

Regional and National

- As the NCAL develops in future phases additional regional and national organizations will be included and programs refined to meet evolving market and national needs.

- Like Ohio, Pennsylvania has a strong university base in manufacturing, as well as non-profit organizations like TechSolve in Cincinnati, the Ohio Aerospace Institute in Cleveland, the Doyle Center in Pittsburgh and the National Center for Defense Manufacturing and Machining Center in Latrobe, as potential regional partners.

Key Program Elements

Connecticut
- National Center provides focal point
- Build capabilities and facilities
- Address tech transition and supply chain competitiveness

Ohio
- Capitalize on strong, recognized university centers of excellence
- Provide guidance for systems and supply chain requirements

Pennsylvania
- Provide established role in addressing national supply chain
- Utilize existing centers of excellence for technology transition

This task focuses on establishing core program elements which address the need for both entrepreneurs and a motivated and educated workforce to transform and transition new technologies. The creation and growth of new enterprises can serve to develop and sustain new technologies. An educated and motivated workforce is also essential to deployment on a wider scale.

2.1.1. National Center for Aerospace Leadership Development Planning

In NALI Phase I, initial planning was started to create a plan the would lead the development of the CCAT's NCAL as a fully functioning entity that would be recognized national leader in aerospace technology for manufacturing, workforce development and education, and knowledge center. The NCAL development plan focuses on providing unique operational paths to accelerate transformation in aerospace manufacturing and sustainment through technology applications. The plan describes the desire for the NCAL to be a "skunk works" for facilitating 21st Century agile aerospace technology transition and operations. As well as becoming a respected national leader based on excellence in performance, and seen as trusted, reliable and transparent by its government, industry, academic and professional stakeholders. Key features of the end state for the NCAL, described in the plan, are:

- USAF (and DoD) adoption by demonstrating high value; providing unique capabilities that make an impact
- Regional Identity and Value for New England manufactures in advanced power systems; and to be a partner with regional companies and organizations to advance technology and global competitiveness
- National Purpose and Value in support a national aerospace manufacturing supply chain network that uses a national network of capabilities found in academia, industry and technology innovators.

- A major emphasis on supply chain effectiveness for the small/medium size manufacturers and sustainment service providers.
- Developing a workforce capable of using next generation manufacturing technologies.

The initial draft plan was developed in a team environment using group systems software and a proprietary process, Advanced Management Catalyst™ (AMCat™) that has been proven to facilitate participant consensus building and speed plan development. The methodology allows for the measurement of objectives and task as well as assigning relative importance. Six major objective areas to secure the vision for the NCAL were identified:

1. Perform as a Value Adding Resource
2. Cultivate, Inspire, Empower and Value Our people
3. Assure Financial Flexibility
4. Shape and promote Careers in Manufacturing Technology
5. Provide Facilities to Deliver NCAL capabilities
6. Implement Processes to Enable Superior Performance

The AMCat™ Matrix (Figure 1) of strategic opportunities to achieve CCAT's desired NCAL end state shows the prime objective, how it relates to the subordinate constraints and where effort and resources are needed, and what classes of action are required to move forward. An action plan of 25 major tasks was developed to achieve the strategic opportunities identified.

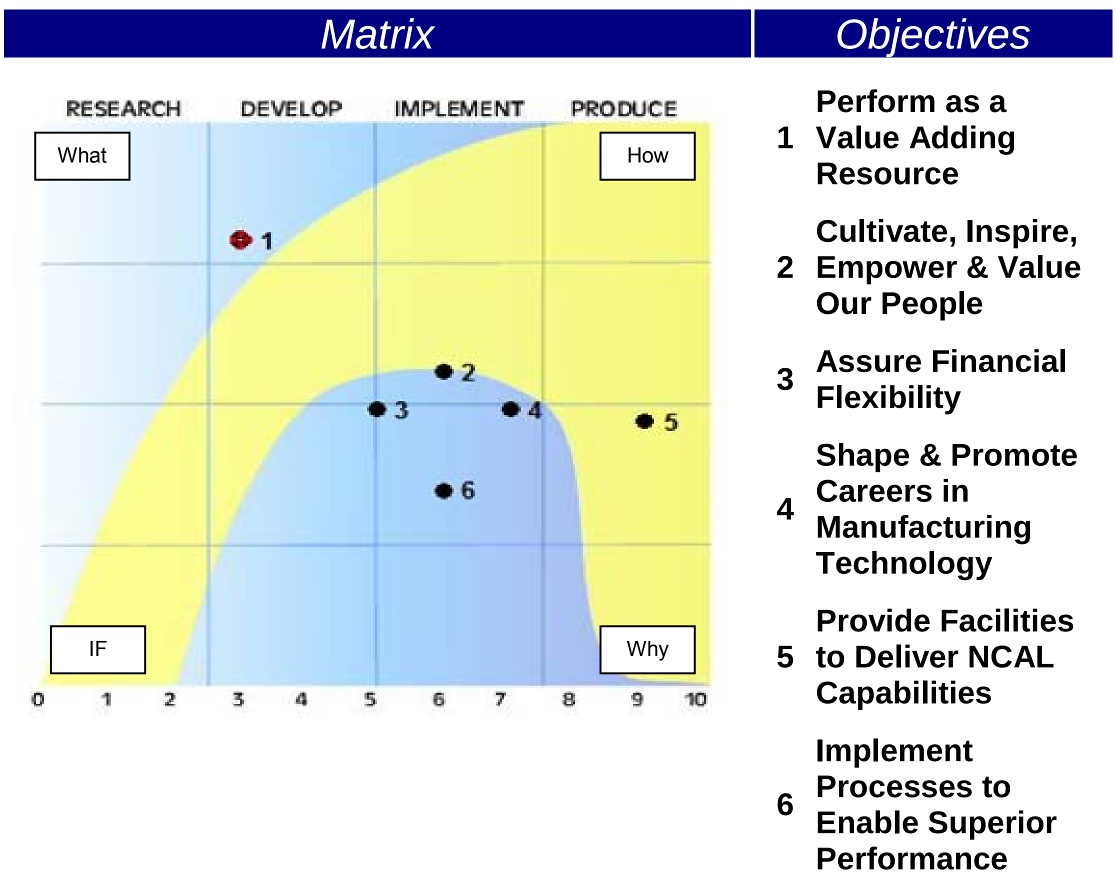

Figure 1 AMCat™ Matrix for Initial NCAL Development Plan

2.1.2. Enterprise and Innovation Activities

Innovation and enterprise activities conducted under NALI Phase I have centered on gaining the collaboration and/or participation of small companies who can act as transition agents for advances in the manufacture and sustainment of Air Force systems. These small, entrepreneurial companies are often the recipients of SBIR or contract funding from the Air Force to develop and implement new technologies. However, they require assistance to address key issues or to find existent manufacturing companies who have established track records for delivery of value to the Air Force. This is a role NCAL begins to perform in Phase I.

Innovation at Work

CCAT's NCAL collaborated with the Connecticut Technology Council (a membership of over 300 regional technology companies) to create a one day workshop titled "Innovation@Work." This program was designed to facilitate the collaboration between NALI consortium members and selected medium and small sized technology companies. The December 2005 event centered on the aerospace manufacturing industry and NALI-funded initiatives that are focused on supply chain improvement. Several of the presenting companies were selected for further collaboration with NALI consortium members in areas of metrology, risk assessment, composite materials, and plastic component manufacturing.

SBIR Manufacturing Conference

NCAL and its consortium partners collaborated with CCAT's Connecticut SBIR Office to create a two day conference, "The Future of Manufacturing is Innovation" in June 2006. This Conference drew national participation with attendees coming from as far away as Washington State. Over 300 people attended the meeting along with representatives from five federal agencies and six major prime contractors. NALI program goals and the needs of the Air Force and other agencies were presented to provide guidance for the discussions. The principal focus of the meeting was to bring together small manufacturers with SBIR entrepreneurs and aerospace OEM's to identify opportunities for collaboration that can shorten the time for technology implementation in the Air Force manufacturing supply chain. The meeting was highly successful and provided a template for similar meetings to take place in both Ohio and Pennsylvania in ensuing years. The attendees also overwhelmingly indicated the continuing need for such meetings, focused on manufacturing. As a result, this meeting was held again in June of 2007 with approximately 400 people attending.

2.1.3. Educational Activities

Leaders in government agencies, the aerospace industry and in most major industries in the United States universally agree that one of the single most challenging issues facing the United States is the production of a future work force that possesses the mathematic, scientific, engineering and technical skills required to maintain national competitiveness in emerging global markets. In light of that need CCAT, Avetec, and CTC have aggressively pursued educational outreach activities designed to support students and teachers in science, technology, engineering, and mathematics (STEM) areas. Educational outreach efforts for the NALI phase I program were focused on increasing the quantity of students and teachers and quality of teaching in STEM subjects and providing experienced learning experiences. The following is a brief summary of program accomplishments:

NALI-funded educational activities support the development of programs that advance scientific and technological literacy, while simultaneously inspiring students to meet the future workforce needs for a 21st century aerospace industry. Our goal is to engage students in activities that are based upon best practices for hands-on learning in science, technology, engineering, and math.

While consuming only a minor portion of the NALI program resources, the program team believes that these early efforts to engage both students and teachers can be exceptionally important in gaining interest to assure the future of the Air Force's supply chain workforce. Activities occur on both the national and regional levels.

National Educational Programs

The LaunchQuest™ program, funded under the NALI and administered by CCAT's Educational Initiative, was established on a national level to spark students' imaginations, encourages interest in science and technology, and to enhance middle and high school curricula throughout the United States. LaunchQuest™ is a partnership among CCAT's NCAL and its consortium partners, and UP Aerospace. The program was designed to inspire students on a number of different levels: it gives them the opportunity to design a real scientific investigation; to interact with scientists and engineers from throughout the United States; and to collaborate with their peers in a web-based learning environment.

The students who participated conceived, created, and launched a research experiment into space. Student-designed scientific experiments few aboard an UP Aerospace SpaceLoft™ sub-orbital sounding rocket, with a flight profile of approximately 65 miles. Five minutes of microgravity time occurred during the flight. After the launch, the experiments were recovered and returned to students for their analysis. Post-flight, students examined payload and data against pre-flight predictions/hypothesis, and created a final report for posting to the LaunchQuest ™ website. The program introduced students to standard terms and design processes used in the aerospace industry, gave students the opportunity to apply advanced math and science knowledge in a real-world manner, and encouraged innovation and enterprise by exposing students to the next frontier in aviation history. The partnership provides students with a unique opportunity to experience how entrepreneurship and scientific progress go hand in hand.

Schools from Connecticut, Ohio and Pennsylvania have participated in LaunchQuest I, as well as teams from NASA Explorer Schools around the country; a total of 38 different experiments from 25 schools were planned to be flown. Student teams have collaborated on project ideas, and written concept-level descriptions of their experiments, including background information, design, hypothesis, and control. Each student group was provided with a "T-SAT" ("Tiny SATellite") container to house their experiment materials. In true measure of the power of entrepreneurial science, a student team from one of the Project Lead the Way (pre-engineering program) schools developed, designed, and manufactured these wedge-shaped containers. The initial idea was to have the 12th grade engineering class build a payload housing system for cylindrical experiment jars; however, the students determined that this design wasted space, a precious commodity within a rocket. The students involved in this project will now forever leave a mark on commercial space travel, as the invention they created will fly on the UP Aerospace rocket.

More than 1,000 students from 50 middle and high schools (grades 5-12), NASA Explorer Schools, representing 17 states and the Netherlands, have participated in LaunchQuest. To date, student teams have flown over 75 experiments, which range from simple "fly and compare" (seeds, yeast, popcorn) to far more complex biological and materials science, and technology and engineering experiments. All experiments were designed to measure, in one way or another, the effects of various conditions that will occur during the rocket's flight. By engaging students in real science and technology projects, the LaunchQuest program develops interest in 21st century aerospace and engineering careers, and the partnership with UP Aerospace gives students a unique opportunity to experience how entrepreneurship and scientific progress go hand in hand.

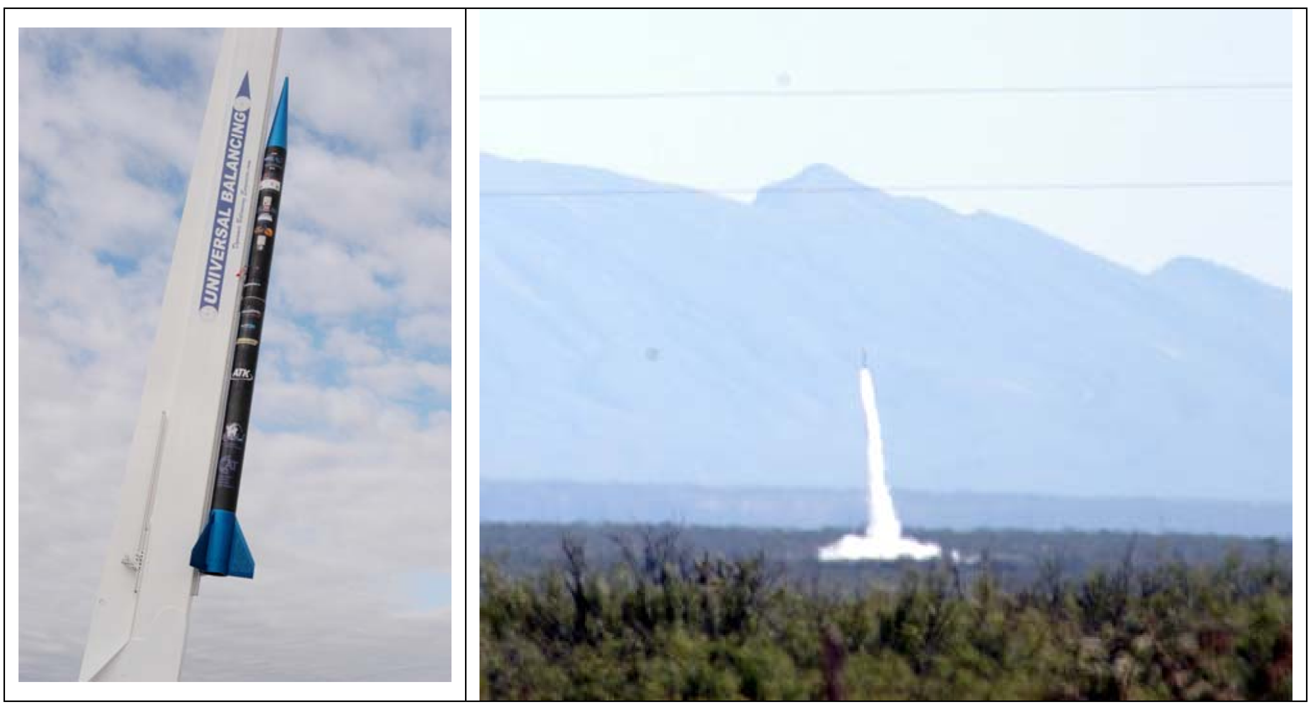

Figure 2 Close-up of LaunchQuest Rocket and Rocket Lift-off

Figure 3 LaunchQuest students examine objects that were launched into space

Regional Educational Programs

We have additional local activities in our consortium regions to stimulate student interest in the future of the aerospace industry and the Air Force's mission. The various types of initiatives occurring in each region are summarized here.

Ohio Region

Avetec's educational outreach efforts focused upon increasing the Quantity and Quality of Science, Engineering, Technology and Math (STEM) graduates. The following were accomplished in NALI Phase I:

1. A new Robotics curriculum has been introduced in the Springfield City Schools system for 45 high school juniors and seniors. Avetec provided curriculum support and supplied materials, field trips, faculty advisors, student mentors and other support.
2. Avetec has provided funding to expand the WPAFB/DOD STARBASE program to 200 fifth graders and their teachers in Springfield City Schools.
3. Avetec has placed a full-time loaned executive with Wilberforce and Central State Universities to assist in creating new internships for students attending these 2 HBCUs and has directly hired 10 high school and college interns to work on Avetec's research and educational activities.
4. Over 90 school teachers worked with Avetec this summer in teacher development activities in science, math and technology for the local schools' curriculum.

5. Avetec has served on faculty selection and advisory committees and is directly sponsoring faculty development programs, including participation in SC06.
6. Avetec has created a series of "Tec Talk" programs to provide informal science education to over 75 students and members of the community and is sponsoring a NASA Art of Engineering Design program bringing informal science education to thousands of Springfield museum of Art visitors.
7. Avetec has worked with the University of Cincinnati to evaluate our educational activities to help assist us in determining the effectiveness and impact of our activities.

STARBASE-Department of Defense (DoD)
The DoD funds a STARBASE program at Wright Patterson Air Force Base (WPAFB) to involve fifth graders in STEM learning. Avetec provided funding to expand the WPAFB/DoD STARBASE program for an additional 200 fifth graders and their teachers in Springfield City Schools.

Robotics
Avetec responded to a need identified by the Springfield City Schools (SCS) to create a STEM elective program at North and South High Schools. During NALI I, 45 high school juniors and seniors participated and two teachers were trained using a Lego's based robotics learning program. The program was aimed at creating interest for high school students to enter STEM careers. Avetec provided curriculum support and materials, field trips, faculty advisors, student mentors, and other support. As of 2008, the SCS is now able to sustain the program paying for the teachers and related student expenses without further financial support from Avetec.

Figure 4 STARBASE students demonstrate Bernoulli's principle

Figure 5 A student at Catholic Central High School adjusts his robotic car

STEM Co-op, Internship and Employment Opportunities
Avetec placed a full-time education consultant with Wilberforce and Central State Universities through NALI I funding to assist in creating new internships for students attending these two historically black colleges and universities (HBCUs) and to work with faculty on curriculum development to support NALI's aerospace leadership mission.

The following is an article about the Wright Scholar internship program that was featured in the July 2006 issue of the Accelerator:

High School Students Become Researchers (July 2006)
The Wright Scholar Research Assistant Program has been in existence for four years, and no one from Clark County has participated... until now! Five hardworking students from Clark County were among those selected for this year's summer research program which takes place at the Air Force Research Laboratory at Wright-Patterson Air Force Base. These five students: Trevor Carroll and Ali Hashemi (Catholic Central High School), Sarah LeMay (Northwestern High), Connie Estep (Shawnee High), and Raghuram Vellanki (Springfield North High) will all be Avetec employees for the summer, and will be immersed in a hands-on learning environment.

While on Base, students will work directly with researchers and scientists in the Air Force Research Laboratory, taking part in experiments and collecting and analyzing data. They will also attend pre-engineering classes at the University of Dayton.

Avetec is excited about hosting the five students from Clark County, and about the many opportunities that this summer program offers them. Any students wishing to participate in next year's program are encouraged to contact Avetec this fall.

"It's not too early for students interested in applying for 2007 to begin thinking about the process, and we'd like to see ten students from Springfield selected next year!" noted Cathy Balas, Avetec Director of Education.

Talented Tenth
Avetec and Central State University's (CSU) education department partnered to offer a summer program called the Talented Tenth to 20 inner-city Springfield middle school students. The purpose of the program was to interest low-achieving but high-potential students in STEM careers, and particularly in STEM teaching careers. As of 2008 CSU has sustained the program and is operating it without further financial support from Avetec.

The following is an article about the Talented Tenth program that was featured in the July 2006 issue of the Accelerator:

> **Aspiring Teachers Get Their Feet Wet**
> Avetec has partnered with Central State University to sponsor The W.E.B. DuBois Talented Tenth Teacher Training Summer Academy. The two-week program, designed for high school students ages fourteen through sixteen, is a

learning intensive academy that will dive into the fields of math, science, and technology.

Not only do students have the opportunity to learn a myriad of facts and figures from each field, they will also have the opportunity to teach those facts. One of the program's components gives the students the chance to take the new lessons that they learn and create their very own lesson plan. The students will then utilize that lesson plan and teach what they've learned to a group of younger students.

"*One of the best ways to learn something is to have to teach it, so this program not only gives them a working knowledge of math, science, and technology, it also provides them with an opportunity to test their skills as teachers*," explained Cathy Balas, Director of Education. The program is being held in the Avetec facilities, and students will also participate in off-site field trips.

The first week of the program was successfully conducted on June 26th-30th, and the second week will take place this month from the 10th to the 14th.

Connecticut Region

1. CCAT Education Initiative partnered with Central Connecticut State University (CCSU) to establish the concepts for a K-12 Pre-Engineering Curriculum which uses modeling and simulation technology as the mechanism to inspire young people to consider careers in science, technology, engineering and mathematics. This was a critical first step to get young people thinking of this direction for their future in order to be able to deliver a skilled capable workforce to the aerospace industry. The CCAT/NCAL Modeling and Simulation team has worked with local industry to identify summer internship candidates from regional schools. CCAT helped place eight students from several colleges: University of Connecticut, University of Hartford, Western New England College, CCSU, and Trinity College. Feedback from the industrial participants' has been very positive and they were very satisfied with the performance and contributions made by this class of interns.

2. CCAT's NCAL has established a program with MSC Software to use the Modeling and Simulation Laboratory's Theater facility as the classroom for the training of local manufacturers in the use of finite element analysis tools on part/product design. Six classes were scheduled between September and December of 2006 to expose and train customers on Nastran, Patran and Marc technology solutions. Companies from all over the northeast were invited to these classes.

Pennsylvania Region

CTC has actively supported the NALI-funded LaunchQuest effort, which provided high school students with the opportunity to conceive, create, and launch a research experiment into space and have it recovered for data collection and subsequent analysis. In order to initiate the LaunchQuest program in Johnstown, Pennsylvania and surrounding region, three schools were contacted. Forest Hills High School, located in a predominantly rural suburb, chose to participate in the project. *CTC* provided on site assistance for the school's efforts to facilitate collection of the required registration information.

CTC sponsored a training session January 26, 2006, at CTC training facilities in Johnstown, Pennsylvania. Sue Palisano, CCAT Director of Education, conducted training with CyberACT, the Web-based information and collaboration application used by NALI consortium members to support the LaunchQuest project. The training was attended by Doug Smith, Joel Kosmac, Matt Hautz, and Pat Nelen who are science instructors from Forest Hills School and Elaine Fenton, Scott Sheets, and Kevin Brandon from CTC.

The Forest Hills Middle School LaunchQuest had two experiments, based on biology and physics. Biology in the form of agriculture has been a major part of life and has been performed by humans since the caveman times. Computer technology has had a major impact since the first calculator was invented. Forest Hills Middle School had chosen bean seeds and thumb drives to send to space to represent biology and technology. The experiment intended to answer the following questions:

Q1. What effect will space travel have on bean seeds?
Q2. Will foil shielding protect the seeds from radiation and other possible harm?
Q3. What impact will space travel have on computer storage media (thumb drives)?
Q4. Will foil shielding protect the thumb drives from radiation and other possible harm?

The NALI Consortium continues to build and foster the regional education programs and STEM activities beyond NALI Phase I.

2.1.4 NCAL Outreach

To be effective and credible a National Center for Aerospace Leadership must become an integral part of the local, regional and national aerospace environment. This means identifying and understanding key stakeholders, similar organizations, past efforts and where there may be points of collaboration or conflict.

Initial outreach activities revolved around the USAF, New England and Ohio aerospace manufacturers, Connecticut and Ohio schools and higher education institutions, and various state government agencies. Many of these outreach activities are described in following sections of this report. As Phase I matured additional outreach activities were pursued.

A closer relationship with the Air Force Research Laboratories (AFRL) at Wright-Patterson AFB, OH was pursued. This led to a full time materials scientist (Ph.D.) being assigned to the NALI program, and specifically as part of the NCAL team.

The importance of sustaining in-service weapons systems and the opportunities for aerospace manufacturers led to establishing a relationship with the Air Force Material Command's Directorate of Logistics manufacturing technology program. The NCAL now provides technology advice for improvements in the Air Logistics Centers and has offered several pilot projects under the NALI Grant now under consideration.

In consideration of the business transformation underway in the Department of Defense and the Military Services, particularly those changes that will impact the small to medium aerospace manufacturer; like Performance Based Logistics (PBL) and integrated supply chain management: the CCAT/NCAL began reviewing how best provide a value added capability. One effort has been to build relationship with top national schools in the field. Relationships have been established with Clarkson University in Potsdam, NY, one of the perennial top ten supply chain schools in the nation as well as the Wharton School at the University of Pennsylvania, another top business school and Auburn University in AL: both have done leading work in PBL. These relationships will provide business insights from basic research and analysis that can be passed on the supply base.

The CCAT/NCAL has carefully looked at various professional organizations that service aerospace and manufacturing. Memberships have been taken in the National Defense Industries Association (NDIA), the Aerospace States Association, the National Council for Advanced Manufacturing (NACFAM), and the Supply Chain Council. Through these venues the CCAT/NCAL stays current on relevant events, builds relationships with key people, and makes its presence known.

Important too is attending relevant DoD and commercial conferences and symposia. The CCAT/NCAL and its Modeling and Simulation and Laser Application Laboratory teams attend high value defense conferences like the Defense Manufacturing Conference, the AFRL Wright Dialogues and the Turbine Engine Technology Symposium; additional outreach activities are detailed in the Project Summaries for Tasks II, III, and IV. Members of the CCAT/NCAL teams are often requested speakers at conferences relating to various aspects of aerospace technology, manufacturing, workforce, as well as related business and logistics topics.

The CCAT/NCAL has created two annual outreach events: The Annual NALI Review and the Symposium for Applications of Lasers in Aerospace (SALA). The Annual NALI Reviews summarize the progress to date that the Consortium members have made towards accomplishing the task objectives of the NALI Grant. In conjunction with the review, workshops are held to provide a deeper understanding of the technologies that have been developed by the NALI Consortium. The SALA is a forum for describing and showcasing advances in the use of lasers in manufacturing. It combines the presentation of CCAT/NCAL Laser Applications Laboratory advances with other papers and lectures on specific laser capabilities, and includes workshops. The most recent SALA event held in April 2008 marked the third year that this outreach event was completed.

Members of the CCAT/NCAL staff and our two Consortium members have also participated in a number of local events in CT, OH and PA which have helped raise awareness of the work being done.

2.2. Task II – Enhance the Application of Modeling and Simulation to Accelerate Technology Transition and Effectiveness of an Integrated Supply Chain

This task established the use of Modeling and Simulation (M&S) as the foundation for product development and total life cycle effectiveness to enhance the accelerate technology transition and effectiveness of an integrated supply chain. Aerospace systems and their design, building and in-service support are hugely complex. To effectively enhance interactions, processes and machines, modeling and simulation is needed. Through M&S, complexities of the response of the network of activities can be better understood and decisions made that reduce unanticipated negative results. The use of M&S provides the ability to reduce risk of changes while seeing potential results more clearly. Each of the NALI consortium members brought key strengths to the M&S activities to address several objectives in:

- Gas turbine engine performance modeling (led by Avetec)
- Machining modeling and process/factory modeling and optimization (led by CCAT's NCAL)
- (Supply Chain Modeling led by CTC is reported under Task IV)

2.2.1. Introduction and Scope of Avetec's M&S Efforts

The Advance Virtual Engine Test Cell (Avetec, Inc.) was established as a non-profit, public benefit research corporation in Springfield, Ohio, and is one of the three NALI consortium companies. Avetec has established a National Center for Advanced Modeling and Simulation to use advances in modeling, simulation, and advanced computing to address the research and national competitiveness needs of the aerospace industry supply chain. Working in collaboration with the NALI consortium members, Avetec addresses critical needs of the Air Force that include 1) use of modeling and simulation to support next generation propulsion and weapon system platform acquisition programs, 2) issues related to aircraft sustainment, 3) high performance computing and information system infrastructure, and 4) educational outreach to prepare the next generation work force.

Part of Avetec's NALI Phase I funding has been applied towards supporting the National Center for Aerospace Leadership and garnering support from Ohio on key goals of the initiative. Avetec supported and participated in the development of a consortium agreement that established the National Center for Aerospace Leadership with the purpose of enabling collaboration and transition of research and development efforts effectively. Phase I funding was also applied towards the support of the assembly of research teams across the aerospace industry, government, and academia. Research teams in Ohio were formed, and efforts focused on propulsion and power related goals of the consortium and critical needs of the Air Force.

Section 2.2.1 of this report summarizes Avetec's M&S role and accomplishments in the National Aerospace Leadership Initiative, including details of the work scope. Avetec completed the objectives of the Phase I work scope through the execution of a series of collaborative projects during the period of the grant. Summaries of the projects, their results, and impacts are given in

Section 2.2.1. That Section concludes with observations and a preview of efforts on follow-up phases within the NALI program.

The National Aerospace Leadership Initiative proposed work scope addressed program goals through a set of four tasks. Avetec's role within the task structure was concentrated in Task II with the purpose to enhance the application of modeling and simulation (M&S) to accelerate technology transition and effectiveness of an integrated supply chain. Task II was based on the belief that M&S is critical to the future success of the supply chain at all levels of endeavor. The Task II activity established two major areas of interest. The first applied M&S to manufacturing processes and supply chain effectiveness. The second activity applied M&S for accelerating the transition of new technologies.

Avetec approached the work by attacking a Grand Challenge problem to model and simulate a complete aircraft turbine engine. This research goal was established based on discussions with industry experts, research recommendations formulated by Air Force and Department of Energy researchers, an interest in national competitiveness and the desire to leverage the strengths in aircraft propulsion found in Ohio. To further define the approach to Task II, the work scope identified three objectives:

- Objective A: Establish a M&S activity closely teamed with the manufacturing, overhaul and repair supply chain.
- Objective B: Establish focused activities that apply M&S to accelerate the transition of new technologies, reduce acquisition cost, and increase the reliability of current systems to meet Air Force needs.
- Objective C: Establish Avetec's focus on M&S capabilities and gas turbines-Grand Challenge.

The work scope in Task II also addressed the national need for leadership in the advancement of science, technology, engineering, and mathematics (STEM) education in order to develop the next generation of America's workforce. Although Avetec's execution of Task II was closely related to all three objectives and Task II's over-arching goals, research efforts planned for Avetec were concentrated in Objective C, and focused on the advancement of propulsion technology in support of Air Force needs. The remainder of this section further describes the approach taken and rationale outlined in Objective C of Task II.

The U.S. economy and national defense are highly dependent on air vehicles. Design and development of aircraft propulsion systems is one of the most technologically complex and costly endeavors undertaken in our country. Currently, industries build prototypes of new engine component designs, test those prototypes and revise the design. This iterative approach, required to balance the many competing design and performance requirements, contributes significantly to the approximate $2 billion development cost and 7 to 10 years of development time required to bring a new turbine engine to market. Avetec undertook a program to develop advanced M&S tools that targeted the turbine engine design process and studied the reduction of physical testing using innovative applications of M&S during the development process.

In order to accomplish this, Avetec planned to establish and develop a National Center for Advanced Modeling and Simulation to house and support high performance computing and visualization equipment for use by Avetec researchers. This center was to be created in a new facility located in the NextEdge Applied Research and Technology Park under development in Springfield Ohio. Avetec also developed research plans to collaborate with government, small and large businesses in the American aerospace supply chain, and academic organizations.

Enabling technologies in M&S, high performance computing, and infrastructure development were identified for Phase I. High fidelity computational fluid dynamic simulation tool development and validation capability by a team of university, government and industry researchers was a central part of the planned work scope and was accomplished during the execution of the phase I grant. High performance computing technology development – including investigation of problems in data manipulation, locality, movement, and storage – were also targeted for research efforts. Infrastructure development and planning associated with the National Center for Advanced Modeling and Simulation were also required in the scope of the first phase of the NALI program.

In the execution of the NALI Phase I program, Avetec established a research effort that focused on the development of detailed coupled engine simulations that incorporated both computational fluid dynamic simulations and more traditional zero and one-dimensional engine modeling techniques. In addition to high fidelity modeling and simulation tool development and validation, research also investigated simulation architecture development and integration. These technology development efforts were required to support the Avetec concept of a virtual engine test cell that could be used to reduce the amount of physical testing required to bring future engines to market.

The Phase 1 work scope set the stage for collaboration with engine original equipment manufacturers, and help set those manufacturers up to validate and transition the tools toward industry adoption. The Numerical Propulsion System Simulation tool with a high fidelity toolkit was supported as a framework for full engine simulation. This work was completed in partnership with researchers from the Air Force Research Laboratories, NASA Glenn Research Center, and university researchers from the Ohio State University, the University of Cincinnati, The University of Toledo, and the University of Dayton Research Institute. Researchers working directly with Avetec also focused research efforts directed to propulsion system sustainment for U.S. Air Force. Initial planning for an engine health management system research program and supporting technologies was also completed during Phase I.

Avetec invested in the development of high performance computing technologies and other necessary planning and infrastructure development required to support the concept of a virtual engine test cell in the NextEdge Technology Park. These technologies include the initial planning for research in data intensive computing areas related to large scale data manipulation, movement, data locality, and data storage. Planning for the Center for Advanced Modeling and Simulation including a land use study was completed. Planning for high speed network connectivity to national level high performance computing infrastructure was also initiated.

The efforts completed as a result of Phase I have been instrumental in later phases of the program. As a result of these efforts Avetec has demonstrated the art of the possible for transitioning new M&S technology into the United States aerospace supply chain. Avetec also used Phase I funding to initiate successful educational outreach efforts that are critically important to the development of the next generation of the American workforce. Details of the execution of Avetec's NALI funding are described in terms of funded projects in the following section of this report.

2.2.2. Avetec M&S Project Summaries

Phase I projects encompass these primary business areas: M&S, high performance computing, and education. Specifically, these tasks are categorized as propulsion systems M&S, high performance computing research and support, educational outreach and infrastructure, program management and support.

These Phase I projects support both the development of a world-class modeling and simulation capability and the advancement of STEM programs to build the next generation workforce. The results of these efforts have impacted the advancement of propulsion technology in support of U.S. Air Force needs. The Phase I projects in each of the business areas outlined above are described in detail in the following sections.

2.2.2.1. Propulsion System Modeling and Simulation

The main Avetec program emphasis was the M&S capability for propulsion technology. These efforts foster collaboration between academia, government, and commercial resources. This initial work focused on the fundamental understanding of the critical needs, as well as the underlying technologies to enhance the capability and infrastructure that will validate the models and findings within the propulsion research area.

The initial approach – through participation with leading industry, government, and academic professionals via a discussion panel on high fidelity modeling and simulation – established the foundation for strategic planning and research guidance under the NALI program Other collaborative efforts led to the development of several models and tools that will foster the development of propulsion technology. These efforts include work done with Ohio-based universities as well as government organizations, such as NASA-Glenn Research Center (NASA-GRC) and the Air Force Research Laboratory (AFRL). The tools and models developed through these collaborations are fundamental for a complete simulation of propulsion systems.

Research efforts included the infrastructure within the collaborative environment. Establishing a common environment is important and the framework was established through the Common Collaborative Engineering Environment. Understanding this environment is essential with the development of the Engine Health Management System (EHMS).

The EHMS research helps solidify the overall approach of end-to-end integration for fleet management. This research establishes a solid foundation that integrates the common collaborative environment approach. The framework will enable the use of tools, models, and data without regard to physical location of each of the elements. Propulsion systems M&S provides the initial definition as well as tools, models, and methodologies to provide long-term engine health management, technology integration, power systems development, and eventually total fleet management.

IGTI 2006 Panel Discussion on High Fidelity Modeling and Simulation

The International Gas Turbine Institute (IGTI) TurboExpo is an annual international conference that deals exclusively with the gas turbine engine research community world wide. A committee structure is used to organize the conference and other IGTI sponsored events during the calendar year. Avetec-collaborating researchers Mark Turner at the University of Cincinnati and Steve Gorrell at the Air Force Research Laboratory Propulsion Directorate worked with the IGTI Aircraft Engine committee to organize an exciting world-class panel session at the 2006 Turbo Expo conference held in Barcelona, Spain, on May 11, 2006. The panel discussion pulled together world wide industry leaders to discuss the status and direction of high-fidelity engine simulations, which are key to Avetec's concept of the virtual engine test cell. This panel discussion was held in conjunction with Avetec's announcement of the first full-annulus (tip to tail) high-fidelity engine simulation at the 2006 Turbo Expo in Barcelona, Spain. The vision of the virtual engine test cell including technical, funding and, cultural challenges was discussed by distinguished panel members. Avetec used the results of this panel discussion for strategic planning purposes and to guide continuing research in this area under the NALI program.

The following panelists were invited to present industry perspective on the concept of high-fidelity, 3-D, time-accurate engine simulations:

- Om Sharma, Pratt & Whitney: "Pratt & Whitney Perspective on High-Fidelity Engine Simulation"

- Juan Alonso, Aerospace Design Laboratory, Stanford University: "Stanford University Perspective on High-Fidelity Engine Simulation and the Department of Energy Advanced Simulation and Computing Program"

- John Moran, Rolls-Royce, Derby: "Rolls Royce Perspective on Computational Combustion and High-Fidelity Engine Simulation"

- Steve Gorrell, Air Force Research Laboratory: "U.S. Air Force Research Laboratory Perspective on High-Fidelity Simulation"

- Charles Hirsch, Vrije University and Numeca International: "A European Perspective on High-Fidelity Engine Simulation

- Graham Holmes, GE Global Research Center: "GE Perspective on High-Fidelity Engine Simulation"

- Arun Sehra, NASA Glenn Research Center: "NASA Perspective on High-Fidelity Engine Simulation

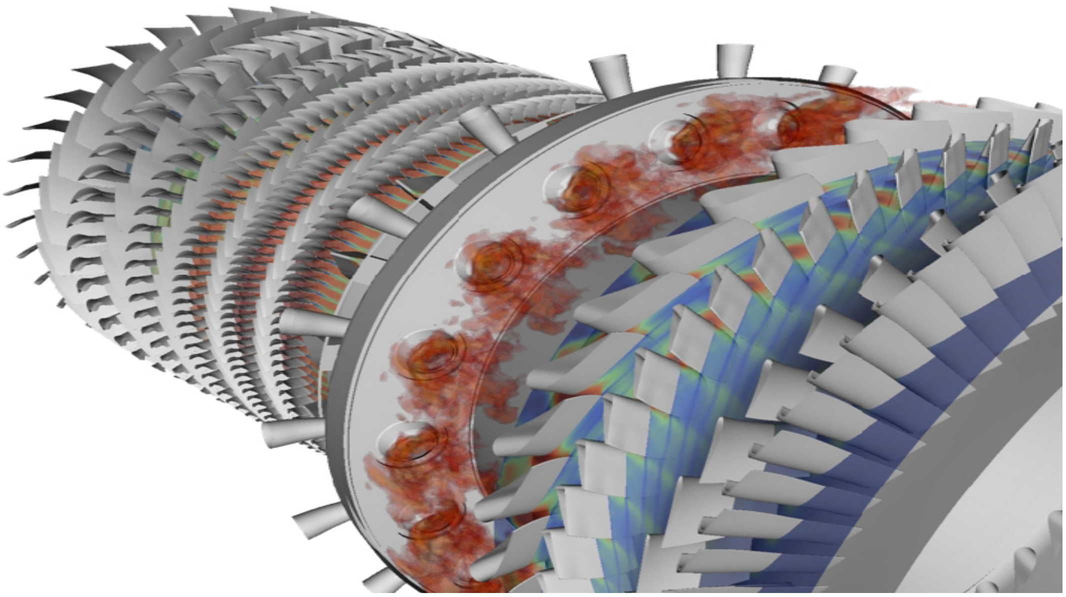

Figure 6 Stanford engine simulation

Figure 7 Virtual engine test cell concept

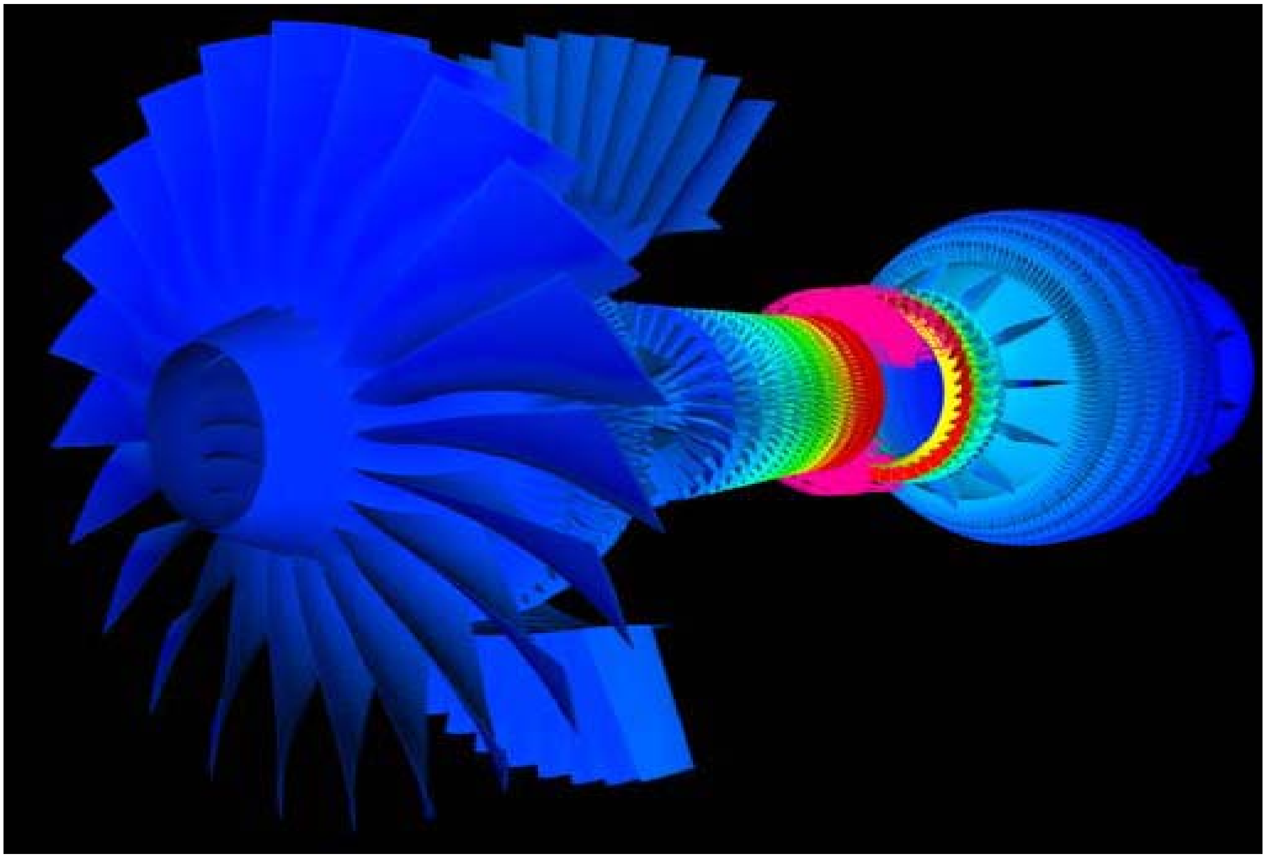

Figure 8 NASA, UC, GE, Avetec GE90 full engine simulation

Figure 9 Distinguished IGTI panel members discuss virtual engine test
Left to Right: Charles Hirsch (Vrije University), Jayant Sabnis (Pratt & Whitney), Arun Sehra (NASA),John Moran (Rolls-Royce), Graham Holmes (GE), and Juan Alonso (Stanford).

Turbo Machinery Modeling and Simulation (The Ohio State University)

The development of high fidelity simulation models for understanding flow physics in turbine engines is a critical technology for the virtual test cell concept. Validated Computational Fluid Dynamic (CFD) codes that can be used for time accurate, full annulus flow studies can be used to understand how decisions in the design of turbo-machinery affect engine performance. If a validated code can be used during the conceptual, preliminary and detailed design stages then it may be possible to reduce the number of design iterations and physical testing. Avetec employed NALI phase I funding to recruit Dr. Jen-Ping Chen, an internationally recognized scholar in CFD tool development, to join the faculty at the Ohio State University and to build research programs in CFD tool development. This section details initial work completed to build this capability.

Staffing and Building Computational Laboratory

The first task in this period was to recruit researchers and to build a computational laboratory at The Ohio State University's Department of Aerospace Engineering. A block of three offices were designated as the site of the computational lab. Eight Linux workstations and two Windows desktops were purchased and installed to form a network dedicated to Avetec research. Two layers of firewall were established to protect the system from unauthorized access. Two faculty members, two full-time researchers, six graduate students and one undergraduate student were hired under the project. Jen-Ping Chen led the team.

Multi-Block Capability

The purpose of this task was to expand TURBO code capability to allow multiple blocks on a single processor for parallel operation. A major change to the TURBO code was needed to implement this capability. The implementation is completed and is currently undergoing a series of validations. The NASA compressor Rotor 35 has been used as one of the validation cases. This case includes investigation of the rotating stall simulation that requires the calculation of the full annulus of the rotor. Since this rotor is tip critical, it is important to resolve tip clearance flow and its interaction with the main passage flow to understand the mechanism of the stall inception process. The multi-block capability permits a better load balance to include the tip grids. The full-annulus case, with tip grids included, requires a minimum total of 192 CPUs and is currently conducted on the Ohio Supercomputing (OSC) Itanium 2 Linux cluster and NASA Columbia systems.

Development of DES Turbulence Model

The current turbulence model used in TURBO is a Reynolds-Averaged Navier-Stokes (RANS) based k-ε turbulence model specially designed for turbo machinery flows. However, it has been generally recognized that RANS turbulence models work adequately for attached flows and those with shallow separations. They do not consistently predict flows with massive separations and vortical flows. Large Eddy Simulation (LES) is more suitable for separated/vortical flows away from walls, but requires a much finer grid to resolve the flow near walls. This feature makes LES very expensive for full-annulus turbo machinery simulations. The Detached-Eddy Simulation (DES) offers LES-like prediction at affordable costs. Based on a single RANS turbulence model, the DES model functions in two continuous modes: the LES sub-grid-scale (SGS) mode for flows away from walls, and the RANS mode for flows close to walls.

As a hybrid of LES and RANS, DES combines the accuracy of LES for separated and vortical flows and the reliable prediction of RANS for attached flows and those of shallow separations. Because the RANS model can use a coarser grid within the boundary layer, the overall grid size needed for the combination is generally much smaller than that of a full LES simulation. As a result, this is a more practical approach for the 3-D, unsteady simulations required in the close examination of the massive separated flow that can occur in turbo machinery.

In this period, our efforts have been focused on the following: (1) literature review on RANS, LES and DES turbulence models; (2) implementation of Smagorinsky LES model; (3) implementation of two DES models; and (4) planning for code validation.

Turbulent Flows Simulation with DES Model

To better predict the actual performance of highly loaded turbo machinery across its operation range, it is important to accurately resolve the internal turbulent flows. Besides high-resolution grids and high-order-accuracy numerical algorithms, development and implementation of accurate turbulence models is inevitable.

Time-accurate Reynolds-Averaged Navier-Stokes (RANS) simulations have been widely used for turbo machinery flow analysis. It has been generally recognized that RANS simulation (1) works adequately for attached flows; (2) does not need high-density grids to reach acceptable results for engineering applications; and (3) is not suitable for separated flows. Due to the development of vortices motion from blade-row interaction and boundary separation near surge condition, the third feature limits the RANS model application to turbo machinery.

To improve solution accuracy of the unsteady flow features inside turbo machinery, the Large Eddy Simulation (LES) is a reasonable choice. Compared to RANS models, the LES is (1) suitable for separated flows; and (2) requires high grid resolution. For wall-bounded regions, the LES needs special treatment to account for wall effects, which may degrade the LES prediction. To improve LES simulation with wall-bounded domains, high-grid resolution is needed for regions close to wall and needs more computer resources.

To obtain the LES prediction accuracy and solutions to problems with reasonable cost, the Detached-Eddy Simulation (DES) is an encouraging method. As a hybrid of LES and RANS, the DES combines the accuracy of LES for separated flows and the reliable prediction of RANS for attached flows. That is, the DES becomes RANS close to walls and switches to LES away from walls. Briefly, the DES solves a transport equation, or a set of transport equations, across the whole domain. The transport equation or equation set is the original RANS turbulence models such as the one-equation Spalart-Allmaras (SA) model or two-equation k-ω model, in which sources terms, turbulence production terms and destruction terms consist of the distance to wall to account for wall effects. For DES purpose, the distance to wall in the source terms are modified with a distance switch to activate RANS function close to walls and LES function away from walls. With such a treatment, the DES is a non-zonal model. That is, mode switching between LES and RANS is “automatic” and requires no user-specified zones. Research showed that the switch between RANS and LES is smooth and requires no user intervention. With grid refinement, DES gradually evolves to standard LES. DES can also be expanded based on two-equation RANS models (Strelets, 2001).

General Domain Interface

The goal of this task was to develop a conservative method for two arbitrary grids to pass information between each other. If successful, this will greatly simplify the task of making grids for complex problem domains. During this period we have conducted (1) literature research; (2) implementation of a simple interpolation algorithm that maps two domains of different topology; and (3) preparation to implement this algorithm in TURBO.

Heat Transfer Capability

In the short and medium term, the following plan has been adopted to provide heat transfer capability to the TURBO code:

- Incorporation of a constant wall temperature boundary condition. This capability will be expanded to allow for other types of boundary conditions such as conjugate heat transfer in the future. (Completed)
- Establishment of the confidence in the code by ensuring agreement with analytical laminar flat plate heat transfer solution. (Ongoing)
- Calculation of turbulent heat transfer solution on a flat plate using the existing turbulence models in TURBO or those planned to be implemented to establish the accuracy of the methods. (Ongoing)
- Simulation of Tech 56 turbine blade. (Ongoing)
- Development of post processing utilities for analyzing heat transfer results. (Planning)
- Use of GE TACOMA in the simulation of Tech 56 turbine. (Planning)

DUST Compressor Half-Annulus Simulation

The focus of this task was to resolve the complex vortical dynamics caused by the strong interaction of Stator 1 and Rotor 2. This interaction is thought to be the possible cause of the unresolved loss seen in several previous Computational Fluid Dynamics (CFD) simulations conducted by GE and NASA. Collaborating with the University of Cincinnati team and Tim Beach, Avetec is working to (1) generate the passage grid for the first three blade rows; Rotor 1 (R1), Stator 1 (S1), and Rotor 2 (R2); and (2) set up a case to run the half-annulus simulation of the three blade rows with use of 494 CPUs. It is planned to increase the grid resolution between S1 and R2 to resolve the details of the vortex structure.

Multiple simulations were conducted in order to validate experimental findings of the General Electric (GE) compressor in the DUST program. This initial study, which included a half annulus as well as a phase lag simulation, involved the first three blade rows of the rig: R1, S1, and R2. Upstream inlet duct geometry as well as the inlet guide vane (IGV) was ignored. The initial simulations correctly predicted the problems encountered by GE, such as reversed flow on S1 due to the close proximity of the upstream rotor as well as the trailing edge vortices generated by the interaction of the wake of S1 with the propagation upstream of the shock generated by R2.

The simulations were carried out on the Air Force Aeronautical Systems Center's Eagle Supercomputer. The axisymmetric computational domain, which included R1, S1, and R2, was generated by Turbo machinery Gridding System (TGS) which was created by Mr. Tim Beach. Inlet and exit boundary conditions were consistent across simulations. The inlet was dictated by a total condition profile, provided by the CFD solution, while the exit was held at a constant mass flow of 28.6 kg/sec.

Preprocessing of the computational domain utilized TGS and GUMBO. The computational resolution of the blades was as follows: R1 domain consisted of 202x81x78 cells, S1 and R2 domains consisted of 243x81x104 cells. Each blade allocated 4 cells both to the hub and tip gaps, where appropriate. Utilizing GUMBO, the Phase Lag simulation involved three passages for a total of 5.37 million cells divided into 21 blocks, while the half-annulus simulation involved 67 passages for a total of 126 million cells divided into 494 blocks.

The half-annulus simulation produced data that matched well with the physical experiment. Adiabatic efficiency predicted in the simulation averaged around 87% which was higher than the data calculated in the physical rig. Flow data extracted from S1 shows reversed flow near the leading edge, thought to be produced by the interaction of the wake of R1 with the tip vortex of S1. The reverse flow occurs at the tip of S1, mid-passage. Also seen on S1 were the trailing edge vortices predicted by experiment. The interaction of the trailing edge wake with the upstream propagation of the leading edge shock of R2 were thought to be the cause. More simulations will be carried out to further support this hypothesis. The lower adiabatic efficiency of the experimental rig was thought to be caused by these phenomena.

Future work on this problem will provide better insight into the causes of the discrepancies between the experimental rig with the CFD simulation. A highly unsteady full annulus simulation will be carried out. The computational domain of the inlet and exit will be artificially extended in order to prevent interaction of the propagating wake of the rotors with the inlet and exit boundary conditions. Also, to better analyze the effect that S1 and R2 has on adiabatic efficiency, the spacing between the two blades will be increased to lessen entropy generation.

URETI Turbine Simulation

The University Research Engineering Technology Institute (URETI) project is a NASA research project currently awarded to the OSU Gas Turbine Lab (GTL). A Honeywell single-stage turbine is used as the test case. Both cooled and un-cooled test data have been collected at the GTL. A joint agreement was reached for Dr. Jen-Ping Chen to conduct a TURBO simulation of this case. This test-rig is similar to the GE Tech 56 turbine stage. Due to the single-stage configuration, the time-shift mode of TURBO can be used to model the unsteady blade interaction. This allows the use of a minimum of 13 CPUs for parallel processing. The procedure learned in performing this simulation can be directly applied to the Tech 56 turbine simulation. Currently, a solution at a lower-flow-rate-than-design condition was obtained. This solution has a pressure drop much smaller than the design operation. As we tried to bring down the exit pressure we realized the flow in the turbine was choked. As a result there is a numerical difficulty to maintain the same flow rate when bringing down exit pressure. The exit boundary condition to handle this situation would have to be examined in details to overcome this difficulty.

High Fidelity Engine Simulation Research (University of Cincinnati)

Under NALI funding, The University of Cincinnati (UC) and Avetec made great progress in the M&S effort. Collaboration with The Ohio State University (OSU) allowed for complimentary efforts where UC focused on test-case set-up, visualization, post processing, and alternate codes, while OSU focused on the solver, Turbo, and a large simulation. OSU also made other efforts including cooled turbine modeling. Much of the UC effort has been documented in recent papers and thesis. A summary of the major efforts is below,

AFRL CFD Validation using BRI Rig data

The Blade Row Interaction (BRI) rig is a test rig located at the AFRL Compressor Aero Research Laboratory (CARL). The BRI rig has been used to conduct flow experiments of trans-sonic compressors to better understand how the design and configuration of jet engine compressor blades affect compressor performance. The BRI test rig uses a swirler-deswirler combination to generate wakes through a diffusion process. The objective of the test rig was to simulate an embedded transonic fan using realistic thin trailing edges in the stator vanes. The results of tests at the AFRL CARL facility produced experimental data that could be used to validate CFD simulation results.

In research conducted at the UC, a matrix of quarter annulus, time accurate CFD simulation runs for the first three blade rows of the test rig compressor were constructed. Within the test matrix, blade spacing was varied at selected stagger and clocking in order to study the physics of loss mechanisms in the flows. Figure 10 shows one example typical of the results obtained in this study. The figure shows entropy contours at a single instance in time with blue regions representing a minimum value of entropy and red representing a maximum value. Increasing entropy is related to total pressure losses and reduced efficiency across compressor rotor stages.

These kinds of phenomena are missed if grid densities are not high enough in numerical simulations; higher grid densities require significant computational resources. Simulation studies showed that losses can be controlled by appropriate selection of blade spacing. Time accurate simulations constructed as a result of this effort used high performance computing codes that were highly parallel and scalable. In some simulation runs over 900 processors were used to complete the simulations. Details of the studies have been documented in references [1, 2, and 3].

3 Stage HPC Simulation Validation Effort

One stage of a highly loaded compressor was simulated with the hub cavities using a proprietary solver. Results were included in a Master's thesis by Derek Smith [4]. This was a complimentary effort to a 3 blade row simulation ran at OSU using TURBO.

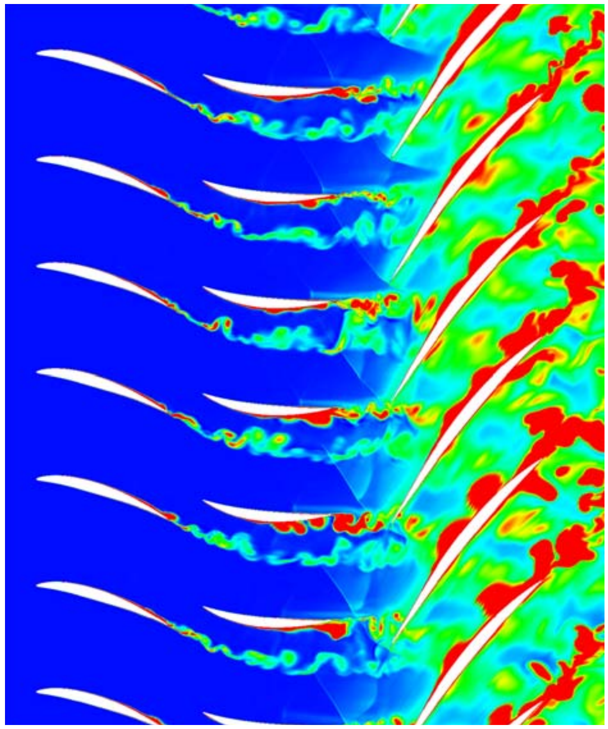

Figure 10 High fidelity simulation of blade row interaction in a transonic compressor

Code Enhancement Efforts and Grid Generation

The application of TURBO and close collaboration with Professor Chen at OSU has led to some key enhancements to TURBO as described in the TURBO section of this report.

Avetec research scientists and OSU have worked together to enhance, debug, and utilize the Turbo machinery Gridding System (TGS). A demonstration of TGS for parallel gridding was shown by Kamp et al. [5]. The work illustrated several unique aspects of the gridding system: 1) The gridding process begins with an axisymmetric view; 2) It is command driven and batch oriented so new geometries can be automatically gridded; 3) It features an interactive component interface that allows for visualization of new geometries; 4) It has been specifically designed for turbo machinery applications; and 5) It features both a serial and a parallel gridding capability for individual blade rows. An example gridding application showed that a parallel implementation of TGS, a grid for a 10 stage compressor with over 33 million grid points could be generated in less than 5 minutes of wall clock time (see Figure 11).

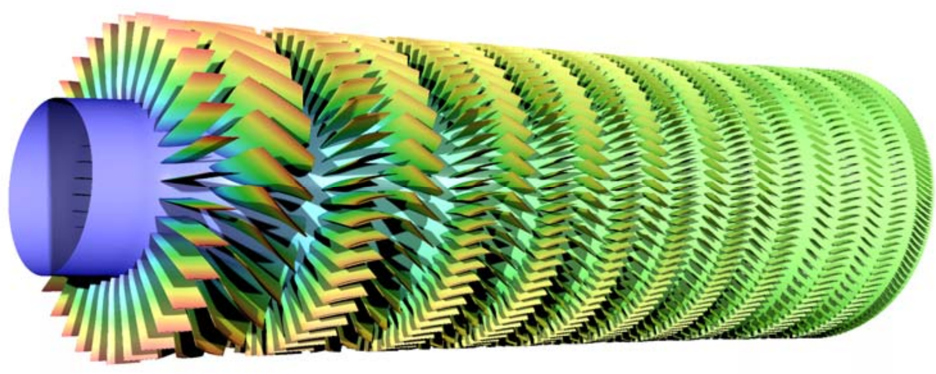

Figure 11 Ten stage compressor model with over 33 million grid points.

Post Processing and Visualization Effort

Post processing and visualization play a key role in the understanding, interpretation, and explanation of unsteady results. Research in this area completed by the University of Cincinnati team focused on the development of parallel visualization and post processing and co-processing methodologies. The post processing studies used parallel codes in jobs ranging from 23 to 88 processors in a Linux based commodity cluster. The work established high resolution visualization using both still images and animations as a standard element in flow studies and analysis at UC. Techniques for interactive visualization in real time were developed and used in the work.

The research used a parallel extension of the Visual3 system developed by Robert Haimes for parallel visualization and data analysis [6]. For post processing, all data generated as a result of flow studies must be loaded into memory distributed across the computing cluster. The work also used Start-to-Quit Ultimate Image Builder (SQUIB). SQUIB prepares data generated from the CFD studies for ray tracing by fusing time step information, camera location information, lighting locations, color scale ranges, and other data required to construct the scene for analysis. Ray tracing was accomplished using the freely available POV-Ray ray tracing code.

The visualizations were displayed in the UC Gas Turbine Simulation Laboratory (GSTL) using an integrated display composed of four 30-inch, high resolution monitors for a total resolution of 5120x 3200 pixels. The displays were driven by a graphics workstation developed specifically for this application. This work station contains 16 GB of RAM on a server motherboard with two dual-core Intel Xeon processors, and an NVidia FX 4500 x2 graphics card. The GSTL also developed a stereo visualization capability. The graphics workstation is connected to a 900 processor heterogeneous cluster with 1 GB ram per core. Figure 12 and Figure 13 show results that were rendered as a result of this work. In Figure 7, static pressure isosurfaces in a compressor stator passage were rendered using POV-Ray ray. Figure 8 shows a rendering of isosurfaces colored by the axial velocity component in a Large Eddie Simulation Study (LES) of turbulent flow. These visualization and post processing efforts have been documented by List et al. [7].

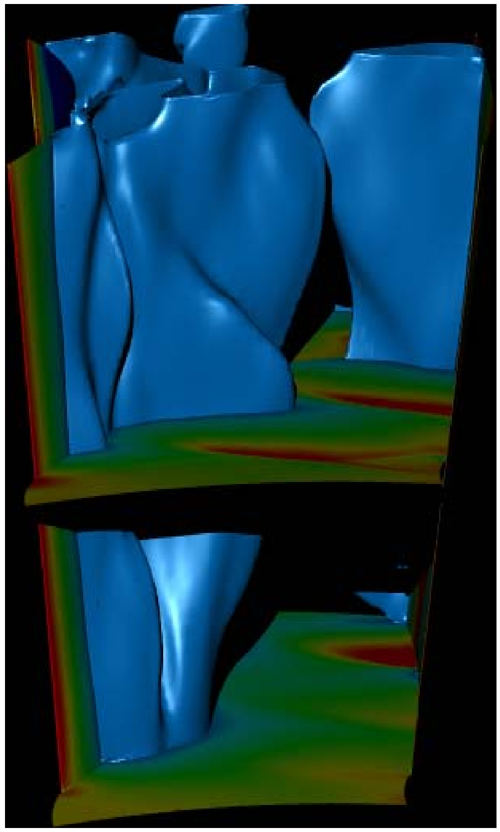

Figure 12 POV-Ray turbo-machinery fluid rendering

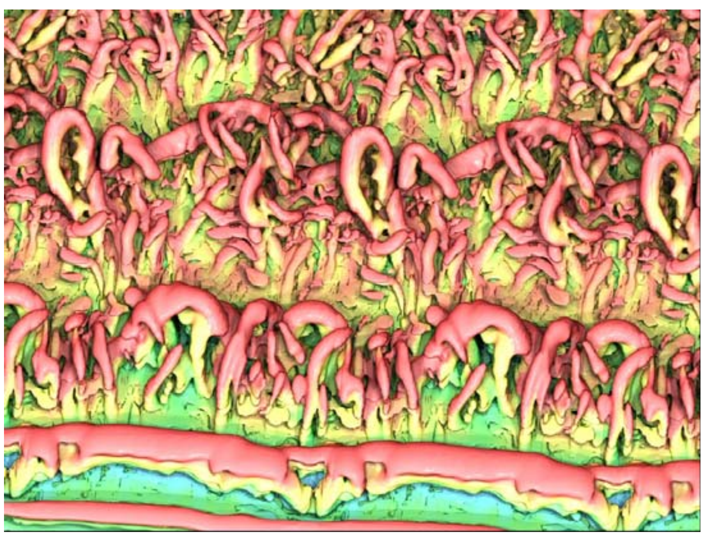

Figure 13 Rendering of turbulent flow isosurfaces

GE90 Steady State Simulation Support with NASA

The UC research team has played a key role on a collaborative team of industry, government, academia in the continuing development of a GE90 Full Engine Simulation. These researchers have worked closely with the NASA team that had the lead role in this work. Preliminary results of this effort were reported by Claus et al [8].

High Performance Computing
A key feature of the Avetec effort is High Performance Computing (HPC). Ideas for benefits of further development and application of HPC were presented by Mavriplis et al [9].

Counter-Rotating Aspirated Compressor
Industry experts contend that an understanding of unsteady flow phenomena is critical to future development of gas turbine engines. The goal of this research was to accurately model an aspirated counter-rotating fan test rig used at the Massachusetts Institute of Technology Gas Turbine Laboratory in a full annulus, high fidelity simulation model. The advantage of the counter rotating fan architecture was the elimination of stator vanes in the compression system of a jet engine which could lead to better efficiency in the turbo machinery. One of the design issues in this configuration was high incoming Mach number require that tip speed in the second rotor be reduced. As a result of lowering tip speed, a higher blade loading was required and that led to reductions in fan efficiency. Researchers explored aspiration as a means for offsetting these losses. Repeated build-test cycles in the laboratory are expensive and a validated simulation of the test rig could reduce the physical testing required to understand the impact of design choices. UC researchers developed a computational approach for further studies and validated high fidelity flow simulations against data collected in the laboratory at MIT. Simulation studies were conducted to study the expected benefit of aspiration. Comparison with data for the aspirated solution was good especially near the tip.

Measured experimental efficiency was 87.9%. Computed efficiency was 89.4%. Results of simulated aspirated and non-aspirated cases showed a 2.2% improvement in efficiency for the aspirated case. These simulation results have shed light on improving flow range and stall margin in counter rotating aspirated designs. Details of this work have been documented by Knapke and Turner [10]. This work formed the basis for a 3 blade row full annulus simulation model that will eventually be used to explore distortion.

Educational Outreach
Several of Avetec's Educational Outreach efforts were supported. A UC student assisted in Lego Robot instructional work sessions at two Springfield high schools. Several presentations on visualization were also given to high school students.

Education and Training of Students as Future Aerospace Engineers for the USA
The education of the future work force in the aerospace industry is a key element in the National Aerospace Leadership Initiative. Avetec's programmatic approach employed students at both the Undergraduate and Graduate levels to conduct research and exposed them to a world class research environment. The following UC students were trained as part of the modeling effort (Because of the proprietary or export control nature of the work, all students were U.S. citizens):

Masters Students
- Michael List, currently working at AFRL
- Derek Smith, currently working for Belcan in South Carolina to support GE Energy
- John Fussner, currently working at ASE Technologies in support of GE Aerospace
- Raymond Wagner, currently working in Gas Turbine Simulation Lab

Coop (Undergraduate) Students

- Jason Nimersheim
- Daniel Galbraith
- Michael Kamp
- Robert Knapke

Zooming Methods for Gas Turbine Engine Simulation (University of Toledo)

The general objective of the Avetec engine systems simulation program is to develop the ability to create mathematical models that are physics-based and have varying levels of fidelity. Variable fidelity is known as zooming, whereby an engineer can increase the level of resolution on a particular component in a system-level model in order to examine the physical processes within that component in greater detail. Conversely, the technique also allows results from a detailed analysis to be integrated within a system analysis performed at a lower level of detail. This is the un-zooming process.

Work at the University of Toledo (UT) was aimed specifically at developing an un-zooming strategy for coupling the three-dimensional APNASA CFD flow solutions for the GE90-94B engine with a one-dimensional Numerical Propulsion System Simulation (NPSS) model. The research addressed the following topics:

- Development of a suitable methodology to address the modeling issues inherent in the simulation due to the mismatch in fidelity between the 3-D CFD flow solution and 1-D NPSS turbine and component models
- Investigation of 1-D versus 3-D consistency issues and development of techniques to resolve these issues
- Improvement in the entropy-loss model for use in turbines and its subsequent application to compressors
- Development of a “pluggable” loss model for the NPSS 1-D turbine and compressor code

The zooming concept, first introduced by Claus et al. [11] as part of NASA’s Numerical Propulsion System Simulation program, was demonstrated in the GE90-94B full engine simulation project originally sponsored by NASA. The simulation coupled the NPSS thermodynamic cycle modeling system to a high-fidelity, full-engine model represented by a set of three-dimensional CFD component models, as shown in Figure 14. Zooming and un-zooming were used to reduce setup and run times for the 3-D analysis by connecting the cycle model to the 3-D code. Operating characteristics of the three-dimensional component models were integrated into the cycle model via partial performance maps generated automatically from the CFD flow solutions, using 1-D meanline turbo machinery programs. The cycle model used these “mini-maps” to obtain a balanced steady-state engine conditions and boundary conditions to run the 3-D simulation. Earlier contributions to the full simulation of the GE90-94B engine under the NASA program can be found in References [12, 13].

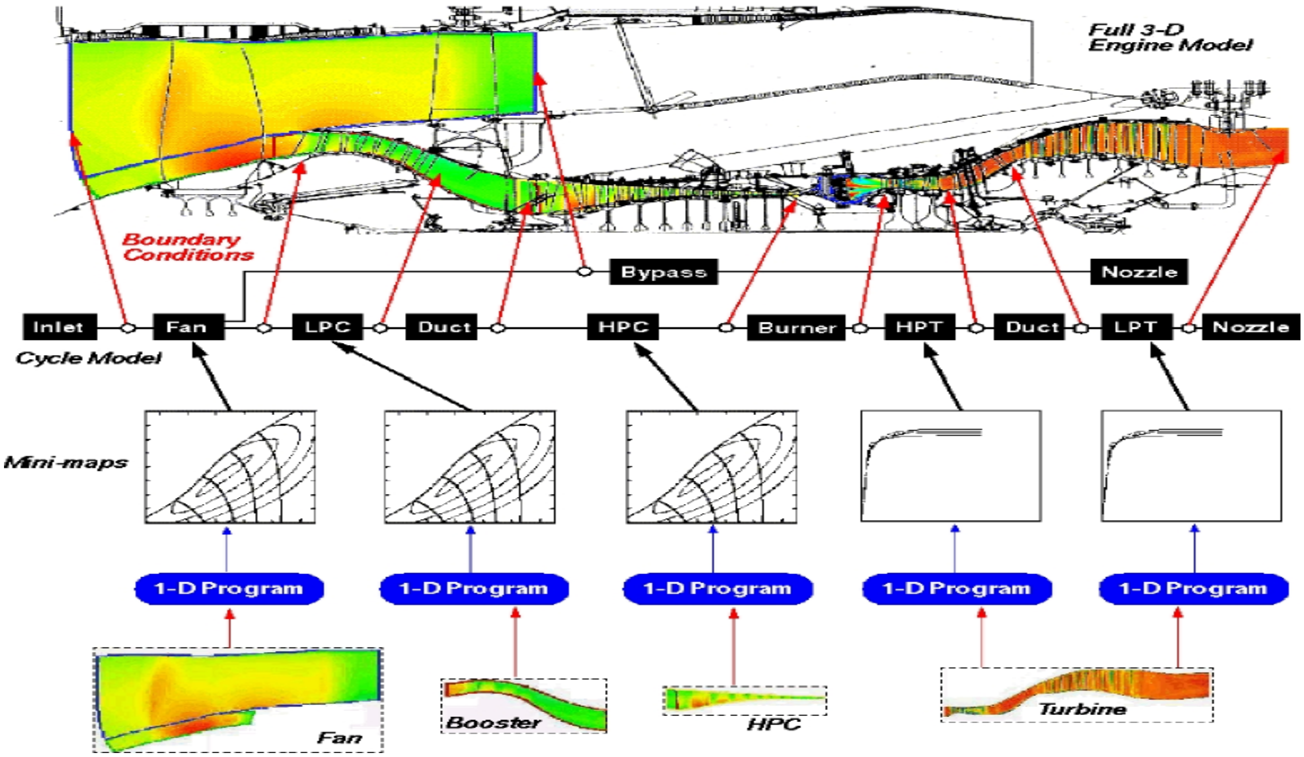

Figure 14 Coupling of 3D full engine model with 0D cycle model

From bottom to top: 3D CFD component model flow solutions are automatically used by 1D meanline NPSS codes to generate mini-maps. Maps are included in appropriate components in GE90 cycle model. Converged cycle boundary conditions are used to set boundary conditions in CFD components for coupled full-engine simulation. Top of figure shows axisymmetric plot of absolute Mach number overlaid on GE90 engine geometry.

The 3-D model was based on Turner's 3-D CFD models [14] of the fan, booster, high-pressure compressor, and combined high-pressure & low-pressure turbine (HPT & LPT). The 1-D model was the UT/UC NPSS entropy-loss based mean-line code, and the 0-D was the NPSS GE90 cycle model. During the development of the GE90 simulation, several issues came to light that were to be addressed in order to effect un-zooming. They fall into two closely related categories:

1. *Conservation.* Conservation refers to adherence to conservation laws of mass, momentum and energy. The challenge comes in connecting models which adhere to these laws to varying degrees. For example, even a well-converged 3-D CFD turbo machinery model does not conserve mass perfectly; the averaged mass flow rates at a blade row inlet & exit may not match. On the other hand, a 1-D mean-line model does conserve the mass flow rate perfectly. Moreover, these differences complicate the other conservation equations, as they include mass flows.

2. *Consistency.* Many examples of consistency occur in thermodynamics. Although the thermodynamic laws are well-known and consistent, different thermodynamics models will have different implementations which may produce different answers. This can lead to situations where equations in one model are satisfied perfectly, but are not perfectly satisfied in others.

This raises many questions, such as "Which model is correct?", "Will a single approach work for all cases?", and "Are problems caused by the zooming or un-zooming techniques?"

This effort focused on the continuing development of a comprehensive un-zooming methodology between the GE90 3D APNASA CFD data and a 1-D mean-line blade row model. The remainder of this report describes the development of the 1D NPSS mean-line compressor and turbine codes used to support *un-zooming* in the Avetec GE90 full-engine simulation. A discussion of the issues related to conservation and consistency between models is presented in the context of the un-zooming process between the APNASA 3D CFD data and the NPSS 1D mean-line compressor and turbine models.

A method for un-zooming between the compressor and turbine components of a full 3-D CFD gas turbine engine simulation and 1-D NPSS blade row model has been developed. Simulation techniques are described to extract data automatically from the circumferentially-averaged CFD flow solutions, auxiliary bleed & leakage source data and to generate input for the 1-D blade row model. This has been demonstrated for the GE90-94B engine.

Two main issues relating to conservation of the governing laws and consistency between the 3-D and 1-D models have been addressed and several approaches to satisfying the constraints of the problem were examined. After investigating the different options, it was decided to include "delta terms" in the governing mass, energy and angular momentum equations to account for the lack of conservation in the 3-D CFD flow solutions. These terms, were generally small and allowed the 1-D model to be consistent with the circumferentially-averaged 3-D values at the blade row leading and trailing edges. The seal leakage models were removed, making the 1-D model more consistent with the workings of the 3-D APNASA turbine and compressor models.

The original intention was to make use of our entropy-loss model for both the turbine and compressor 1-D components. A big advantage of the entropy-loss model was that all of the input data needed for the model could be obtained for the averaged CFD flow solutions, making it possible to fully automate the simulation process. The entropy-loss model had previously been validated against GE Energy Efficient Engine (EEE) HPT and LPT component test rig data and appeared to work well for the GE90-94B HPT and LPT. However, when applied to the GE90 HPC, problems arose which were apparently masked by the larger pressure gradients in the turbine. After considerable effort to resolve these issues, it was decided that more research would be needed.

As an alternative, a pluggable loss model framework was developed for the 1-D NPSS code which allows different loss models to be "plugged" into the model. For the turbine, the Axial Off-Design (AXOD) loss model was adopted. The Blade Row Stack (BRSTK) loss model was chosen for the compressor. These were used to generate performance map curves from the sea-level take-off GE90-94B APNASA flow solution. Fortunately this point is near the component design points, allowing the 1-D loss model input parameters to be determined automatically. Due to the proprietary nature of the GE90-94B data, exact comparisons could not be made with the numerical results for the NPSS 1-D HPC & HPT simulations. However, the results were qualitatively correct.

The un-zooming strategy presented here was simple and flexible. The approach was based only on conservation laws and a control volume. Further work is needed to determine how to generate the necessary input parameters to utilize the AXOD and BRSTK NASA codes for engine design at off-design points automatically. Alternatively the entropy-loss model can be used directly for the CFD flow solutions, but only after resolving some of the current issues. Finally, additional consistency issues, such as the differences in thermodynamics, must be addressed. In the present work, both NPSS and APNASA implement their own thermodynamic relationships. NPSS provides a mechanism to change the thermodynamic routines used by NPSS elements at run-time. One solution is to develop an APNASA thermodynamics package for use in NPSS to make the models more consistent.

Inlet/Fan Aeromechanical Simulation (NASA Glenn Research Center)

The Inlet/Fan aeromechanical simulation project involved work in collaboration with government researchers at NASA Glenn Research Center and industry researchers at Honeywell. The objective of this project was to validate CFD tools in a simulation that investigated simulation across the traditional inlet/compression system boundary. Traditionally, the inlet portion of the simulation is owned by airframe prime contractors and the compression system portion is owned by engine companies. This project involved the integration of inlet and engine components. It is further distinguished in its consideration of the mechanical response of fan blades due to pressure distortions that occur at the face of the fan. The remainder of this section was taken with permission from the executive summary of a final report for the project.

"The goal of the Integrated Inlet/Fan Simulation (IISim) program was to validate a CFD modeling tool and develop best practices for modeling fan aero-elastic characteristics due to low engine order inlet distortion and fan flutter in the presence of IGVs. Once developed, this program would provide a model for validation and predictive methods to predict future inlet/fan configurations. It would reduce the amount of distortion testing that is required and provide a key step toward developing capability for quantitative predictions of inlet distortion for commercial fans. Due to reduced funding within the program, the program was de-scoped by eliminating the fan flutter validation effort and reducing the fan forced response effort.

The present program was a follow-on effort to the Versatile Active Integrated Inlet/Fan for Performance & Durability (VAIIPR) program. The VAIIPR program was sponsored by the U.S. Air Force and was conducted by Lockheed Martin with the assistance of Honeywell. This testing was performed in the Compressor Research Facility (CRF) at Wright-Patterson Air Force Base. It provided an opportunity to collect data on the impact of inflow distortion on fan performance and mechanical response. The data acquired during the VAIIPR program was to be used under the current effort for validation of analytical and predictive tools.

The first objective under the current program was to extract and reduce the data from the VAIIPR program and then select the data sets best suited for the validation effort. During the data reduction and review process, issues with several test data tapes were encountered. A small portion of the tapes were not readable. Although a reduction in funding and scope resulted in not needing the flutter data for a computational fluid dynamics (CFD) correlation, some of the Kulite data from flutter testing was not recoverable. The recoverable data was reduced and provided good quality and repeatable data for the remaining de-scoped forced response analysis and mistuning analysis. Measured data showed significant dependence of blade response on rod orientation.

CFD analysis provided several important conclusions from the study. The effort showed that high fidelity full-annulus multi-row analysis is feasible within a reasonable time provided massively parallel compute architecture is available. The effort also showed that although the compute time is reasonable, data and resource management required significant effort and time.

Good correlation was found for the performance quantities between the multi-stage analysis results and measured data and, the full-annulus and phase-lagged analyses were found to compare well with full-annulus multi-stage analysis However, the unsteady pressures showed a significant difference. This difference was attributed to the difference in treatment of inlet boundary distortion to prescribe the inlet condition in absence of other measured conditions at the inlet, assumptions were made to the nature of static pressure and axial velocity distribution at the inlet. Full-annulus, multi-stage analysis assumed the static pressure distribution to be uniform at the inlet where as the rotor-only phase-lagged analysis assumed axial velocity distribution to be uniform at the inlet. The difference in assumption of inlet condition was attributed to the difference in calculated unsteady pressure between the two analyses. It should be noted that neither assumption may be accurate given the distortion produced by the upstream inlet duct.

Forced response analysis was performed for the two rod orientations using unsteady pressures from full-annulus multi-stage and rotor-only phase-lagged analyses. A fair to poor comparison with data was seen for both analysis methods. For the 0 to 180 degree configuration, both analyses predicted response within a reasonable error range of 50 percent. However, for the 90 to 270 degree rod orientation, neither analysis method captured the response characteristics. Both methods predicted a decrease in response from the 0 to 180 degree rod orientation, whereas the measured response more than doubled. Review of measured data and analyses performed suggested a lack of information of flow field data at the aerodynamic interface plane (AIP). The study identified knowledge of static field distortion to be important for accurate calculation of blade response. Impact of the Inlet Guide Vane (IGV) row was also found to be small on the overall blade steady and unsteady loading.

The VAIIPR program measured blade response using light probe data. This data set provides an excellent tool for validating the mistuning analysis tool. Mistuning in bladed disks could cause blade-to-blade response variation by as much as 3 to 5 times. Under the current effort a mistuned model for the VAIIPR fan rotor was developed using finite element analysis (FEA) tuned Eigen analysis and measured blade frequencies. The light probe data collected during testing was used to validate the developed mistune model of the VAIIPR fan rotor. Excellent correlation was obtained between blade-to-blade response variations for the developed mistuned blade model and measured light probe data. Overall rotor mistuning is low for VAIIPR fan rotor so blade to blade response differences were found to be minor with an average rotor response of +/-15 percent.

Based on the lessons learned during this program, the following four areas were recommended for future work:

1. Simulate the presence of inlet secondary flows and validate TURBO for fan performance calculations.
2. Perform forced response analysis with calculated inlet secondary flow field and validate the response analysis.
3. Develop pre and post processors for TURBO to automate the process, especially for full-annulus analyses.
4. Post process on a parallel architecture due to the very large amounts of data that is generated.

Thermal Management Tool Development (UDRI)

The success of future aircraft and missions depends not only on the availability of an effective thermal management system but also on development of a method to model and design it with sufficient fidelity. In many air vehicles, fuel is used as a heat sink and vehicle thermal management has suffered as engines have become more fuel efficient and therefore require a fuel flow rate which often is too low for the fuel to absorb all system heat loads. These loads come from environmental controls, hydraulics, and electrical generators in addition to waste heat developed by pumping systems and in some situations aerodynamic heating. Increasing the fuel flow rate allows for the fuel to sink these loads. However, fuel flow in excess of combustor need must be diverted back to the fuel tanks, which causes the tank temperature to increase. Because missions are requiring increasingly higher speeds and longer times on station, there is no adequate method to cool this fuel, so the thermal heat sink capacity of the remaining fuel is decreased. Current fuel specifications list a temperature limit beyond which deposition can occur (on engine parts as well as in heat exchanger passageways), leading to maintenance and operability problems. Therefore, system design is critical to the success of planned missions and the corresponding architectures must be taken into account in initial design stages.

Modelogics' Model Engineer (ME) is a thermal modeling and analysis toolkit, based on Microsoft Visual Basic 6's (VB6) environment architecture. It was deemed essential to migrate Model Engineer from VB6 to Simulink because Microsoft no longer supports this platform and many prime military and industrial contractors are now modeling in the MathWorks Matlab/ Simulink environment. Universal Technology Corporation (UTC) was included in the project to assist Modelogics in the translation effort.

To date, much of the research in full-engine simulation has been focused on the GE90, developed by GEAE. Creating a full 3-D turbine engine simulation requires high performance computing and parallel processing resources. Parallel computing involves dividing a problem into multiple programs that can be solved on a cluster of processors simultaneously, reducing the overall time it takes to solve the entire problem. Avetec estimates that it will require dedicated access to thousands of processors. To be compliant with the above constraint, Model Engineer could no longer use its vast array of ActiveX components and Windows based architecture, requiring some creative development as the tool was ported from VB6 to Simulink.

UTC experimented with several translation methods, provided opinion and insight as to project direction, and assisted in the migration of software to translate a fully viable ME into Simulink for use in future Avetec and Air Force modeling endeavors.

Four tasks were defined as a working outline for the project to convert the legacy Microsoft Visual Basic 6 (VB6) based Model Engineer (ME) thermal modeling toolkit into the Matlab/Simulink environment:

1. Review the basic ME library objects for coding/run-time errors and recommend what modifications need to be accomplished to ensure proper component execution within the Matlab environment.
2. Translate/migrate models from VB6 to Simulink, identified as the bulk of the project.
3. Integrate with the National Aeronautics and Space Administration (NASA) Numerical Propulsion System Simulation (NPSS) software.
4. Develop a time-based modeling capability; transient capability;

UTC performed these tasks in the following manner:

1. Reviewed the basic ME library objects for coding/run time errors, recommended modifications to ensure proper component execution within Matlab and assisted in their implementation.
2. Assisted in formulating the "wrappers" required by the legacy FORTRAN ME objects, tested the wrapped Simulink component models and assisted in the conversion of legacy VB6 based ME models to Simulink. UTC also assisted in building graphical user interfaces (GUIs) for a variety of ME Simulink objects and built test models in Simulink in order to test operability of new components.
3. Researched the user requirements for NASA's NPSS and gained rudimentary understanding of the tool.
4. Helped identify those components needing transient (time-based) capability and tested newly developed transient component models.

UTC further supported Modelogics by testing the ME/Matlab environment and provided recommendations for improvements.

At the beginning of the effort, there was a great apprehension regarding the success of the project because a clear direction of the translation process was still evolving. Modelogics delegated tasks early in order to examine as many solutions as possible. The division of labor was based on requirements of the overall task as well as the experience level of each team member. UTC was tasked with making some workable Simulink component models and assessing their performance and feasibility. UTC helped investigate a number of translation methods designed to speed migration as well as keep the new component models close to the Matlab/Simulink environment.

Modelogics sought to keep their legacy FORTRAN objects intact by having Math Works write a C-source wrapper S-function to create Simulink objects from existing FORTRAN source code. A method to translate VB6 coded models into Simulink was explored by UTC using native Matlab functionality; thus preserving a more pure application environment. This yielded impressive differences between the execution times from wrapped objects and Simulink block objects. By using several translation methods, full functionality and a detailed robust nature was preserved in the Simulink model blockset. Once a template was created, it was straightforward to translate other models.

A more difficult objective was dealing with the data ME uses in its components, which consists of a collection of map files in Microsoft Excel format. UTC again stressed a need to retain native Matlab conventions and even rewrote a number of ME maps into Matlab .MAT format. A script to access ME maps as they existed prior to this project was selected as the means of data acquisition. Modelogics had already formulated the method in which the toolbox is made available to a user (the locations of files and data required for models to operate). Thus the installation kit is similar to their current VB6 package and must be executed by MathWorks within the Matlab/Simulink environment prior to first use. In other words, the Simulink modeler requires nothing special to use ME and functions with any other library of components.

Evidence from experimentation suggests that code wrapped as Simulink models and those model blocks using applications outside of Matlab will result in run time penalties during execution. Their magnitudes will be revealed only when ME components are linked to other Simulink block models.

The ME toolkit in Simulink now provides an excellent thermal modeling tool with Matlab capabilities for analyzing complex thermal design architectures at both the component and vehicle level. ME not only functions better than the legacy VB6 version but makes it easier to set up a model. This permits interaction with other Simulink block set models and will still enable the user to handle and access data in an efficient manner.

Universal Technology Corporation's role in this assignment ended prior to the overall project deadline of March 1, 2007. Therefore, the Modelogics Model Engineer Simulink toolkit had not been completed as of the deadline of this report. However, the current results provide a good indication of the future outcome.

Universal Technology Corporation recommended the following action items for follow-up work:

1. Rewrite Model Engineer Help File system and Users Manual for better user access. Effective & efficient application depends on good documentation.
2. Add transient capability to the source code so that component models can benefit from the Simulink fidelity. While discrete time modeling can closely resemble continuous systems, what occurs between states often is of critical importance. Take advantage of the environment by providing a user full transient capability.
3. Develop generic system level models for component level trade studies. There are far more component designers than system architects.
4. Use the toolkit to model some very specific vehicle-level architectures for analysis of current real-world thermal problems, specifically on the F-22 fighter, where no current thermal management model exists.
5. Update and maintain the toolkit corresponding to each new Matlab/Simulink version release.

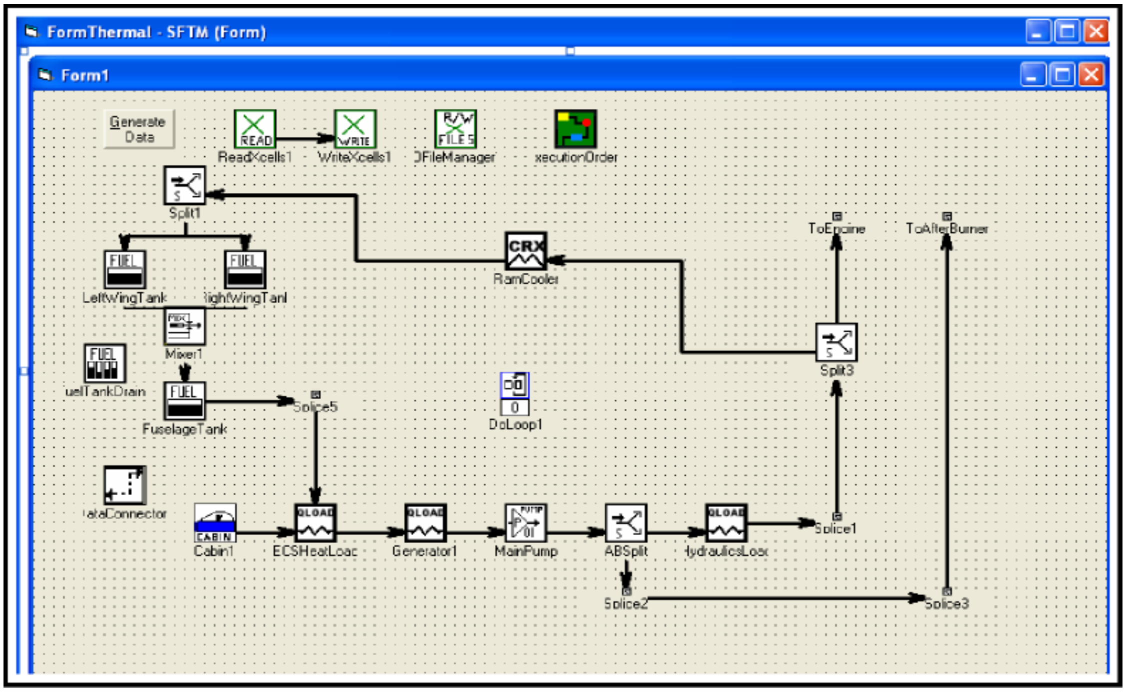

Figure 15 Typical simple thermal management system model

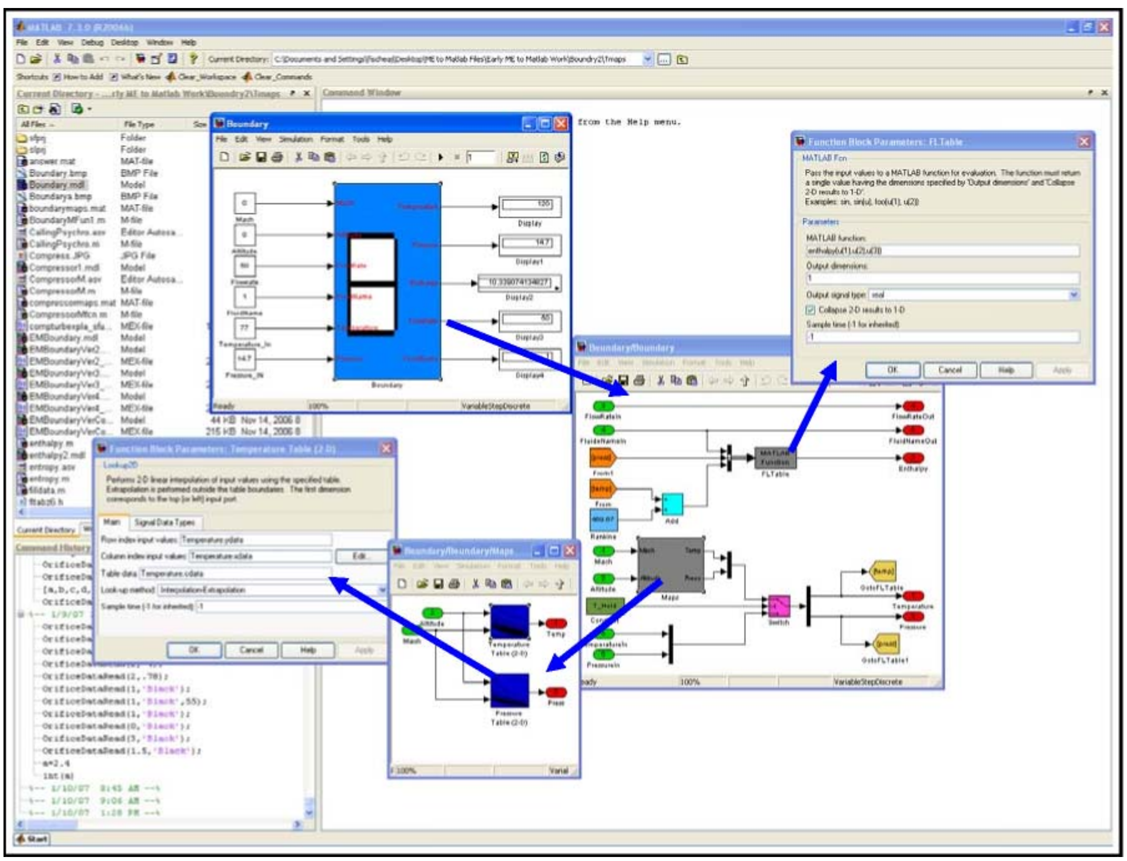

Figure 16 Model Engineer/Simulink boundary component

Collaborative Environment (UDRI)

The Common Collaborative Engineering Environment (C2E2) is the integration of the tools and data into a single work space for research, development, and engineering support. With the world-wide dispersal of resources (including people, data, and tools), it is essential to enable collaboration for the development of complex systems through a common environment. This allows leveraging resources without the constraints of geographical location. In this effort, the preliminary research showed how this type of environment impacts the simulation and modeling efforts for aircraft engines.

In the Common Analysis Environment (CAE), exploration of the commercial products provided the infrastructure and design of possible test bed structures. This allows an integrated, collaborative, or stand-alone development environment through several products including MatLab Simulink, iSight and ModelCenter. It is important to tailor these tools to the working environment within the organization. Most of these tools allow access through a PC-based interface. It is also important to keep all developed tools compatible with the common analysis environment by creating front and back end utilities/applications to manage the execution of each tool as well as its part in the overall data flow.

The Common Work Environment (CWE) established the infrastructure for data acquisition and a repository which enables collaboration between disparate and non-collocated resources. The collaborative work environment provides access to a common workspace and data repository. As with the CAE, projects must be mapped to assure the identification of all participants in a workgroup. We explored the integration of computational tools into the appropriate workspace of the host facilities.

The data repository allows project teams access to all necessary files, applications, and data resources that are specific to their research projects. The primary features of this framework are data, files, and application storage and sharing. This allows team members the ability to disseminate information and collaborate via the internet using virtual project rooms. Navigational aides, such as virtual corridors within the project rooms, allow users to navigate among project rooms to which they are authorized. Authorized users are able to share, store, upload, and download data and applications.

Using the C2E2 environment as a framework to support the overall M&S objectives is essential. These tasks include Engine Health Management Systems (EHMS), Data Storage and Warehousing, and Data Mining. These are also the essential components to the overall EHMS discussed later in this report.

EHMS Support: A survey and literature review was conducted for past and current efforts in Engine Health Management through industry. This included the research presented at several conferences, academic courses, and journal articles. These references were collected and stored in a common work space as a resource and background material. Along with this, an annotated bibliography framework was established. This framework allows access to information such as abstract, reference annotation, key words, notes, and other pertinent information contained within the article or material.

The initial work breakdown structure (WBS) was established for the program. The WBS established the preliminary determination of tasks, manpower, and time required to complete the overall objectives of EHMS. The WBS also incorporated the integrated system which includes the data storage and data mining capabilities. This plan is the foundation of the common collaborative environment. The overall EHMS architecture has a notional design which includes technologies that are being developed or are in place to allow incorporation of the overall vision and capabilities.

***Data Storage and Warehousing*:** Research was conducted on methodologies of mass data storage and warehousing. This included visiting the Teradata training facilities to assess the capabilities available throughout industry. The meeting with Teradata fostered the requirements needed for the internal system for Avetec. This included the system architecture, capabilities, and design. It is important to understand the capabilities of the industry leaders, how they impact the work that is being done in the research environment, and if there are any overlapping areas that would allow for collaboration.

Teradata's main focus was on the retail industry. Teradata indicated that they had technical research capabilities. During the visit, this was not shown nor did they explain in any detail what type of functionality existed. It was deduced that they did have the ability to perform technical research and data exploration but it was not a central focus of their operations. This is an area which can be explored as both a research opportunity and eventually a business function or service that can be offered. The hardware system offered has helped establish a benchmark for the overall integrated environment, specifically for the storage capability and the ability to increase storage space. The system architecture allows for growth in the future without investing in the entire system upfront. This will allow the system to grow as the capabilities and needs increase in the future.

It is apparent that the Teradata business model for data storage and warehousing (as well as mining) can be transitioned into different market places. However, the usage or return on investment must be taken into consideration while venturing in this direction.

***Data Mining*:** A review of data mining techniques, theories, and implementations was conducted. In the review, a presentation of these methods and implementations were described. Reference to this material is essential when designing the strategy for implementation of the knowledge discovery phase of the common collaborative environment. As stated previously, most system implementations are based on the commercial sales, as well as consumer buying/spending habits. This implementation has been utilized to optimize sales or discover fraud. By studying these implementations, research can be leveraged from the knowledge gained as well as explore the possible implantation algorithms that will be better suited in the technical engineering environment.

Overall C2E2: The work within the EHMS, Data Storage and Warehousing, and Data Mining are integral parts of the overall C2E2 system. The goal, thus far, is to understand the current status of the industry as well as defining the capabilities and architecture that is required to take on such an endeavor. These components are a beginning for the overall C2E2 and will allow the tool integration and operation in the development of aircraft models.

Turbine Engine Health Management Studies

The U.S. Air Force has a pressing need for EHMS solutions. Currently aircraft maintenance costs in both time and money consume a large portion of the Air Force's budget. To address this problem Avetec initiated background research on how modeling and simulation technologies can be applied to EHMS for the purpose of managing and maintaining fleet engines within the Air Force.

Typical maintenance systems for aircraft hours are based on total accumulated cycles. This approach to maintenance is overly conservative and does not take into account the operating environment of individual engines. Condition based maintenances systems of the future will reduce life cycle costs by making maintenance decisions based on usage. The goal of this research initiative was to provide the ground work for the development of a test bed for prototyping and testing future engine health management systems. This virtual engine test environment can then be used to prototype and study conditioned based maintenance principles. The savings that result from an efficient EHMS for the military can also have a tremendous impact on the commercial airline industry and the aviation industry as a whole. Our research is directed toward Air Force needs. However, we also motivate the work based on commercial applications. The remainder of this section describes our motivation and vision for an engine health management system that was developed during the NALI phase I effort. The vision leverages related modeling and simulation work and physics based virtual testing and design work in other areas of the research programs to attack U.S. Air Force sustainment objectives.

The world's airlines spend nearly $40 billion annually on aircraft maintenance [17, 18]. This represents approximately 20% of total operating costs and is the third highest expense after fuel and labor [19, 20]. Furthermore, estimates forecast that maintenance costs will rise approximately 5% annually through 2009. For military combat aircraft, engine maintenance alone can take up to 60% of their total maintenance budget [21]. Historically, commercial and military aircraft maintenance cycles have been based on fixed operating hours or elapsed time between cycles. This "brute force" approach has a high price tag, not only in terms of direct costs associated with replacing parts that may still have remaining useful life, but also the indirect costs of operational downtimes. For the military this could mean the inability to meet critical mission objectives at the national security level.

An interesting aspect of the commercial engine maintenance process is that nearly 50% of scheduled maintenance inspections turn up non-routine required repairs [22]. By definition, these non-routine repairs are unexpected, and they are inherently very expensive in terms of labor and loss of operational use. Furthermore, during downtimes, aircraft technicians spend up to 50% or more time on administrative functions. [23]

Further studies have shown that replacement costs can comprise up to 70% of the maintenance bill, but every dollar shifted from replacement to repair can represent a 50% savings. Even a modest shift of 25% represents an annual savings of $4 to $7 billion to the world's airlines. It is expected that military maintenance processes experience similar problems.

Clearly, scheduled downtimes take aircraft from the active inventory along with all the direct and indirect costs that action produces. Besides the maintenance cost issues noted above, post 9/11 cost increases have further forced commercial airlines to invest in a multitude of initiatives seeking to improve all operational processes including maintenance – demonstrating their readiness to accept a cultural change in how engine maintenance is performed.

Although some efficiency can be achieved through better process management, it is only natural to seek improvements through technological advancements. However, further refinement is needed in order to see what technology is available or needs to be developed to meet the aircraft industry's requirements.

From the discussion above, it's clear that a great reduction in maintenance costs can be achieved if the fundamental maintenance process evolves from a time-based maintenance schedule to a condition-based maintenance schedule, where maintenance is performed only when necessary.

Making this paradigm shift requires the development of a comprehensive engine health management system (EHMS) that covers the entire life cycle of the engine system and components and is able to feed back into the design process for the next generation system and components. If successfully developed, the EHMS will reduce costs and increase levels of maintenance predictability and productivity, customer satisfaction and mission availability. Furthermore, the EHMS will provide better information management leading to improved decision making both as a process and as a deliverable.

The next issue to be addressed is what technologies will define the EHMS. Shifting from time-based to condition-based management requires developing new sets of data collection and analysis tools. For example, transitioning from replacing parts to repairing parts requires identifying component wear and tear prior to failure. Therefore, material models based both on manufacturing processes as well as operational stresses are needed. In other words, sophisticated diagnostic and prognostic capabilities must be developed at the component and system levels.

Subsequently, these and other EHMS processes will require handling data at tera (trillion) and even peta (quadrillion) levels of data, and be able to transport that data to remote servers, computers, and end users at very high data transport rates. Related to these EHMS processes are new turbine engine physics models that cover thermal, fluid flow, vibration, and other pertinent processes. However, for this report we will concentrate only on the operational and manufacturing data collection and analysis processes. APNASA

A comprehensive EHMS must have two features. First, it must be able to identify and accumulate enormous amounts of data. Second, it must take the data and process it into useful information. These two features are further broken down into four major subgroups: data warehousing, data mining, data analysis, and data visualization as shown in Figure 17.

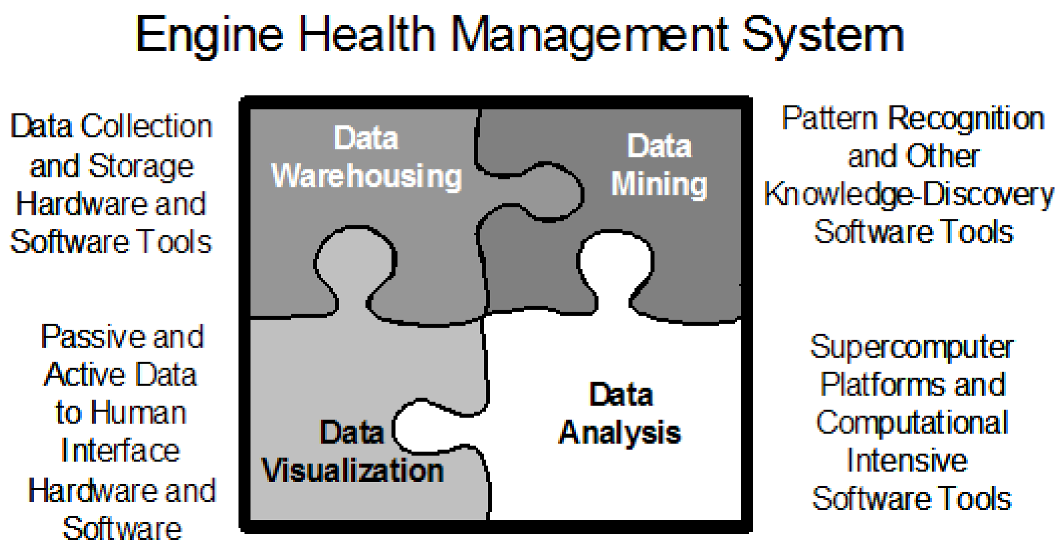

Figure 17 The EHMS includes four major components

Data Collection

Over the years, the aviation industry has invested heavily to accumulate tremendous amounts of engine performance and maintenance data. For instance, the Air Force collects some level of engine data and stores it in various established data warehouses. However, what specific data is being collected and how it is being used (if at all) is not well known. The Air Force is probably not unique in this aspect since collecting data is always inherently easier than using the data.

The first part of any data collection effort has to be a discovery phase establishing the type of data being collected (or not collected) by the customer and how this data is being used. If the data being collected is comprehensive, then improving EHM will become a problem of information management. But if the data is not comprehensive, then processes for gathering the correct data will also need to be established.

An EHMS system has to have the ability to track components throughout their individual life cycles through the use of data warehousing and data mining.

It will have the ability to:

1. Track component manufacturing data
2. Record component testing results from manufacturing production tests through installation tests
3. Monitor component and system operational performance in real time
4. Provide operational history tracking
5. Predict component and/or system failures
6. Provide component analysis at the point when a component is removed from service
7. Tailor data output to specific user needs (i.e. designers, repair technicians, logisticians, etc.)

8. Provide feedback into the design process to improve the next generation component and system

Avetec's EHMS program relies on a data collection interface similar to that under development by collaborating partner, Scientific Monitoring Inc. The System Integration and Design Assurance Laboratory (SIDAL) tool can be used to download critical engine data. Three SIDAL architectural variants were envisioned: 1) an expandable desk top unit, 2) a rack-mountable unit, and 3) a portable device called pSIDAL. Figure 18 shows the desk top and rack mounted units. In each case firmware for the device can be coded in a modern graphical programming language which makes the devices easily reconfigured and adapted for new applications.

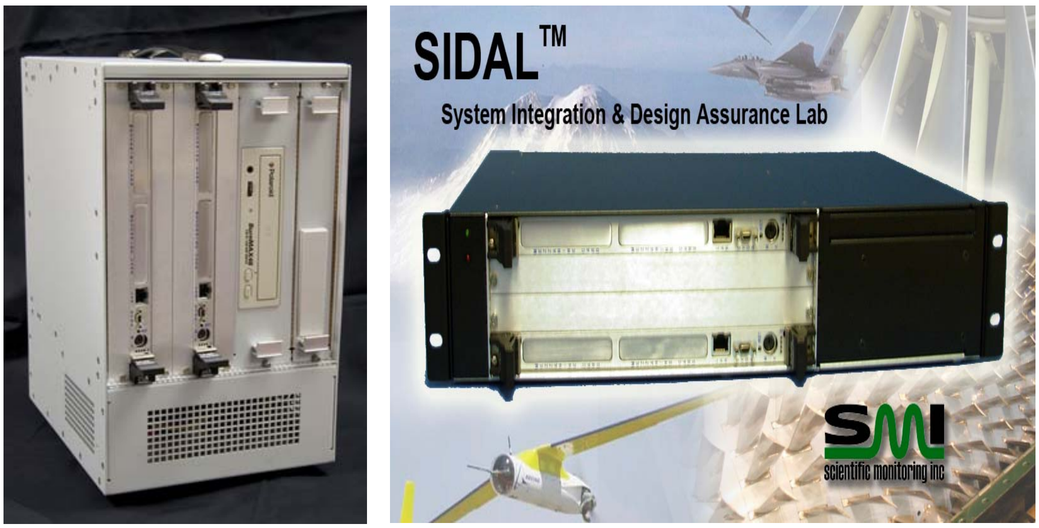

Figure 18 Desk top (left) and rack mounted (above) SIDAL units

Appropriately configured portable SIDAL units will be used at the flight line to download and transform recorded engine performance data from the aircraft engine control unit following the completion of missions. This operation provides the link between the on-board health monitoring system and the data warehouse.

Data Warehousing

Data collected through the SIDAL tool will be housed in Avetec's EHMS data warehouse (EHMS/DW). The EHMS/DW will be based on Teradata or similar technology and will serve as a repository for the engine production, test, operation, performance, and inspection data. In addition, data structures for engine critical component life modeling and manufacturing process data will augment the other data sets to provide a complete picture for life-usage tracking of individual engines in service.

The Teradata Database is an open system, compliant with ANSI standards. It is currently available on UNIX MP-RAS, Windows 2000, and Linux operating systems. The Teradata server accommodates concurrent multiple client applications inquiries. The client platforms can access the database through a TCP-IP connection or across an IBM mainframe channel connection. The ability to manage large amounts of data is accomplished using the concept of parallelism, wherein many individual processors perform smaller tasks concurrently to accomplish an operation against a huge repository of data.

The significant Teradata features are:

1. Single data store for applications
2. Linear Scalability
3. Unconditional parallelism (parallel architecture)
4. Ability to model the business
5. Mature parallel-aware Optimizer (handles multiple complex queries, multiple joins per query and unlimited ad-hoc processing)

The initial data warehouse concept included three Teradata 5400H nodes providing up to 6 Terabytes of data storage and management. The Teradata 5400H was chosen due to its unparalleled linear scalability of up to 1,024 nodes corresponding to petabytes (1,000 terabytes) of data storage. Although data demands are not expected to require the upper limit of the 5400H network in the foreseeable future, the linear scalability of the system allows for smooth expansion if requirements warrant additional nodes.

Although the operational data collection schema has been established, the schema controlling the collection of the other various data sets discussed above is still being developed. The collection and storage of health management related historical data will provide the ability to validate component "lifing" or endurance models that look for correlations between operational and performance histories and engine faults that may occur.

Data Mining

Avetec planned to create an EHMS data mining (EHMS/DM) capability that includes a comprehensive set of sub-tools developed to analyze data stored on the EHMS/DW platform described above. Operational and performance data stored at the conclusion of each mission in conjunction with other engine historical data and data mining operations is designed to provide the customer with a near real-time picture of fleet capability and availability. This analysis can then be used to monitor life consumption of fleet engine components, enable conditioned-based maintenance and establish material and manpower requirements to support the customer's mission.

The goal of data mining algorithms is to make sense out of all this data. When the data mining statistician does a good job, we can learn from the data. There are two types of learning problems:

1. <u>Supervised</u>: predict the value of an outcome (responses/dependent variables) based on a number of inputs (predictors/independent variables).
2. <u>Unsupervised</u>: no predetermined outcome; goal is to describe the associations and patterns among a set of inputs based on no predetermined variables or dependencies.

The supervised types of problems tend to be associated with standard mathematical tools such as regression analysis. The unsupervised problem set is what is usually referred to as true pattern recognition and is currently the subject of intense research.

Although Teradata and other basic data mining concepts are mature, data fusion algorithms and specialized techniques for dealing with engine health management must be developed. This effort also sets boundaries on analysis and visualization tools in the EHMS efforts described below.

Data Analysis
Data analysis is a broad term encompassing a wide range of tools. The data analysis tools referred to here augment the specific data mining tools discussed above. These include system specification, verification, and validation tools that provide a means for the specification of system interfaces. These tools include system-of-systems-level analysis and visualization features.

Condition-Based Maintenance Research Environment (CBMRE) will be used to provide a transition path from conservatively scheduled maintenance practices that are based on fleet-wide averages to maintenance that is performed based on the needs of individual engines within the fleet. CBMRE requires input data on component life usage that results from the analysis that is performed by EHMS/DM and knowledge-based rule sets that define maintenance requirements from the engine manufacturer. The results of CBMRE analyses, in conjunction with other logistics requirements, are used to provide a fleet-wide picture of engine systems health and availability to the customer's operations planning processes. The goals of the CBMRE are to support maintenance personnel in their decision-making process, provide timely access to cross-functional and cross-domain data that can be tailored to the user's needs, and provide a single access point to integrate data horizontally and vertically. The CBMRE serves as an analysis and visualization tool within the EHMS product framework.

The Logistics Optimization Interface (LOI) is an analysis tool to ensure that engine systems and personnel required to support operations are effectively managed and available for use. For example, over the last decade, the United States Air Force has faced challenges that were not foreseen when the Cold War ended. Contingency operations and peacekeeping operations put stress on deployments.

An assessment of current availability and readiness and the ability to predict future readiness under rapidly changing scenarios is critical for supporting both military and commercial missions. Knowledge of current engine and vehicle health, and the ability to predict future health based on scenarios under consideration can be used with logistics simulations for decision support in operations planning. Current logistic planning processes are labor intensive, require detailed specialized training, and are increasing in complexity. The Logistics Interface System provides a mechanism for automatically inserting health assessment data into the construction of logistics simulations and will assist logistics planners in dealing with complexity.

The SIDAL product described above is also ideal for the development of engine control algorithms. The SIDAL/PROGNOSTICS product establishes a test environment for current and future engine control system prototyping and development activities which include on-board health management functions and prognostics. This product is required for end-to-end system testing and evaluation for engine health management products and services and for the continuous improvement of on-board engine control and health management systems. By reconfiguring SIDAL firmware, models of the engine, engine control, and on-board prognostics/health management systems can be prototyped and tested.

Physics-based engine models include thermal, fluid flow, and vibration analysis. These models will be used to complement operational data intensive analysis.

Data Visualization

Data visualization refers to the software and hardware required to present raw or processed data from the flight line to the engineering department to the control room to the board room, including enhanced 3-D visualizations. This equipment is necessary to aid end-users in their efforts to produce methodologies to enhance engine health management. Some of the visualization algorithms will be developed in conjunction with the warehousing, mining, and analysis tools discussed above.

Humans are basically visual creatures – a description possibly best described by the adage "a picture is worth a thousand words." So it is not surprising that discussions with possible end-users have shown that good data visualization is a greatly sought after feature compared to raw or poorly formatted data requiring intensive analysis hours.

EHMS Applications

Figure 19 depicts a schematic of how the complete puzzle of Figure 17 might be used in the real world. In the operational configuration, data from several different resources is collected and stored within the data warehouse. This data can include, but is not limited to, aircraft engine performance data, engine inspection data, engine maintenance data, and engine technical data. In this configuration, additional data sources can be applied to the architecture as long as the constructs are compatible with the data mining and analysis tools.

Users' inquiries include engine maintenance actions, command and control actions, logistics planning issues, and technical analysis. After the user makes an inquiry in the system, the data mining tool extracts the appropriate information from the data warehouse and passes it to the specific analysis tool(s) required based on the inquiry type.

Once this analysis is completed, the user determines if this satisfied the intent of the inquiry. If it does not, a refined inquiry is made and the process is repeated until a satisfying result occurs. The output can take the form of reports, informational displays, or technical processes that must occur to maintain the engine.

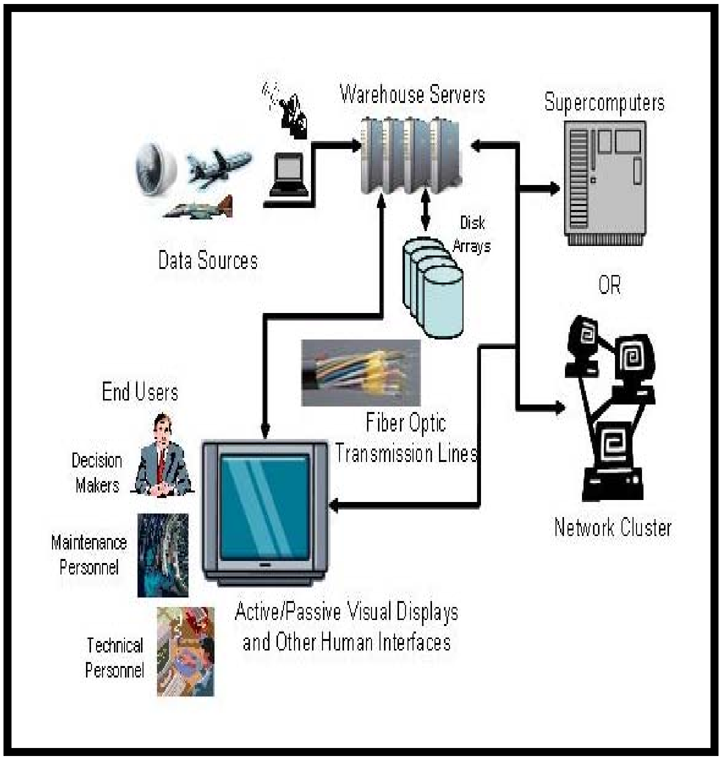

Figure 19 A complete, operational EHMS

The Bottom Line

The EHMS will increase operational capability through better maintenance predictability as shown in Figure 20. Avetec's EHMS will literally save the aerospace industry billions of dollars in maintenance and along with other Avetec initiatives allow design engineers to go from design to flight with unparalleled fluidity.

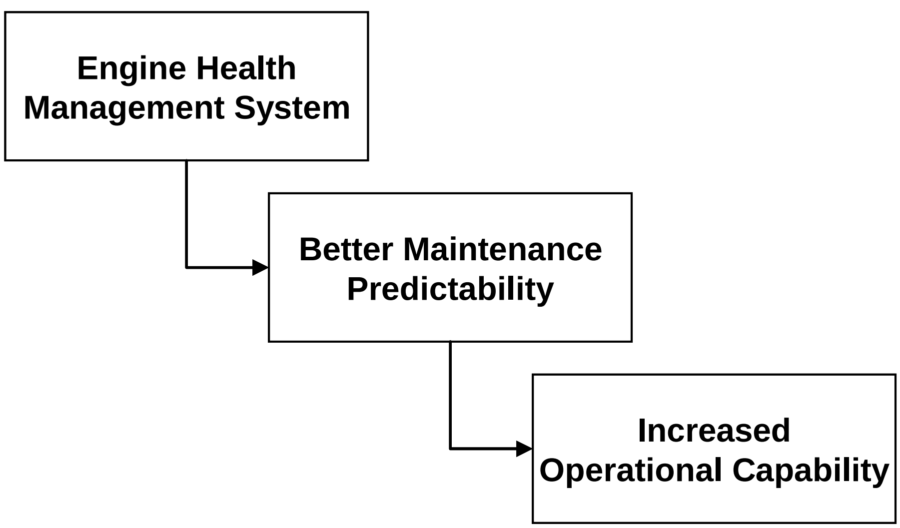

Figure 20 EHMS will result in more flying time and less maintenance down-time

Condition Based Maintenance and SIDAL Development (SMI)

The overall object of this project was to launch the partnership between Scientific Monitoring Inc. (SMI) and Avetec, and to begin positioning SMI's SIDAL unit for commercialization and sales. SMI was tasked to develop the application requirements and business model for SIDAL. The scope of this project included: 1) development of application requirements for SIDAL units; 2) further development of the SIDAL hardware and software requirements; 3) preparation of a detailed Phase II work plan; and 4) development the framework for the SIDAL business model. During the course of the project, the objectives were modified to include a demonstration of a distributed controls application.

Task 1 for this project was to define SIDAL application requirements. SIDAL is a versatile, reconfigurable system bench where the requirements vary depending on the application. Real-time applications may consist of a real-time simulator, Hardware-in-the-Loop (HIL) tester (with input/outputs (I/O's)), a controller (with I/O's) and recording/monitoring capabilities (with I/O's). Off-line applications included analysis and design, simulation (non-real time), remote client for CBM+ and desk-top workstation. Combined applications for a re-configurable system bench can be beneficial for design, modeling, simulation run-time evaluation and V&V (verification and validation). The primary benefit of the SIDAL design is its commonality and flexibility regardless of the specific application and configuration. The SIDAL development path and history are shown in Figure 20.

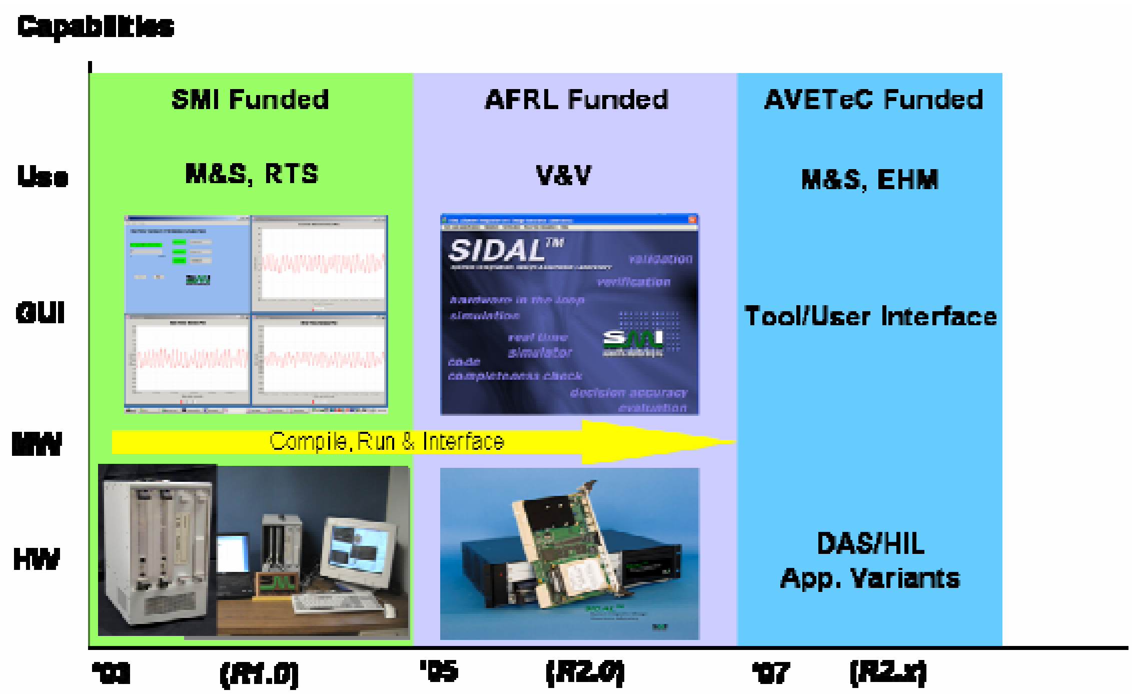

Figure 21 SIDAL development path

The SIDAL can operate with a Windows-desktop operating system or a Unix-like real-time operating system. Various analysis and modeling tools such as MATLAB/Simulink and other scientific and engineering application software can be hosted on SIDAL. SMI has developed a SIDAL user interface and menu shell program and a GUI for run-time display. Middleware has been developed to facilitate code compilation, linking, execution, and communication, along with various types of application software for real-time simulations.

Task 2 for this project was to include a significant demonstration of the SIDAL unit. In particular, the interest was in the HIL capability of SMI's SIDAL. The HIL capability is an extension of the SIDAL's "native" capabilities of modeling, simulation, and real-time applications by providing hardware interfaces with "outside" systems or devices (i.e., sensors, actuators, or controllers positioned locally or remotely) The HIL capability was demonstrated by a remote "smart-node" controller. The controller was a self-contained system for closed-loop control of the rotating speed of an electric motor. The system under test consisted of a drive motor and a load motor which was directly coupled to the drive motor. When the load is varied, the motor speed changes momentarily until the closed loop control system "restores" the speed to the commanded value. The system can be regulated by a distributed controller to perform closed-loop control of the motor speed. The demonstration equipment is shown in Figure 22.

Figure 22 SIDAL demonstration equipment

Task 3 for this project was to develop the work plan for the Phase II effort. This plan consisted of additional work in:

1. Developing a more complete business plan
2. Making a specific product decision as to whether to offer CBM services based on SIDAL's capabilities or a hardware product with associated software.
3. Creating project development plan based on the project decision with a demonstrator or prototype product to be marketed to beta customers to develop market feedback.
4. Creating the partnership and marketing agreements between Avetec and SMI to launch a new company and continue development of the SIDAL hardware and software.

Task 4 was to develop a SIDAL business model. Two potential business models have been explored. One is the sale of the SIDAL system as a product, and the other is value-added services in addition to the product sale. SMI has identified two clear competitors to the SIDAL product line. The first is Intelligent Automation Corporation (IAC) with the IAC1034 Intelligent Machinery Diagnostic System and the other is National Instruments (NI).

The start-up company would present customer-oriented responsive equipment monitoring with the emphasis on the military and defense markets. The equipment to be monitored is turbine engines (fixed and rotary-wing and ground-based), aircraft systems (including hydraulics, environmental and auxiliary power units APUs), and other platforms and subsystems (tanks and other ground vehicles). The new company would offer consulting, condition-based maintenance (CBM) services, a monitoring center (using a basic version of i-Trend®), and an advanced user interface.

The alternate product would focus on the new company selling SIDAL hardware rather than a customer oriented CBM solution approach. The emphasis would be on direct sales of the SIDAL hardware and software as a single integrated platform with support services and upgrades. The platform could function as a data collector, a modeling and simulation HIL test bed, and a verification and validation (V&V) test bed.

The initial product and service is an adaptable monitoring product. The key product elements are i-Trend® analysis software, SIDAL user interface to HIL for specialized, high compute performance simulation/data analysis or data uploading, and seamless integration of the products with existing data sources.

The target markets for the product are military and aerospace systems with high development costs. These customers fall into two major categories. The first includes customers who use SIDAL for data gathering and upload which would include engine OEMs, government test labs, non-military government test labs and any engineering-intense aerospace corporation (i.e. Ball Aerospace). The second category of customers is those who also require i-Trend® monitoring solutions. Contacts that have shown an interest in the SIDAL product include Boeing, Northrop Grumman Corporation, NASA and Hamilton-Sundstrand. Other potential customers include the turbine engine OEMs (GE, Pratt & Whitney and Rolls-Royce), Arnold Engineering Development Center, Tinker Air Force Base, Wright-Patterson Air Force Base, and Rome Air Development Laboratory.

The HIL capability was demonstrated by a remote “smart-node” controller. The smart controller is a self-contained system for closed-loop control of the rotating speed of an electric motor. The speed of the motor can be sensed by a digital encoder or an analog tachometer. The sensed speed signal is sampled by the smart node, and the desired current to track the speed command is calculated and sent to the power supply, which in turn regulates the current going into the motor. Variable loads can be selected by the test operator. These loads are generated by the second motor based on the operator’s selection of load level. The second motor is coupled directly to the first motor (or the drive motor). In this arrangement, the second motor provides resistive load to the drive motor. When the load is varied, the motor speed changes momentarily until the closed-loop control system "restores" the speed of the commanded value.

The results of this demonstration comparing actual motor speed with simulated motor speed can be seen in the figures, below. Figure 23 shows the DC motor and generator speed and control voltage signals under a step change in speed command from 1,000 rpm to 2,000 rpm. Figure 24 shows the simulation results of the same step change in speed command from a physical model of the test system.

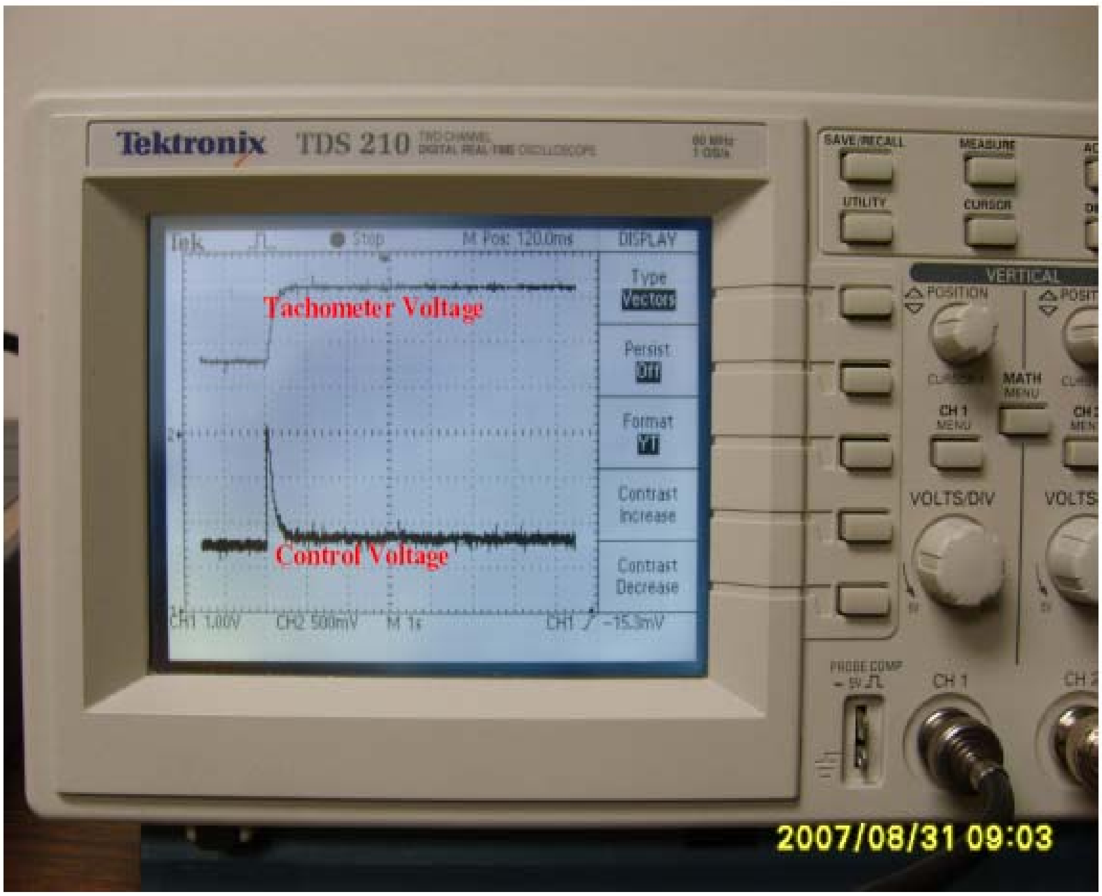

Figure 23 Speed command and motor control voltage for motor acceleration

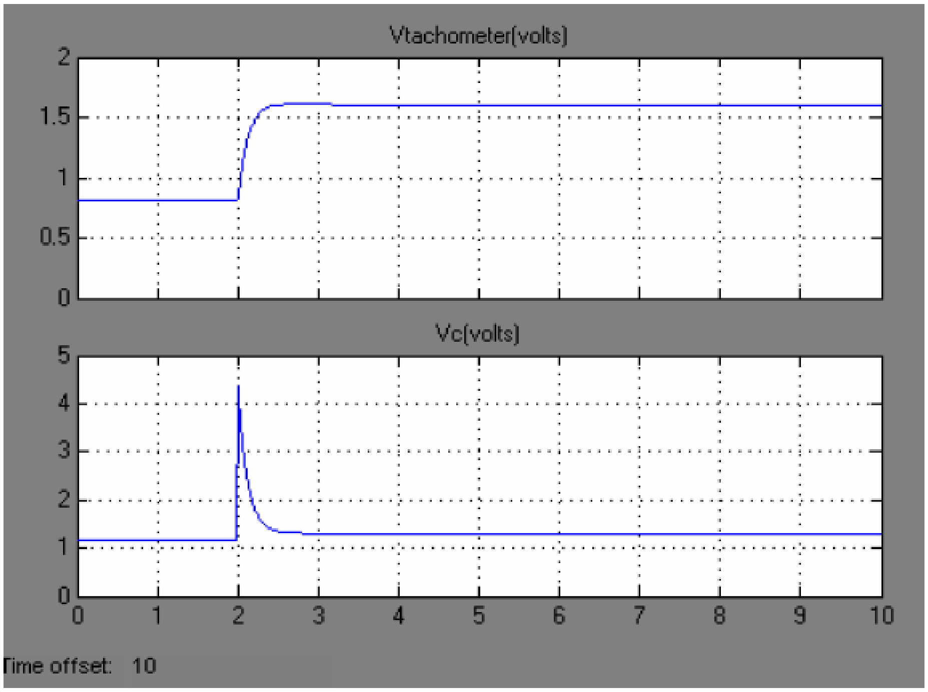

Figure 24 Simulated speed command and motor voltage

Figure 25 shows the DC motor and generator speed and control voltage signals under a step change in speed command from 2,000 rpm to 1,000 rpm. Figure 26 shows the simulation results of the same step change in speed command.

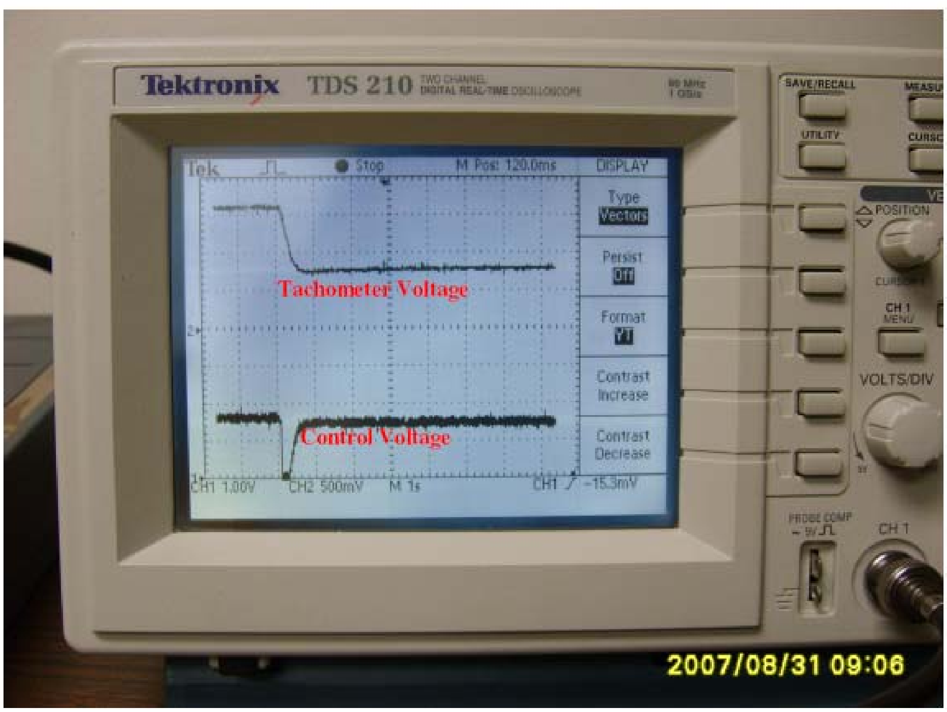

Figure 25 Speed command motor control voltage under deceleration

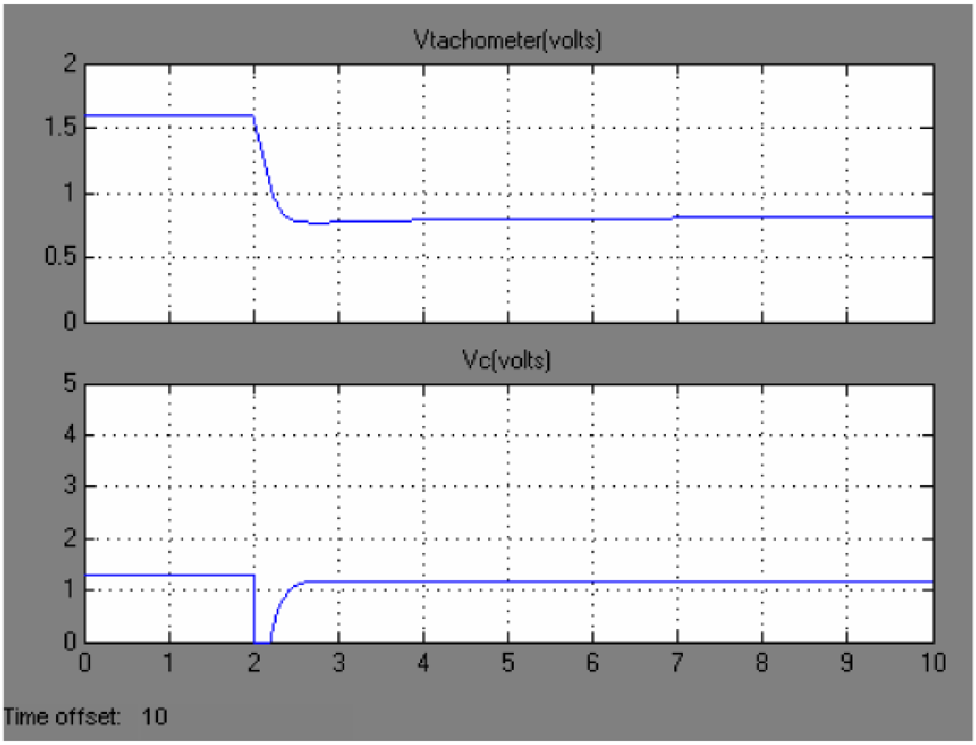

Figure 26 Simulated speed command and control voltage under deceleration

In summary, an electro-mechanical test system has been designed and built to demonstrate the HIL capability of SIDAL. The system can be regulated by a distributed controller to perform closed-loop control of the motor speed. The distributed controller is built by SMI using low-cost, commercial-off-the-shelf (COTS) components, including the micro-processor board, the I/O board, and the real-time operating system (RTOS).

2.2.2.2. High Performance Computing Research and Support

The long-term success of modeling and simulation, EHMS, virtual testing and data management for the aerospace industry base across the United States relies on new and emerging high performance computing technologies to properly store and transfer data for efficient use. Avetec has deployed a Data Intensive Computing Environment (DICE) program test bed to further research industry-wide data management solutions. These solutions will support Avetec's research efforts as well as efforts across the high performance computing community. The Data Intensive Computing research program addresses critical computational and data management needs of the Grand Challenge problem for transitioning new engine technology into Air Force and commercial use.

NALI Phase I funding was used to initiate this research activity in the projects described below. As a result of this initial work, DICE research programs have since been funding through other areas of the Department of Defense and the Department of Energy budgets. NALI funding was used to support program development and management support provided by Computer Sciences Corporation (CSC), research projects involving faculty at the Ohio State University, and a study in data center cooling important for the planning of the Center for Advanced Modeling and Simulation. The remainder of this section contains more detailed descriptions of the work that was done.

DICE Management and Integration (Computer Sciences Corporation)

Over the past decade, computing power has increased extraordinarily, enabling researchers to tackle large complex problems – a great step forward in our ability to model the complex world. This increased capability resulted in massive amounts of data being produced and used by increasingly detailed simulations. It is the location, viewing, manipulation, storage, movement, sharing, and interpretation of this data – now in hundreds of terabytes and growing – that is causing the major performance bottleneck. Data Intensive Computing Environments (DICE) has emerged as a topic to address the problems associated with large data sets.

Avetec, in conjunction with the Department of Defense Major Shared Resource Center at Wright-Patterson Air Force Base, Ohio, the Ohio Supercomputer Center in Springfield, Ohio, the Department of Energy, and NASA Goddard Space Center in Greenbelt, Maryland, has established the DICE program – a test bed environment for active participation in technology evaluation and research of emerging technologies.

The DICE program was established in 2005 with a vision of having an environment where emerging technologies addressing data intensive computing can be evaluated and where government researchers and technology vendors can collaboratively evaluate new technologies. The environment will be a cross-agency evaluation test bed representative of existing high-end computer centers.

A Governance Board provides the strategic guidance for DICE. All policy and procedural guidance within the scope of the existing DICE contracts are subject to the approval of this board. The Technical Review Board (TRB) is responsible for ensuring the smooth operation of the DICE program. This board operates under delegated authority from the Governance Board, specifically for the purpose of managing, integrating, and operating the structure and composition of the systems and networks that comprise the DICE test bed.

During the first two phases of the DICE program several major accomplishments were achieved. The DICE test bed architecture was approved and all the equipment was purchased, delivered, and installed at the three different locations and tested and certified for connection to the different research networks. Two DICE conferences were planned and held in Springfield, Ohio. The first conference had 135 attendees from 33 different organizations. The prime purpose of the conference was to introduce the DICE program and concept to the high performance computing community and solicit potential projects. A total of 23 projects were submitted for evaluations, 12 projects were approved for evaluation. In May 2007, Avetec held a second conference in Springfield, Ohio. Attendance was 200 individuals from 67 different organizations. The call for projects resulted in a total of 20 projects being submitted for evaluations. The TRB completed a technical evaluation and ranked all the submitted projects. During the evaluations process three projects were identified as being very similar with the same basic objective. The TRB determined that the three should be combined into one project. Results of the evaluations were presented to the Governance Board. The decision was made that all of these projects would be placed on hold and all second year projects would be conducted under DICE II.

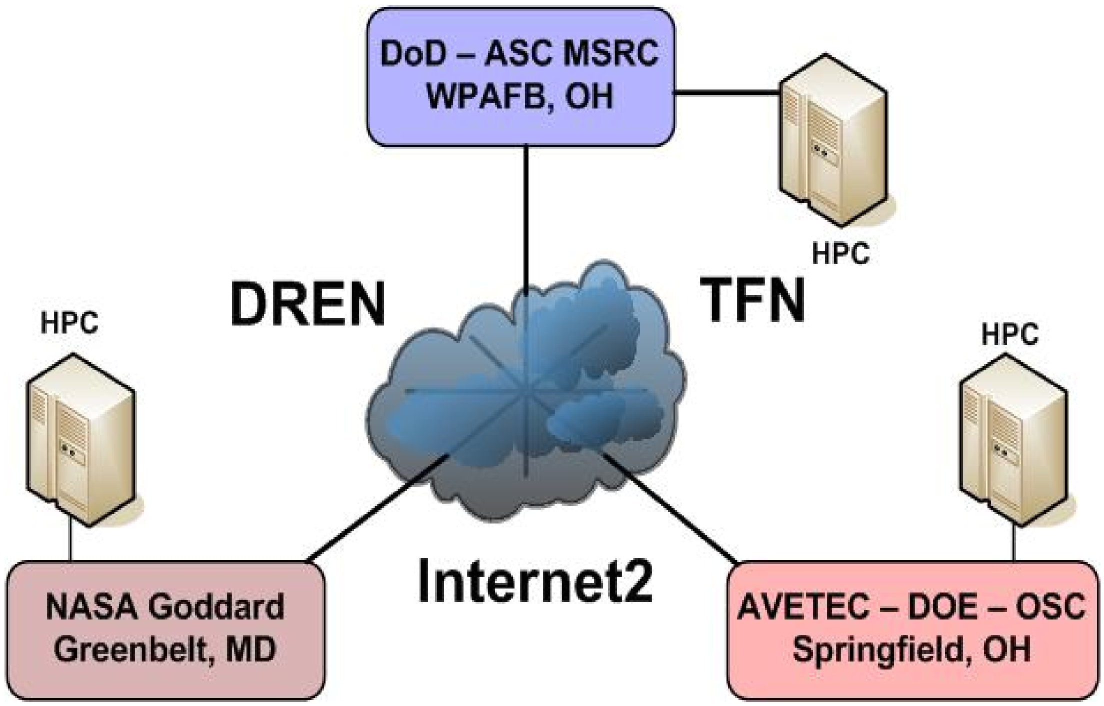

Figure 27 Data Intensive Computing Environment infrastructure

Performance Evaluation Cluster Networking (The Ohio State University)

The federal government and vendors have been struggling with measuring and validating the performance of various interconnection technologies and methods for use in cluster supercomputers in a standardized manner. The objective of this project has been to design, develop, and validate a set of standard measurement tools for evaluating cluster networking and I/O technologies. During this project, a set of Message-Passing Interface (MPI) level benchmarks have been designed. These benchmarks have been evaluated on the DICE test bed: ASC cluster with two different networking technologies, InfiniBand, SDR, and Quadrics.

Future plans include using these benchmarks on other DICE platforms: such as the Avetec cluster with InfiniBand DDR and 10 GigE. The results included in this report for the ASC cluster demonstrate the strengths of these benchmarks to compare performance (strengths and weaknesses) of various networking technologies and MPI libraries for clusters. As these benchmarks are designed, developed and tested, they are also made available to the community through OSU MVAPICH project web site as open-source benchmarks. These are also included in the OSU MVAPICH and MVAPICH2 distributions.

The performance evaluation results of these benchmarks are also being made available. During the first year of this project, these benchmarks have had wide usage and acceptance in the HPC community. Current Open Fabrics Enterprise Distribution (OFED), the main organization behind open-source InfiniBand and 10GigE/iWARP development, include these benchmarks in its distribution. A large number of InfiniBand and iWARP vendors and several Linux distributors also include these benchmarks (known in the community as `OSU Benchmarks') in their distributions.

Future plans on this project include expanding these benchmarks for next generation multi-core and multi-threaded systems as well as I/O environments. It is anticipated that the benchmarks developed through this project will lead to the creation of a complete tool set and the creation of a National facility to evaluate all current and future cluster networking and I/O technologies and produce fair and unbiased reports. The project will significantly help in reducing cost for government agencies and the industry vendors to evaluate next generation clusters.

MSRC Support (The Ohio State University)

The Major Shared Resource Center (MSRC) at Wright-Patterson Air Force Base is one of four high performance computing centers operated by the Department of Defense Modernization Office to support the high performance computing needs of the Department of Defense. Because of its dependence on high performance computing in order to perform much of the research that Avetec has been involved in, Avetec has worked closely with the MSRC at Wright-Patterson Air Force Base. In collaborative work associated with the development and application of turbine engine turbo machinery design code, Avetec has assisted Air Force Research Laboratory Propulsion Directorate researchers. A contract for support from Dr. Jen-Ping Chen at the Ohio State University provided this service through Avetec to support this work.

Systems Support and Design (Alvin Stutz)

Mr. Alvin Stutz provided contract services in support of Avetec's high performance computing initiatives including network design during the initial company start-up. Other services provided ranged from the initial internal company network and computing architecture to external community network development including the initial stages of design for a research network that would connect Avetec's Center for Advanced Modeling and Simulation to research collaborators.

Advanced Cooling Design (Isothermal Systems Research)

Isothermal Systems Research (ISR) conducted a study and provided recommendations for high performance computing and data center cooling system design. This was used as a planning guide for the specification of cooling system requirements in the Center for Advanced Modeling and Simulation. The results of this study are summarized in this section.

The continuing evolution of High Performance Computing has tracked microprocessor development according to Moore's Law which states that *"transistor density on integrated circuits doubles every eighteen months to two years and cost decreases by half."* This is attractive for HPC systems but brings with it new challenges in cost effectively cooling these more densely packed, hotter microprocessors. This significant increase in heat and the need to transport and dissipate this heat has a profound affect on data center infrastructure and design.

Because high performance computing is a critical technology for Avetec research and the Center for Advanced Modeling and Simulation facility, Avetec engaged Isothermal Research Corporation (ISR) to conduct data center cooling studies and recommend an approach to cooling that could be considered in the planning of the Simulation facility. ISR has been deeply involved in research and development of alternate to conventional raised floor, air cooled data center design with their advanced liquid cooling product.

ISR's SprayCool™ advanced liquid cooling alternative uses an evaporative cooling process to acquire heat directly from electronic components. The heat is transported by the SprayCool fluid to a facility chilled water or condenser water loop and removed from the facility. The higher heat carrying capacity of the SprayCool fluid and water compared to air allows for the transport of this heat in a more efficient manner. Further power savings are possible due to the reduction or elimination of fan requirements inside the serves and lower power consumption of integrated circuits when operating at lower junction temperatures.

Thermal problems have existed in data centers for years. But today, thermal problems have created real deployment barriers for data center managers responsible for implementing a wide range of computing systems to meet user demands. The challenges have a direct effect on an organization's ability to control operational costs, increase system performance and deploy next generation computing systems. Some of the key drivers are:

- Significant increases in the cost of power
- Growing server power requirements
- Facility infrastructure incapable of delivering adequate air to individual computer racks
- High costs in both capital and time of data center construction

Advanced liquid cooling technologies present a promising method for reducing the impacts of today's data center thermal management problems. Advanced cooling technologies provide the ability to:

- Effectively acquire heat from microprocessors in a highly efficient manner directly from the source of heat. This enables denser server placement within the data center and will not restrict server scaling from their cumulative thermal loads
- Transport heat in a consolidated medium that reduces facility requirements
- Reject heat utilizing energy efficient equipment

The objective of this study was to investigate the capabilities of an alternate, advanced liquid cooling technology, specifically the SprayCool™ data center product line, as cost effective and feasibly deployable alternative to conventional air cooling of a high performance computing data center. A data center cooling model that addresses power and cooling for typical data centers using currently available cooling technology was explored.

Factors that were considered in the study included data center characteristics such as the geography of the surrounding area, age of the facility type and size of the computational facilities. These unique aspects of the new Avetec data center were considered important factors in the optimal design of a data center cooling system, but also made direct comparison of existing data centers difficult. The analysis provided in the study adopted the following approach to evaluate proposed solutions. Power models were developed to evaluate the efficiency of different cooling solutions. Specific network and server requirements were not provided as guidelines for the study so the following assumptions were made in the context of a two year rollout:

- 6 Computationally Intensive racks at 35 kW each
- 10 Data Intensive racks at 9 kW each
- 7 Low Density racks at 2 kW each

The estimated power requirements were based on the projected heat loads of computing equipment in the 2010 timeframe as predicted by ASHRAE [24] as shown in Figure 28.

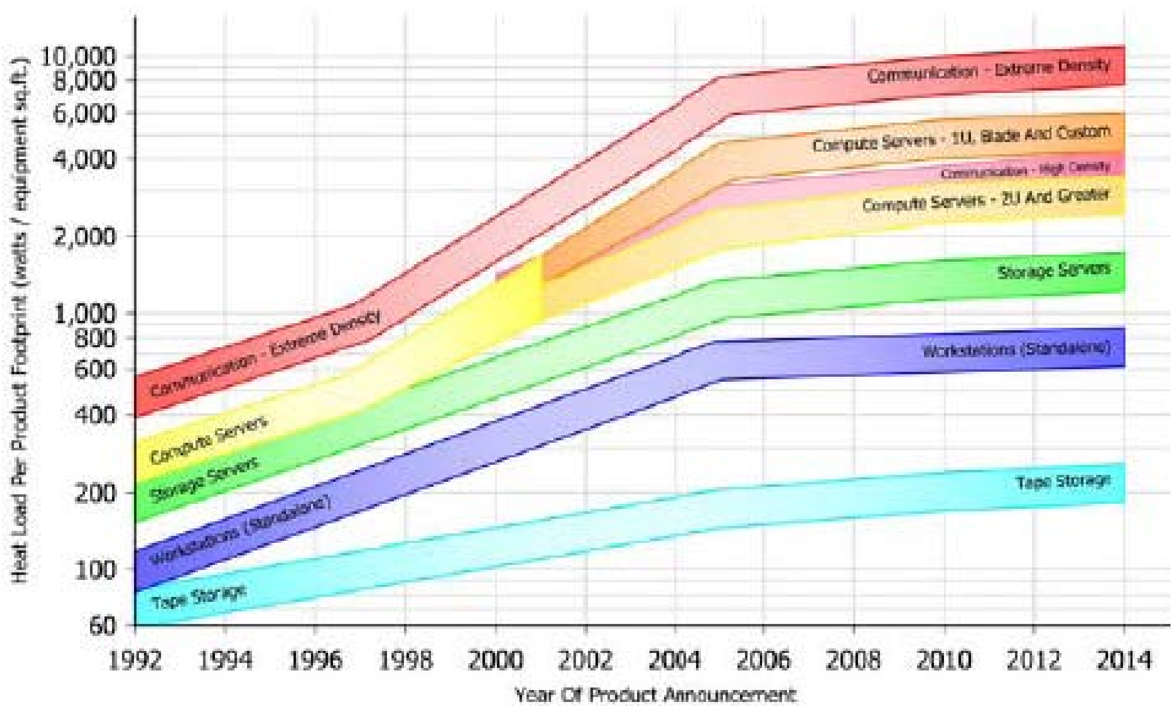

Figure 28 Estimated data center power requirements

Power models were used to compare efficiencies for cooling architectures for each of the three types of computational resource racks listed above. Architectures at the room, rack and chassis level were considered in the analysis.

A graphical representation of the base level facility model is show in Figure 29 below. The model assumed a that a chiller would produce a sub-ambient water supply delivered to a computer room air handler that blows air across cooling coils containing the chilled water. Heat rejected to a secondary water/glycol cooling loop from the chiller was assumed to be fed cool water from a water tower exterior to the building. A schematic diagram is shown in Figure 29 below.

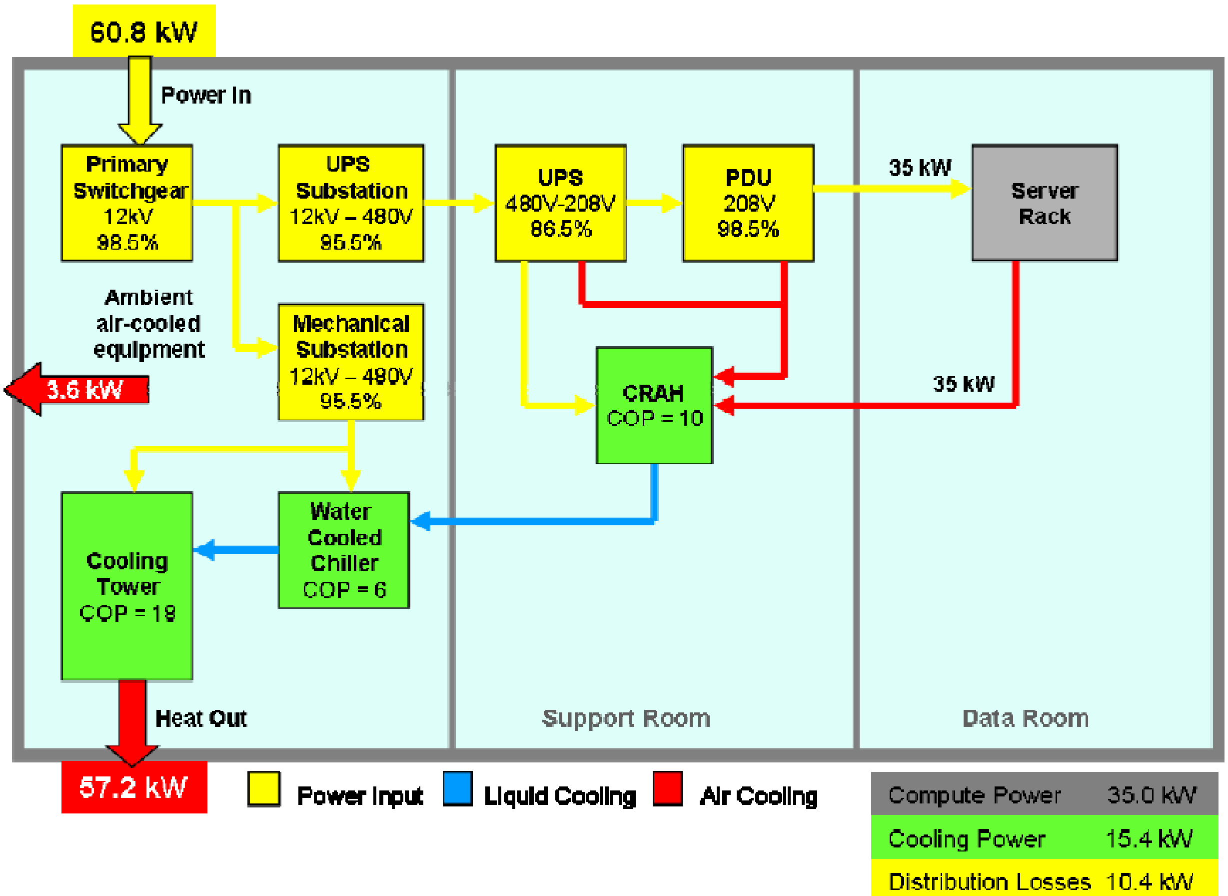

Figure 29 Base level facility model

The study also considered the use of an air cooled chiller based design as a lower cost, smaller facility alternative to the configuration described above. The air cooled chiller and water cooled chiller described above were the alternatives considered for cooling at the room level and analysis of these designs provided the basis for rack level efficiency analysis.

At the rack and chassis level the following architectures were considered in the study. The SprayCool M Series solutions use a SprayModule^{TM} in place of air cooled heat sinks at each of the processor modules. These modules reject heat from each processor directly to a specialized fluid that is placed in contact with the processor. Heat is subsequently rejected to water in the building cooling loop. The IBM Rear Door Heat Exchanger (RDHX) model uses temperature controlled chilled water routed through coils integrated into each rack. The Hewlett Packard Modular Cooling System is a fully enclosed rack cooling system and was assumed representative of fully enclosed rack system from other vendors. The SprayCool G Series Blade Module is a next generation cooling solution that extends processor level cooling to a fully integrated blade level cooling solution to capture heat from processors, memory, support chipsets and at the board level within individual blade modules. This analysis compared a standard air cooling solution with SprayCool M-Series and G-Series Blade products along with two popular rack level cooling solutions.

The IBM RDHX and the HP MCS systems both use air to cool servers but are more efficient than room level air cooling solutions. This is due to capturing the air close to the source of heat dissipation and not allowing this warm air to mix with cooler air in the room. The mixing of warm and cool air lowers cooling efficiency since a greater volume of air must be circulated to obtain the same cooling performance. Both of these solutions also allow for higher heat loads in the rack but pay a price with less dense rack spacing in the data center.

All of the alternative solutions analyzed require changes to the facility in order to connect the racks to water loops via under floor piping. These added infrastructure costs allow for denser data centers with lower operating costs and the ability to add capacity in the future as the density and power requirements of computing equipment continues to rise. Based on the results of this study and projected computing needs over 3-5 years, ISR provided the following recommendations to Avetec for consideration in the planning stages of the National Center for Advanced Modeling and Simulation.

ISR provided recommendations for both SprayCool based solutions and alternate solutions for liquid cooled data centers. The recommendations were described in terms of 1) data center floor configuration, 2) Under floor airflow design, 3) Liquid flow requirements, 4) Water temperatures, 5) Water pressures, 6) Water supply and water content, 7) Leak detection and measured response, 8) Power provisions, 9 Instrumentation, and 10) Green cooling considerations.

In order to accommodate growth over time the system design must be able to tolerate drastic changes in airflow requirements, water utilization and load balance without user intervention. Optimal shape for small data center is a square based on rack density.

SprayCool based solutions appear to be promising as an alternative to conventional air cooled systems. However since this is different cooling approach that requires ancillary equipment with high capital expense (e.g. geothermal heat exchangers or water tower), an unbiased third party evaluation and validation of the technology would be prudent before adoption.

Infrastructure, Program Management and Support

Information Technology (IT) expenses during the NALI I grant period covered the acquisition and installation of several key components of the Avetec network infrastructure. Network switches, servers, computer stations, and telephones were purchased with funds from the NALI I grant. The network switches were purchased for internal connectivity. Servers that were procured with NALI Phase I funds consist of the research server and its associated storage, the servers that make up the collaborative SharePoint environment and their associated storage, and the spam filtering server. There were also several notebook computers that were purchased for users on the Avetec network.

Miscellaneous items for the continued operation of the network were purchased with this grant as well. These items include cabling, back-up tape, library accessories, and a refresh of backup tapes.

There were key software purchases in the NALI I grant. Licensing and media for Microsoft SharePoint and Structure Query Language (SQL) database server were purchased for the collaborative environment. The Altiris Total Management Suite was also purchased to facilitate management of the IT network.

Additional costs directly associated with infrastructure development and consulting services were used to support initial company startup. These included:

- Project Management and Support from the Greentree Group
- Consulting Services from David Milam for Interfacing with program funders
- Office-related programming and core planning by Laughlin and Scanlan

A detailed land-use planning study was conducted to support the development of Avetec's presence in the Nextedge Technology Park.

2.2.3. Conclusions of Avetec M&S Projects

In the proposed work scope for the first phase of National Aerospace Leadership Initiative funding investigators for each consortium company described a vision for leadership in the aviation industry that addressed U.S. Air Force needs. In Objective C of Task II within the NALI Phase I proposal, Avetec's role in that development and a vision for an Advanced Modeling and Simulation Center to support modeling and simulation technology development were described. The work of the Phase I effort laid the ground work for fulfilling this vision and the approach and motivation for the work have been described in this report. Technical research programs driven to establish leadership in both the aerospace industry and in the high performance computing industry in support of a Grand Challenge problem aimed at reducing the time and cost of future Air Force acquisition programs have been conducted in NALI Phase I. NALI Phase I resources were also applied to support planning and infrastructure development for the Advanced Modeling and Simulation Center. This report documents the projects in these three areas that support the goals of the program.

The following are key results of this effort:

- We have established national and international recognition as a contributor in modeling and simulation research. As a result of the work described, we have impacted the way we think as an industry about advanced modeling and simulation in the aerospace supply chain.
- High performance computing has a critically important role in this work. It is an enabling technology for advances in propulsion system modeling and simulation. As a

result of the program, Avetec has been recognized as a strong advocate for high performance computing and its application in American industry.

- The Grand Challenge problem in propulsion requires collaboration. As a result of Phase I funding, Avetec forged government, industry and academic partnerships that are instrumental for later phases of the program.
- Educating the next generation of scientists and engineers is critical to our future. Avetec educational programs have been initiated and are impacting the lives of students in Ohio.

2.2.4. Avetec Acknowledgements

Avetec graciously acknowledges the many contributions made by individual researchers involved in the success of the NALI Phase I research programs. The project summaries contained in this report are extracted from individual contributions submitted to Avetec in the form of project final reports. Without the tireless efforts of our collaborating partners the work that we have done would not be possible.

The table on the following page lists key research personnel for the NALI Phase I research efforts, their positions and organizations (both currently and at the time of their project contributions), and their contact information.

Table 1 NALI Phase I Key Research Personnel for Avetec Efforts

Name	Position and Organization: Prior	Position and Organization: Current	Current Address	Current Email
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Jen-Ping Chen, Ph.D	The Ohio State University Aerospace Professor	The Ohio State University Aerospace Professor	319B Bolz Hall 2036 Neil Avenue Columbus, OH 43210	chen.1210@osu.edu
Mark Turner, Ph.D	University of Cincinnati Aerospace Professor	University of Cincinnati Aerospace Professor	730 Rhodes Hall University of Cincinnati Cincinnati, OH 45221	mark.turner@uc.edu
John Reed, Ph.D	The University of Toledo Senior Researcher	The University of Toledo Senior Researcher	2801 W. Bancroft St Toledo, OH 43606	jreed@eng.utoledo.edu
John Lytle, Ph.D	NASA Project Manager of Space Flight Systems Advanced Capabilities	NASA Project Manager of Space Flight Systems Advanced capabilities	MS 77-7 21000 Brookpark Rd. Cleveland, OH 44135	john.k.lytle@nasa.gov
Rakesh Srivastava	Honeywell Aerospace Engineering Methods & Integration	Honeywell Aerospace	111 S. 34th Street, MS 301-134 Phoenix AZ 85034	rakesh.srivastava@honeywell.com
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Cathryn S. Balas	Avetec Education Director	Avetec Education Director	30 Warder Street, Suite 210 Springfield, OH 45504	cbalas@avetec.org

2.2.5. Avetec References

1. List, Michael G., Steven E. Gorrell, Mark G. Turner and Jason A. Nimersheim, "High Fidelity Modeling of Blade Row Interaction in a Transonic Compressor," AIAA 2007-5045, Cincinnati, OH, July, 2007.

2. List, Michael G., "Quarter Annulus Simulations of Blade Row Interaction at Several Gaps and Discussion of Flow Physics," August, 2007, University of Cincinnati M.S. Thesis.

3. List, Michael G., Steven E. Gorrell, and Mark G. Turner, "Investigation of Loss Generation in an Embedded Transonic Fan Stage at Several Gaps Using High Fidelity, Time-Accurate CFD," ASME Paper GT2008-51220, Berlin, Germany, June, 2008.

4. Smith Derek, "Analysis of Unsteady Effects in the Rotor Forward Hub Cavity of a Highly Loaded Transonic Compressor," June, 2007, University of Cincinnati M.S. Thesis.

5. Kamp Michael A., Jason Nimersheim, Tim Beach, and Mark G. Turner, "A Turbomachinery Gridding System," AIAA 2007-18, Reno, NV, January, 2007.

6. Haimes, Robert and M. Giles, "Visual 3: Interactive Unsteady Unstructured 3D Visualization," *29 Aerospace Sciences Meeting,* 1991, AIAA Paper no. 1991-794.

7. List, Michael, Mark G. Turner, Daniel Galbraith, Jason Nimersheim, and Marshall Galbraith, "High Resolution, Parallel Visualization of Turbomachinery Flowfields," AIAA 2007-5043, Cincinnati, OH, July, 2007.

8. Claus, R., S. Townsend, D. Carney, J. Horowitz, and M. Turner, "A Case Study of High Fidelity Engine System Simulation," AIAA 2006-4971, Sacramento, CA, July, 2006.
9. Mavriplis, Dimitri J., David Darmofal, David Keyes, and Mark Turner, "Petaflops Opportunities for the NASA Fundamental Aeronautics Program," AIAA 2007-4084, Miami, FL, June, 2007.

10. Knapke, Robert D., Mark G. Turner, Michael G. List, Daniel S. Galbraith, Tim Beach, and Ali A. Merchant, "Time Accurate Simulations of a Counter-Rotating Aspirated Compressor," ASME Paper GT2008-50877, Berlin, Germany, June, 2008.

11. Claus, R.W., Evans, A.L., Lytle, J.K. and Nichols, L. D., 1991. "Numerical Propulsion System Simulation," Computing Systems in Engineering, 2, No. 4, pp. 357-364.

12. Reed, J.A., Turner, M.G., Norris, A. and Veres, J.P., 2003. "Towards an Automated Full-Turbofan Engine Numerical Simulation." ISABE Paper No. 2003-1235.

13. Turner, M.G., Reed, J.A., Ryder, R. and Veres, J.P., 2004. "Multi-Fidelity Simulation of a Turbofan Engine with Results Zoomed into Mini-Maps for a Zero-D Cycle Simulation,"ASME Paper No. GT2004-53956.

14. Turner, M.G., Norris, A., and Veres, J.P, 2003. "High Fidelity 3-D Simulation of the GE90." AIAA Paper No. 2003-3996, June 2003, Orlando, FL.

15. Adamczyk, J. J., 2000. "Aerodynamic Analysis of Multistage Turbomachinery Flows in Support of Aerodynamic Design." J. Turbomach. 122(2), pp. 189-217.

16. Versatile Affordable Advanced Turbine Engine Thermal Management System Study, Mach 2-4 Platforms, 2003-2005, AFRL/PRTG/TM, Limited Distribution.

17. Hirschman, Cords and Hunter, Strategic Direction, Airline Business, October 2005.

18. Boeing 717 News Release on development strategy focused on maintenance and reliability, Seattle, May 28, 2002.

19. Horder, Peter, Airline Operating Costs, Managing Aircraft Maintenance Costs Conference, Brussels, 22 January, 2003.

20. Seeliger, Awalegaonkar, and Hunter, Can Lean Maintenance Help Save the Airlines? The drive to eliminate waste improves both costs and quality, Mercer Management Journal, Issue 20, November 2005.

21. Torre, Mel, To Reign in Costs in the Aerospace Business, Attention Turns to Prolonging Engine Life, American Society of Mechanical Engineers, New York, January 27, 2004.

22. Seidenman and Spanovich, "Airlines Spending Money on IT," *Overhaul & Maintenance*, December 2004.

23. Ibid.

24. ASHRAE 2005, "Datacom Equipment Power Trends and Cooling Applications," ASHRAE TC9.9 Mission Critical Facilities, Technology Spaces and Electronic Equipment, 2005.

2.2.6. Introduction and Scope of CCAT/NCAL's M&S for Manufacturing Efforts

The principal task coordinator for the CCAT's NCAL M&S for Manufacturing efforts is Mr. Thomas Scotton, tscotton@ccat.us.

The CCAT/NCAL M&S team established the following as its program objectives:

- Develop a world class Modeling and Simulation Program with a skilled application staff and establish a nationally distributed team of technology partners.
- Establish a world class Modeling and Simulation Laboratory focused on Air Force manufacturing and product maintainability.
- Apply modeling and simulation tools to aerospace supply chain issues to improve and expand manufacturing capability and production volume within the supply chain.
- Include modeling and simulation for kindergarten through 12th grade (K-12) as a key component of the CCAT/NCAL educational initiative to develop the Air Force 21st Century workforce.
- Identify and transition key technologies.

The need to achieve wide spread impact of our activities has led to the following stepwise approach to carry out activities:

1. Assess Industry Needs – To date this has been done with interactive visits to aerospace component suppliers, mapping how they conduct production today, what tools they use, and ascertaining their views on their future direction.
2. Identify Modeling & Simulation Solutions – Activities include the following: Participation at technologies conferences such as WinterSim and the Internal Manufacturing Technology Show to help identify the leading edge technology that industrial engineers and manufacturing engineers are using today throughout industry. Investigating technology capabilities via interaction with universities and colleges. Conducting technology surveys via the worldwide web to help collect potential solutions to problems identified during company assessment visits. Visits to the OEM level companies also provide us with additional insight to new technology that could be of value to the supply chain as well.
3. Demonstrate & Validate – Upon identification of state of the art solution technologies, the CCAT/NCAL team acquires the solution and executes demonstration projects with local companies to validate the capabilities in the real world, and to determine limitations as they exist in the solution.
4. Develop Partners – Work with solution providers to identify limitations and possible improvements that could be developed.
5. Deploy & Educate – The CCAT/NCAL team works with the solution providers to make the solutions available to local colleges and universities as appropriate to provide students with a learning experience on applying these technologies as they move out into industry. The CCAT/NCAL team also uses internships and contracting mechanisms to help expose individuals in more depth to these technologies.

6. Seminars/Workshops Local Mentoring – The CCAT/NCAL team serves as the facilitator for locally held seminars and workshops, again in conjunction with local educational organization. Meetings are hosted both at local conference venues as well as in the modeling and simulation theater.
7. Technology Improvement – As technology partners and CCAT/NCAL customers interact on execution of demonstration projects, and understanding the limits of the existing tools, it is natural for the team to come up with ways to improve the technology. The team can act as the facilitator of these improvements by assuring that there is a customer base ready to implement the improvements.

Using the above approach, the CCAT's NCAL Modeling and Simulation team has focused its Phase I efforts within two areas of activity: Machining Process Modeling and Digital Factory Modeling with the desire to create a digital manufacturing environment that will significantly enhance the small to medium aerospace manufacturer to compete globally and better meet U.S. Air Force needs.

Methods/Procedures

In order to support the above approach, the CCAT/NCAL Modeling and Simulation (M&S) team has continued to grow as a capable organization of local employees and a distributed network of consultants and educators for execution of projects. We are currently executing factory modeling activities, and machining process analysis projects for supply chain companies. Over the course of the past 3 years of activity we have grown the CCAT/NCAL M&S team to include a combination of seasoned technology leaders and junior technology application engineers. This group provides many years of experience in the use of technology for all of the subjects listed below:

- Tom Scotton - Manager, Modeling and Simulation Team (29 years, UTRC, DS/Delmia)
- Brian Kindilien – CAD/CAM Solutions (20+ years)
- Jonathan Fournier – Factory Modeling, Value Stream Mapping, VR Technology
- Matthew Lloyd – Machining Modeling, NC Verification
- Chris Pfeifer – Machining Modeling, FEA Analysis, Immersive Learning Environment
- Susan Coffey – Value Stream Mapping, Data Analysis (20+ years,
- Nasir Mannan – Assembly Sequencing, Metrology, Reverse Engineering, Robotics, VR Technology
- Greg Hasko – Composites, Welding, Casting Process Modeling (25+ years, PWA, NASA, small composite manufacturers)
- Dr. Tony Dennis (Part Time) – FEA Analysis Tools (30+ years UTRC, PWA)
- Bob Memmen (Part Time) – Project Management, VSM & KBE (30+ years, PWA-GEB)
- Tom Meyer (Part Time) – Structural Analysis, Part Lifing Assessment (30+ years, UTRC, PWA, HS)

Under this Task, the following projects have been executed and a summary of the activity is reported for each project within the remainder of this section within this report.

- 2.2.7 CCAT's NCAL Modeling and Simulation for Machining Process Modeling
  - 2.2.7.1 Physics Based Machining Process Analysis
  - 2.2.7.2 Physics Based Simulations for Chatter
  - 2.2.7.3 CAD/CAM Best Practices Assessments
  - 2.2.7.4 Evaluation of DELPHI Physics Based Process Simulation tool
  - 2.2.7.5 Development of VERICUT Machine Models, Tools, Fixtures, Electronic Library of Models
  - 2.2.7.6 Development of Interactive Learning Environment for teaching the concepts of NC Programming
  - 2.2.7.7. Implementation of Digital Manufacturing Solutions for demonstration projects with Industry.

- 2.2.8 CCAT's NCAL M&S Enterprise Modeling-Factory Floor/Operations
  - 2.2.8.1 Aerospace Factory Floor Modeling for validation of production level capacity
  - 2.2.8.2 Development of Factory Modeling Tools to teach concepts of Lean Manufacturing
  - 2.2.8.3 Development of Spreadsheet/VSM interface with factory model building Environments
  - 2.2.8.4 Value Stream Mapping of Machining Operations
  - 2.2.8.5 Value Stream Mapping of Small Hole Drilling
  - 2.2.8.6 Evaluation of Virtual PLC Programming environment, and implementation of educational laboratory.
  - 2.2.8.7 Implementation of Factory Modeling Laboratory for educating industry and workforce in the principals of Lean Manufacturing.
  - 2.2.8.8 Modeling of ADI lean activities.

- 2.2.9 CCAT's NCAL M&S Assembly Sequencing for the Creation of Electronic Work Instructions.
  - 2.2.9.1 Technology Demonstration of Electronic Work Instructions based on Assembly Sequence Modeling
  - 2.2.9.2 Ergonomic Modeling of Human activity during the assembly process of a multipart assembly.

Conclusions

A team of 11 professionals has been assembled to form CCAT's NCAL M&S team to focus on the understanding and application of state of the art modeling and simulation tools. Over 20 projects were initiated by the team to serve as a method of educating industry and the education community on the power of modeling and simulation software tools to enhance the development and execution of manufacturing processes for the aerospace supply chain level companies. In addition a number of projects were funded regionally to develop a workforce from the technical high schools, community colleges, and universities that have the skill set required to implement these technologies as employees at these companies.

2.2.7. CCAT's NCAL Modeling and Simulation for Manufacturing Project Summaries

2.2.7.1. Physics Based Machining Process Analysis

Overall Summary of Task
In this project we are executing a series of technology demonstrations to validate the capabilities of physics based modeling software to provide improved operational parameters for machining processes that will result in overall improvement in the process by reducing the cutting cycle time and/or improving the part quality.

Project team: Brian Kindilien (CCAT/NCAL), Matt Lloyd (CCAT/NCAL), Chris Pfeifer (CCAT/NCAL), Third Wave Systems, CNC Software, United Technologies Research Center, Rensselaer at Hartford-branch campus of Rensselaer Polytechnic Institute

Introduction
The CCAT/NCAL M&S team conducted a number of evaluations of technology in the emerging field of physics-based modeling and simulation for manufacturing. With intense competition, manufacturing industries strive continuously to seek efficiencies in machining processes through selecting suitable cutting parameters such as feed rate, cutting speed, rake angle, work piece hardness, etc. Traditionally this has depended on the skills and experience of engineers, numerical control (NC) programmers, and shop-floor machine-tool operators. Typically, the method used has been to select conservative handbook based cutting conditions and tool selections at the process planning level.

The use of commercial software tools that predict metal cutting responses such as forces, power, temperature, stresses, and tool wear is becoming more commonplace to enhance productivity, increase process efficiency, and reduce cost. Many approaches have been proposed to simulate machining processes and a number of these are successfully employed in industry.

The CCAT/NCAL M&S team considered a number of approaches for physics based machining process analysis:

- Reducing product development cycle time through simulation and analysis
- Improving productivity and part quality through process optimization
- Promoting the functionality of digital manufacturing process design tools.
- Validation of commercial off-the-shelf (COTS) analysis and optimization software solutions and determining how to make widely available for aerospace supply chain sized manufacturing companies

Methods / Procedures
Recent advances in physics-based software tools for the simulation of various machining processes makes it possible for manufacturing industries to develop simulation-based empirical models for the machining process responses and utilize those models to further optimize the machining processes.

There are several key technologies that the CCAT/NCAL M&S team examined to conduct machining optimization. A survey of these tools is shown in the table below:

Table 2 Survey of CCAT/NCAL M&S Tools

Optimization Technology	Software Developer	Application in Machining Process	Technology Capabilities
AdvantEdge FEM	Third Wave Systems	Design and optimization of new machining processes	Materials-based finite element modeling software for optimization of metal cutting processes
Multiple Response Statistical Optimization (MRSO)	Developed through a CCAT/NCAL and United Technologies Research Center (UTRC) Collaboration	Design and optimization of new machining processes	Generate multiple optimization strategies using AdvantEdge and Minitab to reduce on machine testing and the number of simulations by relating cutting parameters to machining responses
Production Module 3D	Third Wave Systems	Optimization of existing machining processes	Conduct cutting force analysis, reducing cycle time and maximizing machine performance through cycle time calculation, including cut/non-cut time, and instantaneous force and power prediction
VERICUT OptiPath	CG Tech	Optimization of existing machining processes	Based on the amount of material removed in each segment of the cut, the software calculates and inserts improved feed rates where necessary
Mastercam Intelligent Feed Rate Optimization	CNC Software, Inc.	Optimization of existing machining processes	Automatically apply variable feed rates to their 2- and 3-axis machining operations in the Mastercam CAM system
Machining Gamer Changer	CCAT/NCAL, Third Wave Systems, and CNC Software Collaboration	Optimization of existing machining processes	Reduce machining cycle times, apply minimal effort to gain these efficiencies, manage only one version of the tool path file to maintain by employing the Production Module optimization technology within the Mastercam CAM interface

Third Wave Systems' AdvantEdge™ FEM

AdvantEdge is a materials-based solution for optimization of the metal cutting processes. This physics based modeling and simulation software provides the user with the ability to do a detailed analysis of milling, drilling, and turning processes. It provides the user with the ability to iteratively improve material removal rates, part quality, and tool performance as they design their process for machining of new parts, as well as improving existing processes.

Today, the process designer typically selects removal rates from available speed and feed tables, either provided by tool suppliers or the Machinery's Handbook. While these tables provide a good approximation of the best selection of operating parameters, manufacturers strive to obtain the optimal selection for their process. To do so, they will most commonly perform on-machine tests of the selected cutting tools to gain a better understanding of how they will perform. Throughout these tests, the machinist will often observe the effect these cutting parameters have on process constrains such as spindle power and amount of wear on the tool. By running a variety of cutting conditions, it is possible to determine which selection leads to the greatest reduction in manufacturing costs associated with tool life, part cycle time and those associated with chip control. This iterative process, however, takes equipment out of production for the development of the process.

To assist in this method, AdvantEdge™ FEM provides the ability to perform simulated test cuts in a physics based virtual environment. Within the FEM software, it is possible to represent most aspects of the metal cutting process to predict cutting conditions. To fully model the process, the user is able to enter tool information, ranging from geometry, material (including coatings), workpiece information (including advanced material models), and process conditions, such as feed, speed, and tool engagement. Using these inputs, the software then computes a variety of process conditions beyond what is available from on-machine cutting. In addition to the machine power and tool wear, the software is also able to provide predicted responses for forces, temperatures and tool stresses (for the tool and the material being cut). By performing these tests off-line, the costs associated with the iterative on-machine testing are greatly reduced. The production machines are able to continue producing deliverable parts and the cost and time for both the physical test part and tools is dramatically reduced as well.

Within the software, it is possible to represent most aspects of the metal cutting process to predict cutting conditions. To model the process, the user is able to enter tool information, work piece information, and process conditions.

Tooling Capabilities

- Standard cutting tool geometries with rake and clearance angles
- Full drawing capability to define custom tool geometries with chip breaker features
- Definition and resolution of cutting edge radius (sharpness)
- Tool coating layers

Materials

- Library of experimentally and numerically validated material models for work piece and tool
- Custom material input capability for elasticity, strain hardening, strain rate dependency and thermal softening

Machining Parameters

- Process type options include: turning, sawing, broaching, up milling, and down milling
- Ability to input machining parameters such as feed, speed, depth of cut, length of cut, radial engagement, etc.
- Burr simulation capabilities

Based on these inputs, the software computes responses beyond what is typically available from on-machine cutting like spindle power and tool wear. Although temperature and forces have a great impact on these responses, they can only be inferred by the measurable results on the shop floor. It is these responses that give the manufacturer insight on how the cutting parameters affect the overall process.

Visualization of Results

- Automated Analysis Tools
- Graphical display of analysis output
  - Chip characterization
  - Cutting and thrust forces
  - Tool/work piece temperatures and heat generation rate
  - Plastic strain and strain rate
  - Misses, pressure and maximum shear stresses

To improve a process, AdvantEdge can typically used in a manner such as the following example to improve tool wear. The manufacturer begins by gathering pertinent resource information. This information will be used to characterize the tool and work piece. Varying process parameters are then selected for testing. These selected values often come from programmer knowledge, or are similar to those provided by speed and feed tables. Once the simulations are completed, the automated tools within the software can then be used to determine a numeric value for the critical process parameter of choice. The flow chart below shows how the process could be used to select the optimal processing conditions to minimize tool wear as an example.

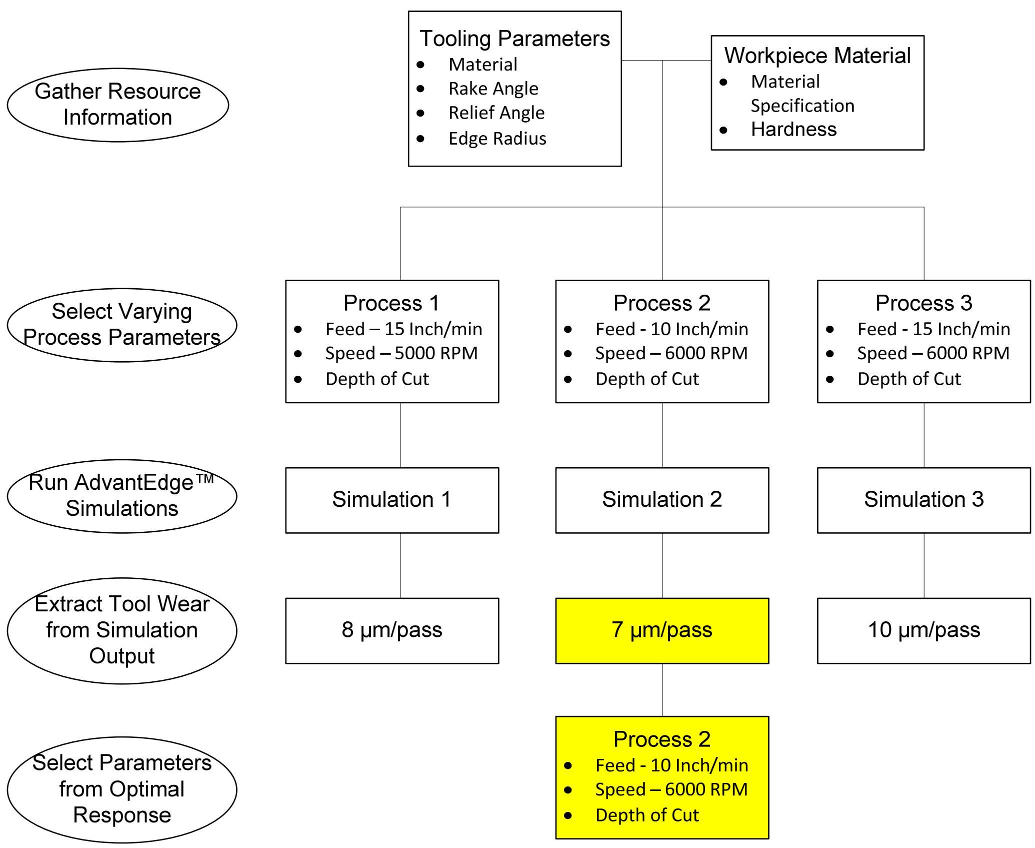

Figure 30 Example Process Flow Chart

During the execution of this project activity, the CCAT/NCAL M&S team attended AdvantEdge product training at Third Wave's facility, and hosted training events for its staff and industry partners at the CCAT facilities in East Hartford, CT. CCAT/NCAL engineers became adept at using the system, and even developed an associated technology, called Multiple Response Statistical Optimization (MRSO), to facilitate ease of generating machining simulations in AdvantEdge.

Multiple Response Statistical Optimization (MRSO)

The CCAT/NCAL M&S team and engineers from United Technologies Research Center (UTRC) identified a method of streamlining the simulation approach of Third Wave AdvantEdge, employing a strategy referred to as Multiple Response Statistical Optimization (MRSO). This approach reduces the number of AdvantEdge simulations required to achieve optimal cutting parameters. The approach uses both AdvantEdge, for its detailed materials-based FEM analysis of metal cutting processes, and Minitab, a statistical analysis package known for its ability to conduct design of experiments, statistical data analysis, modeling, and response optimization. The key capabilities of this technology include:

- Uses physics based models to simulate machining processes
- Predicts machining behavior in given domain
- Determines machining parameters that jointly optimize single or multiple objectives
- Reduces process time and cost, and increase productivity
- Reduces number of calibration and validation tests

The approach consists of the following six basic steps:

1. Identify machining parameters (factors and responses) to be optimized from AdvantEdge: The user defines the conditions of the given cutting operation, for example, Depth of cut, cutting speed, feed rate, tool material, etc., within the AdvantEdge system.
2. Conduct design of experiment using Minitab: Within the Minitab statistical analysis software, the user inputs the domain of each input factor. Minitab sorts the data into a matrix of varying cutting condition parameters that represents the simulations required to model the given domain of factors.
3. Run simulations using Third Wave AdvantEdge: The user runs the AdvantEdge physics-based simulation technology to model each set of cutting conditions suggested by Minitab.
4. Gather data from simulation: The user passes the data generated from AdvantEdge into a visualization software tool to extract the desired responses for each set of cutting conditions, for example Force, Temperature, and Stress.
5. Build statistical analysis & model using Minitab: The user passes the simulated responses into Minitab where an empirical model is fit to the range of the data.
6. Optimize responses optimization using Minitab: In this final stage, the user can set a target and weighting factor for each response. Minitab will then select the best input parameters to achieve these set targets based on the models created in step 5.

In all, the MRSO approach reduces number of AdvantEdge simulations required to optimize the machining approaches.

Once completed, an empirical model is found that relates the cutting parameters to the machining responses. With this model, users can predict the change in responses immediately without the need for further testing at those particular parameters. This method is more effective then previous methods of trial and error on a machine tool. This allows for the selection of optimized cutting parameters both quickly and efficiently.

Thus far, this method has been utilized internally within the CCAT/NCAL M&S Team to verify and validate various projects completed in AdvantEdge Production Module. The CCAT/NCAL M&S group has also presented this method of machine optimization at the 2007 Third Wave Users Group Conference in Seattle, WA. This approach can be extended to other machining processes to determine parameter settings that jointly optimize a single response or a set of responses. If applied appropriately, this application can significantly reduce process time and cost, and increase productivity. However, the CCAT/NCAL M&S team discovered that statistics-based empirical models for responses are not substitutes for physics-based models; they can interpolate reasonably well but the quality of extrapolation beyond the range of the available data can be poor. Additionally, there is a risk of over-estimation of its capability; it is a method to exploit available information from simulation, not to search for new information.

AdvantEdge Production Module

Gcode Before Production Module	Gcode After Production Module
X-35823Y11932	X-35823Y11932
Z64080	Z64080
G1Z63080F30.0	G1Z63080F50.0
X-32793Y9723F10.0	X-32793Y9723F20.0
X-11580Y7462	X-11580Y7462F13.6
Z63735	Z63735F50.0
X-10666Y7867	X-10666Y7867F20.0
G0Z74000	G0Z74000
X-35820Y11968	X-35820Y11968
Z64000	Z64000
G1Z62485F30.0	G1Z62485F50.0
X-32789Y9759F10.0	X-32789Y9759F20.0
X-12407Y7586	X-12407Y7586F13.6
Z63116	Z63116F50.0
X-11493Y7992	X-11493Y7992F20.0
G0Z74000	G0Z74000
X-35816Y12004	X-35816Y12004
Z63000	N161Z62890
G1Z61890F30.0	G1Z61890F50.0
X-32785Y9795F10.0	X-32785Y9795F20.0
X-13262Y7714	X-13262Y7714F13.6
Z62504	Z62504F50.0
X-12348Y8119	X-12348Y8119F20.0
G0Z74000	G0Z74000
X-35812Y12040	X-35812Y12040

Figure 31 Comparison of Machining Gcode Before / After

The software evaluated and employed by the CCAT/NCAL M&S team for physics based machining process analysis included a system from Third Wave Systems, Inc., called AdvantEdge Production Module. This package integrates CAD, CAM, machine dynamics, and work piece material properties into one model. Developed in conjunction with General Motors research (GM), this module is specifically designed to conduct cutting force analysis, reduce cycle time and maximize the machine performance. The system features complete CAD and G-code import for tool path visualization and ease of work piece set-up. The software's capabilities include cycle time calculation, including cut/non-cut time, and instantaneous force and power prediction, resulting in optimized machine utilization. This optimization is achieved through a method of load balancing on the tool by changing feed rates throughout a given machine code. The image on the right shows a sample of the before and after Gcode format that has been "optimized" using this force balancing approach. All ISO-standard tool geometries and tool-holder configurations are used in modeling turning, milling, and drilling processes and finished parts can be exported for analysis of subsequent operations. All ISO-standard tool geometries and tool-holder configurations are used in modeling turning, milling, and drilling processes and finished parts can be exported for analysis of subsequent operations.

The CCAT/NCAL M&S team worked with a number of aerospace engine component suppliers with the purpose of utilizing physics based machining process modeling technology to accurately model and optimize the machining processes of aerospace materials. The team conducted a pilot study on the roughing operations of part provided by one such company, Sterling engineering. The team employed a combination of Third Wave Systems' Production Module 3D and CG Tech's VERICUT software tools to investigate a roughing operation for a supplier of military helicopter components.

The team analyzed the roughing process of the part using Production Module 3D. After importing the necessary tool path and geometry information, the software returned information on tangential force over the entire cycle. Taking the approach of load balancing, each tool was independently optimized. By assuming the tool can withstand the highest force predicted by the software, it steps through each line in the code to increase feed rates. These increase feed rates raise the tangential force to no larger then the maximum force, and in turn reduces the time required to cut the part. With this approach, a 25%-reduction in total production time was achieved for the current tool material and geometry.

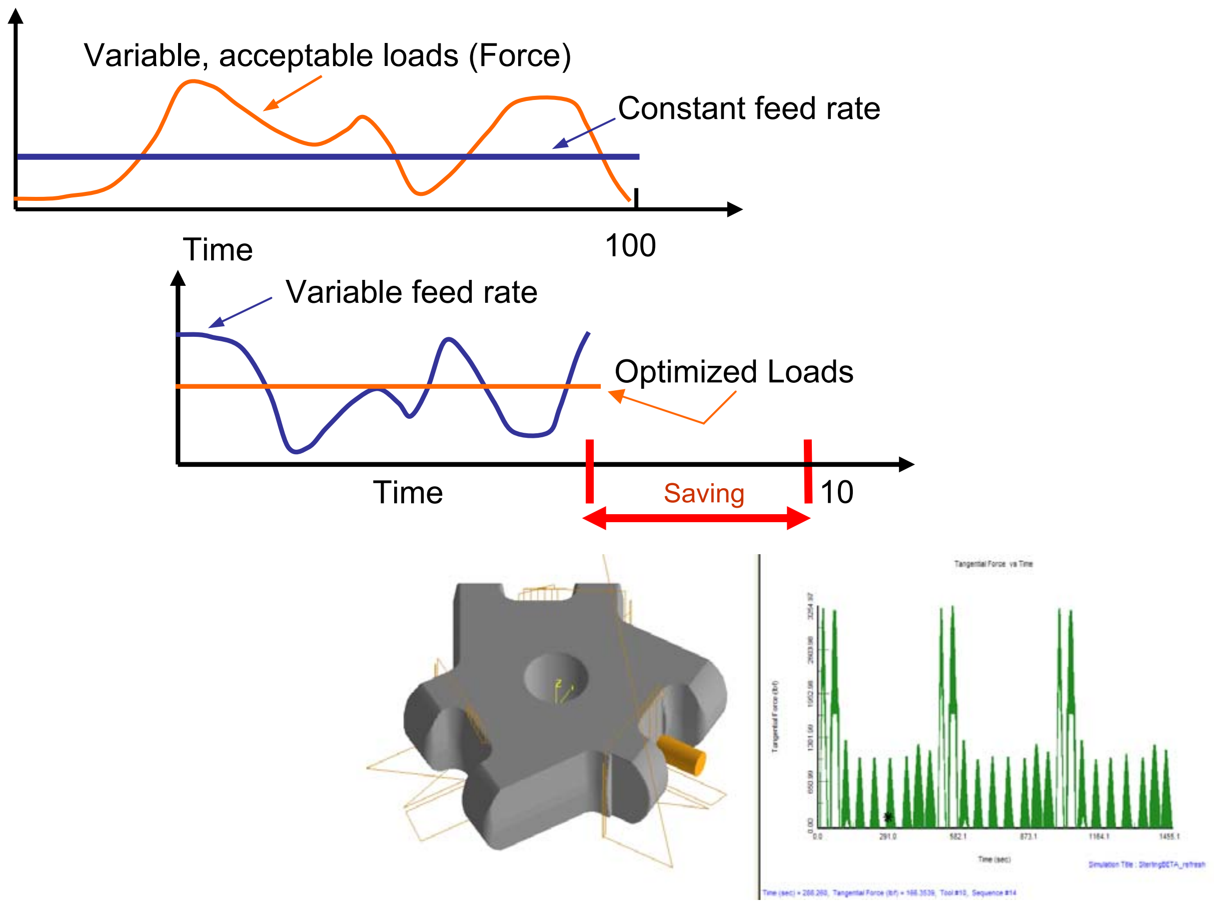

Figure 32 AdvantEdge Production Module Optimization Process

In addition to the Production Module analysis, a VERICUT machine simulation analysis of the cutter path indicated that several tools were in contact with work piece in the rapid feed mode, resulting in very high forces. The team concluded that the tool path's rapid feed rate had to be reduced. Also, by changing the insert carbide from GC 2040 to GC 4030, as recommended by the company's tooling suppliers, Sandvik and Kennametal, a 50% reduction in total cutting time was achieved. The CCAT/NCAL M&S team provided the supplier with a new machining centerline data file.

Overall, the analysis of the roughing process on this part suggested a 25% reduction in machining cycle time could be achieved by changing cutting speed and feed only within the tool path. The team also was able to show that an additional 50% reduction in machining time could be achieved if the tool insert material could be changed.

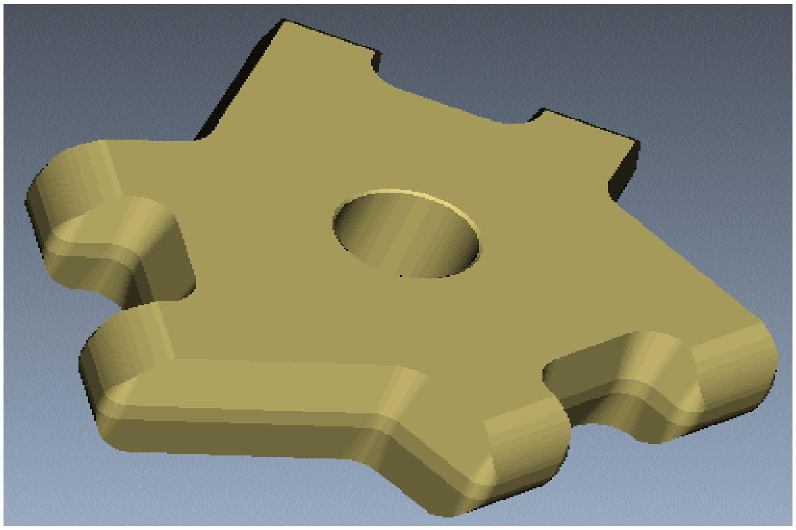

Figure 33 Forging Geometry Displayed in VERICUT

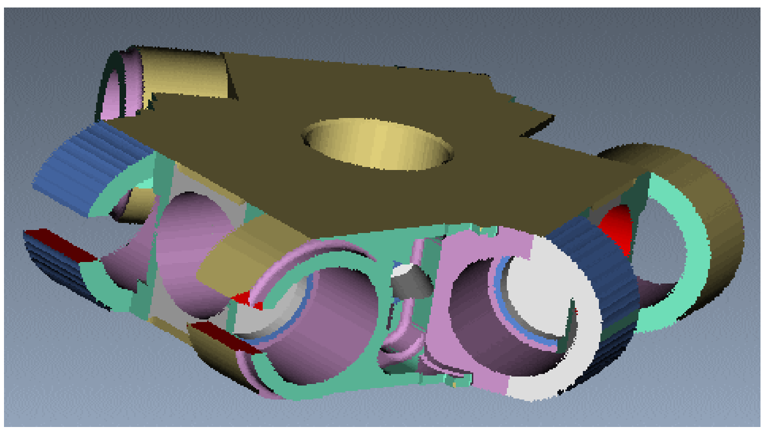

Figure 34 Part Geometry after Roughing

The key to applying machining optimization technology is to look at the process in a holistic way: Considering tool geometry, part geometry, cutting tool forces, etc. all as critical elements of the potential to optimally apply efficient cutting parameters. Additionally, applying a number of technological approaches worked most effectively.

The Maximum tool / work piece interface can be obtained using VERICUT and by applying Production Module 3D recommended feed changes and increase speed to lower cycle time for several identified tools.

Mastercam Intelligent Feed Rate Optimization

The Mastercam Intelligent Feed Rate Optimization technology allows the user to automatically apply variable feed rates to their 2- and 3-axis machining operations in the Mastercam CAM system. CAM software applies a single feed rate on tool path operations as a standard. An entire job at a single feed rate reduces efficiency.

Running the same job at varying feed rates can save time, tool wear, and money. Mastercam's Intelligent Feed Rate Optimization function can optimize any 2- or 3-axis tool path based on volume of material being removed and machine tool limitations to give an efficient, varied feed rates tailored to each job. The Mastercam Intelligent Feed Rate Optimization system accomplishes the following:

- Automatically vary feed rates based on volume. More material and the cutter moves slower; less material and the cutter moves faster.
- Automatically ease the tool into and out of corners.
- Create libraries of optimization settings for different jobs.

OptiPath

OptiPath reads the NC tool path file and divides motion into a number of smaller segments. Where necessary, based on the amount of material removed in each segment, it assigns the best feed rate for each cutting condition encountered. It then outputs a new tool path, identical to the original in its geometric path shape but with improved feed rates. The software does not alter the trajectory. The user inputs ideal feed rates for a number of predetermined machining conditions. CG Tech's OptiPath automatically combines them with factors such as machine tool capacity (horsepower, spindle type, rapid traverse speed, coolant, etc.); fixture and clamp rigidity; and cutting tool type (material, design, number of teeth, length, etc.), to determine optimum feed rate for each segment of each cut. OptiPath also considers factors dependent on the nature of the tool path such as:

- Cut depth
- Volume removal rate
- Entry feed rate
- Cut width
- Cutter wear
- Cut angle

This solution is automatic and determines the best feed rates before the program is loaded on the machine. It also uses the expertise of the NC programmer and machinist to determine the best feed rates for specific cutting conditions.

The CCAT/NCAL M&S team applied OptiPath to Fenn's NC program and reduced machining cycle time by nearly 10% overall. This was through feed rate changes and additions only. Fenn's programmer also reprogrammed several portions of the path to increase step over tools was able to reduce machining time by an additional 30%.

The combined reduction in cycle time is to be verified on the machine during the next production run. Production Module, another optimization package from Third Wave Systems was also considered but was not used due to the complexity of processing 5 axis G code and Fenn's request that the optimization break up existing cuts for additional feed adjustments (a feature that is unavailable in Production Module).

Gaining efficiencies in tool path processes is a critical need for aerospace supply chain manufacturing. The CCAT/NCAL M&S team is demonstrating these capabilities to companies and showing them how even a small percentage in reduced machining cycle times can have a profound impact on productivity. The image below shows a before and after section of Gcode as processed within the Optipath module.

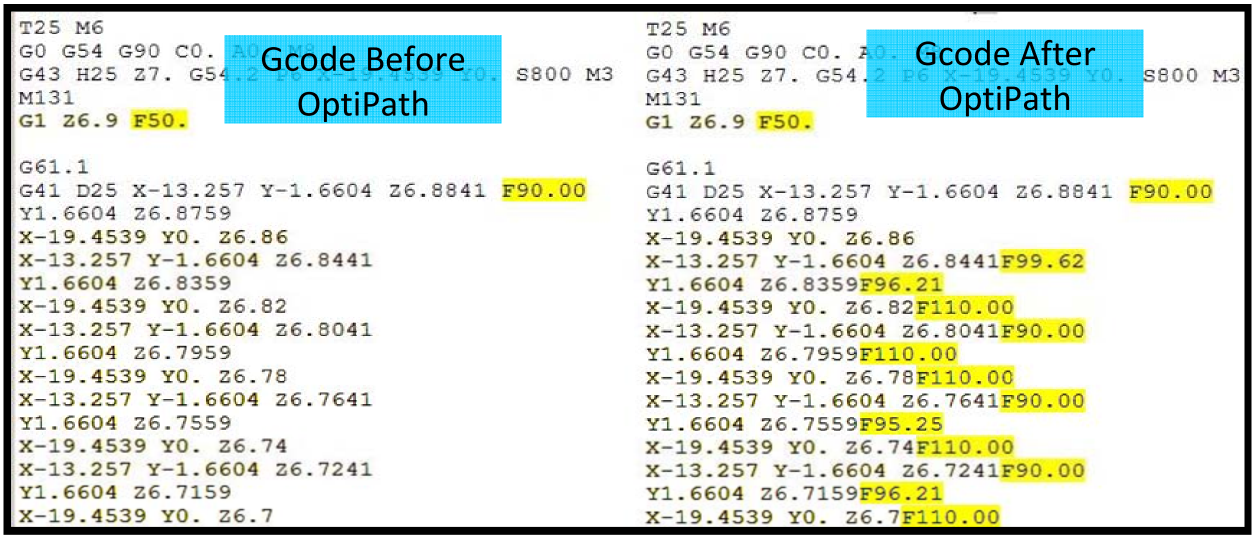

Figure 35 Comparison of Machining Gcode before / After OptiPath

The CCAT/NCAL M&S team noted that OptiPath automatically adjusted feed rates based on the specific cutting conditions for each segment of the tool path, as defined by the Fenn personnel. It is the only product available that optimizes feed rates based on solids verification technology. Rather than react to feedback from the spindle drive motor, as is the case for adaptive controllers on machine tools, OptiPath assigns the best feed rate based on the current cutting conditions (volume of material being removed, depth, width, and angle of cut). Instead of striving for constant spindle load, OptiPath maintains a constant cutter load. For high-tech milling cutters, maintaining a constant cutter load prolongs tool life. OptiPath also appears to be a more cost effective method of feed rate optimization. A small number of software licenses can provide optimization capability for dozens of CNC machines - of all types, driven by all kinds of controls, whereas an adaptive controller is limited to a single machine.

The CCAT/NCAL M&S team engaged with Fenn Technologies, a Newington, Connecticut aerospace supply chain manufacturer, skilled in the production of structural parts and precision assemblies. The company identified a helicopter production part with long machining cycle time. To increase productivity the cycle time required for this part needed to be reduced from approximately six hours. Fenn worked closely with the M&S team to plan approaches to reduce the machining cycle time of the part.

Fenn was already attempting to reduce overall machining cycle times on this particular process by manipulating their tooling and tool path operations. The company provided this operation setup to the CCAT/NCAL M&S team in CG Tech's VERICUT, which allowed the team an opportunity to test and demonstrate CG Tech's OptiPath optimization module, a technology that

Fenn does not currently own. VERICUT Module: OptiPath adjusts NC program cutting speeds to make the machining process faster, more efficient, and of higher quality. OptiPath works on a straightforward premise: Based on the amount of material removed in each segment of the cut, the software calculates and inserts improved feed rates where necessary. In areas of light material removal OptiPath speeds feed rates, and decreases the feed rates as more material is removed. Without changing the cutting tool trajectory, the updated information is applied to a new tool path.

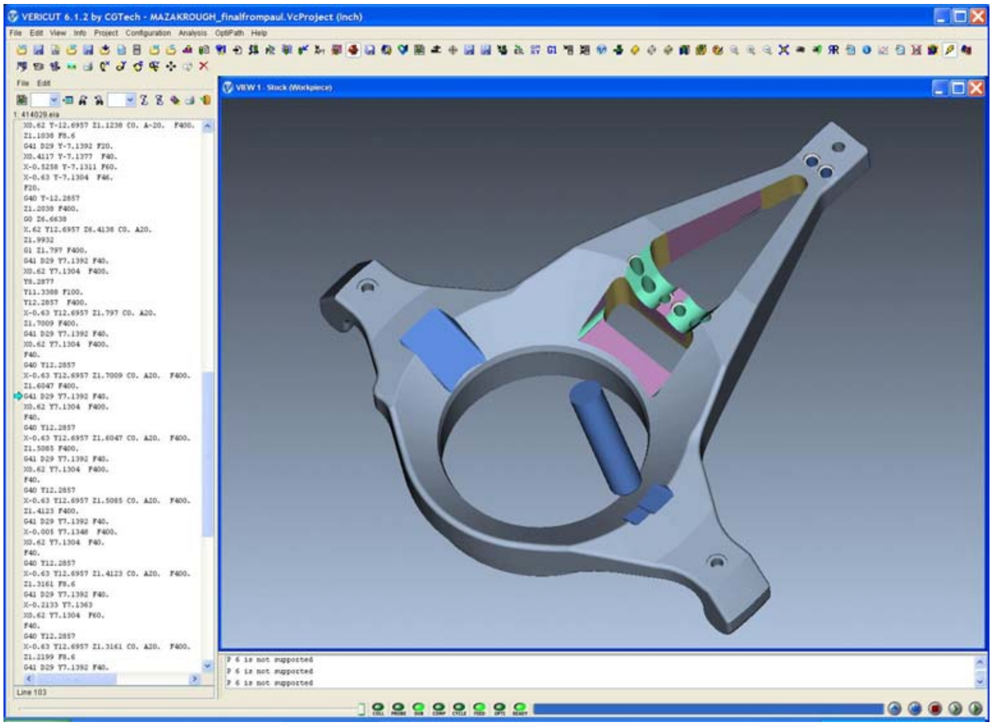

Figure 36 Component Displayed In VERICUT System

Machining Game Changer

New software technologies are emerging that engage sophisticated algorithms to seek out significant efficiencies in machining understanding the physical properties of the part and the tool machining it. The CCAT/NCAL M&S team identified the value of combining the latest CAM software technology with an emerging physics-based optimization software system. The team saw the advantage of reducing machining cycle times while not affecting the original tool path. Called physics-based machining optimization software, this technology represents one of the next frontiers of machining capability.

The team encouraged the development of a specific technology interface between the most commonly implemented CAM software system, CNC Software's Mastercam and a leading edge physics-based machining optimization technology, third Wave Systems' Production Module 3D, with the purpose of making these technologies readily available to the aerospace manufacturing supply chain. The CCAT/NCAL M&S team tested the new concept in a field setting.

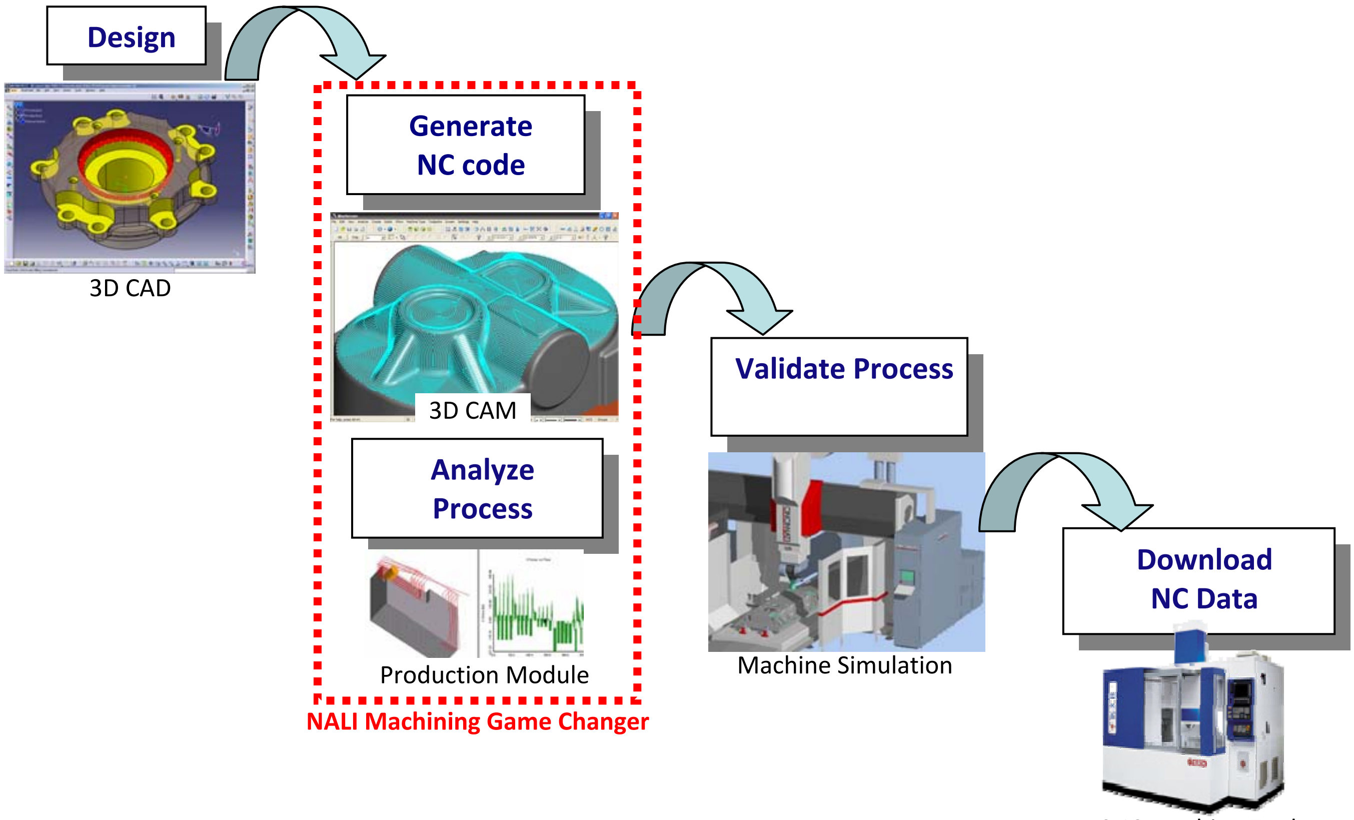

Figure 37 CCAT/NCAL Machining Game Changer Process

CCAT's NCAL M&S team conceived a revolutionary approach to implementing machining optimization: The Machining Game Changer. The M&S machining specialists developed a plan to combine the machining optimization capabilities of Third Wave Systems' Production Module system into the interface of a CAD/CAM software technology that would be commonly employed in machine shops: CNC Software's Mastercam CAD/CAM system. Users of Mastercam could realize the advantages of engaging a physics-based optimization technology into the CAD/CAM software they work with every day. The benefits of this technology include the ability to significantly reduce machining cycle times, apply minimal effort to gain these efficiencies, manage only one version of the tool path file to maintain.

CNC Software's Mastercam CAD/CAM technology is the most commonly used CAM software worldwide (source: CIMdata, Inc., www.cimdata.com) and remains a top program of choice among CNC programmers. Mastercam is a comprehensive milling package with a simplified, customizable interface, more power, and even faster, robust tool path calculations. Mastercam offers solutions for designers and NC programmers involved in milling, turning, wire EDM, router programming, plasma cutting, lasers, and 3D design and drafting. CNC Software's customers range from one-person job shops to Fortune 100 manufacturers. The same software that is utilized by corporations such as Boeing, IBM and Sikorsky is still affordable enough for the small job shop. To ensure a new generation of trained metalworking personnel, Mastercam is available to educational institutions.

Third Wave's Production Module 3D is an advanced analysis and optimization tool for CNC milling. Though the benefits of applying the software are great, issues with time involved to setup the case and the fact that once an optimization is run there are two code streams to maintain hinder its usefulness to small manufacturers. The CCAT/NCAL M&S team proposed the idea that PM3D be directly linked to CAM in order to maintain association. Its technology was developed, and field testing of the system was required. The goal was to generate optimized code through the Game Changer that was still associated with the CAM system and reduce the machining cycle time of the test part.

CNC Software programmed a circle diamond square machine acceptance part for the testing and demonstration of the Game Changer. Once tool pathed, the Mastercam file was passed to the CCAT/NCAL M&S team for optimization. The Game Changer interface was used to export the roughing operations into the optimization environment and with minimal additional effort forces were calculated and the optimization was run. Optimization involved adding or changing feed rates throughout the path to balance loading on the tool. Once optimization was complete code was imported back into the Mastercam and posted out to the machine from the CAM software. CNC Software's Makino S56 was used for the testing. Cycle time for roughing on the part as programmed ran 30 minutes and 29 seconds. After optimization with the Game Changer interface the cycle time was reduced to 22 minutes and 15 seconds, a 27% reduction in roughing cycle time. This was an impressive result attained by an independent party, CNC Software personnel. In fact, CNC Software had been developing a feed rate optimization technology for their own CAM software.

Conclusions

CCAT's NCAL M&S team, after conducting the above-noted field demonstrations of the technologies described above, has learned important lessons about the constraints, limitations and capabilities of these technologies, and we have outlined them in the table below.

The initial success of the Machining Game Changer was seen as encouraging to the CCAT/NCAL M&S team. There are several important conclusions to be drawn from the analysis. The Game Changer provides a significantly streamlined and easier to use user interface, as compared to the interface and methodology of the Production Module 3D system, which might make the Game Changer an easier technology to leverage into small- to mid-sized manufacturers who are currently Mastercam software users. Beta testing is required to validate the capability of the technology at aerospace suppliers. To accommodate the abilities and economies of scale within the aerospace supply chain, it is imperative that Third Wave Systems develop something like a "Production Module 3D Lite" system, effectively a scaled back version of their full fledged product. The production would present fewer advanced options, offer a project setup wizard to mandate the selection of parts and processes that clearly fit within the product's capability, and offer that system at a price point that the average Mastercam software user would be able to absorb.

The CCAT/NCAL M&S team feels strongly that by following these conclusions, the implementation of the Machining Game Changer could radically impact American manufacturing, increasing productivity and reducing inefficiency. The CCAT/NCAL M&S team believes that the Machining Game Changer has the potential to increase American machining capacity by greater than 20%.

Table 3 Capability Matrix of Simulation/Optimization Technologies Evaluated by CCAT/NCAL M&S Team

Capabilities / Technologies	AdvantEdge FEM	Multiple Response Statistical Optimization (MRSO)	Production Module	VERICUT OptiPath	Mastercam Intelligent Feed Rate Optimization	Machining Gamer Changer
Finite Element Modeler	☑	☑ via AdvantEdge	■	■	■	■
Machining processes	Milling, drilling, turning, sawing, and broaching	Milling, drilling, turning, sawing, and broaching	Milling, drilling, and turning	Milling	Milling	Milling
Multiple optimization strategies	☑	☑	☑	☑	■	☑
Optimization Approaches	Optimize for machine cycle time, tool wear, chip control, etc.	Optimize for machine cycle time, tool wear, chip control, etc. via AdvantEdge	Primarily tangential force balancing Temperature Power Chip load	Volume of material removed Chip Load	Volume of material removed	Primarily tangential force balancing Temperature Power Chip load
Axes	■	■	Up to full 5 axis	Up to full 5 axis	2 and 3 axis	Up to full 5 axis
Data input	■	■	APT CL Gcode Tool data input	Gcode	Mastercam MCX	Mastercam MCX APT CL Tool data input
Break cuts	■	■	Feed rate changes to available lines of code only, no added or modified geometry	Option to break up cuts for smoother feed transitions and elimination of air cuts	Breaks up cuts for smooth ramp up and down of tool feeds	Feed rate changes to available lines of code only, no added or modified geometry
Association with CAM program	■	■	■	■	☑	☑
Unique capability	Robust finite element modeling of machining strategies	Reduces number of simulations required to achieve optimal results	Ability to analyze a variety of parameters throughout the path	Significant ease of setup and use for VERICUT users	Direct link to industry accepted CAM system	Ability to analyze a variety of parameters throughout the path within industry accepted CAM system
Limitation	Time to run simulations is substantial	Requires knowledge of AdvantEdge and Minitab software	Substantial learning curve	NC program looses association with CAM	Limited to 2- and 3-axis milling	Currently functions only with Mastercam

☑ *Has this capability* ■ *Not applicable*

References

- *A Multiple Response Statistical Optimization Approach for Machining Processes through Design of Experiments and Physics-Based Simulation*, Dr. Peng Wang, Dr. Tahany el-Wardany, United Technologies Research Center. October 2006.
- *AdvantEdge Production Module Demonstration*, Third Wave Systems.
- Connecticut Center for Advanced Technology, Inc. and Third Wave Systems, Subcontract Agreement # 06-NO03, August 3 1,2006.
- Information on AdvantEdge and AdvantEdge Production Module technologies provided by Third Wave Systems, Inc., 7900 W 78th St., Suite 300, Minneapolis, MN 55439, www.thirdwavesys.com
- Information on CUTPRO and SHOP-PRO technology provided by Manufacturing Automation Laboratories (MAL) Inc., 2829 Highbury St. Vancouver, B.C. Canada V6R 3T7, malinc.com
- Information on Mastercam technology provided by CNC Software, Inc. 671 Old Post Road, Tolland CT, 06084, www.mastercam.com
- Information regarding OptiPath provided by CGTech, 9000 Research Drive, Irvine, California 92618-4214, www.cgtech.com
- *Machining Process Optimization Using ThirdWave Production Module, VERICUT & CutPro*. Presentation by Dr. Tahany el-Wardany, Dr. Peng Wang, United Technologies Research Center. June 2006.
- *Modelling and Simulation of High-Speed Machining*. Paper by T.D. Marusich and M. Ortiz, Division of Engineering, Brown University, Providence RI 02912, www.thirdwavesys.com/pdfs/tech/hsm.pdf
- *Optimization of Roughing Processes Through Modeling*. Presentation by Dr. Tahany el-Wardany, United Technologies Research Center. May 2006.
- *Project Reports: Interface of Third Wave Systems Production Module with a Market Leading PLM/CAM package*. By Sarang Garud, Project Engineer, Third Wave Systems, Inc. reports submitted periodically between: 10/18/2006 and 12/15/2007.

Participating Companies

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Sterling Engineering	236 New Hartford Road Barkhamsted, CT	John Lavieri, President Tim Conway, Eng. Manager
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TRUMPF Inc.	3 Johnson Ave. Farmington, CT	Holger Schlueter, Vice President Laser Alexander Teufel, CNC Programmer

2.2.7.2. Physics Based Simulations for Chatter Prevention

Overall Summary of Task

Work with local industry to evaluate and demonstrate the capabilities of COT solutions to evaluate chatter conditions to improve the quality of part machining.

Project team: Brian Kindilien (CCAT/NCAL), Matt Lloyd (CCAT/NCAL), Chris Pfeifer (CCAT/NCAL)

Introduction

An important technology the CCAT/NCAL M&S team employed in conducting physics based simulations for chatter prevention was from a company called Manufacturing Automation Laboratory (MAL). The two technologies the team used for physics based machining process analysis were called CUTPRO and SHOP-PRO. The CUTPRO technology is an advanced machining software that can help companies achieve the highest possible material removal rates, long tool and spindle life. The goal of the technology is to be able to manufacture parts correctly at the first trial with reduced production cost and machine down time.

Methods / Procedures

Cutpro

The CCAT/NCAL M&S team invested in two CUTPRO options for its physics based machining process analysis demonstrations: CUTPRO Milling and Modal Analysis modules. The Milling module is an accurate and comprehensive simulation software for optimum planning and troubleshooting of milling processes. The system has several significant capabilities:

- Simulates regular cylindrical endmills, variable pitch cutters, ball endmills, indexable cutters, serrated cutters and endmills with any user-defined geometry.
- Has built-in properties of variety of materials such as Waspalloy, Inconel, Aluminum and Titanium alloys, Steels, and standard Sandvik materials.
- Accepts dynamics parameters of the machine tool and workpiece manually by the user or in variety of formats (i.e., frequency response functions (FRF), uff, HP sdf, cmp files) created in CutPro or other commercial modal analysis software packages.

The CUTPRO Milling module can support machining processes by making the following predictions and analysis:

- Cutting forces in three directions
- Vibrations in the feed and normal directions (x,y)
- Surface finish caused by feed marks, static and dynamic (chatter) deflections
- Stability Lobes: Most accurate predictions of chatter free axial and radial depth of cut and spindle speeds
- 3D Chatter stability diagrams
- Design and analysis of inserted/indexable cutters
- Design and analysis variable geometry helical end mills
- Design of variable pitch cutters tuned to a specific material and spindle for chatter suppression
- Design and analysis of serrated cutters
- Experimental modal analysis at the tool tip (automatic identification of natural frequencies, modal stiffness and damping ratios)
- Automated identification of cutting constants from milling tests
- User specific material data entry

- Simulates stability lobes and forces for a batch of conditions with multiple immersions

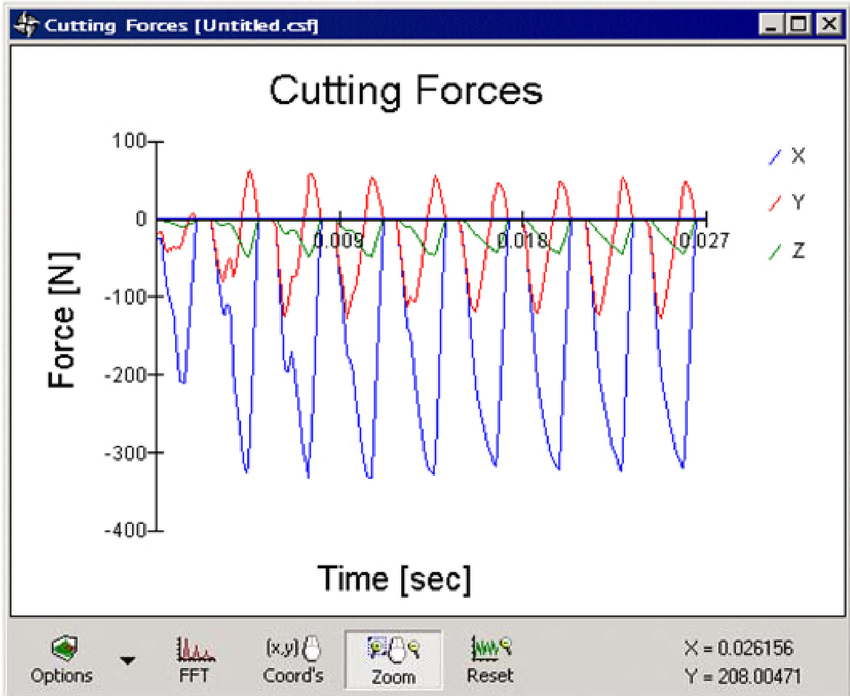


Figure 38 Measured Cutting Forces Within CUTPRO

The CUTPRO Modal Analysis module, adopted by the CCAT/NCAL M&S team, is a hardware/software combination that determines the dynamic characteristics of a machine tool system and mode shapes from FRF that are measured at various geometric locations on a system using transfer function measurement software called MALTF, an impact hammer and an accelerometer. The CCAT/NCAL M&S team identified the following critical features of the CUTPRO Modal Analysis system:

- Predicts natural frequency, damping ratio, and stiffness of each mode from FRF measurements at the tool tip
- Receptance Coupling of defined end mill with the measured spindle/tool holder
- Flexible tool analysis that allows the user to predict the transfer function on a slender tool tip where accurate measurement cannot be performed due to multiple hits
- Predicts and displays mode shapes (1D-2D) and modal parameters from FRF measurements made along the structure axis, i.e. spindle, thin webs, machine tool column or fixture
- Accepts FRF measurement files in MALTF, ASCII, HP SDF, UFF file formats

Because the CCAT/NCAL M&S team realized that accurate measurement from the tool to analyze tool chatter conditions, they also invested in the MAL MALTF system, a versatile transfer function measurement program, tested for National Instruments DAQ Card AI-16E-4 (a PCMCIA card used in notebook computers) and PCI MIO 16E 4 (a PCI card used in desktop computers). The transfer function measurement is performed with impact hammer tests. The results from these tests can be displayed in different formats, and saved to disk to be imported into modal analysis software. After performing a series of impact hammer tests, the resulting transfer function will be displayed on screen. Various display options can be changed during and after the impact hammer tests to alter the way in which the information is displayed on the screen. The transfer function itself can be viewed in magnitude-phase mode, or alternately in its real and imaginary components.

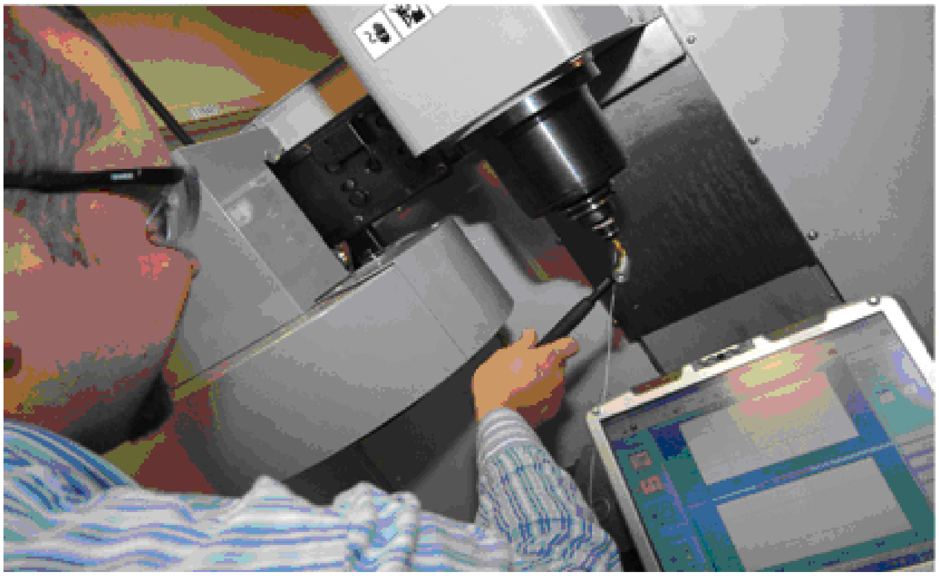


Figure 39 CCAT/NCAL Engineer Testing Cutting Tool

The linear part(s) of the transfer function can be viewed as linear or logarithmic values. To check the validity of the results, the input signals can be viewed in time domain, or as a frequency spectrum. In addition, the transfer function can be saved in binary format and opened with the all measurement settings at a later time. The CCAT/NCAL M&S team identified the following critical features of the MALTF system:

- Allows measurement in multiple directions
- Allows to use different output sources (i.e., accelerometer, displacement sensor, shaker and force sensor) and displaying the results in any format of a/F, X/F or F/F
- Has expert system that automatically investigates the quality of the measurement and leads the user what to do in the next step until all measurements meet certain quality requirements. This reduces the inexperienced-user's faults in the measurements and provides consistency in the measurement quality
- Displays input and output signals in time domain, Magnitude & Phase, Real & Imaginary part, Power spectrum and Coherence
- Displays input and output signals in time domain, Magnitude & Phase, Real & Imaginary parts, Power spectrum and Coherence of the measurement
- Saves the measurement data in a standard format (frf) that can be directly used in the process simulation modules in CutPro or other software packages

Finally, the acquisition of data in CUTPRO requires the use of a technology called MALDAQ, a highly versatile PC-based data acquisition and analysis software. The program was developed and tested for the National Instruments DAQ Card AI-16E-4 and 6062E, which are PCMCIA cards used in notebook computers. The software is also compatible with many analog data acquisition devices available from National Instruments. The CCAT/NCAL M&S team identified the following critical capabilities of the MALDAQ system:

- Max. 500 kHz sampling frequency
- Up to 8 channel data acquisition
- Logging and streaming data to disk until the disk gets full
- Monitoring real-time data
- Displaying data in time or frequency domain
- Loading and analyzing any range of saved data
- Digital filtering options

Figure 40 CCAT/NCAL Engineers Testing Tools With CUTPRO

SHOP-PRO

SHOP-PRO is a cost effective and practical chatter avoidance tool kit to achieve high speed-high performance machining. It is an entry level, effective, integrated machine tool testing and chatter vibration avoidance product. It can easily be used by machine tool operators and production engineers due to internal logic and a simple graphical user interface. After a few minutes of tap testing, chatter vibration free spindle speeds and depth of cuts are found and the material removal rates are significantly increased. SHOP-PRO's integrated expert system automatically generates a machining problem diagnosis by reading data on recorded sound and specified cutting conditions. The system employs the following process:

- Cutter and material type selection by the user
- Voice-guided, quick tap testing of machine tools with an impact hammer
- Graphical output displays chatter stability lobes and corresponding torque/power curves
- Expert system diagnoses and avoids chatter, tool setting and tolerance violation errors

Examining existing production machining processes for opportunities to gain efficiencies in machining time, tool wear, and overall throughput is a critical requirement for aerospace suppliers. The CCAT/NCAL M&S team conducted a series a demonstrations applying advanced physics-based software systems, as well as some hardware-based diagnostic technologies, with the goal of validating these tools in the minds of aerospace engine component manufacturers.

B&E Tool, a Southwick, MA aerospace supply chain company approached the CCAT/NCAL M&S team to help diagnose a problem with a specific part and machine tool that were experiencing significant "chatter". Chatter is unwanted vibration during the cutting process, and can occur for many reasons. Chatter is a very common problem throughout the machining industry, and the ability to diagnose and solve such problems can be elusive. This issue created a noise hazard at the facility and made ear plugs a requirement. To combat the issue the CCAT/NCAL M&S team was asked to analyze the situation and make recommendations.

The MAL SHOP-PRO equipment was brought to B&E and used to take measurements on the current tool. B&E was using a 4 flute bull end mill to rough out Al6061-T6. Initial tap results showed that with the current setup they were running well above the recommended stability lobe curve. Though these recommendations would have eliminated the problems they also would have lengthened the process to an unacceptable cycle time. Instead the M&S team utilized the data gathered to interpolate results of a 3 flute cutter. Three flutes yielded better results at similar cutting parameters to their current process.

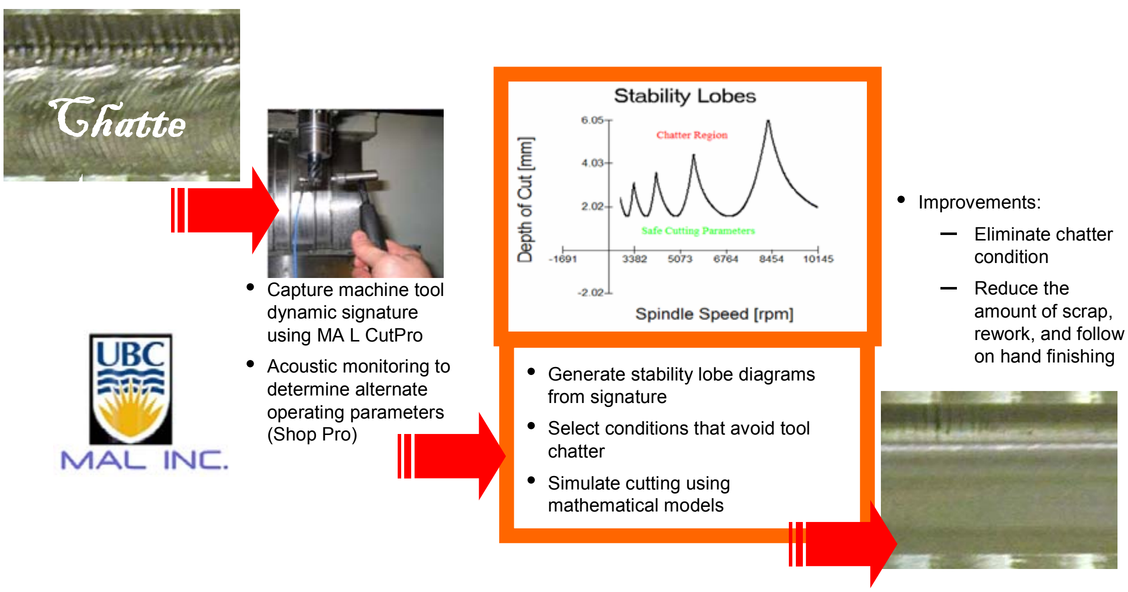


Figure 41 Chatter Analysis Process with CUTPRO

The CCAT/NCAL M&S team recommended making the change from the current 4 flute cutter to a 3 flute of the same geometry and modify the feed and speed slightly to maintain proper chip load on the tool. B&E purchased this tool and ran it on the next production cycle. Chatter was significantly reduced.

This capability is proving very significant to the aerospace supply chain because machine chatter is a significant problem. The CCAT/NCAL M&S team is applying this approach at several companies now, with positive results in reducing chatter, improving tool life, and preserving machine tool reliability.

Tool Monitor Adaptive Control System (TMAC)

Another important technology that the CCAT/NCAL M&S team considered carefully for physics based simulations for chatter prevention was a tool monitoring capability that could predict and interface with the machine tool controller to prevent failures. Caron Engineering's Tool Monitor Adaptive Control System (TMAC) functions to protect the CNC machine while providing valuable information about the cutting process. The system reduces the high cost of replacement tooling, lost production and rejected parts by effectively measuring tool wear in real time. It operates on the principle that the horsepower required to cut a part increases as the tool's cutting edges deteriorate. The TMAC accurately measures and displays true motor horsepower for spindle and/or feed axes, determines when a tool is worn or broken, and commands the machine control to take corrective action before tools or parts are destroyed.

A horsepower transducer is connected in line with the spindle motor. The TMAC system learns the peak cutting horsepower for each tool. You program extreme, wear and undercut horsepower limits, and the machine monitors the spindle horsepower and compares it to these limits. If the measured horsepower exceeds a limit, the machine responds by:

- Issuing a feed hold
- Interrupting the cutting program, then calling a sub-program to retract the tool
- Incrementing the tool life management
- Other actions based on customer requirements

Adaptive Control allows the TMAC to regulate the machine's feed rate override, maintaining a constant spindle motor horsepower during cutting. This feature optimizes cycle times, and includes Adaptive Extreme Limit checking. Adaptive Control reduces cycle time by optimizing feed rates, reducing feed rates in hard spots, and increasing them in soft areas or voids. Tool life is extended when a tool continually cuts at its optimum horsepower. This feature optimized cycle times and still provides limits to protect the machine and tool.

Although the CCAT/NCAL M&S team has not implemented this capability, the TMAC can be configured to monitor four separate channels of coolant flow information. Coolant flow volumes can be set for each tool and section for precise monitoring of through-the-tool coolant flows. Coolant flows can be learned for each tool and flow limits applied. When coolant flow drops below the programmed flow limits, the system will issue a coolant flow alarm.

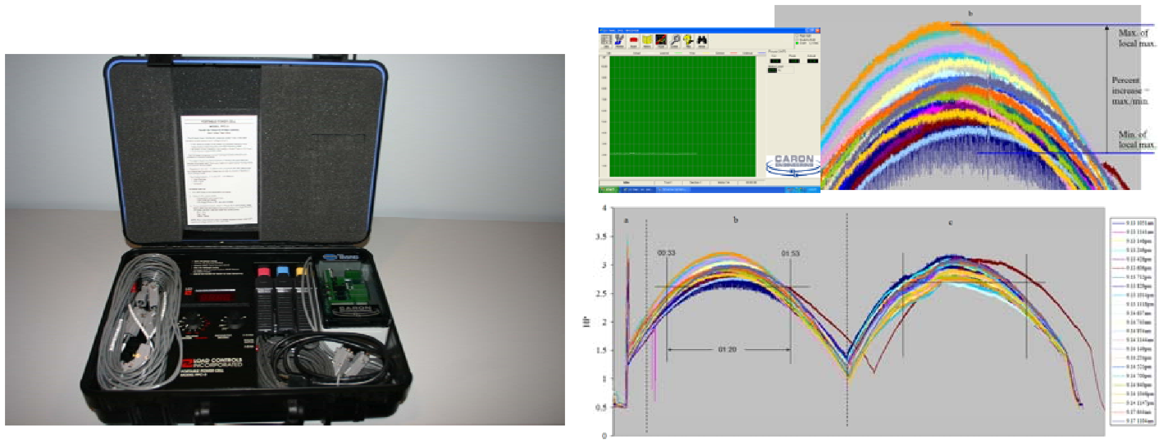


Figure 42 Caron Engineering Adaptive Tool Monitoring Field Unit and Data Display

Automatic Time Incremented Limits provide the capacity to alter the monitored limits based on a timer rather than specific directions from the CNC program. A start command from the CNC starts a timer. A job operation can be programmed to invoke different cut limits based on the timer. This can be useful for monitoring "canned cycles" where start and stop commands can not be inserted directly into the CNC program. The feature is also useful for doing broken tool detection at the end of a cut. TMAC Viewer records and stores cutting horsepower, start/stop signals, alarms, spindle speed and coolant flow during cutting operations. This data can be saved to a file and printed.

The CCAT/NCAL M&S team engaged with Alpha Q Inc., a producer of complex closely toleranced machined components for the aerospace and power generation industries. Because of the high value of the parts being machined at Alpha Q it is vital that part damages due to machining remain low. For this purpose, the CCAT/NCAL M&S team introduced Caron Engineering's TMAC system to the company in hopes to start beta testing the new portable console unit.

A 5 axis CNC machine was outfitted with the TMAC system and a preliminary run in learn mode on a specific part run. The results where recorded and analyzed using Microsoft Excel. The increase in the required motor horsepower to drive the dulling tool was analyzed. The percent increase in HP between new tool and worn tool was calculated for each respective time slice and used as the tool's limiting horsepower, where if the same job was re-run in monitor mode the TMAC system would automatically stop the CNC machine from continuing its cutting process if the limiting value was reached, preventing any part damage. These values where inputted into the TMAC system for future monitoring of that specific job. This capability is being demonstrated to aerospace suppliers because it is critical to be able to predict tool wear and breakage, making the machining process more reliable and productive.

One significant result from this activity was the development of a portable field test unit for demonstration purposes. The CCAT/NCAL M&S team advised the Caron Engineering team on the specifications of the device, and thee Caron engineers provided it. This portable unit will be instrumental in testing this system.

The CCAT/NCAL M&S team noted several opportunities for further analysis. In particular, the team observed that several tool failures occurred in the demonstration. These tool failures occurred on parts not regularly cut on the particular machine. Undercut limits where only set for the two parts cut regularly on the machine, based on 10 repeated cuts. No limits where set up for the parts that caused the failures.

The limits are calculated based in percentage HP increase in a predefined time interval (time slice). For facing (rough cut) of an aluminum part, the system was getting a maximum horse power reading of about 3.2. For the aluminum part, the horse power increase preceding tool failure was about 15 %, and the magnesium was 9%.

Another result of this activity was that the CCAT/NCAL M&S team discovered the importance of relaying costs savings data to the suppliers employing the adaptive tool monitoring technology. The CCAT/NCAL M&S team developed an MS Excel spreadsheet, shown below, that provided and easy to demonstrate display of data of the efficiencies gained by employing the tool monitor.

Known as the CCAT/NCAL Tool Monitoring Cost Calculator work sheet, the instrument helps to estimate the amount of money the monitoring system would save for measured jobs over a one year time period (assuming alerts set would prevent tool or insert breakage and part damage). The M&S team identified critical data needed from the supplier to complete the worksheet:

- Log records for the jobs dating for the past two to three months before measurement began
- Estimates of tool/insert repair and replacement costs, and an estimate of the part cost of the measured jobs

Alpha Q produces parts in a variety of comparably “soft” metals, like magnesium and aluminum. The team concluded that it might be better to do testing on harder metals, as aluminum and magnesium parts do not seem to produce significant change in horse power according to the results taken from Alpha Q.

The CCAT/NCAL Tool Monitoring Cost Calculator work sheet is also a very effective instrument to help companies gauge the scope of costs involved with tool replacement and damage, a significant influencing factor in decided to implement a tool monitoring technology.

TMAC Cost Savings Calculator

New Job

Cost Inputs

Machine #	Job #	Tool #	Insert Repair	Insert Replace	Tool Repair	Tool Replace	Part Repair Total Repair Time (hr.)	Part Repair Machine Time Loss (hr.)	Part Scrap Part Cost	Part Scrap Machine Time Loss (hr.)
5	2402480	58	$0.00	$0.00	$0.00	$0.00	1	0.25	$10,000.00	0
		59	$0.00	$0.00	$0.00	$0.00				
	18422450	47	$0.00	$0.00	$0.00	$0.00	1		$20,000.00	
		48	$0.00	$0.00	$0.00	$0.00				
		49	$0.00	$0.00	$0.00	$0.00				
		50	$0.00	$0.00	$0.00	$0.00				
		51	$0.00	$0.00	$0.00	$0.00				
		52	$0.00	$0.00	$0.00	$0.00				
		53	$0.00	$0.00	$0.00	$0.00				
		54	$0.00	$0.00	$0.00	$0.00				
		55	$0.00	$0.00	$0.00	$0.00				
		56	$0.00	$0.00	$0.00	$0.00				
		57	$0.00	$0.00	$0.00	$0.00				
		58	$0.00	$0.00	$0.00	$0.00				
		59	$0.00	$0.00	$0.00	$0.00				

Cost Summary

Repair	$25,250.00
Replace	$0.00
Scrap	$40,000.00
TOTAL	**$65,250.00**

* Occurances Per Year: Number of times the coresponding insert, tool, or part was repaird, replaced, o

* Cost Inputs: Cost coresponding to repairing, replacing, or scraping the particular insert, tool, or part.

Pre existing data (pre TMAC)

Cost

Figure 43 TMAC Cost Calculator Spreadsheet

Conclusions

The CCAT/NCAL M&S team is working with the supply chain level manufacturers to evaluate and demonstrate the capabilities of COTS solutions to analyze chatter conditions to improve the quality of part machining, which has led to a variety of opportunities that for improvement at these companies. The team identified and demonstrated measurement systems that can be applied to machine tools directly, giving machine operators a measurable optimal machining frequency that will preclude chatter. The team also developed a field testing and data collection system that will work to measure and prevent chatter conditions and tool breakage. These demonstrations of COTS technology will have significant impact on these participating companies and can be more broadly applied within local industry.

Through the execution of this project, we have greatly expanded the knowledge and capability of the CCAT/NCAL M&S team with the ability to apply CUTPRO Milling and Modal Analysis modules as well as the Caron Engineering's Tool Monitor Adaptive Control System (TMAC). The CCAT/NCAL M&S team has successfully engaged with a number of companies to perform technology demonstration projects, being able to analyze a machining configuration of cutting tools and machines to collect the dynamic signature and make recommendations on new cutting feeds, and tool shape to eliminate chatter conditions. The CCAT/NCAL M&S team is able to bring the portable TMAC system into machine shops to monitor the horsepower processing schedule to prevent the breaking of tools. A spreadsheet based cost calculator was created to help companies identify the value of implementing these types of technologies. These are tools that the CCAT/NCAL M&S team will be utilizing in the follow-on phases of the NALI Program.

Participating Companies

Company	Address	Point of Contact
Alpha Q	87 Upton Road Colchester, Connecticut	Stephen Prout, CEO Richard Hurley, VP, General Manager
B&E Group, LLC	10 Hudson Drive Southwick, Massachusetts	John Wilander, President/CEO Paul Wilander, Senior Programmer
Caron Engineering	1931 Sanford Road Wells, Maine	Rob Caron, President Mark Munroe, National Sales Manager
GKN Aerospace	273 Adams St Manchester, Connecticut	Brian J. Wilczynski, Continuous Improvement Manager Al Neuser, Plant Manager-CT
Sterling Engineering	236 New Hartford Road Barkhamsted, Connecticut	John Lavieri, President Tim Conway, Eng. Manager
TRUMPF Inc.	3 Johnson Ave. Farmington, Connecticut	Holger Schlueter, Vice President Laser Alexander Teufel, CNC Programmer

References

- Information on CUTPRO and SHOP-PRO technology provided by Manufacturing Automation Laboratories (MAL) Inc., 2829 Highbury St. Vancouver, B.C. Canada V6R 3T7, malinc.com
- Information on Tool Monitor Adaptive Control System (TMAC), Caron Engineering, 1931 Sanford Road, Wells, ME 04090, www.caron-eng.com
- *Optimization of Roughing Processes Through Modeling*. Presentation by Dr. Tahany el-Wardany, United Technologies Research Center. May 2006.

2.2.7.3. CAD/CAM Best Practices Assessments

Overall Summary of Task

Work with industry to better understand the interactions between OEM and supply chain manufacturers for information exchange and the interaction of part definition for execution in CAM environments.

Project team: Brian Kindilien (CCAT/NCAL), Matt Lloyd (CCAT/NCAL), Chris Pfeifer (CCAT/NCAL)

Introduction

The CCAT/NCAL M&S team has worked with a number of aerospace suppliers that sought to reduce time spent on design to manufacturing process development. The first step in this effort is to conduct a thorough analysis of the design and manufacturing processes within the organization, known as computer-aided design/manufacturing (CAD/CAM) best practices assessment. The purpose of these assessments is to understand and then document a company's workflow, with the goal of identifying areas that might be improved, either by developing efficiencies, upgrading skills and knowledge, or training the workforce in best practices approaches, while demonstrating the benefits of such approaches.

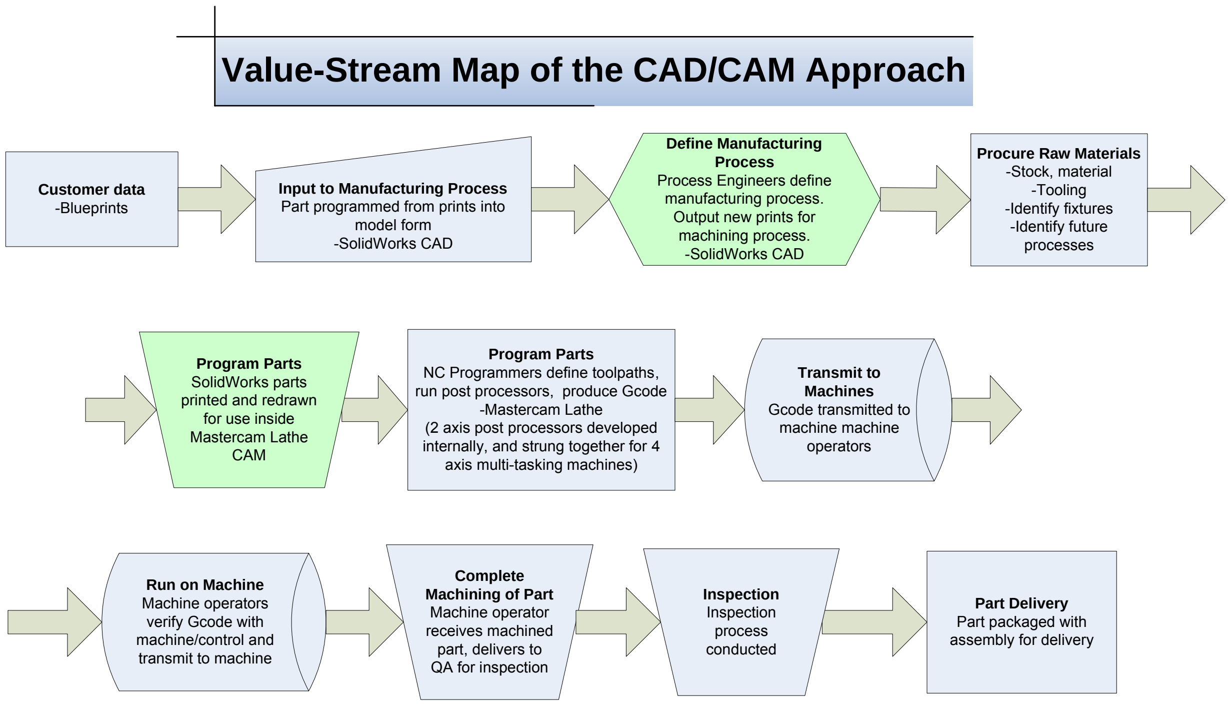


Figure 44 Value Stream Map Diagram

Methods / Procedures

In conducting the assessments, the CCAT/NCAL M&S team develops a process flow diagram, similar to the one shown below. The team works closely with the company to outline the work flow and understand their manufacturing processes. Ultimately, the team will identify areas of improvement and make recommendations for technology improvements and or training. In many cases, the improvements are not significant investments in equipment, rather, they are extensions of current technology already available within an organization.

Often, the CCAT/NCAL M&S team their current method employed techniques of drawing the necessary geometry within their computer-aided manufacturing software (CAM) for creating tool paths. This method, although sometime necessary depending on the skills of the people involved, leaves room for significant improvement. The CCAT/NCAL M&S team frequently identifies a method of utilizing geometry already required in their computer-aided design software (CAD) to reduce machining processing time.

Value Stream Mapping

Several companies the team has interacted with were struggling with a significant process challenge: Developing a more efficient way of moving their data between their CAD and CAM software systems. Technology advancements in recent years now make this possible: Parametric solids, whose dimension values can be changed on the fly as needed. The simplistic manner in which data can be transferred has made the more repetitive tasks such as creating the necessary 2D drawings a thing of the past.

Now, a solid model need only be referenced, and most CAD packages will generate the drawings necessary. With such a powerful tool at designer's disposal, the use of solids has become an industry standard that can be found in most engineering companies.

The CCAT/NCAL M&S team developed a process that allows a great reduction in processing time, and has the potential to save companies up to 90% of its design to machining processing time. For manufacturing companies in today's industry, this savings can have a significant impact, as it allows programmers to, as one company put it, "…focus on cutting chips rather then redrawing geometry."

The challenge remains that companies are often unwilling to change unless the cost of such inefficiency is clearly identified. Many companies are also hesitant to add the burden of additional product training on their already overtaxed staff; however, the M&S team has found that once the benefits of CAD to CAM interoperability are clearly identified and the time savings demonstrated, there is often willingness of upper management to leverage the training.

Another significant area of concern for aerospace suppliers has been the type of CAD/CAM software technology the employ. Many of these companies have grown in size and capability over the years, and the software tools they used in the early years may be perceived as insufficient as the company grows and requires more capability. The CCAT/NCAL M&S team often assists companies by providing an objective analysis of the capability of various software systems, based on the industry surveys conducted. Further, the CCAT/NCAL M&S team often recommends upgrades and advanced training on the company's currently employed system, rather than recommending a change in the technology.

These manufacturing process assessments are critical to understanding how manufacturers utilize their technology and process in the most efficient manner. By carefully documenting and understanding internal work flow, the CCAT/NCAL M&S team can highlight those areas where inefficiencies may be significantly affecting the flow. Seemingly simple improvements in CAD to CAM interaction can have profoundly significant impact on overall cycle time and factory productivity.

Automated Tool Sheet Generator for Aero Gear Inc.

In this project, CCAT/NCAL M&S has developed an Application Programming Interface (API) inside the CAD software package SolidWorks® to generate a Tool Sheet to be used at a local Small Manufacturing Enterprise, Aero Gear Inc. This tool sheet will gather information from a predefined tool database, and create a necessary documents based on Aero Gear's standard drawings.

Aero Gear (Windsor, CT), a leader in providing geared systems for the aerospace industry, worked with the CCAT/NCAL M&S Team on several successful projects throughout the course of NALI Phase I. Through regular talks during the course of these projects, the subject of Tool Sheets arose, particularly the added time during process planning. Current methods involve selecting graphical patterns and manually entering the data for each tool in an outdated CAD package, only kept for the purpose of creating these sheets. When Aero Gear selected Edgecam as its Computer-Aided Manufacturing (CAM) software package, the CCAT/NCAL M&S team saw the opportunity to utilize the pre-existing Tool Database information as a means to automatically generate Tool Sheets.

Edgecam is capable of programming milling, turning and mill-turn machines. Edgecam combines unrivaled ease of use and sophisticated tool path generation. Edgecam is a complete CAM software solution for production machining and mold & die applications. Edgecam is designed to cope with programming the simplest to the most complex components and offers full support for the latest CAD, machine tool and tooling technology. Edgecam also contains a Tool and Job Database to store all relevant information to the manufacturing process. This database, run through a series of Planit developed graphical interfaces, is managed by a Microsoft SQL Database. By utilizing this database, the CCAT/NCAL M&S team developed a method to import this data into Aero Gear's CAD software SolidWorks®. By reusing information that is already necessary to define the manufacturing process, the API is capable of generating Tool Sheets that match previous methods, with little to no interaction of the user, saving valuable processing time for Aero Gear.

Since a method like this had previously not been available to Aero Gear, their current Tool Database does not contain every tool used in their shop. It also does not contain all necessary data for the manufacturing process, as this information was added when the Tool Sheet was created. Because of this, a new method of process development is currently being tested. This method has the programmer enter all relevant information for tools as they create the machine code. As they use this system, the need to enter tools becomes less as the information will be stored in the database. Through this method, the database can be generated quickly during the process so the automatic generation can be realized.

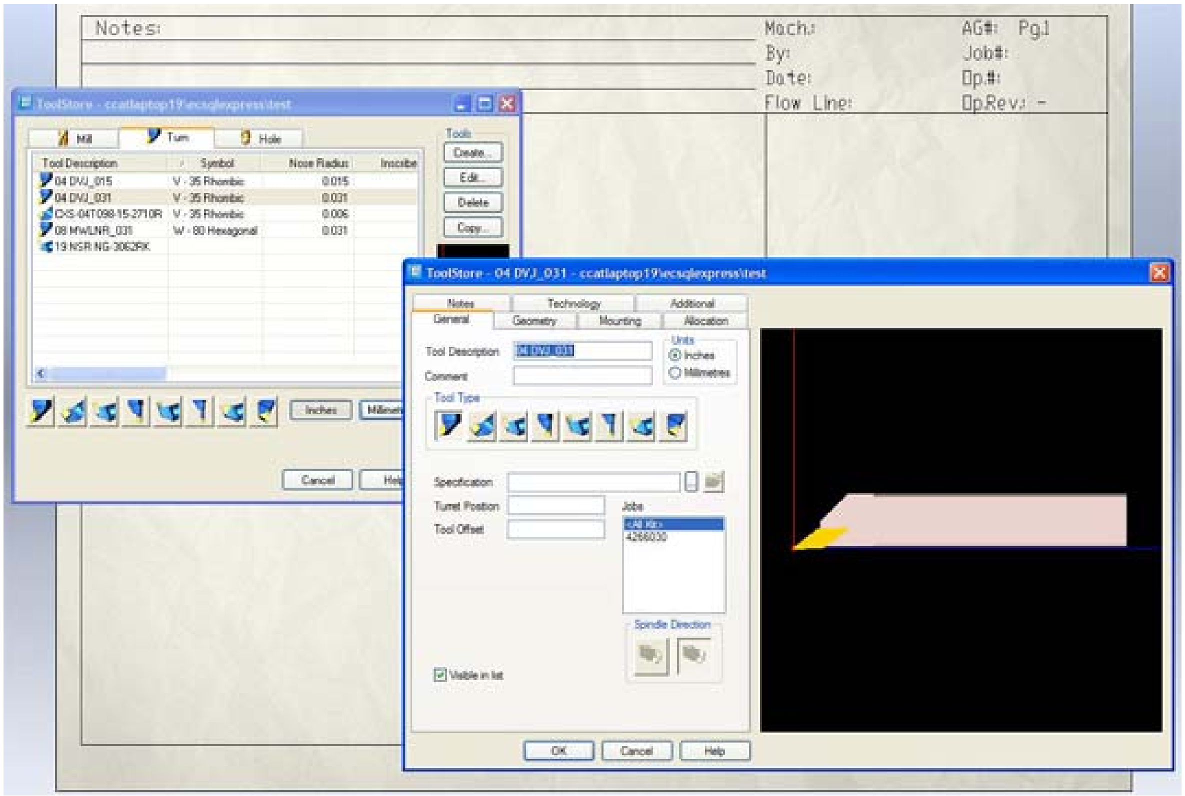


Figure 45 Tool Sheet

This project is currently on going, as the new development method is still being tested. Since turning tools require less information to identify, the testing has begun with the Lathe processes. If found beneficial, this method will be expanded to the Mill processes as well, so that Aero Gear may fully realize the benefits of such a tool.

Conclusions

Through the execution of this project, we have greatly expanded the knowledge and capability of the CCAT/NCAL M&S team with the ability to assess a company's processes for generating the NC programs for their machines. Value Stream Mapping tools are used to document the process and visually confirm how they have implemented their CAD/CAM solutions. The VSM serves as the basis for executing an assessment of the existing process for CAD/CAM, to identify where the limitations of the process are for rapidly generating new process plans and the supporting data files. The CCAT/NCAL M&S team has been trained in how to use many CAD/CAM solutions in a best practices approach. Execution of engagements with local companies have helped the team to develop innovative approaches utilizing the capabilities of these software tools such as the development of a method for automatically generating the Tool sheets directly tool definitions currently defined in an external database. These are tools that the CCAT/NCAL M&S team will continue to be utilizing in the follow-on phases of the NALI Program.

Participating Companies

Company	Address	Point of Contact
Aero Gear	1050 Day Hill Road Windsor, Connecticut	Douglas Rose, President Mike French, Manf. Eng. Manager
B&E Group, LLC	10 Hudson Drive Southwick, Massachusetts	John Wilander, President/CEO Paul Wilander, Senior Programmer
BNB Manufacturing Co., Inc.	200 Price Road Winsted, Connecticut	Tony Nanni, Vice President, Engineering & Quality
Delta Industries	39 Bradley Park Road East Granby, Connecticut	Bill Evans, President James E. Janiak, Engineering Manager
FENN Technologies	300 Fenn Road Newington, Connecticut	Scott Summers, Sales Manager Alfred Sturtevant, Process Engineer
Senior Aerospace	4 Peerless Way Enfield, Connecticut	Paul Murphy, CEO Stan Cothran, Process Engineer
Sterling Engineering	236 New Hartford Road Barkhamsted, Connecticut	John Lavieri, President Tim Conway, Eng. Manager

References

- Information on Edgecam technology provided by Edgecam, a Planit group company, 3000 Town Center, Suite 830, Southfield, MI 48075, www.edgecam.com
- Information on Mastercam technology provided by CNC Software, Inc. 671 Old Post Road, Tolland CT, 06084, www.mastercam.com
- Information on SolidWorks technology provided by SolidWorks Corporation, a Dassault Systemes S.A. company, 300 Baker Avenue, Concord, MA 01742, www.solidworks.com

2.2.7.4. Evaluation of DELPHI Physics Based Process Simulation Tool

Overall Summary of Task

DELPHI Technologies is considering the release of an internally used physics based machining process simulation tool as an off the shelf software tool. The CCAT/NCAL M&S team is exercising the code on real Aerospace applications to validate the functionality and applicability for the release of such a product.

Project team: Brian Kindilien (CCAT/NCAL), Dr. Tony Dennis (CCAT/NCAL consultant), Chris Pfeifer (CCAT/NCAL), and support from the Rensselaer at Hartford-branch campus of Rensselaer Polytechnic Institute

Introduction

DELPHI Technologies Inc. (DTI) of Troy, Michigan utilized an internal software tool to simulate and optimize machining processes referred to as Math-Based Metal Removal (MBMR). MBMR focused on modeling the processes of turning, drilling, face & end milling to predict force and power based on cutting conditions. Through these predictions, it might be possible to not only provide visualization of the process, but also optimize the cutting conditions to decrease cycle time or increase tool life.

The CCAT/NCAL M&S team was tasked to evaluate the MBMR software and determine its viability as a commercially available product. To do this, a set of sample cases was proposed to test and validate the code. The results of these case studies were to be compared with both experimentally found results as well as results from other predictive software.

Methods / Procedures

A set of five material removal processes was to be selected with the concurrence of the DTI project representative. Criteria for selection was to include the availability of G-code, previous computer predictions, as well as available experimental data. The example processes was to be selected to represent a broad range of cutting conditions commonly encountered in practice. The DTI's MBMR software was to then be used to produce predictions of cutting forces in five selected situations. Other software was to be used as needed to produce results for comparison with MBMR. The alternate software was the AdvantEdge Production Module technology from Third Wave Systems, CutPro by MAL, and GrindSim by Prof. Stephen Malkin of the University of Massachusetts in Amherst, MA. Five proposed sample cases are listed below. Only aluminum and steel workpiece materials were to be analyzed.

1. Case 1 to analyze a more complicated tool path, though still a 3-axis
2. A 5-axis milling case and/or a cylindrical grinding case
3. The machining of a company logo, using the CNC program
4. The roughing operation of a steel rotor

Once the project begun, it became apparent that the delivered version of the software contained several bugs that prevented the cases from being completed. After discussions between DTI and CCAT/NCAL M&S team, a DTI engineer was assigned to fix the known issues so work could continue. After a period of several months, CCAT/NCAL M&S team was informed that there was a reorganization, which left DTI without the resources to continue development.

Conclusions

It was at this point the project was concluded. Although CCAT/NCAL M&S team never got the opportunity to evaluate the technology directly, its promise of capability was significant, and the team remains committed to evaluating the software should it ever become available. In November of 2007, a group consisting of educational entities, Michigan State University and Georgia Technical Institute, and industry entities, Pratt & Whitney and Caterpillar, were investigating predictive software code to invest in to develop for use among the group of collaborators. MBMR was identified as a potential candidate for this project. The CCAT/NCAL M&S team was contacted through UTRC to become a facilitator to these meetings, and possibly become the primary possessor of the developed software to distribute to the collaborative entities. To date, the CCAT/NCAL M&S team has yet to receive a response from all entities involved.

2.2.7.5. Development of VERICUT Machine Models, Tools, Fixtures, Electronic Library of Models

Overall Summary of Task

Identify limitations and restrictions for implementation of this technology for the supply chain level of machining job shops. The CCAT/NCAL M&S team will create libraries of re-usable entities by industry for inclusion in machining simulations. These will be available via the NALI website (www.usnali.org). The electronic library of models will include machine, cutting tools, fixtures, and controller functionality.

Project team: Brian Kindilien (CCAT/NCAL), Matt Lloyd (CCAT/NCAL), support from CCSU

Introduction

CG Tech's VERICUT simulates CNC machining and the machines themselves so companies can be more efficient, more competitive, and more profitable. A machine crash can be very expensive, potentially ruin the machine, and delay a company's entire manufacturing schedule. With VERICUT, companies can dramatically reduce the chance for error and avoid wasting valuable production time proving-out new programs on the machine.

Methods / Procedures

Machine Simulation detects collisions and near-misses between all machine tool components such as axis slides, heads, turrets, rotary tables, spindles, tool changers, fixtures, work pieces, cutting tools, and other user-defined objects. Users of the software can set up "near-miss zones" around the components to check for close calls, and even detect over-travel errors.

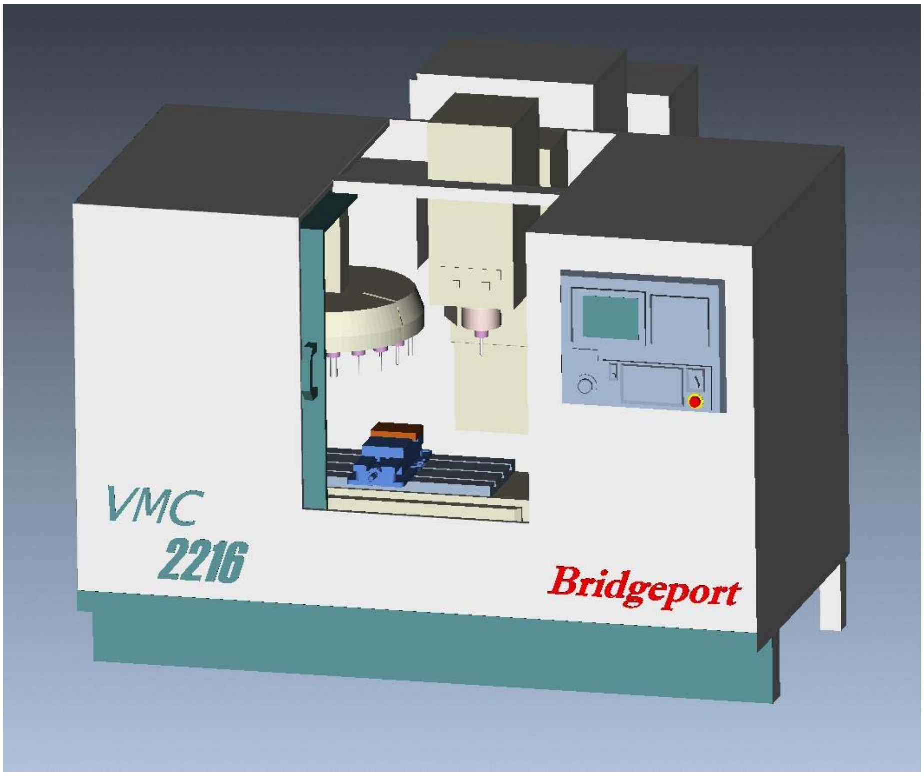


Figure 46 CCSU Machine Modeled in VERICUT

CG Tech – VERICUT Machine Modeling

VERICUT allows realistic 3D simulation of entire CNC machines, just like they behave in the shop environment. The software detects collisions and near-misses between all machine tool components such as axis slides, heads, turrets, rotary tables, spindles, tool changers, fixtures, work pieces, cutting tools, and other user-defined objects. VERICUT Machine Simulation supports:

- G-codes and provides multi-axis support for milling, drilling, turning, grinding and EDM machines
- Simultaneous mill/turn on different spindles and workpieces.
- Machines with multiple synchronized CNC controls
- Auxiliary attachments: tail stock, steady rests, part catchers, bar pullers, etc.
- Automatic workpiece transfer to pick-off or sub-spindles
- IGES or STL model import for building virtual machines

A selection of customizable machine models is included. Or, users can build models from scratch. Machine components can be designed in a CAD system or defined in VERICUT. A “Component Tree” feature makes it easy to connect the pieces and manage the kinematics of the machine.

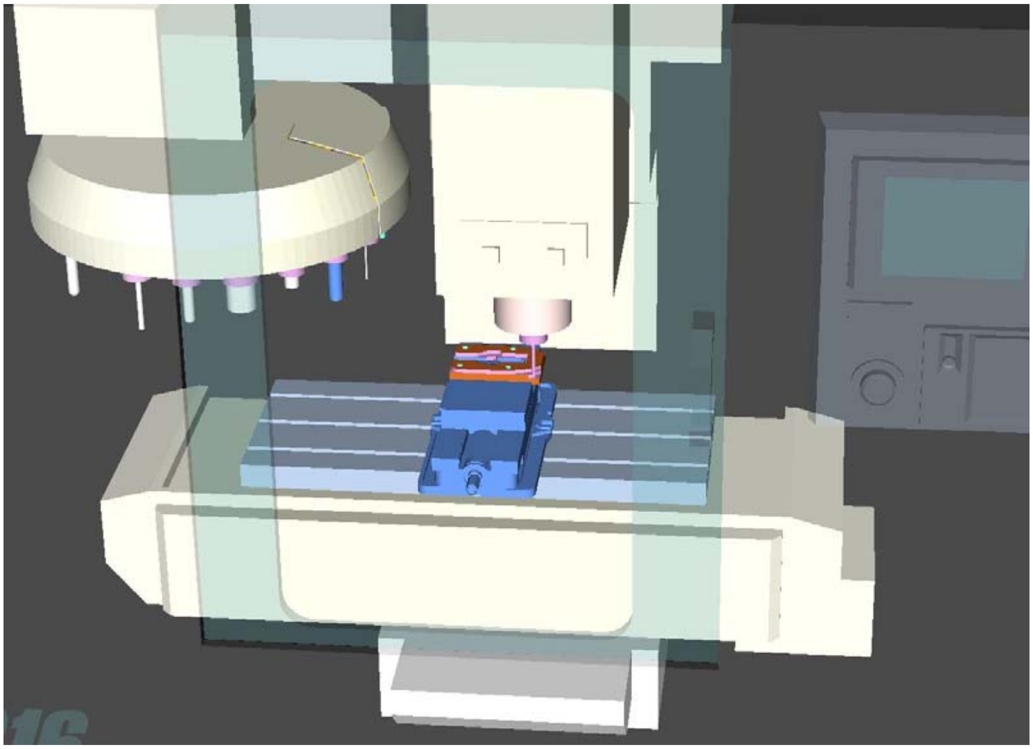


Figure 47 CCSU Machine Cutting Envelope Modeled in VERICUT

VERICUT accurately emulates CNC control logic. Each control in a user's shop can be accurately simulated to account for different types of machines, programs, parts, and functions. No special programming language is required to simulate most CNC controls. VERICUT is designed to support advanced control functions including:

- Look-ahead or 3D cutter compensation
- Tool tip programming & tool length compensation
- Gage length reference point programming
- Canned cycles and fixture offsets
- Rotary axis pivot points
- Variables, subprograms, and macros
- Subroutines, looping, and branching log

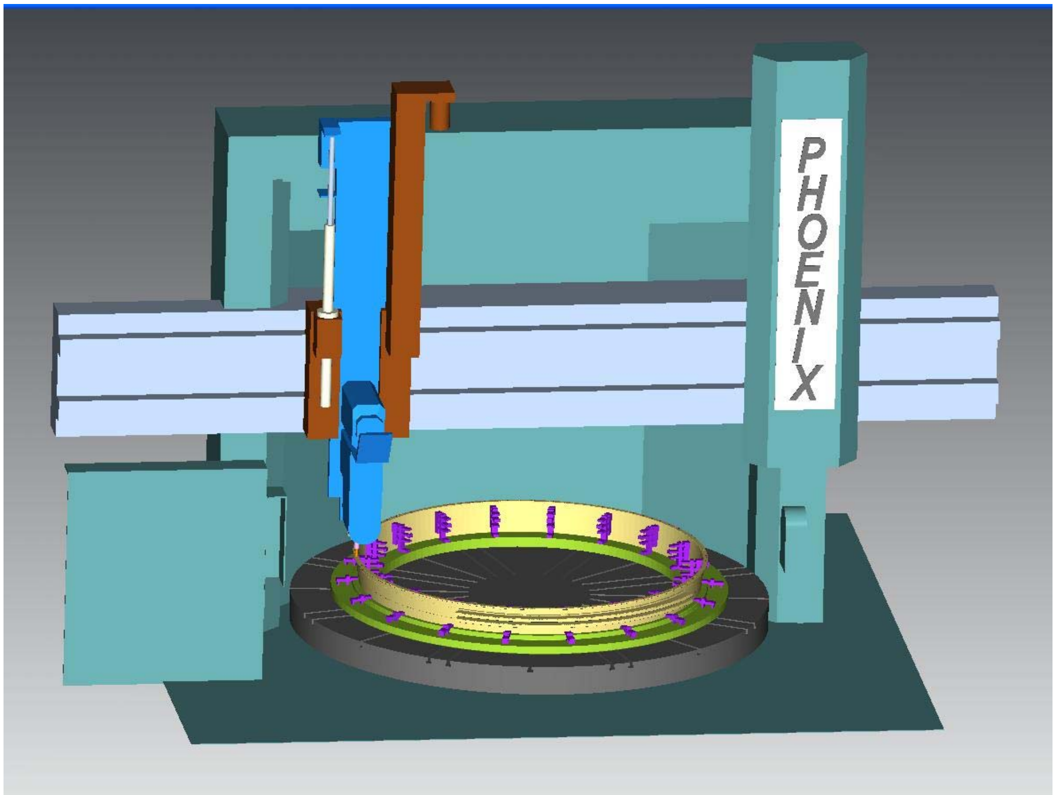


Figure 48 Phoenix Machine Modeled in VERICUT

VERICUT users also get the flexibility to customize controls. Using pull down dialog boxes, G-code characters and numerals are defined in a logical "word/address" format, and then configured to call VERICUT action macros which simulate control functions. The control logic also supports conditional checks (other codes in the block, current variable values, machine states, etc.) that can alter how the word/address is interpreted.

Using the VERICUT machine and controller software technology, the CCAT/NCAL M&S team, in conjunction with students from Central Connecticut State University (CCSU) modeled the 3 axis Bridgeport CNC machining center located on the CCSU campus. The machine is used for NC programming demonstrations as well as creating one off student designs. Although the machine had been with CCSU for a number of years they had no way of verifying NC programs without posting to the machines control and conducting a dry run. This practice was effective but time consuming and not practical to perform in the short class periods. VERICUT, a product from CG Tech was recently acquired for the purpose of verifying programs off line.

In order to fully benefit from VERICUT the Bridgeport was fully modeled, all kinematics were identified, and controller logic was defined. AutoDesk Inventor and SolidWorks were used for the 3D solid modeling of the Bridgeport's components. Each moving part essential to the verification of NC code was modeled separately (X, Y, and Z axis along with the machine base, enclosure, and tool changer).

The students physically measured the machine components to create the models used in VERICUT. Once created each model was imported as an STL into VERICUT, aligned with its mating components, and assigned a direction of motion. Controller logic was replicated by studying the machines motions, identifying all G and M codes present on the control and then selecting macros in VERICUT and assigning them to specific commands to simulate the desired actions in the software. Finally several test parts were then run on the simulated machine to ensure accuracy of the final product and debug any simulation errors that were identified. The completed VERICUT machine was delivered to CCSU for use in their machining lab in 2007.

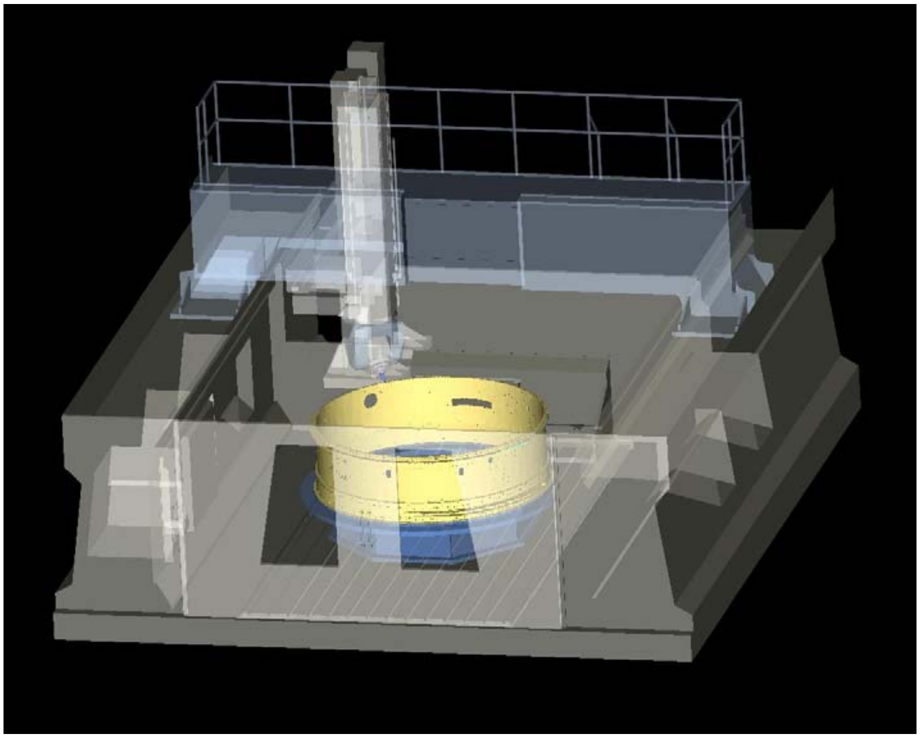


Figure 49 Zimmerman Machine Tool Modeled for Volvo Aero in VERICUT

The project allowed student to experience an aspect of manufacturing not usually taught in college classrooms. They learned advanced CAD modeling methods, controller logic, and CNC programming language.

The CCAT/NCAL M&S team engaged with Volvo Aero Connecticut, a Newington, a Connecticut-based aerospace supply chain manufacturer. They asked for assistance in gathering the data required to construct in a virtual environment, two of their machine tools using VERICUT from CG Tech. Using an advanced machine/control simulation technology such as VERICUT might offer the company a full simulation of the work piece and tool and also the entire machine kinematics. Volvo was struggling to produce the data required to construct the machine themselves, a critical function in order to engage the models in reducing machine cycle times and verifying machine code accuracy.

The first machine, a Phoenix VTL with a 5 axis milling head retrofit posed some unique challenges due to its one-off nature and lack of reliable documentation. The CCAT/NCAL M&S team visited Volvo on several occasions to obtain data and measure the machine. We created machine models for the Zimmerman and assembled the models for use in VERICUT. The CCAT/NCAL M&S team delivered a complete kinematic machine model along with the required information for CG Tech to begin construction of the Phoenix's Fanuc control and perform final setup of the machine model. Volvo is now employing this advanced model to simulate the machine processes of this complex machine tool. The work that the CCAT/NCAL M&S team developed is important to the U.S. aerospace supply chain because it is clear that developing advanced machine and machining process models will help such companies reduce scrapped materials, develop more efficient machining process, and improve the safety and quality of these critical aerospace components.

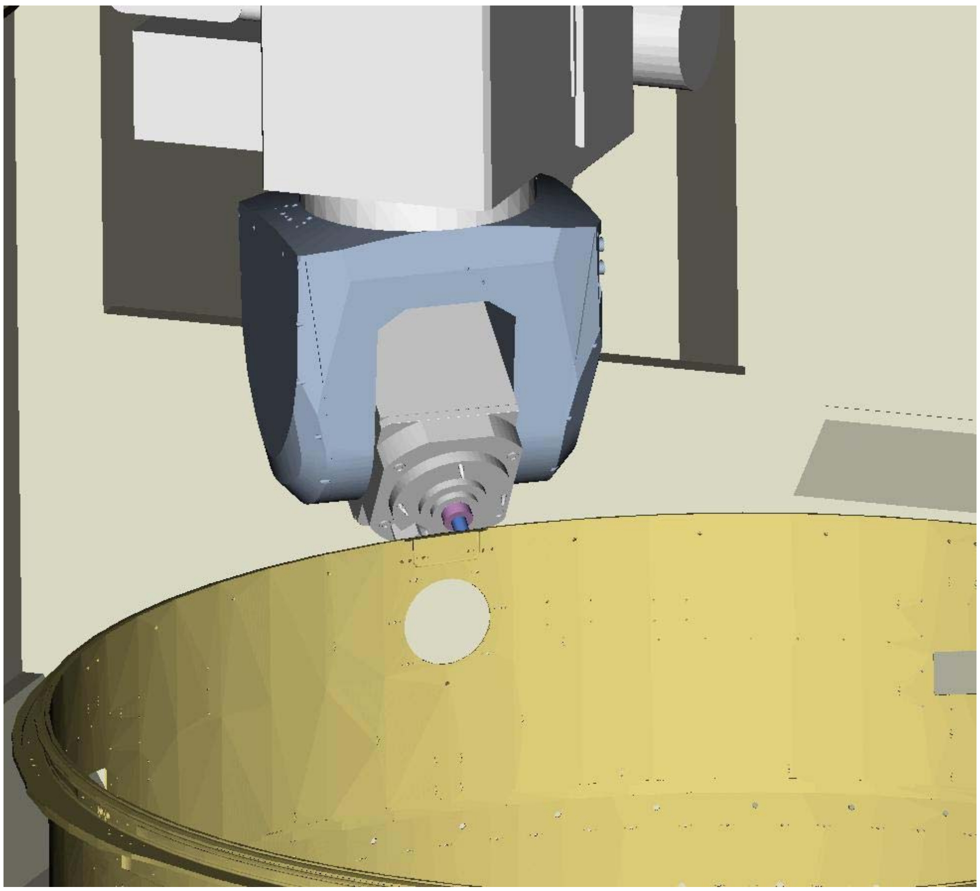


Figure 50 Cutting Features Modeled for Volvo Aero Using VERICUT

Conclusions

Through the execution of this project, we have greatly expanded the knowledge and capability of the CCAT/NCAL M&S team, as well as, developed a solid process for generating virtual machine models within the CGTech – VERICUT software for use in validating NC programs and for applying the OptiPath option. The CCAT/NCAL M&S team is now capable of generating all of the components of a VERICUT machine model, and they have begun to maintain an internal library of model elements and machines to reference in future tasks. Discussions have been held with tool manufacturers such as Sandvik and Kennametal regarding the potential for getting 3D definition of their cutting tools for importing into our library.

Several full machine models were created for our participating companies and CCSU for use in their manufacturing curriculum.

Participating Companies

Company	Address	Point of Contact
B&E Group, LLC	10 Hudson Drive Southwick, Massachusetts	John Wilander, President/CEO Paul Wilander, Senior Programmer
Central Connecticut State University (CCSU)	1615 Stanley St. New Britain, Connecticut	Dr. Paul Resetarits, Chairman and Professor, Dept. of Manufacturing & Construction Management
FENN Technologies	300 Fenn Road Newington, Connecticut	Scott Summers, Sales Manager Alfred Sturtevant, Process Engineer
Sterling Engineering	236 New Hartford Road Barkhamsted, Connecticut	John Lavieri, President Tim Conway, Eng. Manager

References

- Information regarding VERICUT provided by CGTech, 9000 Research Drive, Irvine, California, 92618-4214, www.cgtech.com

2.2.7.6. Development of Interactive Learning Environment for teaching the concepts of NC Programming

Overall Summary of Task

In this project we will implement a web based interactive learning environment with a fully interactive emulation of the machine.

Project team: Tom Scotton (CCAT/NCAL), Brian Kindilien (CCAT/NCAL), Chris Pfeifer (CCAT/NCAL), Shanelle Cousins (CCAT/NCAL intern), Kantius Joshua (CCAT/NCAL intern), College of Technology, NGRMS, CBIA

Introduction

The small manufacturing enterprises in today's aerospace industry are constantly searching for experienced machine operators. With a large amount of the workforce being comprised of recent graduates, and retrained workers, the need for machine training has become of great interest. Due to high demand of manufacturing resources, lending machine and operator time to train new operators has become an ineffective method of development. Coupled with a lack of advanced machining laboratories in technical schools, the use of a virtual training environment has a great potential to compensate for this shortage.

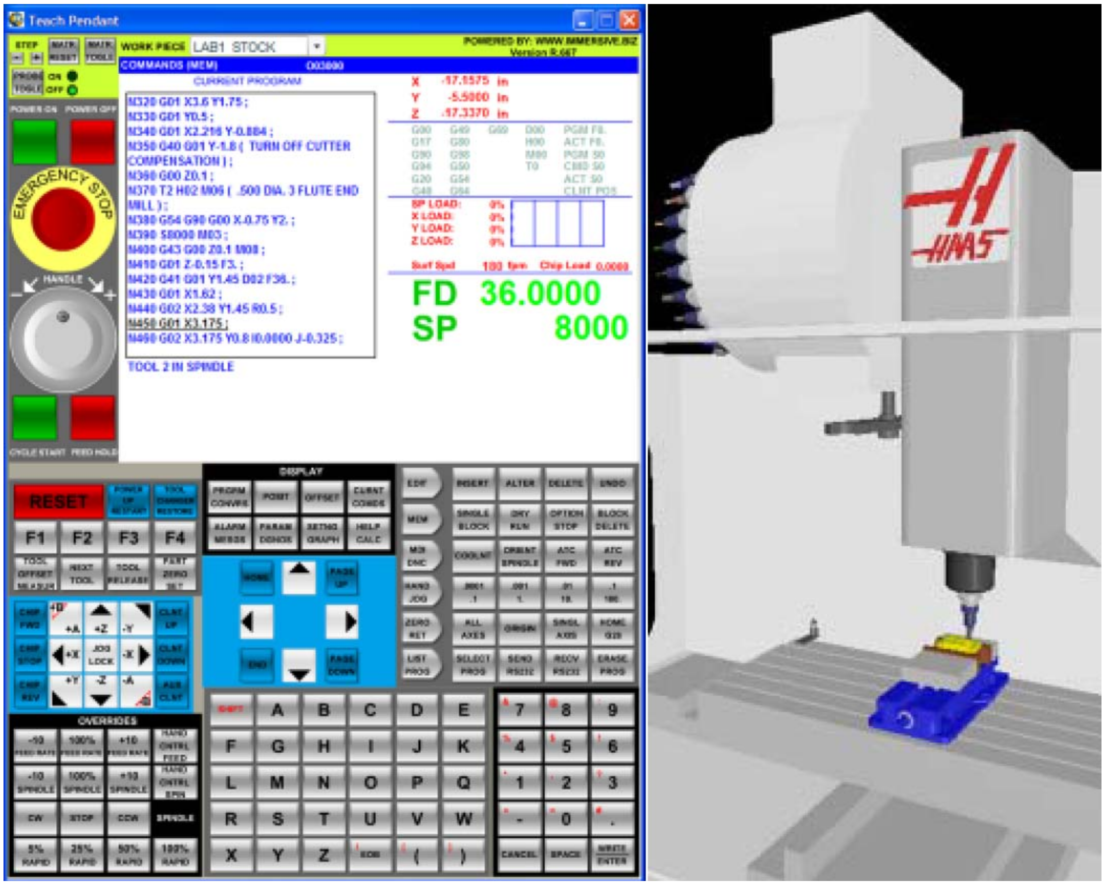


Figure 51 Haas Controller in Virtual Training Environment

Methods / Procedures

The Virtual Training Environment for CNC (VTE-CNC) provides an automated simulation-based professional development support system to assess skills and to train, certify, and support performance improvement for engineering and other manufacturing personnel. With VTE, employees and students can learn any time, place, and pace while valuable equipment remains in production.

With VTE-CNC Emulator, engineers and operators develop, run, and learn CNC programs and procedures with virtual control panels, machine tools, and equipment used in actual manufacturing environments. Some features include:

- Real-world "what if" Scenarios
- Industry Control Systems
- Multi-axis Milling & Turning
- NC Programs
- Collision Detection
- Material Removal

By emulating actual equipment, controls and manufacturing processes in a virtual environment, learners can concurrently achieve proficiency and rehearse procedures, while existing equipment remains in production, or even during new system integration or procurement.

Figure 52 Fanuc Controller in Virtual Training Environment

Use VTE to rapidly prepare and ramp up a workforce prior to, or during, integration of agile manufacturing techniques and processes. For existing processes, VTE is a support system that can be used throughout product development from reviewing safe operating procedures to viewing actual programs and processes before going into production.

VTE allows organizations to efficiently maintain and transfer knowledge, expertise and skills to support current and next-generation multifunctional teams that are faced with the demands of continually changing work environments.

Figure 53 Schools Engaging VTE System in partnership with CCAT/NCAL M&S Team

The dynamic environment of VTE enables learners to rapidly master new skills, so that they may operate existing and new equipment with greater confidence, proficiency, and efficiency promoting a more streamlined engineering and manufacturing process at a reduced cost.

The VTE-CNC software provides both a web-based learning environment as well as a virtual control pendant that allows students to gain familiarity with a machine control. This machine control will interact with a 3D emulator, which will operate in the same manner as the corresponding machine in a real world environment. By allowing students access to virtual machines, a lot of "on-machine" time can be spent virtually, thus reducing the need for machine resources as well as eliminate costly crashes on a real machine.

The M&S team has utilized the software and validated its use in two manners. A direct comparison approach was used through collaboration with the Connecticut Business & Industry Association (CBIA) in which the CCAT/NCAL M&S team was able to compare VTE-CNC with tools by Tooling University, LLC and Oxygen Education, LLC. VTE-CNC has also been distributed to Connecticut Technical High Schools and Community Colleges to assess the applicability to current curriculums. Each analysis has been useful in identifying this software as the most effective tool to train machine operators of all levels.

For the direct comparison of VTE-CNC, high school students participating in an internship with the M&S team reviewed both Immersive Engineering's software solution and the available alternatives. While Tooling University's solution was found to have the most extensive solution, VTE-CNC stood out due to it's unique ability to couple online training with the virtual emulation of an actual machine. For this reason, the students performing the comparison chose Immersive as the leading environment.

By allowing both community colleges and technical high schools access to the Immersive environment, the CCAT/NCAL M&S team was also able to validate the applicability within the Connecticut education system. Currently, thirteen educational institutes in the Southern New England region have been provided access to the VTE-CNC software, as outlined in the table below. Reception of the software has been positive, with several of the institutions continuing to utilize the environment on a regular basis.

Table 4 Community Colleges and Technical High Schools

Organization	Location	Principle Contact
Asnuntuck Community College	Enfield, Connecticut	Bob Bressani
Central Connecticut State University	New Britain, Connecticut	Paul Resatarits
Fairfield University	Fairfield, Connecticut	Paul Botosani
Housatonic Community College	Bridgeport, Connecticut	Bill Griffin
Keene State College	Keene, New Hampshire	Robert Simoneau
Manchester Community College	Manchester, Connecticut	Mehrdad Faezi
Middlesex Community College	Middletown, Connecticut	Mark Busa
Naugatuck Valley Community College	Waterbury, Connecticut	Richard Weber
Platt Technical High School	Milford, Connecticut	David Tuttle
Vinyl Technical High School	Middletown, Connecticut	Mike Hood
Westfield Vocational High School	Westfield, Massachusetts	Clem Fucci
Western New England College	Springfield, Massachusetts	Tom Keyser

Conclusions

By partnering with Immersive Engineering and the local education institutes, the CCAT/NCAL M&S team has not only been able to validate the software, but this partnership has lead to many improvements in the VTE-CNC software, which only continues to strengthen. This independent comparison agrees with other independent studies. Most notable of these studies is that of Dr. John Irwin of Michigan Technological University. While work continues to improve the software, the CCAT/NCAL M&S team is in current discussions with the Connecticut Technical High School administration for methods to provide access to all schools in the region.

References

- Information regarding Virtual Training Environment for CNC (VTE-CNC) by Immersive Engineering, Inc., 4226 Derry Road, Bloomfield, MI 48302, www.immersive.biz
- Technical Paper: *Enhancement of CAM Course Using 3D Emulation Software*, Dr. John L. Irwin, Michigan Technological University, School of Technology, 2007

2.2.7.7. Implementation of Digital Manufacturing Solutions for Demonstration Projects with Industry.

Overall Summary of Task

In this project the goal was to establish a university based environment to support activity that addresses both technology deployment and also work force development for Digital Manufacturing Solutions. The primary level of effort was to provide Central Connecticut State College to upgrade their software tools and their curriculum to include Digital Manufacturing Technology tools.

Key Players: Dr. Tony Dennis (CCAT/NCAL, Consultant), Tom Scotton (CCAT/NCAL), Dr. Paul Resetarits, CCSU's Department of Manufacturing and Construction Management

Period - 6/06 – 12/07

Introduction

CCSU worked with the CCAT/NCAL M&S team to develop knowledge related to applications of Modeling and Simulation to increase the productivity, quality and effectiveness of the U.S. supply chain. Many primary manufacturers are currently reducing the amount of manufacturing that they undertake in their own facility. Instead they are turning to outsourcing many key parts and components. As this trend continues to expand there needs to be a greater focus on the total supply chain's effectiveness. Any break downs in the supply chain creates delays and quality issues further up the chain.

Education plays a key role in enhancing the effectiveness of the supply chain. The educational process can begin as early as the sixth grade. Through Engineering/Technology Education programs in secondary schools throughout the U.S. students can be taught about the requirements of an effective supply chain and career opportunities in Aerospace. The knowledge and experiences gained in secondary schools will encourage students to advance their studies at community colleges and 4 year universities. CCSU has established a knowledge base that supports efforts at all levels to enhance the total supply chains effectiveness.

Under the NALI Phase 1 Program, a tremendous amount of knowledge related to Modeling and Simulation was reviewed. Some very valuable information was found that can be used to strengthen the manufacturing supply chain. It was learned that the supply chain manufacturers themselves vary widely in their levels of sophistication and use of current technology. The supply chain vendors can benefit from the deployment of Modeling and Simulation technologies but can only do so with a workforce that is trained in these technologies. Educating students so that they graduate with the skills required is one proactive step which has worked very well for the CAD modeling technologies. More research needs to be done in the simulation arena. Additionally, the current workforce in these supply chain companies will need to be educated. The development of new software in Modeling and simulation is a never ending process. There are constantly new revisions to the software and completely new products that become available. Our job is to review and implement new developments in Modeling and Simulation.

The participating faculty included:

Paul J. Resetarits, Ravindra Thamma, Dan Kirby, David Stec, Ronald Grossman, Alfred Gates, Peter Bauman, Nidal Al-Masoud

Methods/Procedures
The following tasks were executed by faculty and staff, under the tutelage of Dr. Paul Resetarits, Department Chair, Manufacturing Technology and Construction. A list of the activities is provided below with a short description of the activity, a more detailed final report as filed by CCSU is available on request.

Review of the Current use of Modeling and Simulation by Supply Chain Manufacturers
As a starting point for our modeling and simulation activity we decided to collect some base line data on the use of Modeling and Simulation software in the Connecticut manufacturing supply chain. In order to fulfill our tasks of technology deployment and workforce development we needed to determine the current level of use of this technology. A survey was developed and administered to small and midsize manufacturing supply chain vendors. Some of the types of questions asked are listed below.

It was found that many companies are using or switching to SolidWorks due to ease of use and the robust nature of solid models. When supply chain vendors received CAD files from their customers they are most often received from SolidWorks or in the IGES neutral format followed by AutoCAD. Mastercam was the most popular CAM software being utilized.

Simulation software currently is very under utilized at this level of Manufacturing. None of the companies reported using any of the commercially available simulation software. The gap provides a great opportunity for the deployment of simulation technologies. Additionally to development of a workforce with knowledge of these simulation technologies is essential in order to sustain the implementation of these tools. The workforce can be seen as students who will become the future employees of these companies as well as current employees of these companies.

Digital Manufacturing
The promise of the paperless factory with its Computer Integrated manufacturing (CIM) system have been discussed for many years and various levels of success have been found by various manufacturers in a range of operational sizes. The current trend is toward Product Lifecycle Management (PLM) systems and a key component of these systems is digital manufacturing. In a digital manufacturing system the definition of the product is modeled digitally. The digital model contains all of the information required to manufacture the product. The key component is the geometric database that is the utilized by other application software in the PLM system. An investigation was undertaken to model a part digitally and take it through the digital manufacturing cycle.

This is an ongoing project that has been undertaken in steps. The discovery of knowledge in the various content areas related to Digital Manufacturing were examined individually and then all of the pieces were brought together to examine the system.

Graduate Assistants were employed to examine Value Stream Mapping (VSM) software and factory floor modeling and simulation with Quest. Undergraduate students contributed to this project by examining all of the remaining areas of digital manufacturing.

Modeling the Part

Digital manufacturing begins with the creation of the digital product definition. There are many commercially available modeling systems better known as Computer- Aided Design (CAD) systems. Each CAD system has its own unique interface and each with its own unique niche market. Unigraphics tends to be the preferred system for jet engine manufactures which airframe manufacturers prefer Catia. These large systems are often cost prohibitive to the supply chain vendors who tend to prefer SolidWorks and Autodesk Inventor. We began by investigating some of the common modeling software found in manufacturing companies in Connecticut. Autodesk Inventor, Unigraphics, and ProEngineer were already available at Central Connecticut State University. SolidWorks educational network license was procured and made available to all faculty and students. To compare the ease of use and how robust the digital geometric database was for transfer to other digital manufacturing applications such as CAM , parts were selected and modeled using the following software ;

- SolidWorks
- Autodesk Inventor
- Unigraphics
- ProEngineer

Reverse Engineering

As a result of our knowledge development activities we have found a need in the area of reverse engineering. That need was discovered while exploring the capabilities of SolidWorks modeling software. We found that it could accept scanned data from a 3D scanner from NextEngine. The NextEngine scanner and Rapidform software, which is used to enhance to the digital data extracted from the scanner, were procured. The Scanner and software currently reside in the new Modeling and Simulation Laboratory which was created on the CCSU campus. This technology on a larger scale is of great need by the U.S. Air Force. A majority of the current fleet of aircraft that are currently utilized were designed and built prior to the wide use of modeling and simulation software. As a result there are in many cases no existing electronic part files for these aircraft. When a part needs to be repaired or replaced their may or may not be a print with the dimensions available. We believe that the use of 3D scanning technologies holds a great deal of potential for supporting the reverse engineering of existing parts. Additionally, scanning can provide a means of creating a digital part library.

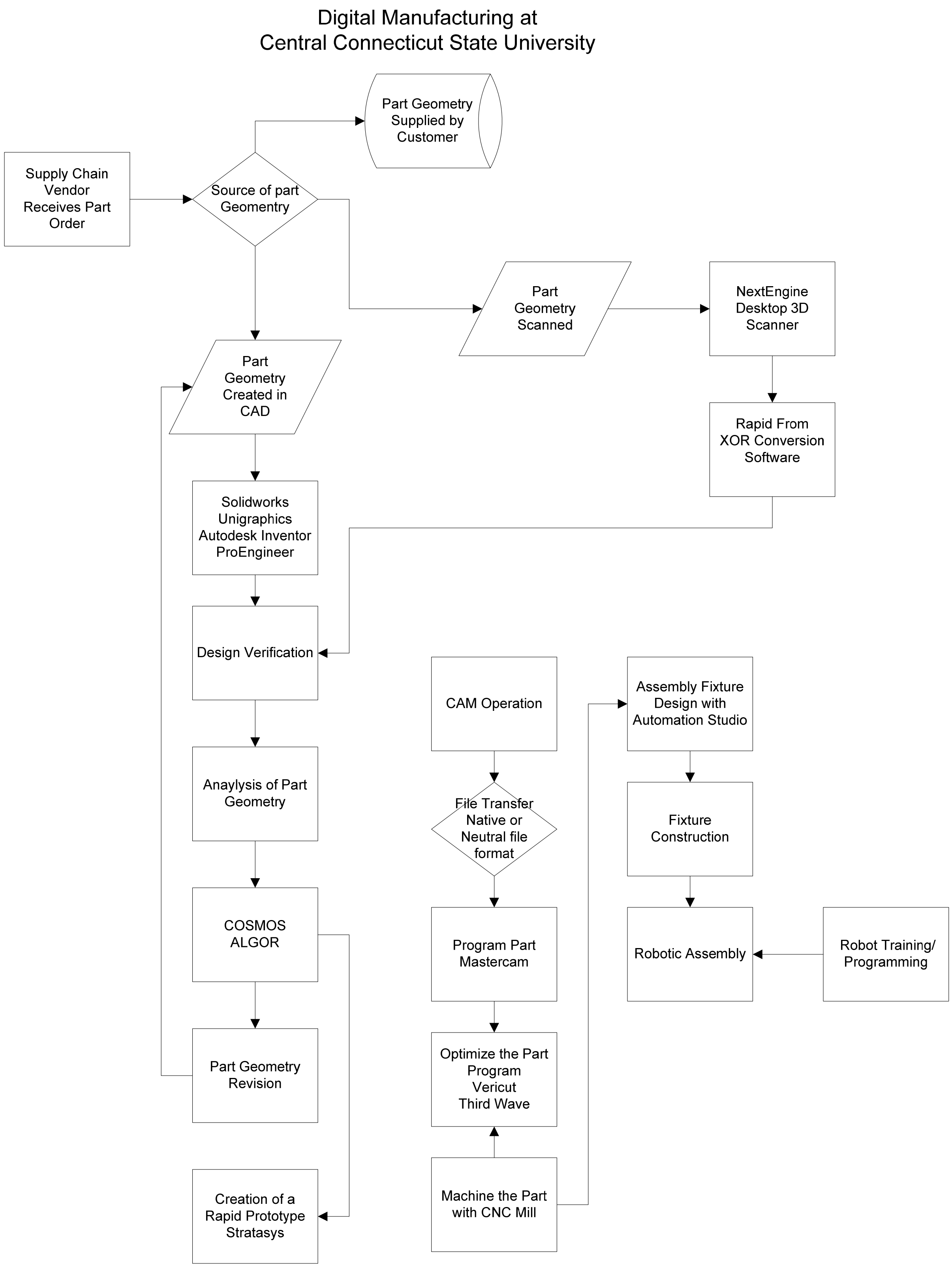


Figure 54 Block Diagram of Digital Manufacturing Process for Part Machining

Finite Element Analysis (FEA) - ALGOR and COSMOS
The next step in the digital manufacturing cycle was to analyze the digital model for stresses and loads. Two different Finite Element Analysis (FEA) software packages were used. COSMOS is included with SolidWorks network license purchased with NALI funding and Algor was the other FEA software that was already available at CCSU. The digital model was successfully read into both FEA systems and analyzed. This step went very well. Once the part was analyzed a fillet was placed in one side of the part for comparison of the strength of the part where the vertical surface meets the horizontal surface. The fillet relieved some of the stresses present at the intersection of these two surfaces.

Rapid Prototyping – 3D Printing with Stratasys Dimension
The edited digital product definition was then sent to a 3D printer to create the part as a Rapid Prototype using the Stratasys Dimension printer. CCSU has been a leader in Rapid Prototyping technology for years and currently owns two Stratasys Dimension printers and a 3D Systems SLA 250. It is an area of digital manufacturing that has great potential as it is a relatively new technology developed in the late 1980's and continue to make breakthrough advancements for all levels of manufacturing enterprises.

The part was made of a durable ABS plastic that can be sanded, milled, drilled, painted and electro-plated. The field of Rapid Prototyping continues to develop with the long term goal to turn the area into rapid manufacturing of parts. There are many other techniques available but the unique thing that they all have in common is that they are additive processes which build parts by adding layers of material as opposed to traditional manufacturing machining processes which are typically subtractive processes. A physical model of our digital part was created in a few hours allowing form fit and function to be checked all in a day's work.

Computer-Aided Manufacturing - Mastercam
The digital model was transferred to the Computer-Aided Manufacturing (CAM) software to create a Computer Numerical Control (CNC) program to mass produce the part. Mastercam software is the preferred CAM software for the majority of supply chain vendors and has been owned and operated at CCSU since the late 1980's. All of the original accuracy of the model came through to Mastercam providing the level of detail needed to accurately machine the part. The model from SolidWorks transferred well and a CNC program was generated. Before the program was run it was simulated in Mastercam. After simulating cutting the part, the program was edited to optimize the NC code.

CCSU's manufacturing laboratories feature an array both manual and CNC controlled machine tools used to teach students manufacturing processes. The part was cut using two different types of CNC milling machines. One was a fully automated Bridgeport CNC machining center with automatic tool changing capabilities. The other was a traditional Bridgeport mill with CNC capabilities that required the program to be paused while the operator changed the tool, resulting in a longer cycle time and a loss of productivity. The machining center was a much more efficient way to create the part but also requires an additional investment. However the return on the investment would be quickly realized when mass producing parts.

CNC Tool Path Program Verification - CGTech VERICUT
CGTech's VERICUT software was procured. This was a great addition to our manufacturing laboratory taking us to another level of simulation. Students modeled a Bridgeport CNC machining center. This is the first step to properly using VERICUT software. A simulation of a part being cut was created to verify that there would not be any cutting tool interference with the holding device or the machining center. The students worked closely with team throughout this project. There has been an ongoing bug with the VERICUT software that has prevented the software from running in our laboratory environment, limiting its use to the two laptop computers originally purchased with the NALI funding for this project. We continue to work to resolve this problem and seem to be near a resolution.

Cutter Tool Analysis - Third Wave Systems
NALI funding was used to purchase Third Wave systems software AdvantEdge and Production Module software after first using a demo copy of it. AdvantEdge™ FEM 5.1 is a materials-based solution for optimization of metal cutting processes. This modeling and simulation software provides detailed analysis of milling, drilling, and turning processes. It allows you to improve material removal rates, part quality, and tool performance while decreasing the need for physical testing. In addition to force and temperature prediction, AdvantEdge™ 5.1 features tool wear prediction capabilities, automated 3D residual stress analysis, 3D tool thermal boundary conditions, 3D initial mesh viewer, and enhanced rake face data extraction capabilities. It will help you machine it faster, machine it better.

Automation Systems Simulations - Automation Studio
Famic Technologies has created a complete simulation software for designing automation systems. It contains subjects related to hydraulic, pneumatic, electrical, PLC and control technologies, the illustration of concepts and the behavior of systems can be simulated. The components required to design and build a system can be assembled and tested through this simulation software. This software is being utilized by students in the Fluid Power and Mechanisms for Automation courses. It has been very well received.

Value Stream Mapping (VSM) of Processes and Production Facilities
An investigation of the various Value Stream Mapping software packages was undertaken. It was determined that this software provided a way to electronically create a graphical VSM which could contain the key data that was required for a Factory Floor Simulation. It is a useful tool for collecting and organizing flow data. Most packages can interface with Microsoft Office products such as Excel or Visio. The software that was reviewed is listed below:

- eVSM
- SigmaFlow VSM
- Igrafx
- LeanView

The M&S team has subsequently developed an interface between eVSM and Quest factory floor simulation software. This interface allows the data collected in the eVSM software to be seamlessly transferred to Quest rather than having to be re-entered.

Research on the Application of Modeling & Simulation software for K-12

When looking at trying to pique the interest of young people in careers related to manufacturing it would only seem natural that this generation of electronic gamers would have a natural affinity for the software tools employed by modeling and simulation. The current generations of students have grown up with electronic games on their computers and television from Playstation to Wii. One software tool that was reviewed is Cosmic Blobs. Cosmic Blobs was identified by the M&S team as a software of interest. The software had an easy to use interface that was geared toward a young person ages 7-13. It contained all of the key features for solid modeling but toward the application of creating models that can be rendered and animated. In the process of creating, rendering and animating the models the students learn the basics for solid modeling. The best use of this software would be for students grades K-8. It could be used for any subject area where a student may currently build a physical model. Now they can create a virtual model. In biology they could learn the parts of a fish through modeling, rendering and animating a model of a fish. A model of the solar system could be created and animated to allow a student to better understand the interrelationship of the planets.

Online Simulation Learning Tools

The evaluation of Online Simulation Learning Tools was undertaken to determine the effectiveness of self directed learning in a simulated environment. In collaboration with the M&S team the Immersive Environment for two different applications were evaluated. The Robotics simulation module was utilized by senior level students in the IT 480 Robotics course. They learned the Fundamentals of Robotics as well as the specifics of controlling the various degrees of freedom in a robotic arm. This knowledge is required in order to program the robot to complete a task.

IT 480 - Robotics
Robotics [c] [GR] Overview of the industrial robot. Introduces the student to the science of flexible automata. Emphasizes features, capabilities, programming, selection and applications of industrial robots.

The CNC training module was introduced in the MFG 216 Manufacturing Processes course and MFG 226 a CNC course. Sophomore level students learned the various G and M codes as well as how to create a CNC program.

MFG 216 - Manufacturing Processes
Manufacturing Processes [c] Prereq.: MFG 118 or ET 150, or permission of instructor. Manufacturing principles for material removal, forming, joining, and casting. Applications of machine tool setup and operation, feeds and speeds, principles of cutting tools, welding, and foundry. Lecture/lab meets five hours per week.

MFG 226 - Prin of Comptr Nmrcl Cntrl
Principles of Computer Numerical Control Spring. Prereq.: MFG 121 or ETM 260 or permission of instructor. Principles essential for computer numerical control part programming and machine tool operation. Laboratory experiences include word address programming, computer-aided programming, and CNC machine tool setup and operation. Lecture/lab meets five hours per week.

The major benefit of having access to both of these tools is that it provides access to the learning concepts with virtual hardware, preventing the need for the schools to invest in capital equipment that in many cases is simply out of reach of the school budget. For those school that are fortunate enough to have this equipment the simulation software provides them with an environment where they are free to learn and make mistakes without having to worry about creating an unsafe condition or crashing the machine and thus having an expensive repair bill. Overall the students review was favorable of the use of simulation technology in the learning environment. A complete summary of the students' opinions can be found in the CCSU final report.

Additionally we have worked with the CCAT Education Initiative and the Connecticut Business and Industry Association (CBIA) in evaluating other Online Simulation environments such as ToolingU and Oxygen Education. In this case we evaluated course modules related to Lean Six Sigma and ISO 9001 quality issues faced by the supply chain vendors. Students in an Online course were given access to these modules and asked to complete them and evaluated them. Subsequently we hosted meeting of CBIA and Industry Representatives for the purpose of evaluating the software and preparing an RFP. The CCSU final report includes the results of the students' surveys.

Improving Design Education with Simulation Workshop

Project team representatives attended a workshop for educators in the field of Design Education that was held at Sinclair Community College in Dayton, Ohio (with funding from the NSF). This knowledge development activity provided insight into how simulation techniques could be taught in a basic design course. Attendance at this workshop provided training in the use of Autodesk Inventor relative to modeling a gear and a gear assembly module. Day two provided instruction in Design Simulation Technologies from Dynamic Designer. The gear assembly was put in motion simulation parameters were added and the output results were obtained. Other problem-based simulation activities included thread and cam modules. It should be noted that the simulation software is very similar to that contained in SolidWorks.

TimeWise Lean Manufacturing Simulation Tools

This experiential workshop was conducted with the CCAT Education Initiative staff to help them learn about the generic principles of Lean Manufacturing in the context of the special circumstances of facilities that produce limited quantities of a wide variety of parts, assemblies or products. In addition to the fundamentals of Lean processes, the Job Shop workshop concentrated on such areas as design engineering, order processing and paperwork flow, quick changeover of tooling, and other specific issues which have greater significance in supply chain manufacturers shops than in the sort of continuous flow manufacturing facilities for which most

Lean awareness training has been developed. The TimeWise kit required form the hands-on activity of building the clock was purchased. TimeWise has also been integrated in the curriculum at CCSU, within MFG 496 Lean Manufacturing and IT 561 Applications of Lean Principles.

MFG 496 - Lean Manufacturing
Lean Manufacturing Fall. Principles of lean manufacturing methodologies. Topics include production flow analysis, value stream mapping, pull systems, cellular manufacturing waste elimination, visual factory, error proofing, quick changeover, change management.

IT 561 - Application of Lean Principles
Application of Lean Principles Fall. Tools and techniques of lean manufacturing as they are applied to an entire organization. Core methodologies in lean production include value stream mapping, teaming, productivity improvement, inventory reduction, pull systems, kanban, standard work, and cost reduction.

Technology Deployment

Horst Engineering and Manufacturing

Over the years Horst Engineering has been quick to adopt new CAD/CAM software and keep current with the ever changing options in modeling the parts they make. Recently they have been transitioning from CADKEY to SolidWorks, from wireframe models to Solid models. The advantages of solid models are numerous because they contain more data about the part than the wireframe model and are easier to create saving time and money. However they were running into a bottle neck in their process of transferring the solid model from SolidWorks into Mastercam their Compute-Aided Manufacturing (CAM) System. Theoretically it is a direct transfer but in practice they were recreating the geometry in Mastercam. We identified this as a significant loss of productivity. CCSU staff arranged meeting to include the CCAT/NCAL M&S team and Horst Engineering Applications Engineers along with their Managers. Through a collaborative effort we were able to streamline the data transfer process from SolidWorks to Mastercam saving Horst Engineering a great deal of time and increasing their competitiveness.

Operational Analysis of a Manufacturing Process and Factory Flow Simulation at GKN Aerospace

The focus of this project is to quantitatively evaluate the production system to identify tooling, capacity, resources, inventory, and technology requirements specific to the fan inlet case. The fan inlet case is a composite structure which requires a great deal of time to manufacture. The goal was to increase throughput of the fan inlet case from the current rate of one per month to a rate one per day by the year 2013.

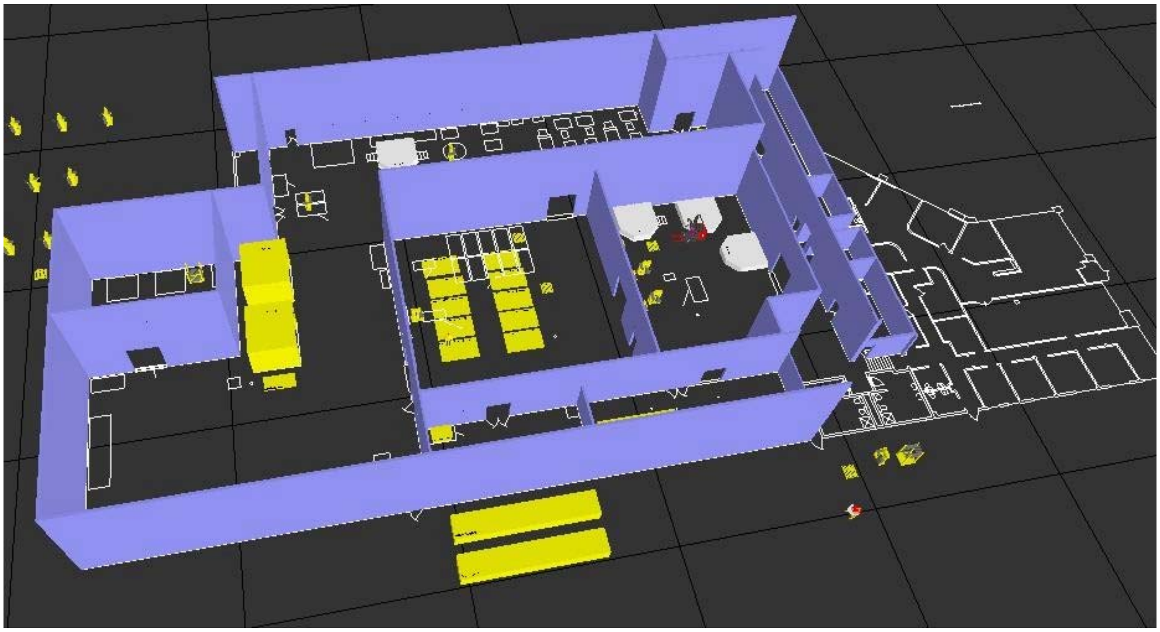


Figure 55 Model of GKN facility

Factory Flow Simulation at Turbine Engine Components Technologies (TECT)
A Factory Flow Model was developed for educational purposes to supplement a graduate course in Operations Management. The model was used to prove/disprove general hypotheses regarding students' intuition relation to reorganizing the production control system. To model & simulate the conversion to a lean manufacturing cellular production system for one of the growth product lines for TECT. Forming a manufacturing cell may not give you the results you expect -- you also have to change your production control system to flow the parts. The model helped to illustrate some of these issues. The modeling interface was again difficult to use. It was recommended the development of an easier to use interface for model building be explored. The CCAT/NCAL M&S team has since developed a better user interface with a third part as well as through the eVSM software.

Factory Flow Simulation at Aero Gear Inc.
Data was collected to use Delmia Quest discrete event simulation software to model & simulate (2) work cells areas at Aero Gear. The purpose was to evaluate potential improvements to the system prior to making any physical changes – in essence, a virtual Kaizen. The plant layouts were completed and the product/process data were formatted for import into the Delmia Quest tool.

Lean Experience (LX) Program
The Connecticut Manufacturing Supply Chain Integration (CMSCI) offered Connecticut students, attending community colleges, state and private colleges and universities, the opportunity to participate in the Lean transformation process in Connecticut companies. For students, this opportunity was a chance to better understand the workplace and to gain practical exposure to Lean/6-sigma tools and techniques. For the host company, the students brought "outside eyes" and another pair of hands to help with the Lean transformation. It also gave the company a chance to assess/recruit future interns and full-time employees. This opportunity was shared with all of the students in classes related to Lean/ 6 Sigma at CCSU.

Supply Chain Risk Analysis Tool
Through CCAT's SBIR Initiative an introduction was made to International Resource Management, Inc. (IRM). IRM had developed a software engine for Risk Analysis. The request was made to develop the content required to be entered into this Risk Analysis Engine. The goal was to provide the manufacturing industry with a means to determine the level of risk they are under in conjunction with their current strategic supply chain plans. The result was the creation of interactive software based questionnaire which allows companies to assess the amount of risk they currently have relative to logistics and transportation of materials within their supply chain. A working copy of the tool was provided to the NCAL, along with a final report.

Electronic Product Functionality Modeling
The CCAT/NCAL M&S team engaged directly with HABCO, Inc., Glastonbury, CT, that provides ground support and testing equipment to the United States armed forces and commercial aerospace manufacturers to investigate the potential benefits of utilizing a capable Computer Automated Design (CAD) software package. With previous CAD software, they were effective in creating manufacturing process sheets and assembly instructions, but sought more functionality to become more competitive in their industry. As a technology demonstration project, the CCAT/NCAL M&S team was provided CAD models of a maintenance crane currently in production to be used to create animated assembly instructions to replace current placards containing steps for assembly.

After importing their current models into SolidWorks®, the CCAT/NCAL M&S engineers were able to convert the previously static model into a series of sub-assemblies and joints which allowed motion from a fully assembled operational state to a storage state. With this capability, it was not only possible to show that all components fit into a storage envelope, but also the full range of motion of the crane.

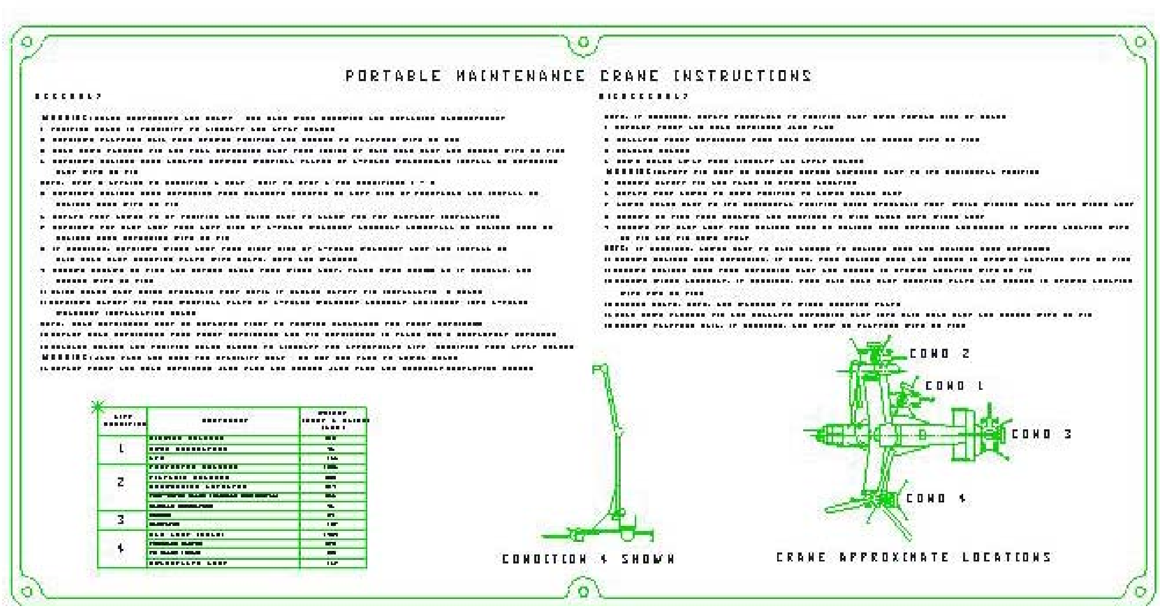
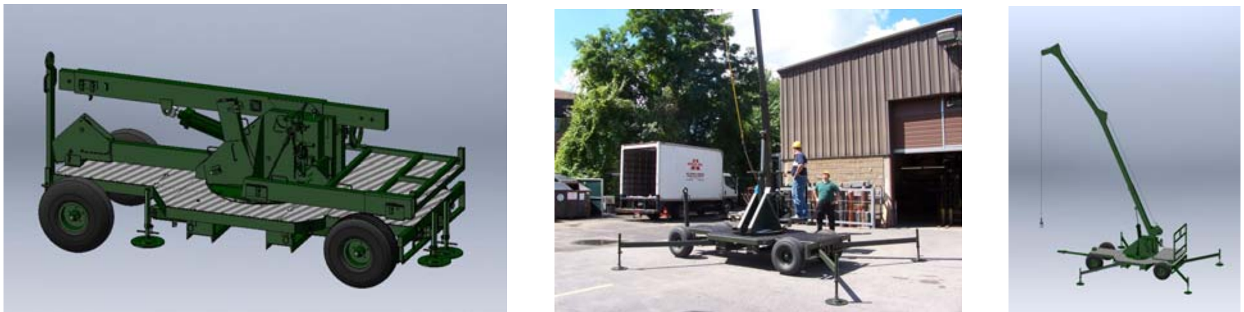


Figure 56 Typical Usage Documentation Plate

With the motion of the crane defined, it was then possible to create an animation of moving from storage state to an operational state. This capability allows a much better understanding of the assembly process then step by step instructions. The same SafeWork model was also used to determine the center of mass for each sub-assembly included within the crane in a matter of minutes. Due to this demonstration of range of motion, HABCO is currently in the process of evaluating CAD software packages with similar features for investment to best fit their needs.



(The Real Crane)

Figure 57 Crane Modeled In SolidWorks
SolidWorks(Extended)

The SolidWorks CAD system was proven to be an easy to use, and comprehensive virtual environment to validate the design and product functionality of sophisticated products, and to serve as the basis for the creation of 3D based simple electronic work instructions for the end user.

Conclusions

The execution of this project between the CCAT/NCAL M&S team and CCSU has dramatically impacted the ongoing teaching process in the Manufacturing Technology and the new Mechanical Engineering programs. Funding from this project provided CCSU with the financial means to update much of the software that is now the basis for teaching within the new Modeling and Simulation center at CCSU. Students now have the ability to see how all these software tools should be applied in industry in terms of designing mechanical systems, validating their functionality, developing the manufacturing processes to produce the parts and then actually create the NC Programs to cut the parts on the real CNC machine. This will lead to the creation of a much more capable entry level engineer for employment for the aerospace industrial companies nationally.

References

"Final Report to the Connecticut Center for Advanced Technology (CCAT) and the National Aerospace Leadership Initiative (NALI)", Paul Resetarits, Principal Investigator, Chairman of Manufacturing and Construction Management Department at Central Connecticut State University (MCM-CCSU), May 1, 2008.

2.2.8. Enterprise Modeling – Factory Floor Operations

Overall Summary of Tasks

Under this level of activity, the CCAT/NCAL M&S team engaged with companies primarily within Connecticut for ease of access, as we investigated the concepts of being able to use factory modeling to help companies implement lean manufacturing systems.

Methods / Procedures

For this activity the CCAT/NCAL M&S team chose to use the DELMIA QUEST discrete event factory modeling software solution because of hands on experience in its application, and because of the open architecture of the solution for importing data, and creating software macros that can automate the mundane repetitive mouse clicking that is required when building models within the as delivered user interface. Discrete event factory modeling tools allow the user to generate models of how the factory operates at a snap shot in time, as the base line operating conditions. The model then becomes the basis for the analysis of "what if" scenarios that are being considered for a future concept for a new way of executing the manufacturing processes.

Successfully implemented discrete event modeling solutions provide the end user with an environment that represents the functionality of the factory so that they can:

- Anticipate the behavior of Plants in operation
- Determine throughput with various product mixes and resource levels
- Evaluate material handling alternatives, number of resources required
- Determine impacts of facility layout
- Determine number of parallel and serial operations required
- Analysis of
  - Flow time
  - Bottlenecks
  - Throughput
  - Capacity
  - Resource Utilization

The goal of the activity under this category was to evaluate the technology and how it can be used to support companies that are trying to improve their efficiency and increase their capacity by implementing lean manufacturing principles. Through technology demonstration projects, we attempted to provide companies with an environment to evaluate these ideas in a virtual environment prior to actual implementation. This type of virtual environment is excellent for being able to see today, the factory of tomorrow.

Conclusions

More than 10 projects were initiated by the CCAT/NCAL M&S team to serve as a method of educating industry and the education community on the power of Discrete Event Factory Modeling and the use of Value Stream Mapping for data collection to enhance the development and execution of manufacturing processes within Aerospace Supply Chain Level companies. In addition, a number of projects were funded regionally to develop a workforce from the Technical

High Schools, Community Colleges, and Universities that have the skill set required to implement these technologies as employees at companies using these technologies.

2.2.8.1. Aerospace Factory Floor Modeling for Validation of Production Level Capacity

Overall Summary of Task
Work with supply chain level companies to model the existing manufacturing production system to serve as the baseline for quantifying improvements for the implementation of Lean Manufacturing concepts. Virtual Kaizens will be supported with this factory modeling technology.

Key Players: Tom Scotton (CCAT/NCAL), Jon Fournier (CCAT/NCAL), Dr. Paul Resetarits, CCSU's Department of Manufacturing and Construction Management

Introduction
In this project, the CCAT/NCAL M&S team engaged with a number of local aerospace supply chain level companies to validate and demonstrate the capabilities of discrete event factory modeling software. The list of participating companies includes Smith Aerospace, GKN Structures, AeroGear, TECT, Kamatics, Kaman Fuzing, Fenn Technologies, Trumpf Inc. and Flanagan Brothers. At each of these companies, as part of the engagement, it was critical that they could provide us with data that represented the existing manufacturing processes and how they are executed within the plant. In some cases, just acquiring this data, and providing it to the modeling team, is more than can be accomplished due to ongoing day to day job requirements. We were successful in getting in-depth information from Smith Aerospace, GKN Structures, AeroGear, TECT, Kamatics and Kaman Fuzing. Initially our hope and expectation was that we could build factory models using the software user interface, and minimal customization of the model control logic.

Methods/Procedures
In the section below we will provide a summary of the activities executed as technology demonstration projects with the supply chain level companies.

Kamatics, Bloomfield, CT - http://www.kamatics.com/
Kamatics Corporation is a subsidiary of Kaman Corporation. They manufacture high-performance mechanical components for aviation and other applications. Products include self-lubricated bearings for aircraft flight controls, turbine engines, and landing gear.

A discrete event simulation model was built for Kamatics Corporation to model the operation of a bearing manufacturing cell. The cell manufactured 32 bearing models, including bearings for JSF assemblies. These models all had identical routings through the cell, with the only difference between the part processes was the actual cycle times and lot sizes at the different work stations in the workcell.

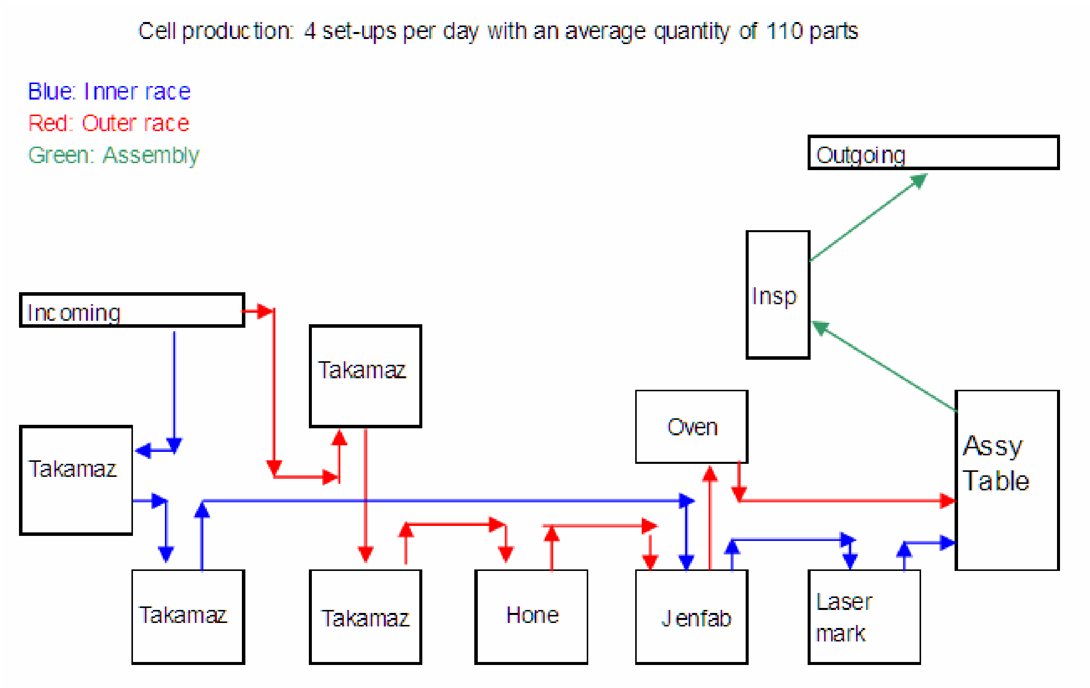


Figure 58 Process Flow Chart from Kamatics

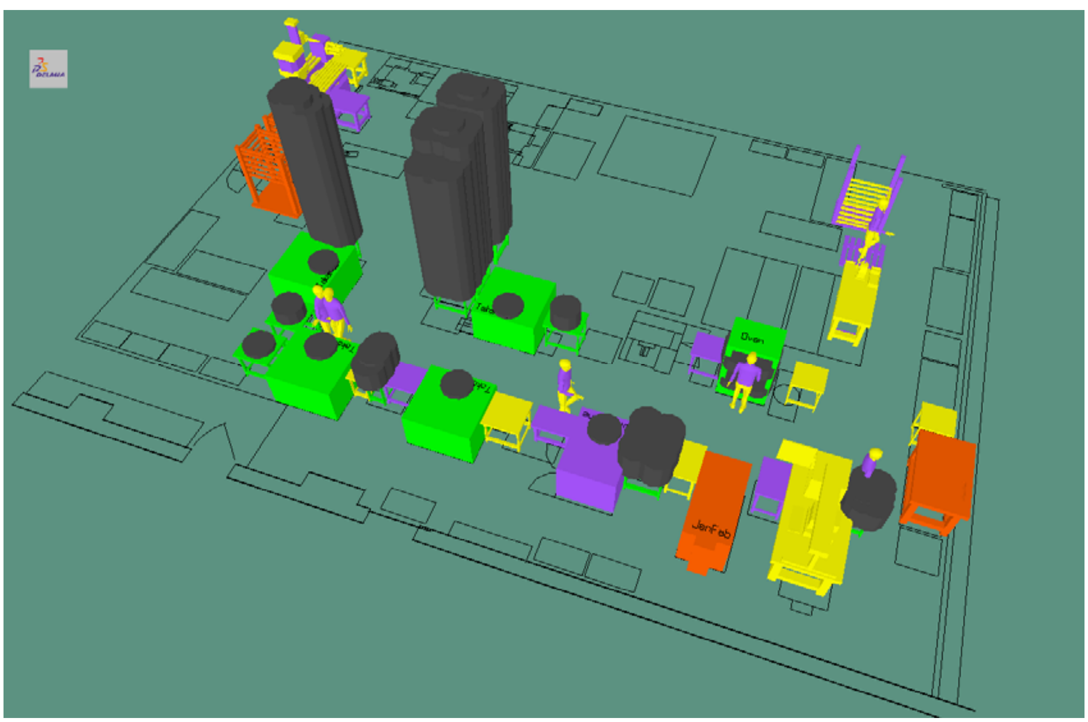


Figure 59 QUEST model of Kamatics bearing cell

This modeling activity was successfully completed, and a recommendation was made to Kamatics that they consider investing in this technology to be able to perform this kind of analysis internally with their own staff. It was possible to validate the model by running real production schedule data through it, and validating that the model showed close agreement with the real production rates, proven to predict within 10% of actual throughput times, and was used as a test bed for trying various lean improvement ideas. The baseline QUEST model is currently being maintained by the CCAT/NCAL M&S team to support them as they identify new "what if" ideas that they would like to evaluate to determine the impact on the need for resources and the impact on production throughput.

Senior Aerospace, Sterling Machine – Somers, CT:

http://www.seniorplc.com/aerospace/company.cfm/33

Sterling Machine is a subsidiary of Senior Aerospace and is a preeminent manufacturer of transmission and rotor-head helicopter components for military platforms. The CCAT/NCAL M&S team engaged Sterling Machine in a technology demonstration project to demonstrate the capabilities of the QUEST software to support the design of a manufacturing cell for the fabrication of retention plates for helicopter transmissions. The goal was to show them how the QUEST software could help them validate the cell layout, capacity, and staffing requirements. The CCAT/NCAL M&S team met with the Sterling Machine project management team and discussed their plans to change the layout of their machines to create this lean manufacturing based cell. A preliminary layout was provided, as well as routing and cycle time information for machining the part. This information was used to build a discrete event simulation model within QUEST. This model mimicked the flow of parts through the cell, including a specialty milling machine capable of loading four parts at once. With the flow verified, laborers were added to the model to test various staffing scenarios, including shift lengths and working weekends.

Figure 60 QUEST Model of Machining Cell Concept

Additional discussions with the Sterling Machine management team brought forward different ideas for layouts as well as staffing levels. A final layout was selected based on the results of the simulations presented and the model was then able to validate that the system could meet expected demand with a minimum amount of staffing. With this technology Sterling Machine was able to make changes early on in the design of the cell regarding floor layout as well as staffing levels while maintaining the capacity to exceed expected demand. Because of the visualization capabilities of the QUEST software, Sterling management and floor-staff were able to participate in layout decisions. Sterling management was also able to identify where bottlenecks would occur in the system to help drive improvements once the cell is implemented. The baseline QUEST model is currently being maintained by the CCAT/NCAL M&S team to support them as they identify new "what if" ideas that they would like to evaluate to determine the impact on the need for resources and the impact on production throughput.

Kaman Fuzing, Middletown, CT. - http://www.kamanaero.com/fuzing.html
Kaman Fuzing is a subsidiary of Kaman Corporation and is located in Middletown, CT. Kaman Fuzing develops and manufactures safing and arming solutions for ordinance applications for the USAF. For this project the CCAT/NCAL M&S team was engaged to support the staff at Kaman Fuzing as they developed the design of a fuze assembly line operation in a new room within their plant. During this engagement, the CCAT/NCAL M&S team was introduced to a value stream mapping software called electronic Value Stream Mapping (eVSM), by a contracted consulting group Techsolve (Cincinnati, Oh). Kaman Fuzing was using this tool to develop a value stream map of their process in the Middletown facility that was being designed based on an existing production facility in Orlando, Fla. The data from the existing facility in Orlando was utilized as the initial information for the implementation of the process being implemented in Middletown. The data was provided to us via the Value Stream Mapping software eVSM mapping. The CCAT/NCAL M&S team was able to extract this data and use it as the basis for the new proposed system to be implemented in the Middletown facility. The CCAT/NCAL M&S team worked with Kaman Fuzing engineers directly to lay out the new facility and determine where different operations would take place, and any improvements that were anticipated for new operation cycle times.

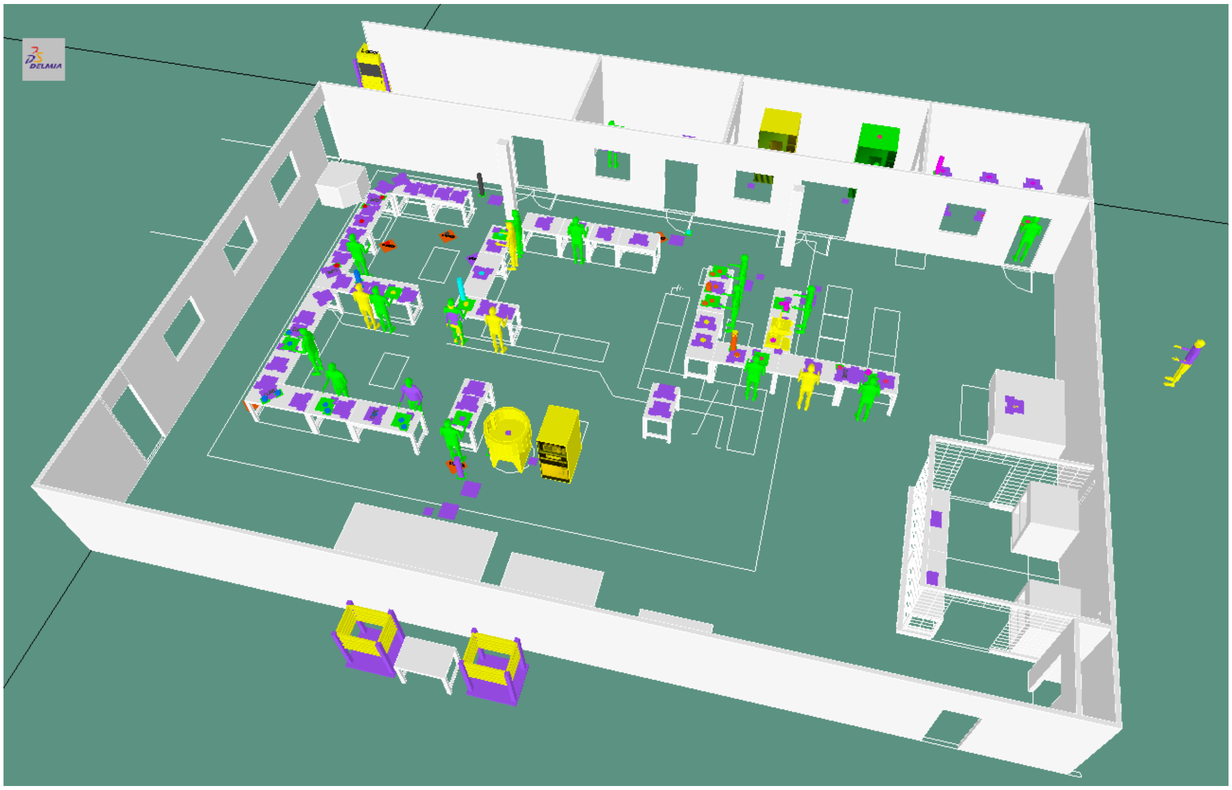


Figure 61 QUEST Model of Kamatics Fuzing Assembly Cell

The completed model provided the Kaman engineers with an environment to address labor requirements of the manually intensive assembly process. Working with the CCAT/NCAL M&S team, they were able to make changes in manpower assignments and see the effect on the throughput of the system. The simulation was able to verify that the line would get the required capacity with less manpower than calculated using traditional methods. The baseline QUEST model is currently being maintained by the CCAT/NCAL M&S team to support them as they identify new "what if" ideas that they would like to evaluate to determine the impact on the need for resources and the impact on production throughput.

GKN Aero Structures - http://www.aerospace.gknplc.com/aerostruct.aspx
GKN Aero Structures is looking to increase the capacity for manufacturing composite fan inlet cases for the F135 engine from approximately one per quarter to one per day within the next 13 years. The CCAT/NCAL M&S team worked with GKN Structures engineers to collect process data and built a simulation model of the operation of the facility. The CCAT/NCAL M&S team then tested several improvement ideas as suggested by GKN Structures engineers. The CCAT/NCAL M&S team also ran the model with different resource quantities in an effort to find resource requirements to meet future demand.

Figure 62 QUEST model of GKN factory floor

As a result of this engagement, GKN now has a list of alternative approaches to increase their capacity over the next 13 years as they ramp up to production. The baseline QUEST model is currently being maintained by the CCAT/NCAL M&S team to support them as they identify new "what if" ideas that they would like to evaluate to determine the impact on the need for resources and the impact on production throughput.

Smith Aerospace, Manchester, CT

This project was an engagement to validate the ability of the QUEST factory modeling software to model a large laser processing cell within the factory that consisted of KanBan supermarkets and Just in Time pulling of parts based on the minimum and maximum values in the racks. It included very complex routing of a large data set of parts. We engaged in the activity as the concepts for the workcell were still being developed. The expectation was that we would be able to confirm that the level of resources being installed would be able to support the production rates of the customers demand.

Figure 63 Smith Laser Processing Cell Concept

The implementation of this model required a lot of custom logic development in order to implement the pull processes utilized by the kanban material flow controlling areas. In addition we attempted to utilize laborers as material handling resources, and ran into control logic issues that resulted in grid lock during the model execution. At the same time, personnel changes at Smith Aerospace due to the acquisition by GE, resulted in less interest from the company for supporting this activity, which lead to a termination of the engagement prior to the completion of the model. A lot of new methods for applying QUEST were learned during this activity which has been of value in other follow-on projects with other companies. The baseline QUEST model is currently being maintained by the CCAT/NCAL M&S team to support them as they identify new "what if" ideas that they would like to evaluate to determine the impact on the need for resources and the impact on production throughput.

AeroGear, Windsor, CT - http://www.aerogear.com

This project was initiated with Aerogear as a technology demonstration project to determine if the QUEST modeling software could be used as a tool to determine better methods for scheduling work through their component machining cell. The CCAT/NCAL M&S team collected routings and cycle times for approximately 15 different part numbers that get manufactured monthly in the cell. The model was also used to demonstrate the impact of decreasing transfer lot sizes on overall throughput and machine utilizations. This project is an ongoing level of effort, with additional activities being planned for execution in follow-on NALI Phases.

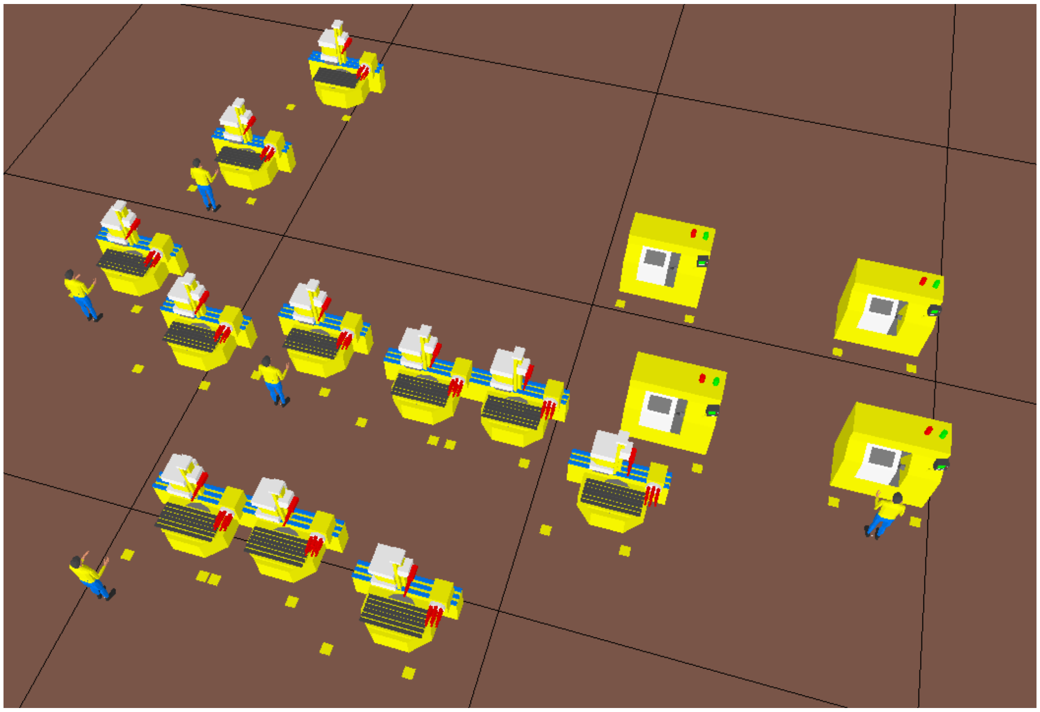


Figure 64 QUEST model of Aerogear bearing cell

The baseline "as is" QUEST model is currently being maintained by the CCAT/NCAL M&S team to support them as they identify new "what if" ideas that they would like to evaluate to determine the impact on the need for resources and the impact on production throughput.

Conclusions

As a result of the activities during the execution of the technology demonstration and validation projects with the Aerospace Supply Chain Companies in the region, the CCAT/NCAL M&S team has been able to expand and enhance our capabilities in the area of building discrete event factory models, and analyzing the simulation output information. A number of custom logic algorithms have been developed to support the use of factory models built in QUEST. As we got more experience with QUEST, it became apparent that one of the limitations in the software was the logic supplied for the use of using laborers as material handlers in the models. Because of this, most of our models are now being built assuming that the material will be handled in an efficient manner, and the use of laborers as the material handling system is not included in the functionality of the models. We hope to revisit this laborer controlling logic in a future project.

In order to be successful in executing these types of projects in the future, the following recommendations are being embraced internally during our execution of future projects in this technology area.

1. Educate the customer on what can and can't be done with these software tools early on. Develop good demonstration success cases showing the power of the solution.
2. Engagement with the customer must include the setting of clear goals for the project. If you don't know what problem you are trying to solve, it is difficult to consider the project complete and successful.

3. At the project kickoff meeting include all the players in the system that is going to be modeled and analyzed. Make sure all participants have bought into the execution of the project. These are the people that will be providing the data for the model. If they provide bad data, the model does not reflect reality (GIGO – Garbage In, Garbage Out)
4. Define a time frame for completion, or delivery of the simulation analysis. Make sure it is within the scope of when the customer needs the results.
5. Always look for methods to simplify the model details. Minimize the complexity of the system at all costs. Simpler models are easier to create, more quickly, and easier to understand. Keep focused on the goal of the project as you build the model.
6. Identify and document all the assumptions that are necessary to keep the model development simple.

We have clearly found that generating models of manufacturing factory systems can be a very complicated and difficult task. Once all the data has been gathered, it is often a tedious, mundane and repetitive process to key in the data through the software provided user interface. This manual method is also prone to possible typing errors that marginalize the results of the simulation. Because of this, the CCAT/NCAL M&S team is always looking for new ways to collect the system data electronically from the customer, so that it can be imported into the modeling software. One of the key reasons that our team selected the QUEST factory modeling solution from DELMIA was the ability to generate custom macros to pull in data and automatically build models from the data. This activity will continue within the follow-on Phases of the NALI program.

2.2.8.2. Development of Factory Modeling Tools to Teach Concepts of Lean Manufacturing

Overall Summary of Task
Working with education organization on the development of models that can be utilized to demonstrate the power of Lean Manufacturing concepts.

Key Players: Tom Scotton (CCAT/NCAL), Jon Fournier (CCAT/NCAL), Dr. A. Ali Montazer (Tagliatela College of Engineering, University of New Haven), Dr. Paul Resetarits (Department of Manufacturing and Construction Management, CCSU)

Participating Companies: GKN Structures, AeroGear, TECT, Kamatics, Kaman Fuzing Fenn Technologies, Trumpf Inc., Gumshoe KI

Period - 3/06 to 12/07

Introduction
A major objective of this task was to establish Discrete Event Simulation labs at two universities in Connecticut, the University of New Haven, and Central Connecticut State University (CCSU). As part of these projects, CCAT/NCAL staff supported the acquisition of the DELMIA QUEST Discrete Event Software and also provided onsite support to the universities for the installation. CCAT staff's also provided technical support for the university faculty as they implemented the tools.

Methods/Procedures
Central Connecticut State University installed QUEST and used it in an Industrial Operations Management class to investigate different lean implementation ideas at a local aerospace machining company, TECT in Newington, CT. The company was looking to establish a cell for machining a part with fairly stable, constant demand. As part of this class exercise, the CCAT/NCAL M&S team participated in the introduction of the software and how it works during several of the class laboratory sessions. We continued to support the students as well as they went through the creation of their versions of the proposed workcell concept for the customer, to make certain that the models reflected reality. The students presented their ideas to company management at the completion of their course work.

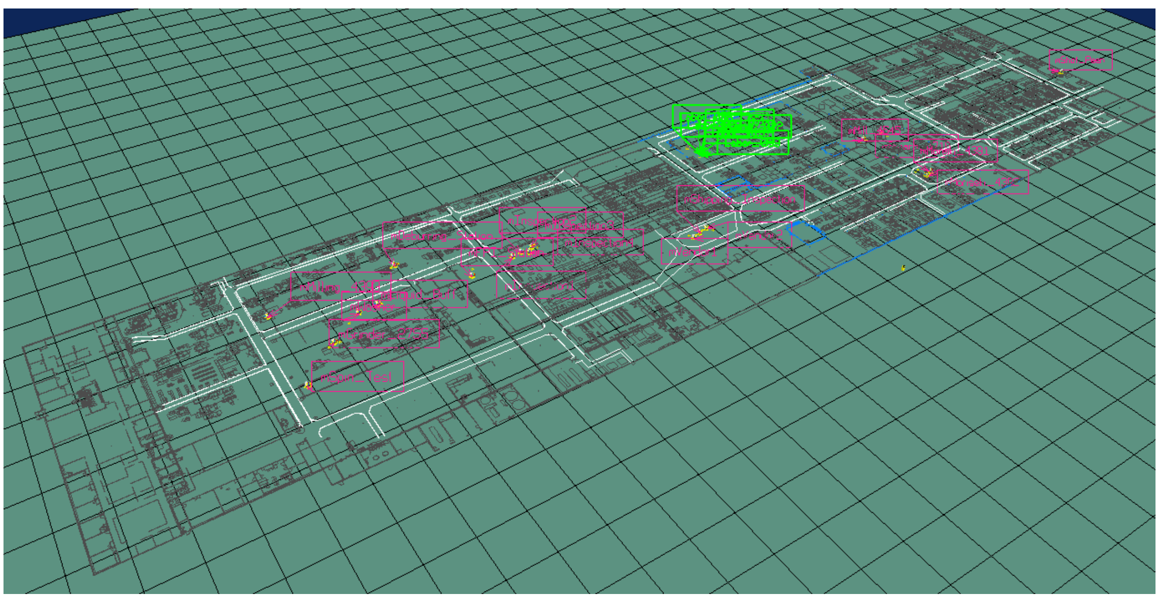


Figure 65 Example QUEST model of the TECT project

Student teams at the University of New Haven engaged in three factory modeling industrial technology demonstration projects:

- Process Simulation of Consolidated Industries Hammer Shop
- Modeling and Simulation of Aircraft Nose Gear Holdback Bar Production Line at Valley Tool & Manufacturing
- Simulation study of the Royal 35W skin stapler for U.S. Surgical

Consolidated Industries Hammer Shop

Consolidated Industries, Inc. of Cheshire, Connecticut, has been in the forging business providing parts to the aerospace manufacturers for over 60 years. The Company, primarily, produces impression or "closed-die" forgings in most metals for the commercial and military helicopter and the aircraft markets. These products include missile components, land-based turbine components, specialty automotive and truck components, and varied forgings in difficult applications for customers in niche commercial markets. Typical forgings range from ounces to 100 pounds. Production rates vary anywhere from small 6 piece batches to shipments of over 100,000 units per year. Consolidated is committed to Continuous Improvement and Lean Manufacturing process deployment throughout the shop and encourages its vendors as well as customers to participate in the development and design of such tools and techniques to help reduce cost and shorten lead times. Forged parts are made through Hammering or Pressing of heated metal parts, depending on the type of metal, shape of the end part and other characteristics of the order and/or customer need.

In this study, the Press Shop process of producing forged parts, mainly for the aerospace manufactures, is simulated using QUEST. The actual process is considerably complex but a macro level and greatly simplified rendering is that the process starts with raw materials (Bar Stocks) which are heated in Conveyor Ovens. Upon heating, the Bar Stocks go through the Press, Trim, Clean, Inspection, and De-burring operations before they are ready to be shipped to the next stage of processing in the plant. There are considerations of metal type, shape and counts for oven and press usages as well as the details of inspections and cleaning that are quite intricate and involved. Data gathering and preparation also presented a significant challenge for us but with the support and cooperation of the personnel at the plant, we were able to design and construct the required data structure in order to successfully simulate the Press Shop process model. The working model can now be used for the purposes of lean studies, bottleneck identification and resolution, lead-time studies and capacity planning. Consolidated Industries as interested in using this simulation model to predict the effect of changes to improve key performance metrics, justify equipment purchases and generally performing “what-if analysis” for new ideas prior to implementing them in the real facility.

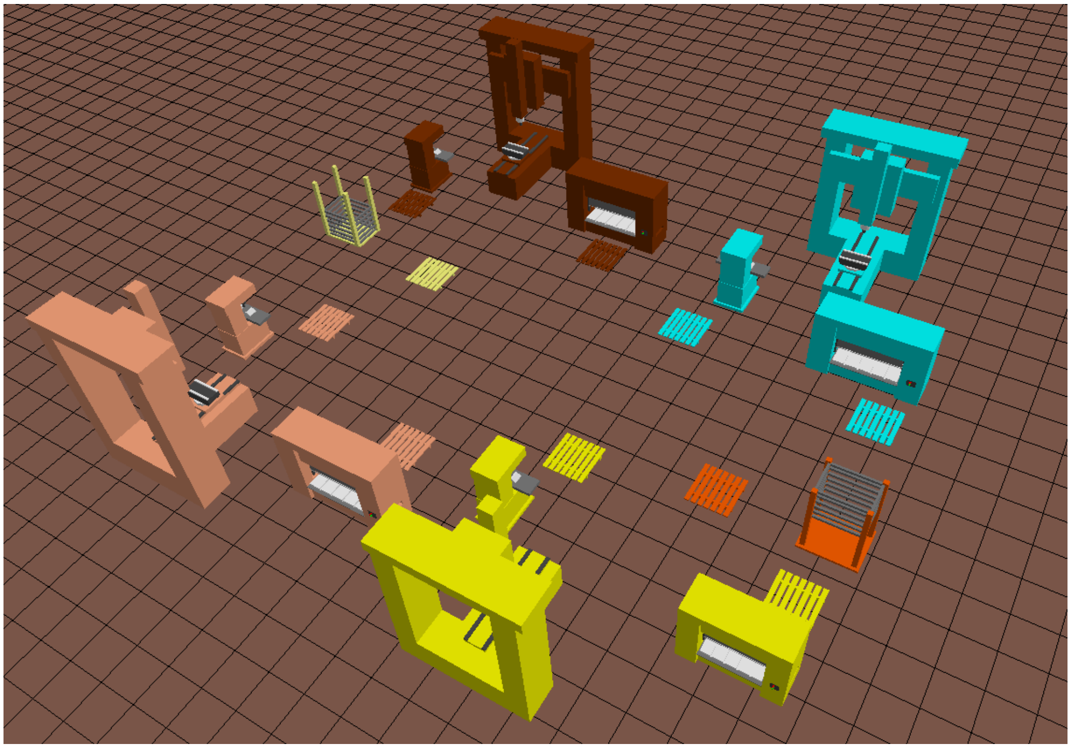


Figure 66 Example of the QUEST Model of Consolidated Industries Hammer Shop

Valley Tool & Manufacturing

Our team conducted a modeling and simulation study of the fabrication process of Holdback Bars used on U.S. Navy Aircraft Carriers. Holdback Bars are located on the nose gear of the aircraft and release the plane when it is ready for launch from the ship. Valley Tool and Manufacturing, (VTM) of Orange Connecticut is evaluating manpower, lead-time, and operational needs to produce various quantities of the bars. The model is a discrete event simulation of the fabrication process of machining and inspection operations. Using ARENA simulation software, the model successfully depicts the time and flow for all the Holdback Bar fabrication processes. By evaluating several alternative production scenarios, a Lean fabrication process using the optimum number of operators and the minimum production time was determined. The alternative scenarios include, adding operators, moving idle operators and various batch sizing implementations. The model was verified and validated to produce results that mimic those of a real production line. A predictive mathematical model has been developed based on the simulation results. The predictive model can be used by the production manager to compute the production time for a given number of bars. The simulation, model output and other findings will be explicitly exhibited.

U.S. Surgical

A factory modeling simulation study was conducted for the manufacture of the Royal 35W skin stapler production line at the United States Surgical Company in North Haven, Connecticut. The Royal 35W skin stapler, with annual production of three million units, is a device used by medical professionals to close wounds and cuts. The production line consists of automated stations followed by manual assembly. In its effort to advance lean initiatives, the company provided an opportunity to develop a simulation model to study the throughput, scrap rate and machine downtimes. Upon observation of the automated production line and with data provided by the company and expertise rendered by a team member employed at the company, our team developed a discrete event simulation model of automated portion of the production line using the ARENA and QUEST simulation software. The model closely mimics the production line in terms of both physical flow and output, as verified and validated by the operations manager. The model can be used for “what if analysis”, bottleneck identification and generally for process improvement and monitoring purposes.

Curriculum for Teaching M&S Principles to Teach Learn Manufacturing Concepts
As part of this program the team at the University of New Haven devised a series of laboratory workshops/exercises for the students to conduct to introduce them to the principles of discrete event factory modeling technology for the use in supporting lean manufacturing. Below is a summary of each workshops objective.

Workshop #1 – Learning Objectives

This workshop is the basic model elements in QUEST and also a single channel queue model (M/M/1) which includes:

- Source.
- Part.
- Buffer.
- Machine.
- Sink.

Workshop #2 - Learning objectives:

- Assigning queue logic to the buffers of the two machines.
- Element connections made between entities.
- Simulation model run.
- Observing results.

Workshop #3 - Learning objectives:

- The assumption of input like Inter arrival time (IAT) for the source and Cycle time for the machine.
- Defining and assigning failure to the machine.
- Defining and assigning repair process for the failure assigned to the machine.
- Status highlighting to show the status of the process while running such as idle, busy, failure in different colors.

Workshop #4 - Learning objectives:

- The assumption of input like Inter arrival time (IAT) for the source and Cycle time for the machine.
- Defining and assigning failure to the machine.
- Defining and assigning repair process for the failure assigned to the machine.
- Concept of element class in creating various similar elements.
- Class connections.

- Route logic for the buffer to route the parts to the 2 machines such as “next free”, “least utilized” etc.
- Status highlighting to show the status of the process while running such as idle, busy, failure in different colors.

Workshop #5 - Learning objectives:

- Concept of element class in creating various similar elements.
- Class connections.
- Route logic for the buffer to route the parts to the 2 machines such as “next free”, “least utilized” etc.
- Changing elements color, display and dimensions.
- To assign travel time for customers using conveyors.
- Creating and assigning labor controller and labor to the elements.

Workshop #6 - Learning objectives:

- Using multiple sources to create more than one part with different inter-arrival times.
- Assigning part fractions for the sources.
- Route logic for the 2 buffers to distribute the different types of parts to the 2 human operated machines.
- Creating and assigning labor controller and labor to the elements.
- Advanced simulation.

Workshop #7 - Learning objectives:

- Using multiple sources to create more than one part with different inter-arrival times.
- Assigning part fractions for the sources.
- Route logic for the buffer to distribute the different types of parts to the 2 human operated machines.
- Element connection to affect proper part routing.
- Creating and assigning labor controller and labor to the elements.
- Advanced simulation.

Workshop #8 - Learning objectives:

- Using multiple sources to create more than one part with different inter-arrival times.
- Designation of color and attribute assignments.
- Assigning part fractions for the sources.
- Queue logic for the buffer to give priority for Type 2.
- Using user attribute for the parts.
- Route logic for the buffer to distribute the different types of parts to the 2 human operated machines.
- Element connection to affect proper part routing.
- Creating and assigning labor controller and labor to the elements.
- Advanced simulation and modeling logic.

Midterm exam - Learning objectives:

- Concept of element class in creating various similar elements.
- Class connections.
- Proportions and route logic.
- Creating and assigning labor controller and labor to the elements.
- Route logic for the buffer to route the parts to the machines such as "next free", "least utilized" etc.
- Changing elements color, display and dimensions.
- Status highlighting to show the status of the process while running such as idle, busy, failure in different colors.
- Assigning shift breaks to the labor and machines according to the daily schedule.

Final exam - Learning objectives:

- Using multiple sources to create more than one part with different inter-arrival times.
- Designation of color and attribute assignments.
- Assigning part fractions for the sources.
- Queue logic for the buffer to give priority for Type 1.
- Using user attribute for the parts.
- Route logic for the buffer to distribute the different types of parts to the 2 human operated machines.
- Element connection to affect proper part routing.
- Creating and assigning labor controller and labor to the elements.
- Advanced simulation and modeling logic.

Conclusions

This engagement has been quite rewarding for both parties and a great learning experience for all involved, students, faculty as well as the aerospace manufacturers. The grant was a great catalyst to introduce the concepts and techniques of modeling and simulation to aerospace parts manufactures who most probably would never have attempted to use such tools due to the high cost, complexity and more than anything else unfamiliarity with the subject matter and its applications in production and operations management. The manufacturers become much more open to using such tools and techniques when they get to see what modeling and simulation can do for them, especially in relations to lean studies and implementation, bottleneck identification and resolution, lead-time studies and capacity planning. For more details please see the University of New Haven final report.

References

"A Report on the Grant to Create a Center for Simulation Modeling and Analysis with DELMIA's QUEST 3-D Simulation Software", M. Ali Montazer, Ph.D., Principal Investigator, Associate Dean, Department of Industrial and Systems Engineering, Tagliatela College of Engineering, University of New Haven

2.2.8.3. Development of Spreadsheet/VSM Interface with Factory Model Building Environments

Overall Summary of Task
Identify value stream mapping environment and create a semi-automatic method for quickly inputting this data into a QUEST Factory model for showing and validating production capacity in a manufacturing production line.

Key Players: Tom Scotton (CCAT/NCAL), Jon Fournier (CCAT/NCAL), Magnys

Participating Companies: GKN Structures, AeroGear, TECT, Kamatics, Kaman Fuzing Fenn Technologies, Trumpf Inc., Gumshoe KI, Magnys

Period - 3/06 to 12/07

Introduction
As we engaged with the Aerospace Supply Chain companies, we initially had expected that the companies would have access to all of the kinds of data that are required to support the creation of the models. In order to build a factory model it is necessary to know the information about the parts being made (Part Identification, Quantities, Lot sizes, Prerequisites Parts, etc.) in the facility, the processes for the parts (Parts required, tooling, labor, cycle time distribution), and the resources (machines, work stations, labor, etc.) that are used to execute the processes. Gathering this information has turned out to be a bigger challenge than originally thought. Most of these companies have already done a pretty good job of leaning out their staffing structure, and so it has been more difficult for them to do this data gathering as it is not their primary responsibility. The ideal condition is if we can engage with companies that are gathering this data electronically already. Also it became obvious that building factory models to support lean manufacturing requires that we are able to build these models very fast, so that they can be used to test approaches for change. Using the user interface in QUEST to build the models resulted in a very large number of mouse clicks and typing of numerical and textual data. This also lends itself to accidental input of incorrect information. The QUEST software was selected as our factory modeling software of choice based on the knowledge that it has a very open architecture, and the ability to generate custom user pages in the user interface to execute custom macros for automating the creation of models, and importing the data. The QUEST software provides a Batch Control Language (BCL) and a Simulation Control Language (SCL) within the package that are both capable of parsing plaintext files for automatically building simulation components and a complete model.

Methods/Procedures
Our initial solution to the data gathering issue, and rapid creation of factory models for supporting the evaluation of lean manufacturing was to use Excel spreadsheets. Because of this the CCAT/NCAL M&S team contracted with Magnys Corporation to develop a set of BCL and SCL macros to build factory models rapidly from a spreadsheet of information. The team from Magnys delivered a set of QUEST macros and custom page buttons for performing a 15 step model building process. This allowed the M&S team to just ask the customers to fill out a

spread sheet in the required format, and deliver this to us as the input to build the models. The user could then import this data into QUEST and build a model using a set of user buttons in the QUEST environment. There were separate buttons for importing data, then more for placing machines, setting material handling nodes, assigning labor and several other steps as shown below.

Step 1:	Import the Layout into CAD Environment
Step 2:	Check the Scale of the Drawing
Step 3:	Save the Layout
Step 4:	Edit Excel Input Data.
Step 5:	Begin Model Build Process – Load Base Model
Step 6:	Add Layout to the Model
Step 7:	Pre-process the Data
Step 8:	Create Workcells
Step 9:	Create Aisle Network
Step 10:	Create Forklifts
Step 11:	Sharing Labor
Step 12:	Create the Warehouse
Step 13:	Prepare to Run
Step 14:	Run the Model
Step 15:	Review the Results

When using this set of custom interfaces, each time you run the model, the system indexes the run number for that session of QUEST. This run number is used to give a unique name to the report file that is generated. The report file is a tab delimited text file that is saved as an excel file. The report files are located in the OUTPUT directory where the Factory Modeler is installed. The file name is *std_report(run#).xls*. A sample report is shown in Figure 67.

The Magnys User's manual describing the use of these macros is available upon request. The data input file format included machine names and reliabilities, part operation information (cycle time, setup time, etc…) and schedule information.

As we tested this interface we found it was limited in flexibility and would not always be applicable to the many varieties of manufacturing companies that we are working with. For this reason we began developing our own data interface for QUEST for reading in plaintext simulation data from spreadsheets.

std_report3.xls

	A	B	C	D	E	F	G	H	I	J	K	L	M	N
1	************************************													
2	Model Desc: ccat3.mdl													
3	Run Desc: Baseline Validation Run													
4	Analyst: Connecticut Center for Advanced Technology													
5	Date : Monday 8 May 2006													
6	Run No.: 3													
7	************************************													
8														
9	Scheduled Days 2.0 Days													
10	Model Warmup Time 0.0 Hours													
11														
12														
13			Busy	Idle	Down	Block	Load	Setup	Break Time	Off Shift	Max Q	Avg Q	Avg Proc	Num
14	Asset Number	Descriptior	(%)	(%)	(%)	(%)	(%)	(%)	(%)	(%)	Length	Length	Time	Processed
15	--													
16	WKCMachineA_1		18.333	22.91	14.59	0	2.292	2.292	8.333	14.583	5	1.877	0.902	23
17	LMachineA_1	Labor	19.583	0										
18	WKCMachineB_1		12.5	28.117	17.299	0	1.25	1.25	8.333	14.583	3	0.48	1.786	12
19	WKCMachineC_1		18.201	36.029	4.311	0	0.938	0.938	8.333	14.583	3	0.262	1.444	9
20	LMachineC_1	Labor	12.292	0										
21	WKCMachineD_1		8.333	50	0	0	1.042	1.042	8.333	14.583	2	0.397	0.545	11
22	WKCMachineE_1		11.794	46.331	0	0	1.146	1.146	8.333	14.583	1	0.026	0.688	12
23	LMachineE_1	Labor	4.792	0										
24	WKCMachineF_1		25	16.371	16.546	0	1.25	1.25	8.333	14.583	3	0.831	2.613	12
25	WKCMachineG_1		10.417	36.04	11.67	0	1.146	1.145	8.333	14.583	2	0.344	2.511	11
26	LMachineG_1	Labor	4.167	0										
27	WKCMachineH_1		18.75	26.896	12.896	0	0.938	0.938	8.333	14.583	1	0.221	2.041	10

Figure 67 Sample Report of Magnys Macro Output

Flexibility was one of the main goals of the development effort, and so the interface started as a framework for parsing text files, storing user preferences, and adding simulation elements to the model. This way the actual execution of the import could be broken into different sections that could be easily replaced or modified with custom developed code.

As we continued to evaluate this approach, it became apparent that this was not the answer for gathering the data from the customers for the support of the modeling and simulation activity. Even getting the manufacturers to fill out a spreadsheet for data input proved to be too cumbersome and often times the customers struggled to create the spreadsheets of information in timely manner. As we engaged with Kaman Fuzing, we were introduced to an electronic Value Stream Mapping software tool called eVSM from Gumshoe, KI through the consulting group, TechSolve (Cincinnati, OH). The creation of these VSM's requires that the creator gather all the information and input it electronically into an eVSM project that includes most of the information we need to generate a QUEST factory model. The eVSM software is provided as an application that runs on top of Microsoft Visio, and can therefore export visually configured information from Visio into an Excel spreadsheet format. This Excel spreadsheet can then be exported to a text file and then read into the QUEST modeling environment using the BCL and SCL macro approach. By keeping the framework flexible we were able to write VBA macros in Visio that would export the data to Excel and then straight into QUEST, requiring a single mouse click to translate from eVSM into QUEST. This flexibility allows users to extend the functionality of the builder easily with very little code.

This eVSM and QUEST integration allows for the majority of model building to be automated and streamlined, leaving only specialized effort to bring a simulation study to completion.

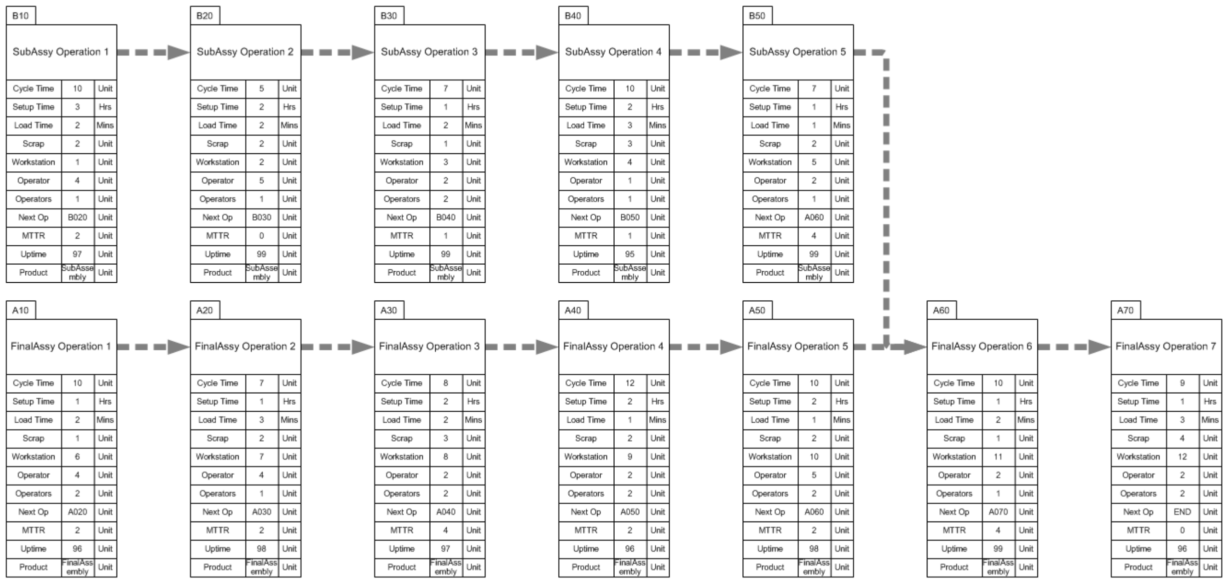


Figure 68 An example of a Value Stream Map in eVSM

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q
1	#Shape	Tag	Operation	Data	Data	Data	Data	Data	Data	Data	Data	Data	Data	Data	VSMX	VSMY	-
2	#Version4(	-	-	cycle time	load time	mttr	next op	operator	operators	product	scrap	setup time	uptime	workstatior	VSMX	VSMY	-
3	#17,14	-	-	unit	mins	unit	unit	unit	unit	unit	unit	hrs	unit	unit	-	-	-
4	#eVSM Op	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
5	{A34895C	A010	FinalAssy	10	2	2	A020	4	2	FinalAsser	1	1	96	6	140	350	-
6	{E51BFE3	A020	FinalAssy	7	3	2	A030	4	1	FinalAsser	2	1	98	7	340	350	-
7	{0E8A0BA	A030	FinalAssy	8	2	4	A040	2	2	FinalAsser	3	2	97	8	540	350	-
8	{9B33100(	A040	FinalAssy	12	1	2	A050	2	2	FinalAsser	2	2	96	9	740	350	-
9	{3E440C5	A050	FinalAssy	10	1	2	A060	5	2	FinalAsser	2	2	98	10	940	350	-
10	{DEEFC1F	A060	FinalAssy	10	2	4	A070	2	1	FinalAsser	1	1	99	11	1140	350	-
11	{A1064D6	A070	FinalAssy	9	3	0	END	2	2	FinalAsser	4	1	96	12	1340	350	-
12	{960413BE	B010	SubAssy (	10	2	2	B020	4	1	SubAssem	2	3	97	1	140	670	-
13	{0D0DAF8	B020	SubAssy (	5	2	0	B030	5	1	SubAssem	2	2	99	2	340	670	-
14	{4A0765C	B030	SubAssy (	7	2	1	B040	2	2	SubAssem	1	1	99	3	540	670	-
15	{5CE24F6	B040	SubAssy (	10	3	1	B050	1	1	SubAssem	3	2	95	4	740	670	-
16	{355C4FF(	B050	SubAssy (	7	1	4	A060	2	1	SubAssem	2	1	99	5	940	670	-
17	#eVSM Op	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
18																	

Figure 69 An example of the exported Excel spreadsheet from eVSM

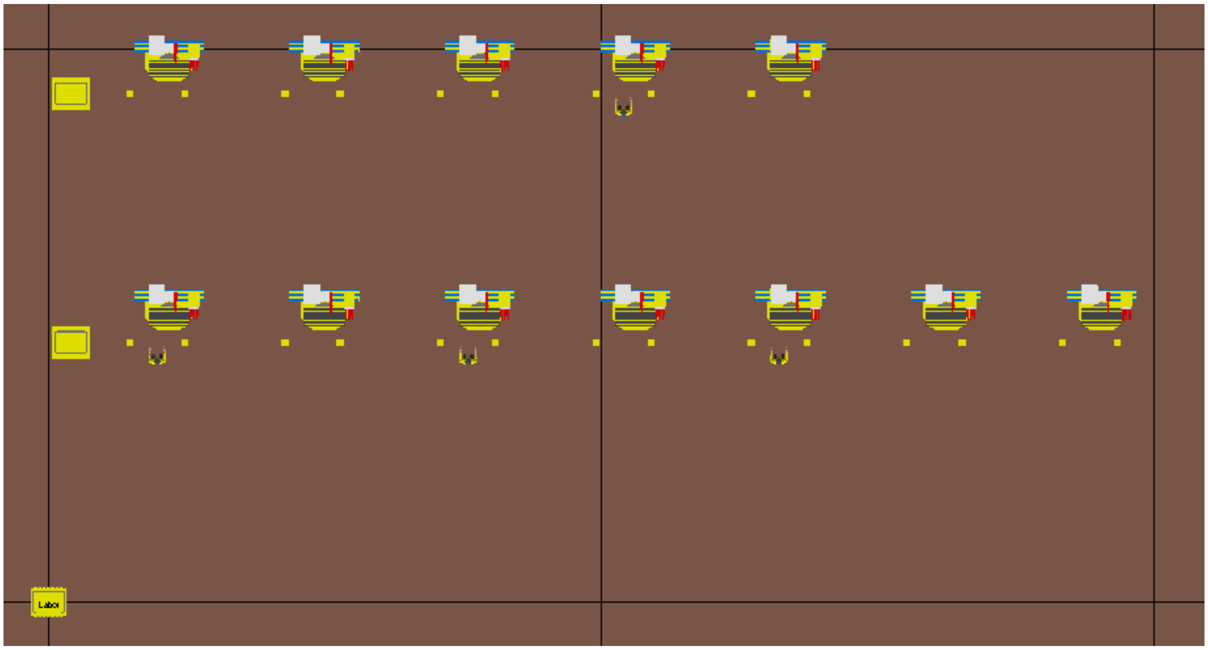


Figure 70 Example QUEST model built in the shape of the Value Stream Map in eVSM

Conclusions

By participating in a series of technology demonstration projects that provide us with a chance to apply the factory modeling software tools in support of lean manufacturing, the M&S team has clearly recognized that there is a need for industry to have tools that are much easier to use for assessing the implementation of lean manufacturing principles. This project was and excellent beginning to better understand the industry need, and to identify potential tools such as eVSM and QUEST as possible solutions for industry. There will be additional activity in this subject area as follow-on for more improvements to the linking of Value Stream Mapping and QUEST, and other software tools, as identified of value.

2.2.8.4. Value Stream Mapping of Machining Operations

Overall Summary of Task

Work with contractor to collect data and generate value stream maps of the production process for the manufacture of titanium integrally bladed rotors. This is a joint project with AMPI. This data will be imported into the factory modeling environment via the interface developed in project #2.2.8.3. and the resulting factory model will be used as a baseline for the evaluation of alternative approaches to the manufacturing process.

Key Players: Susan Coffey (CCAT/NCAL), Jon Fournier (CCAT/NCAL), Terri Marsico (CCAT/NCAL), Tom Scotton (CCAT/NCAL), Bob Memmen (CCAT/NCAL consultant), TechSolve Corporation

Participating Companies: OEMs- PWA, GE, RR, Supply Chain, AMPI, ManTech

Period - 3/07 to 12/07

Introduction

The United States Air Force (USAF) Advanced Manufacturing Propulsion Initiative (AMPI) identified seven board areas of focus to reduce the cost to produce the Joint Strike Fighter (JSF) engines. The areas were: Ceramic Matrix Composites, Organics Matrix Composites, Ceramic Hybrid Bearings, Small Hole Drilling, Advanced Machining, Aerospace Castings and Additive Manufacturing. Both the Pratt and Whitney (P&W) F135 and the Rolls-Royce (RR) F136 engines were considered.

In 2006, CCAT/NCAL team members participated in a series of meetings with AMPI and Metals Affordability Initiative (MAI). The team recognized that there were opportunities for NALI consortium members to participate and to support some of the activities in the areas of focus. Based on the synergy associated with CCAT/NCAL modeling and simulation and advanced laser application activities, it was determined that the best fit was advanced machining and small hole drilling. These activities aligned well with ongoing NALI-funded work that focused on the integration of modeling and simulation with best Lean practices in manufacturing processes key to U.S. Air Force applications. In addition, it was also determined that Value Stream Analysis (VSA) efforts for both areas of focus would be undertaken by CCAT/NCAL.

The AMPI Government Office required a VSA to be performed on each potential/applicable process prior to submittal of White Papers seeking funding. It was determined that the financial analysis performed on the improvement ideas would be a good independent assessment of cost reduction, should they fund a project. In addition, the U.S. Air Force would fund individual projects, based on merit, however, it would be more favorable disposed to joint projects that benefited multiple manufacturers.

Methods/Procedures

TechSolve was selected as a partner to support the development of the VSA activity. This was based on a recommendation from AMPI and similar previous successful engagements. All contracts and Non-Disclosure Agreements (NDA) that covered all parties and both small hole drilling and advanced machining between CCAT/NCAL, TechSolve, General Electric, Pratt&Whitney and Rolls Royce were completed and signed by May 2007.

The procedure for the each Original Equipment Manufacturer (OEM) was to first visit their location. If process/routing sheets were available, a reviewed occurred. The team members collectively walked the applicable process and observed travel and operations from receipt of material to shipping. For processes that were not active, an explanation of the processing steps was provided by the OEM. Process details were captured on Post-It® notes for each operation. If needed, machine operators were available for clarification at each process. Upon completion, all team members convened in a conference area, where the process details were posted in order on a wall. Participants were asked to review the information to ensure accuracy and completeness. Any changes were made at that time. Ideas for process improvements were also solicited, posted and added. A Value Stream Map (VSM) was then created using eVSM™. Additional data blocks, NVUs (Name, Value, Unit) were added to each in-house process operation. Collectively, the data blocks were: available time, batch size, capital cost per station, total machine cycle time, lead time, material cost, nonrecurring expense (NRE), number of operators needed, % rework, % scrap, setup time, number of setups per week, number of work stations, manual touch time, distance traveled to next operation and % uptime. TechSolve also requested machine identifiers, machine class identifiers and machine class quantity data fields to facilitate the CCAT/NCAL 3D Discrete Model development. The eVSM™ data was automatically transferred to an Excel spreadsheet. A copy of the VSM was given to each OEM in a VISIO or PDF format for final approval. The Excel spreadsheet was also provided so that the added data blocks for each location could be populated. These were considered Phase I activities for this project.

Upon completion of Phase I, the advanced machining and small hole drilling maps were reviewed. However, all parts and processes evaluated at each site were dramatically different and no common elements were identified. The VSA continued and common "areas" were to be assessed at the conclusion of the evaluation.

Once the Excel spreadsheet data was received from the OEM's, TechSolve prepared a financial analysis that took material cost into account. It was the value of the raw material (or material) plus any processing cost up to the start of each particular operation. The emphasis was on the costs that were added for each process step being evaluated. TechSolve also added in notional cost factors - consumable costs, a material adder for mark-up and handling, a generic labor rate of $100 per hour, a G&A adder of 25%, a process automation of $50 per hour to account for machine time and10% profit. Many of these dollar amounts and percentages were adjusted to more accurately reflect the OEM's "out the door" engine set costs. Capital tooling costs were also calculated. This financial summary became the baseline and it was duplicated for each improvement step. The difference between the baseline cost and improvement cost was also calculated.

The follow-up visit to each location (Phase II) had several purposes: (1) to ensure that the data was accurate and valid, (2) to evaluate ideas already suggested, and (3) to solicit new ideas. In addition to the cost per process step, a "Like Kind Processes" column was added to the Excel spreadsheet. Examples of "Like Kind Processes" include administrative, inspection, benching, drilling, turning, etc. This data was used to generate pivot tables and pivot charts within Excel. The value of the sum of the cost per "Like Kind" was displayed in descending order to identify the most costly processes and where the greatest cost reductions could be found. This technique can also be applied to other statistics such as TAKT time and inventory.

Within the Excel spreadsheet, an "Improvements" tab was created that contained all the Kaizen bursts from Phase I, as well as any new ideas that were generated. This was the base document used for the Phase II visits with each OEM. In addition to the improvement objective, the proposed method, benefit, estimated savings per ship set, estimated costs to implement, risk assessment (high, medium or low) and risk explanation were included.

CCAT/NCAL M&S consultant, Robert Memmen, along with one or both of the TechSolve Managers, attended all Phase I and Phase II site visits. Additional CCAT/NCAL team members participated as schedules permitted.

Conclusions

The advanced machining Phase I and Phase II site visits included: GE – Hooksett, NH and P&W – Middletown, CT. A summary of the results for each of these activities is shown below. The details of the findings are considered company sensitive, and cannot be included in this general report. They were provided to the participating companies, and could be available upon request with the appropriate levels of approval.

GE – Hooksett, NH

CCAT/NCAL: Susan Coffey, Jon Fournier, Robert Memmen
GE: Donald Lowe, Stephen Carter, Ron Peterson, Roger Lindle
TechSolve: Greg Hume, Susan Moehring
AFRL: Karl Lombard

The GE facility machined Titanium Blisks or Integrally Bladed Rotors (IBR). The process observed was the machining of a F414 first and second stage compressor Blisk. The F414 rotor was selected by GE to represent the process of a F136 rotor. The process was considered to be mature and stable since the F414 is in production. Only in-house processes were observed, however, outside processes were included in the VSM.

A total of sixteen improvement ideas were proposed. Three were consolidated into one similar idea with having the same general benefit. Five were tabled as having benefits outside the manufacturing area. The remaining eight were evaluated.

P&W – Middletown, CT

CCAT/NCAL: Susan Coffey, Jon Fournier, Robert Memmen
P&W: Paul Faughnan, Eric Fromerth, Frank Nardozzi, Terrel Ricks, Stuart Sibley
TechSolve: Greg Hume, Susan Moehring
AFRL: Karl Lombard

GDIT: Paul Hauwiller

The P&W facility machined the F135 fourth stage compressor IBR. The process is not considered to be "mature", however, several Kaizen events have transpired.

A total of thirteen opportunities were identified.

2.2.8.5. Value Stream Mapping of Small Hole Drilling

Overall Summary of Task
Work with contractor to collect data and generate value stream maps of the production process for the manufacture of titanium integrally bladed rotors. This is a joint project with AMPI. These data will be imported into the CCAT/NCAL Factory modeling environment via the interface developed in project #2.2.8.3., and the resulting factory model will be used as a baseline for the evaluation of alternative approaches to the manufacturing process.

Key Players: Susan Coffey (CCAT/NCAL), Jon Fournier (CCAT/NCAL), Robert Memmen (CCAT/NCAL consultant), TechSolve Corporation

Participating Companies: OEMs- PWA, GE, RR, Supply Chain, AMPI, ManTech

Period - 3/07 to 12/07

Introduction
The United States Air Force Advanced Manufacturing Propulsion Initiative (AMPI) identified seven board areas of focus to reduce the cost to produce the Joint Strike Fighter (JSF) engines. The areas were: Ceramic Matrix Composites, Organics Matrix Composites, Ceramic Hybrid Bearings, Small Hole Drilling, Advanced Machining, Aerospace Castings and Additive Manufacturing. Both the Pratt and Whitney (P&W) F135 and the Rolls-Royce (RRC) F136 engines were considered.

In 2006, a team from CCAT/NCAL participated in a series of meetings with AMPI and Metals Affordability Initiative (MAI). The team recognized that there were opportunities for CCAT/NCAL to participate and support some of the activities in the areas of focus. Based on the synergy associated with CCAT/NCAL M&S team and advanced laser application activities, it was determined that the best fit was advanced machining and small hole drilling. These activities aligned well with ongoing CCAT/NCAL work that focused on the integration of modeling and simulation with best Lean practices in manufacturing processes key to U.S. Air Force applications. .

The AMPI Government Office required a VSA to be performed on each potential/applicable process prior to submittal of white papers seeking funding. It was determined that the financial analysis performed on the improvement ideas would be a good independent assessment of cost reduction, should they fund a project. In addition, the U.S. Air Force would fund individual projects, based on merit, however, it would be more favorable disposed to joint projects that benefited multiple manufacturers.

Methods/Procedures

TechSolve was selected as a partner to support the development of the VSA activity. This was based on a recommendation from AMPI and similar previous successful engagements. All contracts and Non-Disclosure Agreements (NDA) that covered all parties and both small hole drilling and advanced machining between CCAT/NCAL, TechSolve, GE, P&W and RRC were completed and signed by May 2007.

The procedure for the each Original Equipment Manufacturer (OEM) was to first visit their location. If process/routing sheets were available, a reviewed occurred. The team members collectively walked the applicable process and observed travel and operations from receipt of material to shipping. For processes that were not active, an explanation of the processing steps was provided by the OEM. Process details were captured on Post-It® notes for each operation. If needed, machine operators were available for clarification at each process. Upon completion, all team members convened in a conference area, where the process details were posted in order on a wall. Participants were asked to review the information to ensure accuracy and completeness. Any changes were made at that time. Ideas for process improvements were also solicited, posted and added. A Value Stream Map (VSM) was then created using eVSM™. Additional data blocks, NVUs (Name, Value, Unit) were added to each in-house process operation. Collectively, the data blocks were: available time, batch size, capital cost per station, total machine cycle time, lead time, material cost, nonrecurring expense (NRE), number of operators needed, % rework, % scrap, setup time, number of setups per week, number of work stations, manual touch time, distance traveled to next operation and % uptime. TechSolve also requested machine identifiers, machine class identifiers and machine class quantity data fields to facilitate the CCAT/NCAL 3D Discrete Model development. eVSM™ has a built-in interface and the data was transferred to an Excel spreadsheet. A copy of the VSM was given to each OEM in a VISIO or PDF format for final approval. The Excel spreadsheet was also provided so that the added data blocks for each location could be populated. All of this activity was identified as Phase I.

Upon completion of Phase I, the advanced machining and small hole drilling maps were reviewed. However, all parts and processes evaluated at each site were dramatically different and no common elements were identified. The VSA continued and common “areas” were to be assessed at the conclusion of the evaluation.

Once the Excel spreadsheet data was received from the OEM’s, TechSolve prepared a financial analysis that took material cost into account. It was the value of the raw material (or material) plus any processing cost up to the start of each particular operation. The emphasis was on the costs that were added for each process step being evaluated. TechSolve also added in notional cost factors - consumable costs, a material adder for mark-up and handling, a generic labor rate of $100 per hour, a G&A adder of 25%, a process automation of $50 per hour to account for machine time and 10% profit. Many of these dollar amounts and percentages were adjusted to more accurately reflect the OEM's "out the door" engine set costs. Capital tooling costs were also calculated.

This financial summary became the baseline and it was duplicated for each improvement step. The difference between the baseline cost and improvement cost was also calculated.

The follow-up visit to each location (Phase II) had several purposes: (1) to ensure that the data was accurate and valid, (2) to evaluate ideas already suggested, and (3) to solicit new ideas. In addition to the cost per process step, a "Like Kind Processes" column was added to the Excel spreadsheet. Examples of "Like Kind Processes" include administrative, inspection, benching, drilling, turning, etc. This data was used to generate pivot tables and pivot charts within Excel. The value of the sum of the cost per "Like Kind" was displayed in descending order to identify the most costly processes and where the greatest cost reductions could be found. This technique can also be applied to other statistics such as TAKT time and inventory.

Within the Excel spreadsheet, an "Improvements" tab was created that contained all the Kaizen bursts from Phase I, as well as any new ideas that were generated. This was the base document used for the Phase II visits with each OEM. In addition to the improvement objective, the proposed method, benefit, estimated savings per ship set, estimated costs to implement, risk assessment (high, medium or low) and risk explanation were included.

Another aspect of the project was to develop a discrete event virtual factory model for each applicable site. This portion of the project was used to test and evaluate a custom algorithm developed by CCAT/NCAL that interfaces between two software packages, eVSM™ and DELMIA QUEST. The algorithm was created to expedite the building of discrete event models used to virtually validate process improvement/changes, resource changes and/or varying production levels prior to implementation.

To supplement the effort, an electronic floor layout depicting the equipment locations and routing of material was requested. Various versions were received. In the cases where an electronic layout was not available, the custom algorithm built a model that mimicked the shape of the VSM created in eVSM™.

Robert Memmen, CCAT/NCAL Consultant, along with one or both of the TechSolve Managers attended all Phase I and Phase II site visits. Additional CCAT/NCAL team members participated as schedules permitted.

Results & Discussion

The small hole drilling Phase I and Phase II site visits included: RRC at Southwestern Laser (SWL) – Tucson, AZ, RRC at Integrate Energy Technologies (IET) – Evansville, IN, GE Lean Lab – Evandale, OH, and P&W – East Hartford, CT. A summary of the results for each of these activities is shown below. The details of the findings are considered company sensitive, and cannot be included in this general report. They were provided to the participating companies, and could be available upon request with the appropriate levels of approval.

Southwestern Laser – Tucson, AZ

Team Members:
CCAT/NCAL: Robert Memmen, Susan Coffey,
Southwestern Laser: Joe Wagner, Joe Crawford, Jason Boles, Mike Grantham
IET: Al VanDoornik
Rolls-Royce: Sushil Jain, Tom Hensler, Bob Moriarty
TechSolve: Greg Hume, Susan Moehring
AFRL: Steve Medieros, Carl Lombard
GDIT: Paul Hauwiller

Rolls Royce selected the F136 Combustor Liner sheets for this analysis. They subcontract the bonding and hole drilling to IET. SWL is a second-tier supplier of laser drilling services for IET. A SWL ship set consists of 2 hot-side and 2 cold-side sheets. Using a single-pulse Nd-YAG laser, they drill 125,000 holes in each hot-side sheet and 65,000 holes in each cold-side sheet. Figure 1 contains the VSM and a portion of a non-proprietary process data block.

A total of 17 ideas were identified and 11 were evaluated. Ideas not evaluated were considered to be either not quantifiable within the current cost model or consistent with normal ramp up activity.

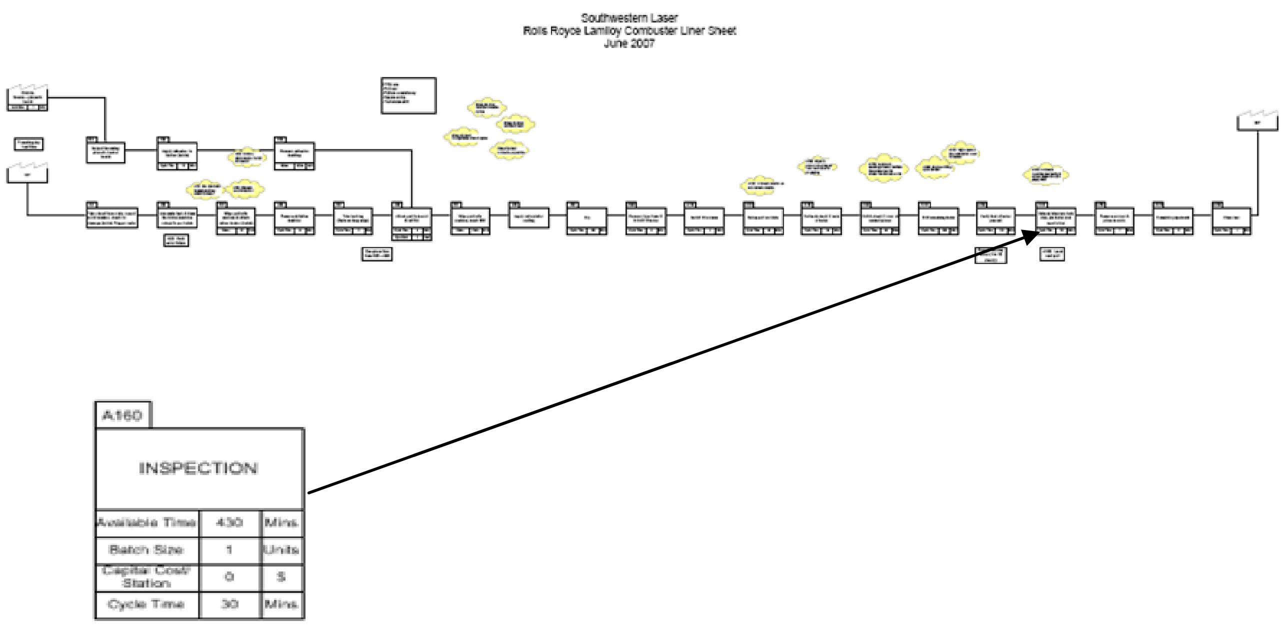


Figure 71 SWL, F136 Combustor Liner Sheets, Value Stream Map

IET – F136 Combustor Liner

<u>Team Members:</u>
CCAT/NNCAL: Robert Memmen, Susan Coffey
IET: Al VanDoornik, Chris Samuels, Dan Davis, Paula Barnett
Rolls-Royce: Don Pinnick, Sushil Jain
TechSolve: Greg Hume, Susan Moehring
AFRL: Carl Lombard
GDIT: Paul Hauwiller

IET site visits and mapping involved processing steps prior to and subsequent to sending the sheets to SWL for hole drilling, The project focus was restricted to hole drilling, therefore, bonding the hot-side and cold-side sheets was not included. Figure 2 contains the VSM and a portion of a non-proprietary process data block.

A total of 18 ideas were generated at IET and 9 were evaluated.

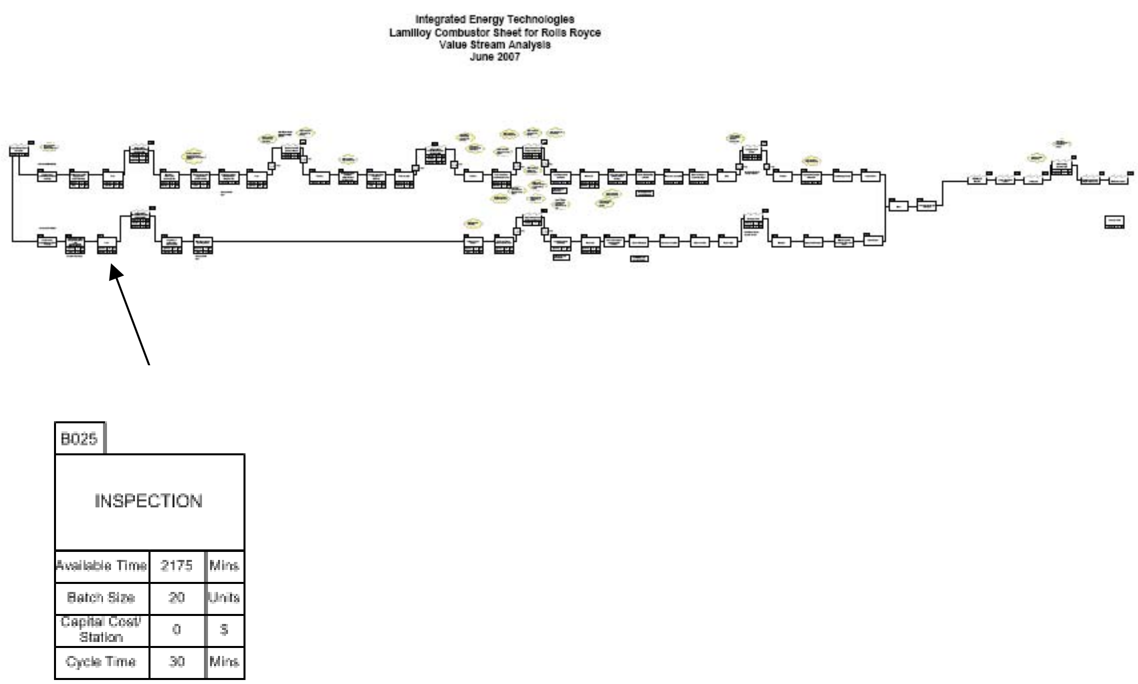


Figure 72 IET, F136 Combustor Liner, Value Stream Map

IET – F136 Combustor Liner

GE –Evandale, OH

<u>Team Members:</u>
CCAT/NCAL: Robert Memmen, Susan Coffey
GE: Todd Rockstroh, John Zurawka, John Alves, Jeff Wessels, Walt Ulanski, Jim Caddell, Doug Scheidt
TechSolve: Greg Hume, Susan Moehring
AFRL: Carl Lombard
GDIT: Paul Hauwiller

GE selected the CFM56 HPT Blade Stage 1 for this analysis. This selection was based on the type of material, the airfoil shape, the cooling hole size and pattern. All of which are similar to that expected for the F136 engine. Electrical-discharge machining (EDM) is the process for producing CFM56 HPT Blade holes and this same process is currently planned for F136 blades. GE did take this opportunity to conduct a comparative analysis of EDM and laser drilling as a possible alternative process. There are 60 blades to a ship set. Figure 3 contains the VSM and a portion of a non-proprietary process data block.

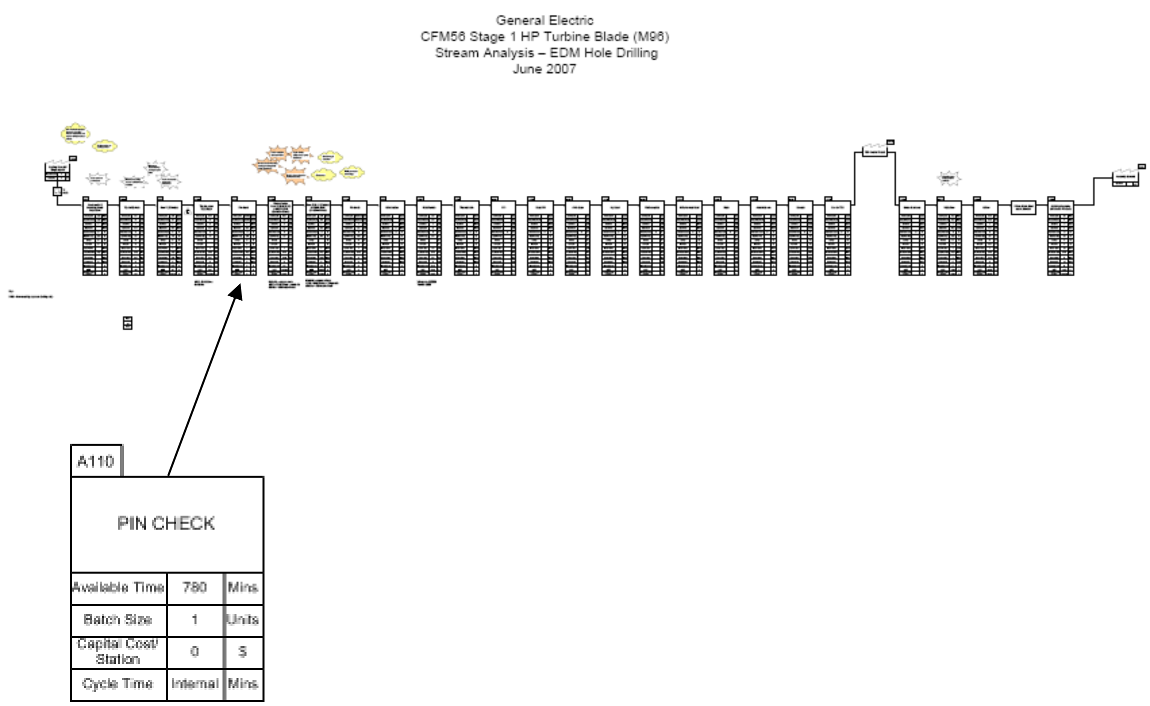


Figure 73 CFM56 HPT Blade Stage 1, Value Stream Map

IET – F136 Combustor Liner

Pratt & Whitney – East Hartford, CT

Team Members:
CCAT/NCAL: Robert Memmen, Susan Coffey, Jonathan Fournier
Pratt & Whitney: Chet Yaworsky, Jack Quitter, David Krysiak
TechSolve: Greg Hume, Susan Moehring
AFRL: Carl Lombard
GDIT: Paul Hauwiller

Pratt & Whitney selected the 34-inch diameter MEC Duct assembly for the F119 Turbine Engine Exhaust Case for this analysis. The material for this part is Waspaloy (AMS 5707) and the part has 16 sections. Two hundred sixty-three holes ranging from 0.145 – 0.151 inch diameter were trepanned by laser, and 1299 holes ranging from 0.018 – 0.015 inch diameter were percussion drilled by laser. Some of the holes were angled and varied in depth from 0.060 inch in thin sections of the part to 0.110 – 0.130 inch in thicker sections. A ship set is one duct. Figure 74 contains the VSM and a portion of a non-proprietary process data block.

A total of 13 ideas were proposed of which 10 were evaluated. The three not evaluated were considered to affect indirect costs only and hence could not be evaluated effectively using the cost model.

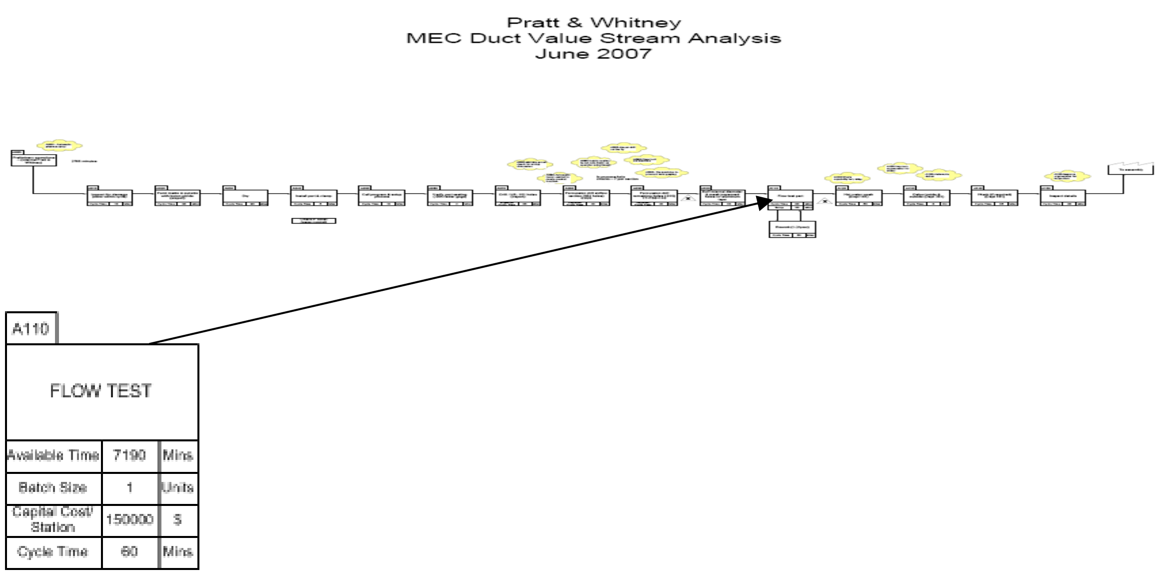


Figure 74 P&W MEC Duct Assembly, Value Stream Map

Conclusions

A two day final project review session was held in December 2007 at the CCAT facility in East Hartford, CT. The OEMs received their spreadsheets and associated data approximately 30 days prior to the meeting to review. In addition, that information also served to prepare them for day two collaborative activities.

The first day consisted of the individual sessions with GE, P&W and RR. At each session, CCAT/NCAL and TechSolve presented the approach, rationale and analysis that was performed. TechSolve familiarized each OEM with the data, layout and functionality of their respective spreadsheets. The VSAs were used to identify areas for follow-up white papers from the OEMs for submittal to AMPI for future funding of further process development.

Paul Hauwiller (Senior Program Manager, Manufacturing, Technology and Production Group at General Dynamics and the AMPI Contracts Manager) was the moderator of the day two collaborative project sessions. The purpose of the session was to engage the participating OEMs in a forum to discuss and proposed future projects that could be collaboratively supported by 2 or more of them. It was determined that the white-papers would be due by February 15, 2008 and the JSF SBIR topics by January 15, 2008.

The collaborative small hole drilling projects and respective white-paper teams are as followed:

1. High Energy Density Lasers.
    a. Lead: Rolls Royce –Sushil Jain
        i. Participants: Todd Rockstroh –GE; Jack Quitter- P&W
            1. Due Date: 15 Feb 2008
2. 3D Imaging and Data Manipulation
    a. Lead: GE Aviation - Todd Rockstroh
        i. Participants: Jesse Boyer – P&W; Kong Ma - RRC
            1. Due Date: 15 Jan 2008
3. Adaptive Control for Drilling
    a. Lead: Pratt & Whitney – Jack Quitter
        i. Participants: Todd Rockstroh – GE; Bob Stusrud - RRC
            1. Due Date: 15 Feb 2008
4. Shaped Hole Drilling Capability
    a. Lead: GE Aviation - Todd Rockstroh
        i. Participants: Jim Leobig – RRC; Jack Quitter – P&W
            1. Due Date: 15 Feb 2008
5. Breakthrough Detection Methods
    a. Lead: Pratt & Whitney – Jack Quitter
        i. Participants: Todd Rockstroh - GE, Jim Leobig - RRC
            1. Due Date: 15 Jan 2008

6. Hole/Airflow Evaluation
    a. Lead: Rolls Royce - Don Pinnick
        i. Participants: Jack Quitter/Jesse Boyer – P&W; Todd Rockstroh – GE
            1. Due Date: 15 Jan 2008

2.2.8.6. Evaluation of Virtual PLC Programming environment, and implementation of educational laboratory

Overall Summary of Task
A Grant was provided to Fairfield University to establish a center for simulation, modeling and analysis of automation systems.

Key Players: Tom Scotton (CCAT/NCAL), Nasir Mannan (CCAT/NCAL), Dr. Paul Botosani (Fairfield University Mechanical Engineering Department)

Participating Companies: None

Period - 4/07 to 12/07

Introduction
The Center was created to become a regional resource for training students in the concepts and techniques for modeling and simulation by using an automation laboratory based on DELMIA V5 Automation software, 3-D simulation software. This resource has been integrated into the curriculum within the Mechanical Engineering department with the goal to be able to provide solutions to industry-sponsored projects dealing with control engineering and automation life cycle management. Work at the Center commenced with simulation studies of aerospace manufacturing cases. The initial focus of the Center is in the use of modeling and simulation of parts manufactured in the aerospace industry. It is expected that those manufacturers will greatly benefit from engineering talent developed at the Center, and from solutions, concepts, and techniques for controlling and monitoring automated systems to ensure quality, improved process efficiency of production lines, and cost-reduction methods. The simulation models developed for aerospace companies, and other manufacturers, will be shared with CCAT/NCAL for use and publication as deemed appropriate.

Results and Discussion
The following accomplishments have been completed.

- A simulation laboratory was established and equipped with the DELMIA V5 Automation in 3-D. This simulation software was installed on a School of Engineering server, available in 10 workstations, for training of students in modeling and simulation.

- Courses in the Automated Manufacturing program in the School of Engineering were re-configured entirely to utilize DELMIA V5 Automation for teaching and training students in simulation, modeling, and analysis in automation.

MF 250 Programmable Logic Control (PLC) Systems
This course introduces the design and implementation of programmable logic controllers for use in industry in the areas of automation, manufacturing, and other related applications. It takes an overall look at Programmable Logic Controllers while concentrating on relay ladder logic techniques and how the PLC is connected to external components in an operating control system. State-of-the-art software used includes: MultiSim, LabView, Cosivis, Veep, and RS Logix 500. The course also covers input/output ports, continuous process control, timing and counting functions, chaining sequences, and digital gate logic. The course consists of lectures, group discussions, case studies, a term project, computer simulation, and laboratory. (Prerequisite: PS 16) Three credits.

MF 250L Programmable Logic Control (PLC) Systems Lab
This course is designed to teach the students to work with the PLC. The student learns to analyze open- and closed-loop control tasks from the field of activities, and to develop structured and PLC-adequate programs in either function plan, ladder diagram, instruction list, sequential function chart, or structured text. Allen Bradley, Mitsubishi, GE, Fanuc and Simens PLC are used. The students must create the PLC programs from description of desired operations. State-of-the-art software used includes: MultiSim, LabView, Cosivis, Veep, and RS Logix 500, Fluid Sym P, and others. (Co-requisite: MF 250) One credit.

MF 350 Advanced Programmable Logic Control (PLC) Systems
This course will give students advanced concepts in programmable logic controllers and their applications and interfacing to industrial controls in the areas of automation, manufacturing, and others. Topics include bit operations, data manipulation, industrial PLC network utilizing Ethernet, ControlNet, and DeviceNet. Data sharing and distributed PLC programming techniques along with fundamentals of touch panel programming and operation are studied. State of the art software used: MultiSim, LabView, Cosivis, Veep, Automation Studio, and RS Logix 500. It will include also: input/output ports, intermittent and continuous process control, arithmetic and comparison instruction, function block diagrams, indirect and indexed addressing, and sequential function charts. The course will consist of: lectures, group discussions, case studies, a term project, computer simulation. (Prerequisite: MF 250) Three credits

MF 350L Advanced Programmable Logic Control (PLC) Systems Lab
This course will introduce the advance design and implementation of programmable logic controllers for use in industry in the areas of automation, manufacturing, and others. It will take an overall look at Programmable Logic Controllers while concentrating on data handling, function block diagram, and industrial networks & distributive control. State of the art software used: MultiSim, LabView, Cosivis, Veep, Automation Studio, and RS Logix 500. It

will include also: input/output ports, intermittent and continuous process control, arithmetic and comparison instruction, function block diagrams, indirect and indexed addressing, and sequential function charts. (Co-requisite: MF 350) One credit.

- Four demonstration models were developed in the DELMIA V5 Automation environment to show how the automation concepts and principles work in real-world settings. An example of one of these models is shown in the image below.
- Fairfield University staff have received training from both the M&S team and DELMIA Corporation
- All the materials (simulation, models, testimonials, lessons learned, pitfalls, etc.) developed at the Center have been made available to the NCAL for its use, publication and posting on their website.

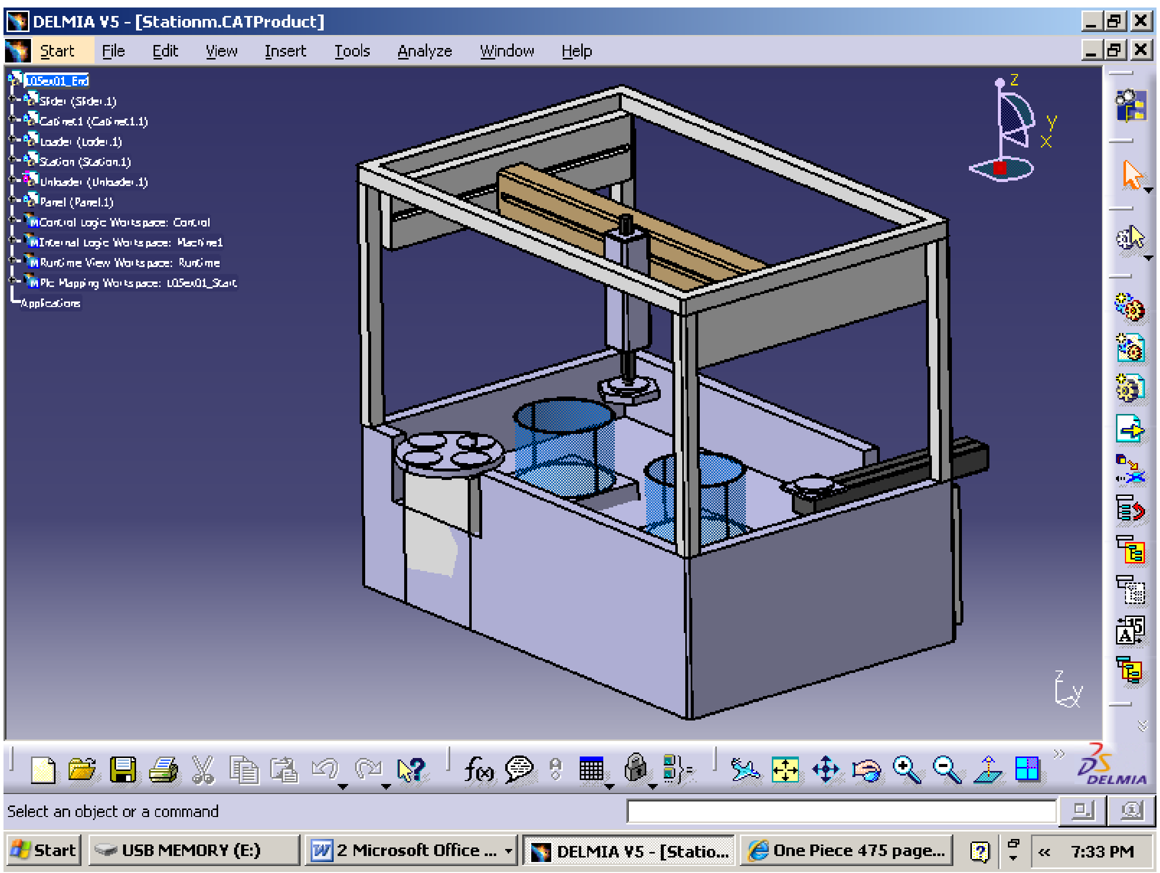


Figure 75 DELMIA Simulation of Automated Workcell

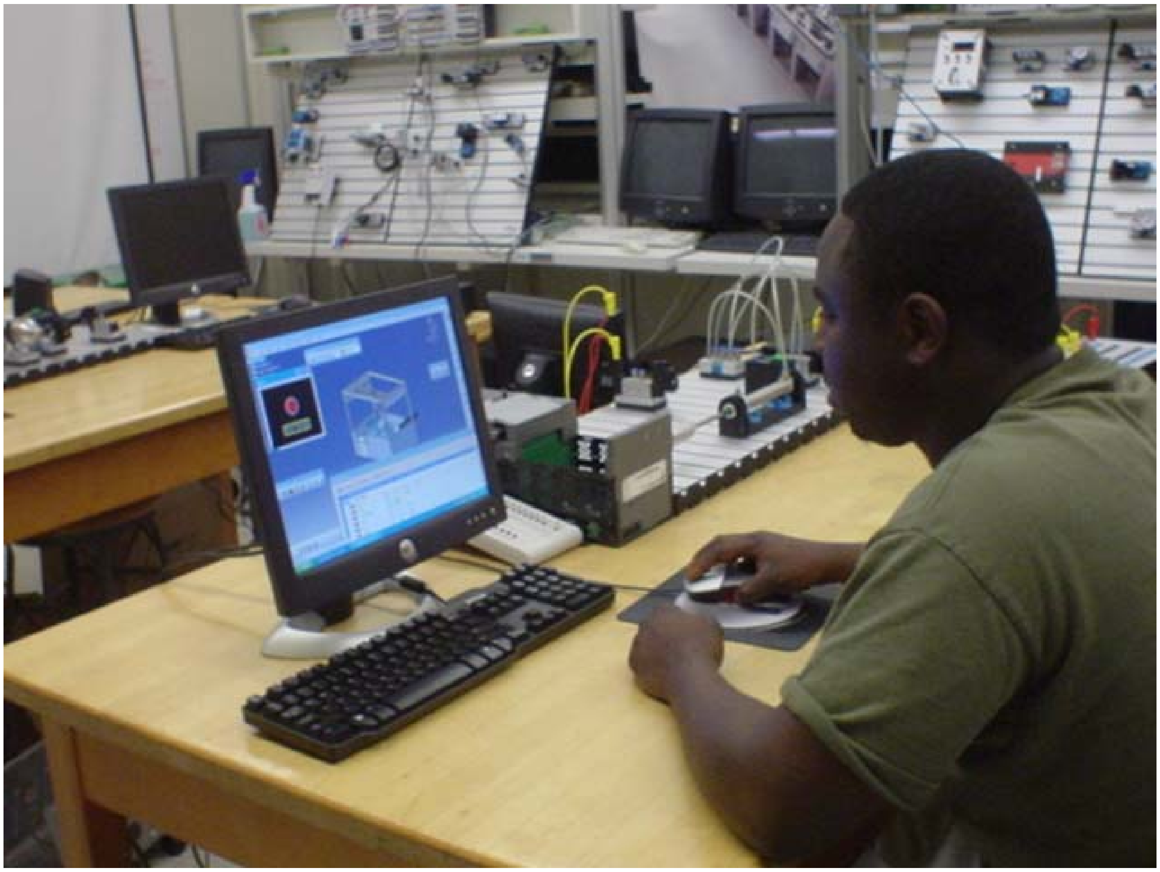


Figure 76 Student working with DELMIA Software in Lab

Conclusions

The Center for Simulation, Modeling and Analysis in Automation is now physically located in the School of Engineering, Fairfield University. This is now a resource for the development of a work force that will graduate engineers with hands on experience in the use of the state of the art virtual environments. The expectation is that these engineers can now server as a mechanism to bring these new technologies out into industry with them, but educating their new employers about what they were exposed to in college. At the same time, the faculty and staff at Fairfield University can also serve as a resource to industry for executing technology demonstration projects for years to come as a result of this investment under the NALI program. A copy of the final report from Fairfield University is available on request from the CCAT/NCAL M&S team.

References

"Final Report, CCAT Grant for A Center for Simulation, Modeling and Analysis in Automation at the School of Engineering, Program in Automated Manufacturing Engineering", Paul Botosani, Ph.D., Coordinator and Professor of Automated Manufacturing Engineering, Director of Engineering Laboratories.

2.2.8.7. Implementation of Factory Modeling Laboratory for educating industry and workforce in the principals of Lean Manufacturing

Overall Summary of Task
Funding was provided to the University of New Haven to support the creation of a "Center for Modeling and Simulation using Delmia's QUEST simulation software".

Key Players: Tom Scotton (CCAT/NCAL), Jon Fournier (CCAT/NCAL), Dr. M. Ali Montazer (Tagliatela College of Engineering, University of New Haven)

Participating Companies: None

Period - 4/07 to 12/07

Introduction
The Center was created to become a regional resource for training students in the concepts and techniques for discrete event factory modeling and simulation technology by exposing the students to the use of the DELMIA QUEST simulation software. This resource has been integrated into the curriculum within the Mechanical Engineering department with the goal to be able to provide solutions to industry-sponsored projects dealing with control engineering and automation life cycle management.

Results and Discussion
Several objectives have been realized as a result of this strategic and important support provided by the CCAT/NCAL M&S team as follows:

- A computing laboratory was brought online running with the state-of-the-art instructional technology and 24 student PC stations all loaded with the simulation software QUEST purchased with NALI grant funding. The software license allows 18 users simultaneously working on QUEST model development. A copy of QUEST is also loaded on a new laptop, purchased with funding from the NALI grant. The laptop is and has been used to learn to develop models using the software off-campus, training of graduate students and for demonstration of QUEST models to industry partners.

- Three student teams worked on three different industry sponsored projects during the 06-07 academic year, culminating in three reports as follows:
    - Process Simulation of Consolidated Industries Hammer Shop
    - Modeling and Simulation of Aircraft Nose Gear Holdback Bar Production Line at Valley Tool & Manufacturing
    - Simulation study of the Royal 35W skin stapler

- These student projects were also presented in a Poster Session at the New England – ASEE Annual Conference at the University of Rhode Island and at the Experiential Education Celebration Day at the University of New Haven in April 2007. Our industry project sponsors are very pleased with the models we have developed for them and the work our students accomplished. They have offered additional projects for future student teams.

- The System Simulation course (IE 681) was offered in fall 2007 using QUEST as the sole simulation software in that course. This was a first course in simulation modeling and analysis with nineteen students enrolled in the course. The CCAT/NCAL M&S team participated in the training and support of the University staff, including presentations at the class, to introduce the technology to the students. A description of the courses that will utilize this software is shown below.

  IE 681 System Simulation
  Prerequisites: IE 601, CS 606 or equivalent, or permission of the instructor. Methods of modeling and simulating man-machine systems. Thorough coverage of discrete event simulation. Random number generators and variate generations discussed. Use of a simulation package and several projects will be required.

  IE 682 Advanced System Simulation
  Prerequisite: IE 681 or equivalent. Emphasis will be on model-building and on design and analysis of simulation experiments for service and manufacturing systems. Student projects in real environments are required.

- A fourth team of three students worked on yet another industry sponsored project during fall 2007 entitled ***"Simulation Modeling of the Press Forging Process of Metal Parts".*** A working model of the process has been developed. We are working on model verification and validation, steps necessary to confirm model fidelity / reliability for it to be of value to the sponsor.

In addition to the software and laptop purchases, miscellaneous expenses including conferences and travel, the faculty advisor time, and two graduate students were supported at varied levels through the funds from the grant.

Conclusions

This engagement has been quite rewarding for both parties and a great learning experience for all involved, students, faculty as well as the aerospace manufacturers. The grant was a great catalyst to introduce the concepts and techniques of modeling and simulation to aerospace parts manufactures who most probably would never have attempted to use such tools due to the high cost, complexity and more than anything else unfamiliarity with the subject matter and its applications in production and operations management. The manufacturers become much more open to using such tools and techniques when they get to see what modeling and simulation can do for them, especially in relations to lean studies and implementation, bottleneck identification and resolution, lead-time studies and capacity planning. For more details please see the University of New Haven final report.

References
"A Report on the Grant to Create a Center for Simulation Modeling and Analysis with DELMIA's QUEST 3-D Simulation Software", M. Ali Montazer, Ph.D., Principal Investigator, Associate Dean, Department of Industrial and Systems Engineering, Tagliatela College of Engineering, University of New Haven

2.2.8.8. Modeling of ADI Lean Activities

Overall Summary of Task
Work with companies that are participating in the implementation of Lean Manufacturing principles with funding provided by the Aerospace & Defence Initiative

Key Players: Susan Coffey (CCAT/NCAL), Jon Fournier (CCAT/NCAL), Dr. Paul Resetarits, CCSU's Department of Manufacturing and Construction Management

Participating Companies: None

Period - 4/07 to 12/07

Introduction
Connecticut Manufacturing Supply Chain Integration (CMSCI) was formed by a legislative act and enabled by the Connecticut Department of Economic and Community Development (DECD). The State of Connecticut, through DECD and the Aerospace & Defense Initiative (ADI), has made $2M available to assist small and medium size companies in the introduction or continuation of Lean Manufacturing techniques within their organizations. Companies can receive up to 50% reimbursement of the cost for Lean services supplied by a registered external service provider. In addition, companies can also receive $5,000 per qualified process improvement project conducted by a registered internal expert.

CONNSTEP operates as Connecticut's Manufacturing Extension Center under the U.S. Department of Commerce's National Institute of Standards and Technology (NIST) Manufacturing Extension Partnership (MEP) program. CONNSTEP's mission is to help Connecticut manufacturers apply advanced manufacturing and management techniques to become more competitive, as well as supporting the growth of Connecticut's economy. Part of the Connecticut Center for Advanced Technology mission is to provide services and resources to entrepreneurs and businesses and, through collaboration with industry, academia, and government, helps companies innovate and compete, thereby strengthening our nation in the global market. The CCAT/NCAL relationship with CONNSTEP focuses on Lean Solutions/Lean Manufacturing.

Methods/Procedures

Lean Manufacturing is a generic organizational method of production and process management philosophy that sprung primarily from the Toyota Production System (TPS) as well as several other sources. Lean Manufacturing tools assist with the identification and elimination of waste. The focus is on greater production efficiencies and maximizing value added activities.

Value Stream Mapping is an important Lean tool that is used to identify opportunities for improvement. It is a visual diagram (or map) to analyze material and information flow required for products or services. The Value Stream Map (VSM) can also help identify inefficiencies and areas of waste. The VSM is a communication tool, a planning tool, and a tool for managing process changes.

Maps have historically been drawn by hand in pencil; to keep the mapping process simple and to allow for corrections. Several electronic Value Stream Mapping software packages have since been created as an alternative. The CCAT/NCAL M&S team currently uses eVSM™ software for the easy and quick creation of value stream maps. The software has a built in Excel spreadsheet interface that is also used to feed the construction of a 3D factory floor simulation model. An example of an eVSM map is shown below.

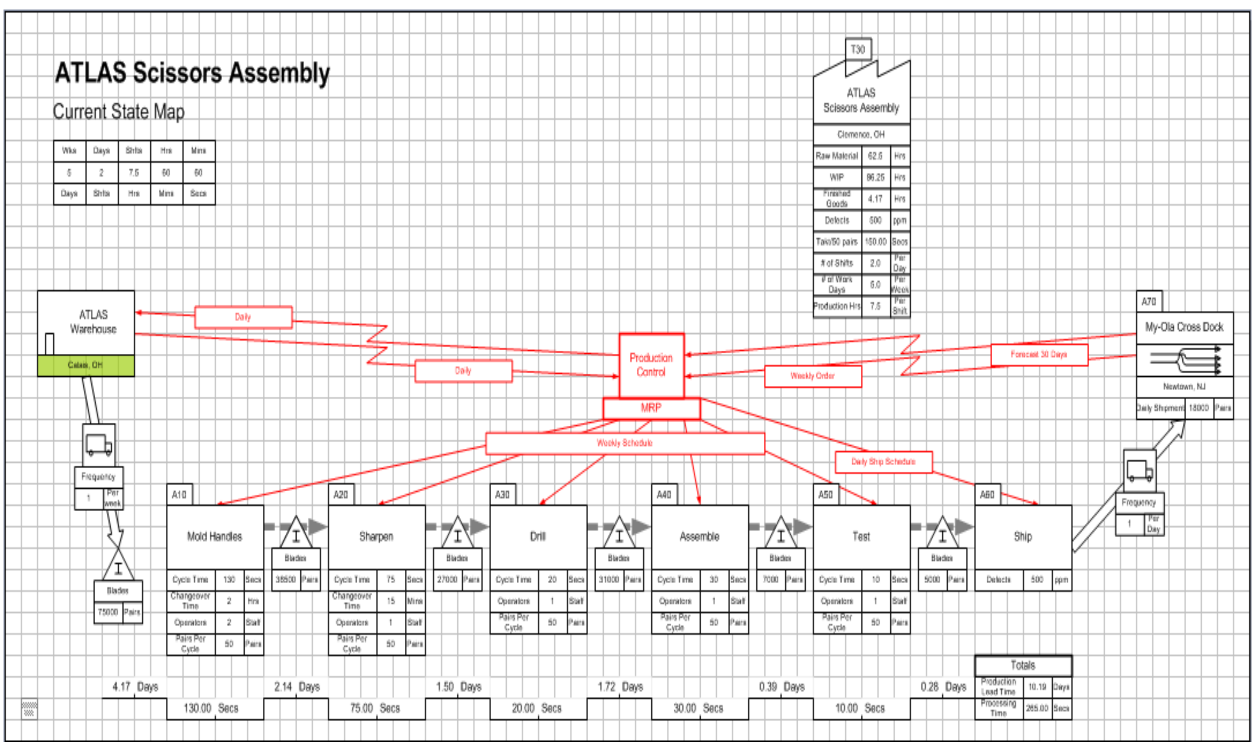


Figure 77 Example eVSM Map

CCAT/NCAL staff introduced eVSM™ to CONNSTEP. Based on their request for assistance, we also developed a comprehensive *Introduction to eVSM™* training tutorial that complemented eVSM™ v3 (version 3). The purpose was to streamline the learning process and to jumpstart each CONNSTEP participant into being able to use the software quickly and efficiently.

Prior to developing the training manual CCAT/NCAL staff reviewed all of the Lessons (Silent Movies) created by the developers of eVSM™, GumshoeKI, Inc. We selected approximately 26 key topics that would fulfill the objective. The manual was created in PowerPoint and was designed to be hands-on and interactive. Each participant worked with their copy of eVSM™ as the instructor demonstrated the concept and methodology. An excerpt from the *Introduction to eVSM™* training manual and a sample nonproprietary Value Stream Map can be found in Appendix A.

In July 2007, the CCAT/NCAL M&S team provided training for five CONNSTEP Field Engineers. Currently, CONNSTEP actively uses eVSM™ and the built in Excel interface for all applicable lean events. The M&S team introduced eVSM™ to CONNSTEP. Based on their request for assistance, we also created a comprehensive *Introduction to eVSM™* training manual that complemented eVSM™ v3 (version 3). The purpose was to streamline the learning process and to jumpstart each CONNSTEP participant into being able to use the software quickly and efficiently.

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CONNSTEP is also a participant in the NIST MEP Accelerate program. Accelerate-funded lean events require CONNSTEP to generate a Manufacturing Critical Path Time (MCpT) metric using software developed for the Wisconsin MEP. MCpT is a metric used in lean manufacturing for the amount of time required to convert an order for a part into a shipment of said part. To determine the MCpT, it is necessary to map out the fulfillment process from order taking through logistics. The MCpT software is also able to factor in calendar time in calculating the MCpT, as well as true ratios of Value-Add to Non Value-Add times.

In the current implementation approach for using the MCpT software, the MEPs were required to manually input the value stream mapping data by retyping the information that was collected utilizing the eVSM software. The feedback from CONNSTEP that we received indicated that this could take several hours to do, and could often result in inaccurate information in MCpT due to typing errors. The MCpT software uses an XML (eXtensible Markup Language) format for storing MCpT information. In September 2007, the CCAT/NCAL M&S team evaluated the capabilities of eVSM and MCpT and were able to generate an enhancement to the MCpT process by developing an Excel Visual Basic Macro that can automatically generate an MCpT project file based on the data exported from eVSM to Excel.

The eVSM software macros for creating QUEST discrete event factory models have also been used in conjunction with these CONNSTEP lean engagements as requested by CONNSTEP.

Results and Discussion

The staff at ConnStep has been very pleased with this capability and are currently using this in practice during their lean engagements with local industry. The CONNSTEP staff estimates it took approximately 4 to 5 hours of manual data entry and manipulation to complete a MCpT analysis. After implementing the eVSM->MCpT Macro the MCpT creation time has been decreased to approximately one hour. Significant cycle time reductions have been found using eVSM™ for value stream mapping. CONNSTEP reported that very lengthy VSMs with eighty or more process steps, can be generated in about 30 minutes. In addition, they have used eVSM™ and the M&S team developed eVSM > MCpT Macro for 20 clients and site visits.

Participating companies:

Supplier	POC	CONNSTEP Lean Consultant	VSM	MCpT	QUEST Model
Aerocraft (Volvo)	Joe Sartori	Laun/Yenkner	X	X	na
Beacon Industries	Dave Adler	Caplan/Laun	X	X	Pending
Gros-ite	Paul Rogers	Caplan/Laun	X	X	X
Milford Fabrication	Joe Connelly	Karbassioon/Laun	X	X	na

Conclusion

The CCAT/NCAL M&S team has accompanied CONNSTEP on several Accelerate-funded lean events. These events included Beacon Industries, Aerocraft (Volvo), Gros-ite Precision Components and Milford Fabricating. eVSM™ was utilized at each event, as well as ADI events for the Current State (CS) and Future State (FS) VSM. The exported Excel data and associated eVSM->MCpT Macro was also used for the MCpT metric for each site. Since developing the *Introduction to eVSM* manual, additional internal and external associates have been trained. The most recent external site was Beacon Industries, a NIST MEP Accelerate program participant. CONNSTEP has also trained additional internal Field Engineers.

CCAT's NCAL M&S team is now available upon request to provide this type of introductory training for the use of eVSM. The team is in the process of becoming a certified eVSM training provider. All of the macros that have been developed to support this activity will be available at both the CCAT website (www.ccat.us) and the NALI website (www.usnali.org).

2.2.9. CCAT M&S for Manufacturing Project Summaries

2.2.9.1. Physics Based Machining Process Analysis

Overall Summary of Task
The modeling and simulation group has successfully established a facility which can be used for both computational analysis as well as interactive development and data analysis.

Introduction
As part of this facility we have implemented a state of the art modeling and simulation theater, with high end dual processor DELL workstation, NVidea state of the art graphics board and CyViz VisWall with passive stereo projection.

Figure 78 CyViz VisWall at CCAT

A portable version of this type of projection system has also been acquired to provide the ability to take the 3D capability to customer sites and educational facilities for support of work force development activities.

Methods/Procedures
With this modeling and simulation theater, the CCAT's NCAL M&S team are now able to host seminars and classes to educate manufacturers on the power of modeling and simulation technologies. As part of the infrastructure for the Modeling and Simulation laboratory and theater environment is the following computer hardware:

2 Dell Multi-Processor Workstations
10 Dell Precision M90 Laptops
2 Dell Precision M70 Laptops
2 Panasonic Tough Books

All these computers are capable of being networked together to provide access to the following Modeling and Simulation software solutions:

Visualization Tools/Data Converters

- 3D Studio Max
- TriDef Visualizer
- Okino Polytrans
- Mercury Amira
- TriDef Visualizer
- VRSim MiniViz

CAD Software

- SolidWorks 2008 (5)
- Autodesk Inventor Suite 2008 (1)
- CosmicBlobs (3)
- Rhinoceros 4
- Google Earth Pro
- Google Sketchup Pro

CAM/Verification Solutions

- CNC Software's Mastercam X2 (3)
- EdgeCAM 12.00 (1)
- CGTech VERICUT (1)

Process Analysis Tools

- Third Wave Sys. – AdvantEdge V5.0 (1)
- Third Wave Sys. – Production Module (1)
- DEFORM 2D V9.0 (1)
- DEFORM 3D V6.1 (1)
- MAL CUTPRO (1)
- MAL CUTPRO Shop-Pro (1)
- BOSS 1.0.2 (1 pending)
- GrindSIM & CDCFG(1)
- ESI-PAM-RTM v2004.1(1)
- ESI-Procast 2007.0(1)
- ESI-Sysweld 2007.0.1(1)
- Minitab 15 (5)
- DELMIA V5 – DPM Assembly (1)
- DELMIA V5 – Robotics (1)
- DELMIA V5 – Ergonomics Complete (1)

Reverse Engineering and Inspection
- Rapidform XOR2 (1)
- Rapidform XOV (1)
- InspectWorks (1)

Factory Analysis Tools
- eVSM (7)
- DELMIA QUEST (2)
- Production Flow Analysis and Simplification Toolkit (PFAST)
- ExpertFit
- SigmaFlow VSM & Modeler
- Visual8 Lean Modeler
- FlexSim
- Extend

In addition to this, we have currently developed a portable virtual reality demonstration suitcase system for traveling presentation media. This will help us to evaluate manufacturing process concepts at customer facilities and to support educational awareness opportunities (working with the education team from the NALI consortium members).

Working with Central Connecticut State University (CCSU), we have established the CCSU/NCAL lean manufacturing concepts simulation based training lab, with the Time Wise simulation training solution system. This facility will serve as a state of the art environment for the teaching of lean manufacturing to industrial participants. These are incorporated on the CCSU Campus.

Conclusions
As a result of this activity, there has been developed a very capable facility resource with hardware and software tools that are now a national resource for working with the Aerospace Supply Chain companies in helping them analyze their manufacturing processes, and learning how to apply them to improve their effectiveness and efficiency. A complete summary of this capability can be found on the CCAT website (www.ccat.us) and on the NALI program website (www.usnali.org).

2.2.9.2. CCAT/NCAL M&S Events

CCAT/NCAL M&S Training in Third Wave Systems Products

On January 17, 2006 the CCAT/NCAL M&S team hosted a training session on machining analysis software that the team has obtained from Third Wave Systems (http://www.thirdwavesys.com). The training resulted from efforts of staff working within the CCAT's NCAL Modeling and Simulation program. Training staff, educational partners, technical resource partners and others applying technology like Third Wave's will help meet the goal of enhancing the aerospace supply chain.

CCAT/NCAL program industrial and academic partners were invited to the training opportunity, and 11 people attended the training, conducted by Luis Zamorano and Andrew Grevstad of Third Wave Systems. The training was offered at Rensselaer at Hartford, a branch campus of Rensselaer Polytechnic Institute, in the school's computer lab.

A key objective is for the CCAT/NCAL team to locate, analyze, and offer advanced 3-D machining process modeling to significantly reduce the cost of advanced materials machining and predict effects on material performance and to link to education and training to assure workforce capable of implementation. Modeling and simulation is critical to the success of all levels of the supply chain. The significance of training opportunities such as the Third Wave Systems and others to be offered in the future is great.

Third Wave staff trained the attendees on the AdvantEdge™ product, a materials-based finite element methodology (FEM) solution for optimizing metal cutting processes. It analyses machining processes and gives you strategies to improve material removal rates, part quality, and tool performance, decreasing physical testing. In addition to force and temperature prediction, AdvantEdge™ features tool wear prediction capabilities, residual stress analysis, and tool rake face data extraction capabilities.

Figure 79 Third Wave Systems Training in progress

The Third Wave team also trained attendees on its AdvantEdge™ Production Module, a package that integrates CAD, CAM, machine dynamics, and work piece material properties into one model. This module conducts cutting force analysis, reduces cycle time and maximizes machine utilization. Production Module 5.0 features complete CAD and G code import for tool path visualization and ease of work piece set-up. Production Module capabilities include cycle time calculation, including cut/non-cut time, and instantaneous tool temperature force and power prediction, resulting in optimized machine utilization. All ISO-standard tool geometries and tool holder configurations are used in modeling turning, milling, and drilling processes and finished parts are easily exported for analysis of subsequent operations.

Future of Manufacturing: Machining

On March 7, 2007, the CCAT/NCAL M&S team hosted a conference entitled "The Future of Machining: Machining". With the expectation that this conference will likely be the first of many to come in the future to offer valuable information and substance to the national aerospace manufacturing supply chain, the conference featured speakers from a variety of disciplines engaged in aerospace machining. Welcome remarks from Tom Scotton, Manager of the M&S team were followed by a keynote address by Mr. Joe Presing, leader of Strategic Manufacturing Processes, Pratt & Whitney, who discussed, from the perspective of a global aerospace company, the concerns about the rapidly rising cost of raw material, the next generation technology to power the growth of corporate aircraft, military engine systems manufacturing and power systems. He covered in some detail the need, from an OEM's view, for modeling and simulation in the machining process and the impact that technology has in cost reduction.

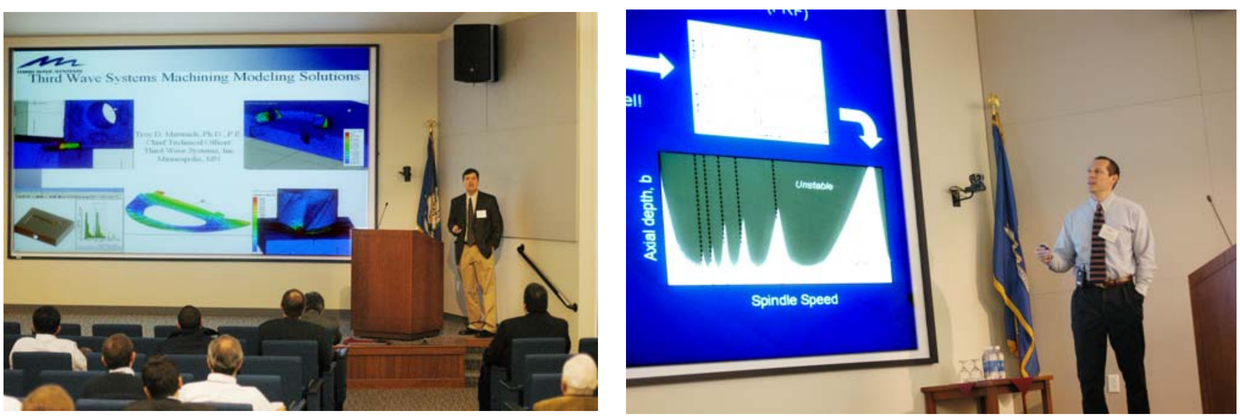


Figure 80 "Future of Manufacturing: Machining" Conference in progress

Dr. Christian Lang, Managing Director, Deckel-Maho Gildemeister (DMG) / Pfronten discussed the organization and structure of his company, the German machine tool builder, purported to be the largest machine tool company in the world now. He discussed the breadth of their advanced aerospace manufacturing systems, with particular emphasis on DMG's philosophy of building more and more capability into a single machining platform rather than requiring manufacturers to employ multiple machines for the same parts. His memorable quote was viewing machining as "sexy." Dr. Tony L. Schmitz, Associate Professor, University of Florida, presented a case for machining modeling and simulation based on a single objective: profit. He discussed his school's work in predictive analysis of machine dynamics, which was extensive. He reiterated that the result of this simulation was to engage machining parameters for maximized profit at the process planning stage. Dr. Troy Marusich, Chief Technology Officer, Third Wave Systems discussed the work his company is doing in material-physics-based machining modeling software and services. He touched on the capabilities of his software product, but with an emphasis on process modeling and design. He also discussed in some length the "Game Changer" project and its potential impact on machining efficiency. CCAT/NCAL's Brian Kindilien tied the conference topics together with a discussion of the machining investigation process that his department engages in. He worked through the assessment process, the tool investigation element, and the level of interactions to be expected with client companies.

Each outside speaker was presented with a laser pointer engraved with the presenter's name and the NALI program website address (The CCAT/NCAL Laser Applications Laboratory team did the engraving.). CCAT/NCAL personnel conducted tours for interested participants of the CCAT/NCAL Laser Application Laboratory and M&S Theater facilities.

Defense Manufacturing Conference (DMC)

The Defense Manufacturing Conference (DMC) is held in the autumn of every year, in various locations around the country. The CCAT/NCAL M&S team maintains a consistent presence at this show, displaying a booth and video technology showing the latest capabilities of the program. The exposition featured a forum for presenting and discussing initiatives aimed at addressing enhanced defense manufacturing capabilities, systems affordability, sustainment efficiency, as well as assuring domestic technology transfer. The CCAT/NCAL team sponsors a 10' x 10' booth featuring information regarding NALI and its consortium companies CCAT, CTC, and Avetec.

DMC 2005, 2006, and 2007 was a combination of technical presentations on topics ranging from metals processing and fabrication, composites, lean enterprise, supply chain advancement to gee whiz technologies and small business innovative research (SBIR). DMC also encompassed an exposition forum where vendors and agencies displayed their company information in booths. The CCAT/NCAL booth, staffed by CCAT, CTC and Avetec personnel, depicted the mission of NALI program, and staff were on hand to speak with visitors about the goals of the programs and network with prospective companies. Staffs members described how the NALI consortium is working to preserve an innovative and highly competitive domestic aerospace manufacturing supplier base to meet the Department of Defense's current and future needs. During the DMC show, many contacts were made with manufacturers and services agencies who expressed an interest in learning more about the NALI initiative.

Members of the CCAT/NCAL M&S team were on hand demonstrating the Delmia Quest product, a factory floor simulation tool that caught the attention of many manufacturers and defense representatives in the exhibit hall. The demonstrations showed how manufacturers could model their factory floors and simulate processes that they undergo in order to improve those processes.

Figure 81 Booth and Display at the Defense Manufacturing Conference

The Launch Quest model rocket was also on display to demonstrate the technology transfer and educational components of NALI-funded programs. CCAT has made possible the partnership with UP Aerospace (www.upaerosapce.com), the world's only private company with a fleet of space-flying sounding rockets, to offer students the opportunity for their own science and technology investigations to be conducted on a rocket fired into space. Students from throughout Connecticut, including teams from Project Lead the Way sites, the CT Pre-Engineering Program, Two Rivers Middle Magnet, University High School of Science and Engineering, and the Science Center of CT participated, as well as teams from 10 NASA Explorer Schools, and school teams from Ohio and Pennsylvania, NALI consortium member states.

Table 5 Events Attended by CCAT/NCAL M&S Team

Event	Location	Start/End Dates	
UTC-2005 Defense Manufacturing Conference	Orlando, FL	11/28/05	12/1/05
UTC-2006 Defense Manufacturing Conference	Nashville, TN	11/27/06	11/30/06
SME-EASTEC 2005 Exposition	West Springfield, MA	6/24/05	6/26/05
SME-EASTEC 2006 Exposition	West Springfield, MA	6/23/06	6/25/06
CGI Tech-VERICUT product training	Irvine, CA	1/21/07	2/3/07
SolidWorks World	New Orleans, LA	2/4/07	2/7/07
SolidWorks product training	Farmington, CT	2/12/07	2/15/07
MAL CutPro Product training	Vancouver, BC Canada	2/19/07	2/23/07
MIT Forum for Supply Chain Innovation	Cambridge, MA	3/1/07	3/1/07
M&S Future of Machining Event	East Hartford	3/7/07	3/7/07
NIST Smart Machining System Conference	Gaithersburg, MD	3/13/07	3/15/07
SME-Composites Manufacturing 2007	Salt Lake City, UT	4/10/07	4/12/07
UTC-Aging Aircraft 2007	Palm Springs, CA	4/16/07	4/19/07
Immersive Engineering Product Training	East Hartford, CT	4/26/07	2/27/07
SME-RAPID 2007 Conference & Exposition	Detroit, MI	5/1/07	5/3/07
Third Wave Systems' 2007 International Users' Conference	Seattle, WA	5/15/07	5/17/07
SME-EASTEC 2007 Exposition	West Springfield, MA	5/22/07	5/24/07
Showcase for Commerce	Johnstown, PA	5/31/07	6/1/07
Atlantic Manufacturing & Design Show	New York, NY	6/12/07	6/14/07
DELMIA Worldwide Customer Conference	Dearborn, MI	10/3/07	10/4/07
UTC-2007 Defense Manufacturing Conference	Las Vegas, NV	12/3/07	12/6/07
Winter Simulation Conference '07	Washington D.C.	12/9/07	12/12/07

2.3. Task III - Transition Next Generation Manufacturing Technologies

2.3.1. Laser Application Laboratory Project Summaries

2.3.1.1. Establish CCAT's NCAL Laser Applications Laboratory (LAL)

Overall Summary of Task
Key Players: CCAT/NCAL Laser Applications Laboratory Staff

Participating Companies: UTRC, Pratt & Whitney, Lumonics, DMG, Nutfield, Trumpf, Kuka, Excel Technologies

Period: 01/06-05/08

Introduction
The CCAT/NCAL LAL staff was tasked with the establishment of a "laser facility to support the aerospace industry". This was to include the acquisition of lasers, laser workstations, support equipment, tools to operate and maintain the equipment, and hardware for the analysis of the work that was accomplished. This was to be accomplished in three primary areas:

- Industrial LAL - This would be lasers and workstations that could be used for the production of aerospace components with special concentration on the laser drilling application. Where possible this would be on "industry ready" equipment and not on "developmental" hardware. While laser drilling was a focus effort, the equipment should be able to be used for welding, drilling, additive manufacturing, and surface modification. These applications were assumed to be areas of future research.
- Establish Micromachining/Marking LAL - This equipment was to allow the LAL group to produce marked parts for analysis and parameter validation. Because the trials that would not be "simple marking", this equipment was not totally "industrialized" so that better control and measuring of parameters was possible.
- Establish Metallography/Microscopy Area - The ability to evaluate processed materials is critical in establishing acceptable and repeatable parameters and procedures. While CCAT/NCAL had agreements with UTRC and UCONN for the evaluation and analysis of specimens/parts, it was often more efficient to have some capabilities internal to the CCAT/NCAL for analysis. For this reason a small metallography area was established for minimal analysis.

Methods / Procedures
Based on the identified needs, a list of equipment was identified. When possible, specific parameters/capabilities were identified for any system. Also limitations on size, utility requirements, and other support issues were also noted. Using this list, acquisition of the equipment was approached in three approaches:

- Procurement- This approach was to purchase the identified equipment for the CCAT/NCAL LAL. In some cases this was the quickest method to place equipment in the facility. In some cases, especially with new systems, the cost of the equipment was negotiated based on the goals of the CCAT/NCAL.

- Consignment- For some equipment, the manufacturer saw that having equipment at the LAL would be to the companies benefit. For that reason some companies were able to place equipment at the LAL for set periods of time for use on NALI funded programs.
- Donation- Similar to consignment, other companies considered donating equipment permanently to the LAL for use. Because of the "non-profit" status of CCAT, this has provided tax benefits for some companies.

Using these approaches, the following major pieces of equipment were acquired under this phase of the program.

Procurement:

- Laser Machining Workstation (with diode pumped Nd:YAG laser); DMG 80 Shaper
- Laser "Shaper"; Yb:Glass Fiber, Q-Switched Laser Marker, Nutfield Technology
- Sealed CO2 Marker, Nutfield Technology Cipher V10
- Robotic Work Station, AH Kuka Robot
- Metallography Equipment; Allied (cut off wheel, specimen mounting press, polisher)
- Optical Analysis Equipment; Keyence (3-D microscope); Excel Technologies (micro- and stereo-scope)

Consignment**:**

- Lamp Pumped Nd:YAG Laser; PRIMA Convergent Lasers P50L; Consigned indefinitely to CCAT/NCAL with 5 axes workstation by UTRC/P&W
- Lamp Pumped Nd:YAG Laser; GSI (Lumonics) JK704TR
- Low Powered CO_2 laser; Coherent Gem 100A; Consigned indefinitely to CCAT/NCAL
- Low Powered CO_2 laser; Coherent Gem Q 700 Consigned indefinitely to CCAT/NCAL

Conclusions

The foundation of CCAT's NCAL Laser Applications Laboratory has been successfully established in this first phase of the NALI Program. With the addition of highly qualified personnel and state-of-the-art laser equipment, the LAL is being utilized to support the LAL project objectives to transition next generation manufacturing technologies to the aerospace manufacturing sector.

2.3.1.2. Establish Laser Applications Laboratory Safety Program

Overall Summary of Task
Key Players: Elizabeth Gounaris (CCAT/NCAL)

Participating Companies: None

Period – 8/06-12/07

The objective of the established Laser Applications Laboratory Safety Program is to ensure the safe use of lasers through engineering and administrative controls for CCAT/NCAL's laser operators, incidental personnel and guests.

Introduction
The overall goal of the Laser Applications Laboratory Safety Program is to provide guidance for compliance with applicable State and Federal regulations along with the American National Standard for the Safe Use of Lasers, ANSI Z136.1-2007. This is accomplished by identifying potential hazards, providing recommendations for hazard control, and training laser operators and incidental personnel.

Methods / Procedures
To date CCAT/NCAL Laser Applications Laboratory has created a written program which resides on our common drive for review by anyone throughout the company. All CCAT/NCAL non-laser personnel have been given a presentation on laser safety awareness and what to expect when they enter the laser laboratories. All laser lab personnel have also been given a laser safety training presentation. In addition any laser employee may watch videos produced by the Laser Institute of America on the general laser hazards and classifications. The American National Standard for the Safe Use of Lasers, ANSI Z136.1-2007 is also accessible to any CCAT employee for review or questions.

Currently, all lasers in the CCAT/NCAL LAL are documented electronically and all information/analysis resides on our common drives. The laser safety officer uses a laser hazard evaluation software produced by the Laser Institute of America to calculate hazard zones, optical density for proper eyewear and acrylic viewing panels.

Posted on all laboratory doors are the Standard Operating Procedures which are reviewed on a yearly basis or sooner if necessary.

Also posted at each laser is the proper safety glasses usage. Based on the laser type and conditions the laser can be run in (class 1 and 4), there are visual controls for anyone entering our laboratories.

All questions or suggestions brought to the laser safety officer are evaluated and addressed in a timely manner. Anyone throughout the company is encouraged to speak up regarding safety issues as this program is continuously being improved and updated.

Conclusions

Having a safe working environment and working with employees to prevent safety incidents is goal number one. As a goal for continuous improvement efforts in safety, we have developed a safety committee which address both EH&S and laser safety topics. For instance, one laser applications laboratory is connected to a training room. In an attempt to keep meeting hosts, guests, and laser operators safe from any potential hazards a presentation is released to the host of the training room when they reserve the room. The slides cover topics such as: laser safety, fire safety, egress, and parking. A new hires program is also being developed by the Director of EH&S and Laser Safety Officer at CCAT. This will allow us to stay up to date on all required training.

References

The American National Standard for the Safe Use of Lasers, ANSI Z136.1-2007

2.3.1.3. Laser Marking in Support of DoD UID

Overall Summary of Task

Key Players: Elizabeth Gounaris (CCAT/NCAL), Scott Davis (CCAT/NCAL),
Susan Coffey (CCAT/NCAL)

Participating Companies: Trumpf

Period - 8/07 to 8/08

In 2005, the CCAT/NCAL Laser Applications Laboratory team was approached by two aerospace original equipment manufacturers (OEMs) to assist in laser marking process development and optimization for use on several alloys in support of meeting the Department of Defense Unique ID (UID) initiative as outlined in MIL-STD-130 (revision N).(MIL-STD-130N, 2007) A review of this document identifies three types of laser marking techniques that will meet the standard.

Introduction

UID is a method, established by the DoD, to identify and track tangible assets through their lifecycles. Tangible assets are those with >$5K value, those that are sensitive/classified, or those that are furnished to third parties regardless of their value. Such records also provide for improved operational efficiency and visibility as well as for more detailed financial management.

Additional information can be found in the *DoD UID Guide.* Acceptable DoD UID part marking techniques must be identified and implemented by the end of 2010.

Direct part marking (DPM) is often used when, for functionality reasons, a label can not be applied or as a matter of convenience. There are several processes that meet MIL-STD-130 and are available for DPM including laser, dot peen, and electrolytic etching. Some of the advantages of using lasers over the other two methods are: no hazardous waste, no consumables, ease of use, high marking speeds, and the ability to precisely and consistently control parameters. However, there are other considerations when selecting the DPM method such as its potentially negative impact on material properties. Mark durability is also a major concern, as the mark must last for the life of the component, which may include survival in harsh environments. Marking of legacy components presents a special challenge because the original design may not have accounted for the potential associated “damage” resulting from the part marking method chosen. Examples of UID marks are shown in the Figures below.

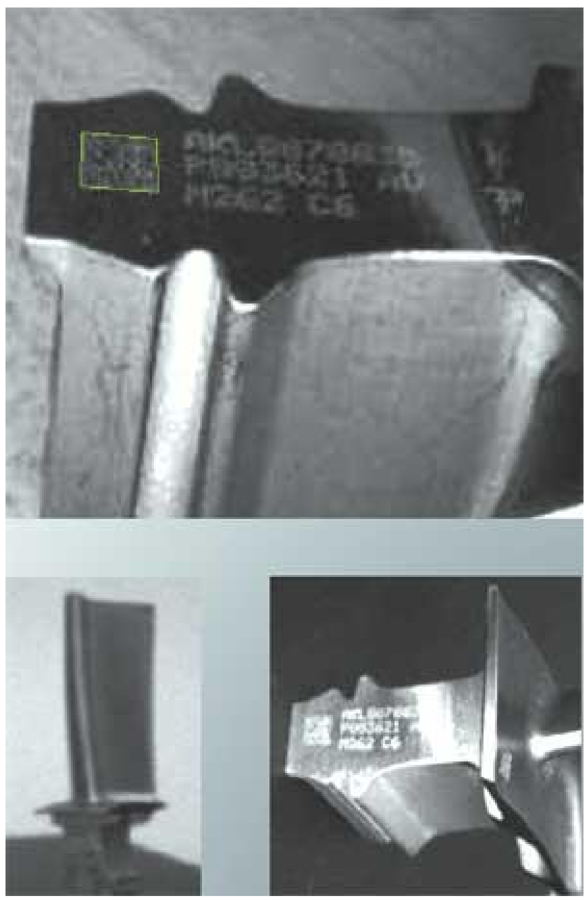


Figure 82 Example of direct part marking of a turbine airfoil

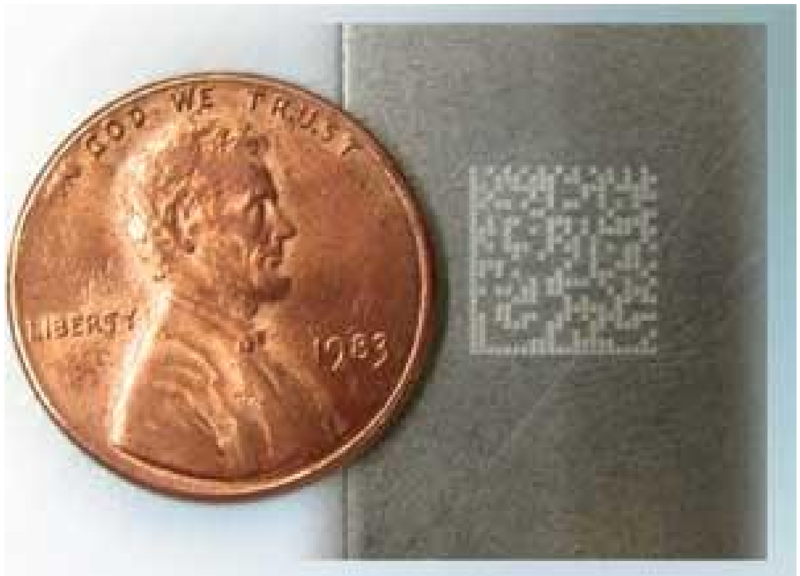


Figure 83 Example of laser UID mark on Al Alloy 7075-T6 coupon

For laser marking to meet the standards on aerospace components, the challenge is to produce robust reproducible parameter work envelopes that enable the mark to be readable and durable but do not result in a fatigue-debit to the material. Capital and process cost effectiveness and timeliness to implementation must also be taken into consideration.

Methods / Procedures

The CCAT/NCAL LAL team evaluated products from 15 different laser marking manufacturers, and then selected and procured three laser marking systems. The selection was primarily based on cost, ease of use, and the expected ability to mark a wide range of materials including difficult-to-mark materials. Lasers selected were: an Yb:glass fiber laser, a CO_2 laser, and a Nd:YVO_4 system. Aluminum 7075-T6 was the first alloy selected for process development, optimization, and qualification because of OEM interest and the large existing OEM mechanical property database available for subsequent comparison to post-processed material. Other materials being studied are Ni-based alloys, Fe-based alloys, Ti-based alloys, and ceramic matrix composites (CMCs). The longer term goal of the UID laser marking program is to develop and implement a methodical systematic approach to identify and optimize laser direct part marking for robust and consistent parameter work envelopes so that these can be used in manufacturing environments to meet the MIL standard requirements and materials mission criteria, that is, a laser part marking database available to OEMs and suppliers.

The first phase of laser DPM process development focused on determining the impact of individual and combined process parameters on the mark depth and resultant material fatigue properties. Initial tests revealed that the CO_2 laser, probably due to its longer 10.6μm wavelength, and relatively low output power, 10W, was inadequate for producing marks deep enough to be read and verified. Subsequent process development was performed using the Yb:glass fiber and Nd:YVO4 laser systems, respectively.

Because of the number of individual process parameters to consider, as shown in Figure 84, a design of experiments (DOE) approach was implemented and is summarized in Figure 85.

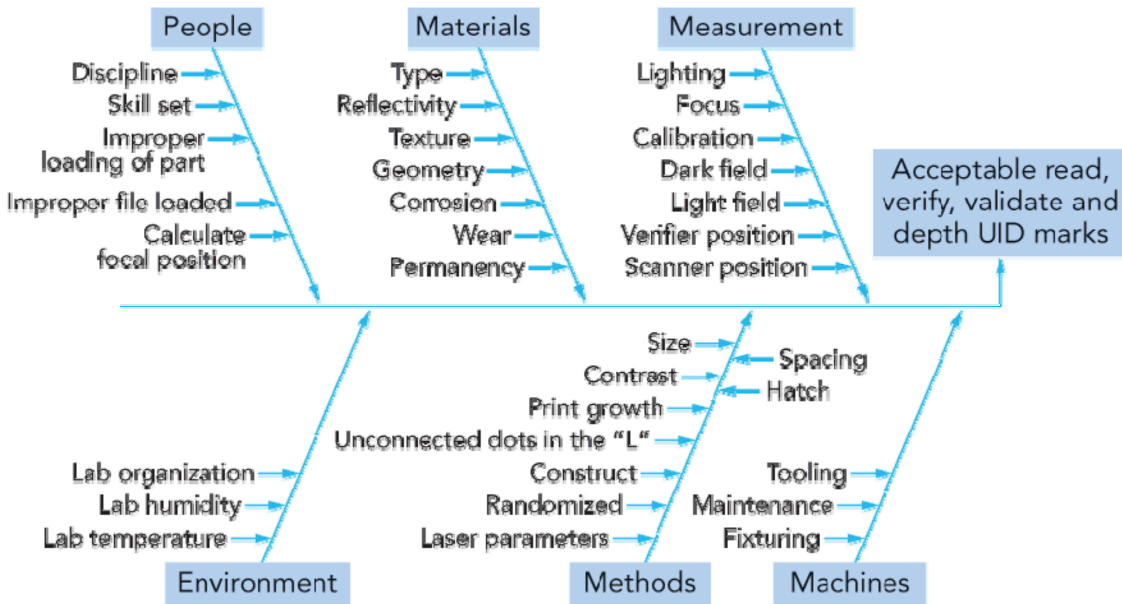


Figure 84 Fishbone diagram shows possible sources of variation to consider in the laser DPM process.

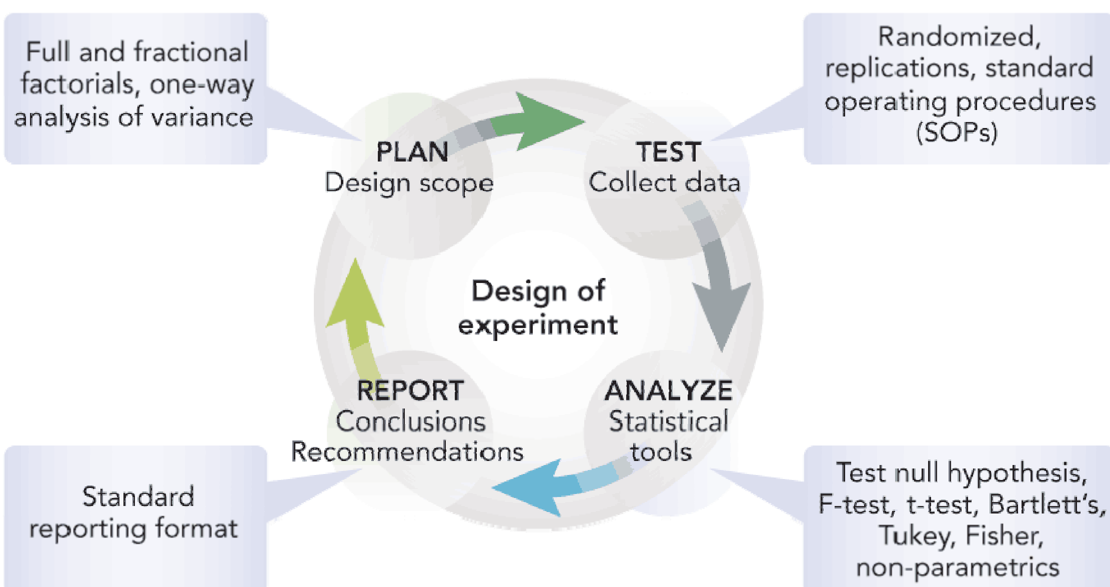


Figure 85 DOE approach used for process development and optimization for laser DPM.

Position of focus, output power, marking speed, and laser pulse duration and pulse frequency were varied. The results of the DOEs were graded from Passed to Not Passed, primarily based on meeting the key process outputs of mark depth below the threshold where mechanical property debit would occur; mark readability; and mark quality (the ability to verify and validate the data). Several rounds of DOEs were required to begin to identify acceptable working envelopes for each laser system. Experimentation is on-going.

Conclusions

Planned future studies toward the optimization and qualification of direct part marked 7075-T6 aluminum on both laser systems using DOE will produce a methodology that will then be applied to select Ni-based, Ti-based, and Fe-based alloys and CMCs. Eventually, the DOEs will incorporate approaches aimed at the laser physics relationships rather than on individual process parameters, and laser marking guidelines will be generated.

References

MIL-STD-130N Department of Defense Standard Practice Identification of U.S. Military Property, U.S. Department of Defense, December 17, 2007.

DoD UID Guide, Department of Defense Guide to Uniquely Identifying Items, Office of the Deputy Under Secretary of Defense (Acquisition, Technology & Logistics), Version 1.6, June 1, 2006.

2.3.1.4. Laser Generation of Crack-Like Features for Materials Validation

Overall Summary of Task

Key Players: Scott Davis (CCAT/NCAL)

Participating Companies: Pratt & Whitney, Hamilton Sundstrand, United Technologies Research Center

Period – 2005- current

Introduction

Hamilton Sundstrand & UTRC approached CCAT's NCAL Laser Applications Laboratory team with an interest in investigating the effects of Laser Generated Crack-Like Features (LGCLF) to simulate surface cracks using a laser marking system. The initial work involved the development of Semi-Circular Surface Crack-Like Features with the CCAT/NCAL LAL 20 watt Ytterbium Fiber Laser.

The main purpose of investigating LGCLF's with Hamilton Sundstrand & UTRC was to evaluate through materials testing:

- Threshold data for specific crack geometries
- Create surface flaws in coupons to validate and generate crack growth data curves
- Generate crack growth data for complex crack geometries.

This analysis will allow Hamilton Sundstrand & UTRC to mimic critical flaws in critical areas of engine components to certify damage tolerance, and test components with existing flaws to determine the true tolerance.

As an outcome from initial tests with Hamilton Sundstand & UTRC an interest in producing LGCLF's in several different materials/parts was sparked. The following companies/agencies have come to the CCAT's NCAL LAL team to produce LGCLF's; Hamilton Sundstrand, FAA, NASA, Pratt & Whitney, and UTRC.

Methods / Procedures

Legacy mechanical property data was reviewed in order to determine a maximum acceptable mark depth corresponding to the material's damage tolerance threshold. The fatigue effects from laser marking were determined by producing marks at known depths and performing subsequent tests. To date, fatigue testing indicates that laser marks behave as pure fatigue cracks equivalent to the laser mark depth, including the heat affected zone, meaning that fatigue debit will increase with increasing laser mark depth; the details of the mechanical property study and the use of laser generated crack-like features for materials validation were presented and published recently by Aaron Nardi of UTRC. A cross section of a laser mark is shown in Figure 1 and that of a laser generated crack-like feature is shown in Figure 2. In addition, standard metallographic and reflected light microscopy techniques (ASTM E 3-80) were used to determine the extent of the formation of any heat affected zones that were found to be dependent upon the selection of laser system and parameters. Direct Part Marking durability was determined by use of a standard Tabor test; results were found to be acceptable. (ASTM D-1044)

Conclusions

Experimentation is on-going with Hamilton Sundstrand, UTRC, and Pratt & Whitney to continue to investigate the effects of laser type and flaw geometry on performance.

References

Aaron Nardi, Stephen L. Smith, "Laser Generated Crack-Like Features Developed for Engineering Assessment of Fatigue Threshold Behavior in 7075 Aluminum," presented at the *36th ASTM National Symposium on Fatigue and Fracture Mechanics* sponsored by ASTM Committee E08, November 14-16, 2007, Tampa, FL USA.

"Standard Methods of Preparation of Metallographic Specimens Standard for Metallography," ASTM E 3-80.

"Tabor (Abrasion) Test," ASTM D-1044.

Figure 86 Cross section shows an example of "deep" laser UID (DPM) mark.

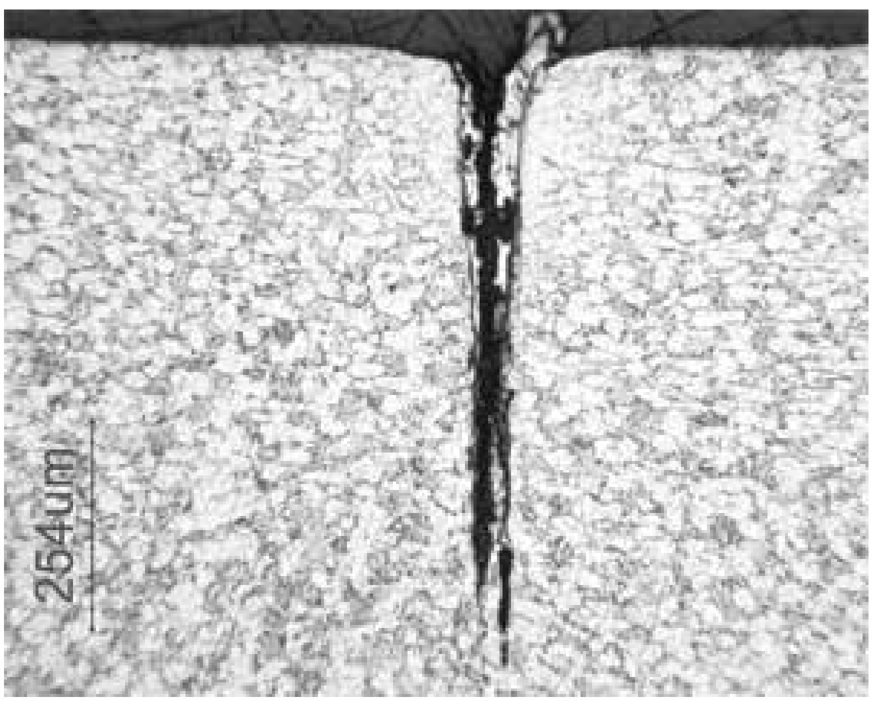


Figure 87 Cross section shows an example of a laser-generated crack-like feature.

2.3.1.5. Laser Beam Cutting of Thin Sheet Metals (for OEM)

Overall Summary of Task

Key Players: CCAT/NCAL LAL Staff

Participating Companies: Pratt & Whitney, Trumpf, Prima, Whitcraft, LFI Inc., Smiths Aerospace (Unison), ARCOR Laser Services, and AGC

Introduction

While precision hole drilling is a key focus of activity, the precision machining of advanced aerospace materials can also include the cutting of thin sheet materials. To address this need the CCAT/NCAL LAL and M&S teams are performing a laser design of experiments (DOE's) to optimize the laser cutting process.

Methods / Procedures

The challenge is to minimize the width of heat affected zone (HAZ), generated to avoid subsequent grain boundary cracking when the metal may be subsequently formed or put to use. The laser process must also be able to meet the tolerances of specifications.

To date, the CCAT/NCAL Laser Applications Laboratory has worked with Pratt & Whitney, Laser Manufacturers (i.e., Trumpf and Prima) and Suppliers (i.e., Whitcraft, LFI Inc., Smiths Aerospace, ARCOR Laser Services, and AGC Inc.) to develop an acceptable consistent laser cutting process. This network of OEM and supply chain companies was selected to assure that realistic requirements are focused on and that key issues facing implementation in the supply chain are addressed. Three different types of laser systems: (1) CO_2, (2) Nd:YAG, and (3) Ytterbium: glass fiber, have been evaluated.

The Ytterbium:Glass fiber system resulted in HAZ's an order of magnitude less than those seen with either the CO_2 or the Nd:YAG lasers most likely due to its incredibly high beam quality and small spot size. However, the Ytterbium Glass fiber laser used in the trials was not coupled with an acceptable motion device, at the time, and so the dimensions of the cut were not acceptable, and the HAZ width was not consistent. ARCOR Laser Services is working on coupling the Ytterbium:Glass fiber laser to an acceptable motion device for further trials. HAZ's <0.001" were produced using the Ytterbium:Glass fiber laser.

CCAT/NCAL LAL staff has performed trials on the Trumpf 2510 CO_2 flat sheet cutter, at Trumpf in Farmington CT, which have shown acceptable results in terms of HAZ width. The Trumpf 2510 is a newly available system and is specifically designed to cut thin sheet metal. There are many Trumpf CO_2 flat sheet cutters at Suppliers today (i.e., Whitcraft, AGC Inc., Smiths Aerospace), but these are older units (i.e., the 2503 and 3030) where it may be possible have the setup modified to cut to required specifications, however, Supplier operators and engineers need additional training to be able to program the units for the optimum process sequence needed during the laser cutting and also for laser parameter optimization. The

CCAT/NCAL LAL team has been working with the Suppliers to help them achieve similar results to those produced at the Trumpf Farmington CT facility.

The CCAT/NCAL LAL team has also performed cutting trials on the Prima Sychrono CO_2 flat sheet cutter in Chicopee MA. This machine is the newest and fastest laser sheet metal cutter available today. The Synchrono produced samples having acceptable HAZ widths, the fastest of all cutting speeds and acceptable formability, however, significant investment by Suppliers (~$1M) would be needed to implement this machine.

Conclusions
Initial results were positive on the cutting of test components. However the economics indicated that stamping or some other method may be more economical when higher production rates are required. But for initial development of designs and prototyping of components the laser cutting process may be the most economical.

Based on these findings the CCAT/NCAL LAL team will continue to work with Pratt & Whitney as needed to "connect with" potential suppliers for conducting further testing on actual components any future efforts in this area.

2.3.1.6. Laser Welding of Invar 36 Mold

Overall Summary of Task:
Key Players: John Washko (CCAT/NCAL), Paul Denney (CCAT/NCAL)

Participating Companies: Coast Composites, Irvine, CA, Scientific & Efficient Technologies, Ltd., Germany

Period: March 2007 – May 2007

In February of 2007, the CCAT was approached by Coast Composites to assist in the laser welding of (4) complete wing skin molds for the Boeing 787 Dreamliner. The CCAT/NCAL LAL team was to provide a laser source (IPG Photonics YLR10000 fiber laser) and technical assistance to facilitate the final assembly welding of these mold sections together into a completed mold unit. Scientific & Efficient Technologies Ltd. (SET Ltd) was to provide a remote beam focus assembly "cart" to deliver the laser energy to the mold components to be welded.

Introduction
This application was required by Coast Composites to enable section-by-section final assembly welding of large molds. These molds are used for molding composite wing-skins for the Boeing

Dreamliner. The overall mold size was too large for manufacture in a single piece, so the laser welded design was chosen. The total number of molds needed was 4, (1) upper and (1) lower of right and left side wings. Total number of welds on upper wing mold was (2) and on lower mold was (3). Longest weld was on upper wing section and was approximately 25 ft. All other welds were across the width of the wing and ranged from approximately 15 ft. to 20 ft.

Methods and Procedures
Technical challenges

1) Guidance of the "cart"

The device that actually carried the fiber and final focus lens assembly across the surface of the mold was guided by a rail mounted to the mold surface. Initial trials on short (3ft) weld samples worked well with pieces of rail "super-glued" to the surface. In actual welding of the molds this became a problem. The heat from the laser weld would cause the glue to soften. Combined with the thermal expansion of the carbon steel thin rail Vs the large Invar structure, the rail would pop from the surface and cause the cart to mis-track the seam. The glue also posed another problem: contamination of the weld seam.

2) Contamination

The final fitting of the mold pieces together was accomplished in a very dust and dirt laden area. This was not avoidable in this particular scenario due to scheduling. The molds needed to be surface finished at the same time that the welding needed to be performed due to manufacturing delays. The primary contributor of the contamination was hand finishing of the mold surface. The as-machined surface had a textured finish left from the ball-shaped end-mill necessary for 5 axis contour cutting. The workers would use a thin coat of a lacquer type paint (Dychem) as a tell-tale, and hand sand the surface until almost all of the dye was removed. Additionally, this same procedure was performed on the mating surfaces of the weld joint. This operation was necessary to enable a precise fit-up of the weld joint. Unfortunately the contaminants left behind from this process were unusually difficult to remove, and caused huge (.06 - .12) long blow-outs in the weld seam. Repairing these blow-outs took far longer than performing the actual first-pass welds. The repair procedure was to cut small pieces of filler wire and stuff them into the holes; then re-weld with the laser at a lower power (approx. 3KW). This procedure was repeated several times for EACH blow-out. On the first few welds the repair area was approximately 1/3 to ½ of the weld length. The repair took days.

3) Poor Depth of Penetration

After performing several trial piece welds, it was found that the penetration varied from acceptable (8 – 9 mm.) down to 5 mm. Penetration was initially tested by butting 2 pieces of the material together and performing several passes across the weld seam. The 2 plates were then broken apart to visually see what the penetration was. The problem with this method is that it only gives you a very small representation of what happens in a full length weld. The rest of the weld samples were 100% full length seam welded, and after cross-sectioning in several places were found to have insufficient penetration.

Solutions

1) Guidance of the cart

Several different solutions were attempted; more glue, chilling the track with liquid "air" from "dust-off" cans held upside down, welding short sections and waiting for the tracks to cool. The only positive results were obtained by TIG-tacking the track to the surface of the molds. This method resulted in 100% solution of the problem.

2) Contamination

The sources of the contamination were determined by process of elimination to be:

a) superglue
b) sanding disc residue in the forms of grit impinged into the surface and grit bond adhesive smeared onto the surface.

The contamination problem was eventually solved by careful cleaning of the weld zone with a NEW, uncontaminated, stainless steel rotary wire brush, then wiping with clean rags soaked in acetone followed again by new clean rags soaked in alcohol. No other method was proven to eliminate the blow-outs. Several welds were performed with the seam prepared using a contaminated wire wheel (previously used on something else) and the results were as bad as no preparation. Also, several welds were performed using only acetone as the cleaning agent, those welds were better but not 100% porosity free. Only the combination of using a clean wire wheel, fresh acetone followed by fresh alcohol proved to be 100% effective in eliminating the blow-outs. Unfortunately this procedure was not developed and followed fully until the last 2 welds on the last mold. However, these last 2 welds totaling over 40 feet long were 100% defect free and required no rework.

3) Poor Penetration

Several trial and error attempts were made to improve the weld penetration: cleaning the lens (which was determined to have a burn spot on it), cleaning the cover glass, changing the cover glass and more power. The only sure way to increase the penetration was found to be to run with the cleanest cover glass possible. If there was contamination in the weld and a blow-out resulted, the thin coating of metal vapor and particulate on the cover glass would immediately reduce penetration by 1 – 2 mm. This could occur in the first mm. of weld, thereby making all the subsequent welding performed with that cover glass have insufficient penetration. Also, if the power was too high (> 6KW) it appeared that a film of metal vapor coated the cover glass and also reduced penetration.

Conclusions

The application of high-powered fiber-delivered laser energy to perform remote welding on large fabrications can be successfully performed. Fully leak-tight welds tested to 1 x (10) -6 std. cc. / sec. helium leak rate were eventually performed at a very reliable rate. Contamination effects due to manufacturing processes performed prior to laser welding can be eliminated with a proper combination of mechanical removal and solvent cleaning. Since there was no cover gas used on this application, the effects of proper shielding and perhaps some plasma suppression could not be investigated.

Note: the weld samples were prepared with the 40 degree chamfer at the top edge, as well as a simple butt configuration. The "humping" results were far less with the chamfer, possibly due to better containment of the weld pool. The customer had requested that the elimination of the chamfer be researched, as it is a labor intensive process that must be performed by hand after the entire mold section has been machined.

Supporting Photographs:

Figure 88 Typical weld joint before alignment and mating

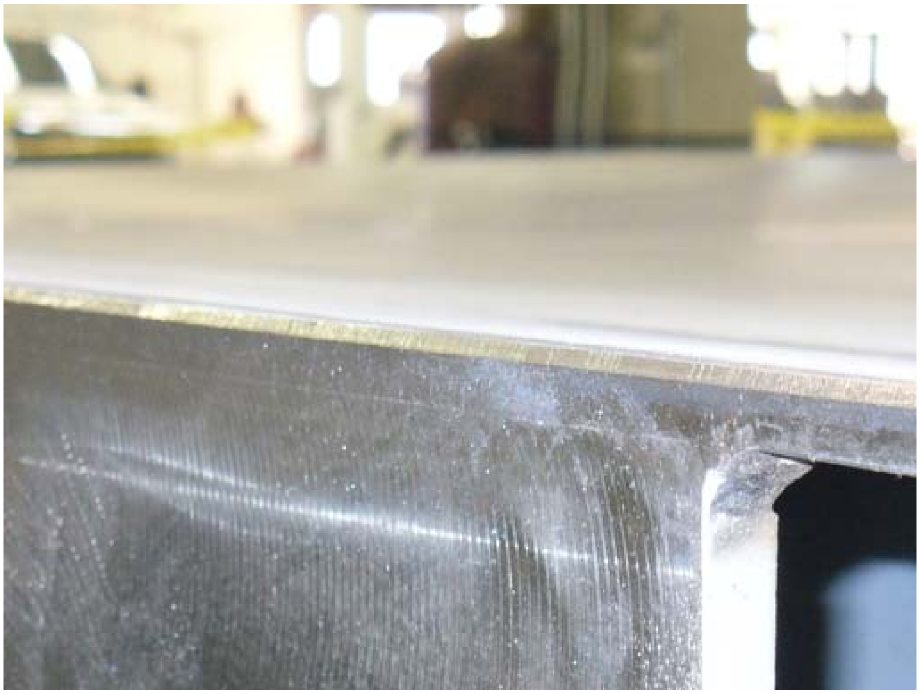


Figure 89 Weld preparation with chamfer close-up

Figure 90 Longest weld joint, parts staged, weld ~25 ft. in length

2.3.1.7. Laser Drilling of Helicopter Components with Fiber Laser

Overall Summary of Task
Key Players: John Washko (CCAT/NCAL), Paul Denney (CCAT/NCAL)

Participating Companies: Honeywell Aerospace (Tucson, AZ)

Period: 08/07-10/07

Introduction
CCAT's NCAL LAL team was contacted by Alex Pohoata, Senior Mechanical Engineer, Engines Services & Systems; at Honeywell Aerospace (Tucson, AZ). They produce many components for rotor wing engines including full tank components for the Chinook helicopter. As part of the production process they must drill a large number of small holes in a wide range of materials. This is a costly process.

Mr. Pohoata was aware of the CCAT/NCAL's 10 kW fiber laser and was interested in whether it was possible to use this laser for drilling holes in potential materials. Since the CCAT/NCAL LAL team was already investigating the use of the fiber laser for drilling, additional trials in other materials was also of interest. It was agreed that the CCAT/NCAL LAL team would accomplish drilling trials on Honeywell Aerospace provide material with the IPG fiber laser for evaluation.

Methods / Procedures
Honeywell Aerospace provided Inconel 718, Haynes 230, Ti-6-4, and Al 6061 that was 0.020" thick. The goal was place 0.020" diameter holes in the plate with the fiber laser. Because these were some of the earliest drilling trials on the IPG fiber laser some of the actual data (pulse width, pulse frequency, and number of pulses to penetrate) could not be documented.

Parameters and comments that were made with regard to the processing are summarized in Table 6.

Processing was accomplished with the 10 kW IPG fiber laser; 200 mm delivery fiber; 125 mm collimator optics;150 mm focusing optics; estimated spot size at focus- 240 µm;

Conclusions
All specimens were returned to Honeywell for evaluation. The comments back from Honeywell were *"These are great results and we are going to move forward. I am trying to get some funds for the next year."*

Table 6 Parameters for Laser Drilling

Trial #	Drilling Type	Power Level (kW)	Pulse Width (on time) (msec)	Pulse Width (on time) (msec)	Number of Pulses	Duration (sec)	Travel Speed (ipm)	Assist Gas; Ar (psig)	Comments
1	Percussion	10	500.0	NA	2	NA	NA	80.0	
2	Percussion	10	750.0	NA	2	NA	NA	80.0	
3	Percussion	10	200.0	1.0	Unknown	0.5	NA	80.0	
4	Percussion	10	400.0	10.0	Unknown	0.5	NA	80.0	
5	Percussion	10	100.0	100.0	Unknown	0.5	NA	80.0	Full penetration only for Al
6	Percussion	10	100.0	100.0	Unknown	1.0	NA	80.0	
1 (Trial 7 on plate)	Trepanning	4	200.0	4.0	Unknown	NA	30	80.0	Focus at top; Not good for Al
2 (Trial 8 on plate)	Trepanning	4	80.0	1.0	Unknown	NA	30	80.0	Worse-more recast/dross; Not good for Al
3 (Trial 9 on plate)	Trepanning	4	400.0	1.0	Unknown	NA	30	120.0	Al only
4 (Trial 10 on plate)	Trepanning	4	200.0	0.5	Unknown	NA	30	120.0	Al only
5 (Trial 11 on plate)	Trepanning	4	100.0	0.4	Unknown	NA	30	120.0	Al only

2.3.1.8. Short Pulse (Duration) Laser Drilling

Overall Summary of Task
Key Players: CCAT/NCAL LAL Staff

Participating Companies: Listed in the Subtask section write-ups (below)

Period: 01/06-05/08

Introduction
The use of "short pulses" for laser drilling of aerospace components has many potential benefits. Present flash lamp based Nd:YAG lasers are limited by design to pulse widths of approximately 300 micro-seconds (μs) to 2 milli-second (ms) at a maximum frequency of approximately 40 Hz at useable energy levels. With today's higher performance designs these parameters may not achieve the minimum HAZ and recast values needed.

With today's new laser technologies it is possible to achieve pulse widths of less than 100 μs at high frequencies (>100 Hz). The result is that the interaction time with the material can be shortened which may reduce the HAZ.

The CCAT/NCAL LAL team investigated two potential laser systems that could better meet new engine design requirements at potentially lower cost and higher repeatability. The following outlines the work that was accomplished in these areas.

Summary of Sub-Task 1: Evaluation of Ex-One SuperPulse Laser Machine Tool
Key Players: CCAT/NCAL LAL Staff

Participating Companies: Ex-One

Period: 01/06-07/6

Introduction:
The ExOne SuperPulse is a workstation designed (and integrated) by ExOne and contains the General Atomics (GA) Photonics Division's Everest SuperPulse laser (i.e., Nd:YAG rod, diode pumped, frequency-doubled). The GA's Everest SuperPulse laser was created to offer an option for a high-speed, high-precision vaporization-dominated laser metal removal process.

SuperPulse is a patented nano-second scale pulse duration format developed by GA that is a laser machining technique where material is locally vaporized and removed before significant thermal diffusion can occur into the material; this is similar to the result produced by ultra-short pulse lasers (e.g., femtosecond lasers).[1] SuperPulse laser machining technology is a very strong candidate for filling the current need for a laser machining process that is superior in quality to that of conventional (i.e., millisecond pulse duration regime) laser machining processes, which result in a combination of melting and vaporization, and that of the ultrashort pulse laser processes which ablate material but must be performed in vacuum and generally have unacceptably low material removal rates to meet most industrial aerospace laser drilling applications requirements.

The primary expected advantage of the SuperPulse laser drilling process over conventional flash-lamp pumped Nd:YAG rod laser drilling is significantly reduced material heat affect zones (HAZ's) (i.e., remelt/recast) due to the use of short pulse lengths, specified to be <5 nanoseconds (ns), but high fluence (i.e., energy per pulse per spot size, energy density), which results in a vaporization-dominated metal removal mechanism when compared to conventional millisecond pulse length durations, which result in a large percentage of metal removal via melting leading to significant HAZ's. Additional expected advantages of the SuperPulse laser drilling process over that of conventional laser machining processes is that, in general, better dimensional stability has been demonstrated when lower pulse energies are used (<10 mJ) rather than machining with a lower number of larger energy pulses as would be performed using a conventional laser machining process. Also, the SuperPulse laser process uses frequency doubled output, where the resultant 532 nm wavelength has been shown to "couple" more efficiently with metals/alloys than the first harmonic 1.06 um wavelength. A primary advantage of the SuperPulse laser machining process over a femtosecond laser machining process is that the SuperPulse process can be performed in air while the high fluence of femtosecond laser machining processes necessitate the use of a vacuum chamber (i.e., the fluence is so great that air is ionized). In addition, due to the complex component architecture required in femtosecond laser systems, their output power is limited, too low in average power to deliver practical processing speeds.

Its also important to note that there are 4 critical factors to consider for successful implementation of industrial laser machining applications: i) capability to machine precise, reproducible, features in a timely manner, ii) low cost of ownership when running and maintaining the process, iii) the ability to successfully machine materials which are difficult or impossible to machine when using conventional processes (e.g., ceramic matrix composites, intermetallics, and coated metals and alloys), and iv) robust equipment which meets today's production and environmental health and safety requirements.

Methods / Procedures:

ExOne consigned a Beta SuperPulse to the CCAT's LAL for approximately 6 months for evaluation and testing. An initial evaluation of the workstation indicated a robust, well-built unit, however, the size of the overall "footprint", ability to extract heat from itself, and operator ergonomics are believed to need further optimization for acceptance into an aerospace production environment. The Workstation "robustness" and operational control were found to be acceptable when compared to current state-of-the-art turbine airfoil laser drilling workstations. An initial evaluation of the laser system indicated freeze damage during shipment because the laser had not been properly drained of coolant. The laser(s) never performed to specifications (Table 7). Data was collected over a parameter range of up to 17.3 W average output power (combined), ~100 nsec pulse duration (as measured directly from oscilloscope) and 10 to 20.5 kHz pulse frequency on 0.050" thick 300 series stainless steel and 0.050" thick Waspaloy materials, respectively. Data was recorded as defined by ANSI C7.2, "*Recommended Practices for Laser Beam Welding, Cutting and Drilling*"[1] and was also "Saved" within the unit itself. However, the output power values that were "self-saved", where the data source was an internal power meter, never matched those taken in real time using an external Field Master power meter. Although the unit is rated at 28 W maximum average (combined output power), the highest average output power witnessed was 17.3 W (combined). Also noted, even when the attenuation of each laser was set at the same value, each laser produced significantly different power levels.

Table 7 General Atomics Everest SuperPulse Laser Specifications

SuperPulse Specifications*		
Wavelength	532 nm	
Pulse Width (each pulse) @10kHz	4 +/- 1 ns	
Energy (both pulses combined) @10 kHz	2.8 mJ	
Pulse Repetition Rate	1 – 50 kHz	
Avg. Power Output (both pulses combined) @ 10 kHz	28 W	
Nominal Beam Diameter	3 mm	
M^2 (Beam Quality)	<1.3	
TEM (spatial mode)	TEM 00	
Pulse-Pulse Stability, 1 s over 10k pulses	+/- 2%	
Pulses	**Pulse 1**	**Pulse 2**
Output Power	0 – 20 W	0 – 20 W
Pulse Repetition Rate	0.5 – 30 kHz	0.5 – 30 kHz
Pulses 1 and 2 Space Time	0 – 187.5 ns	
Pulse Width	<5ns	
Energy Per Pulse	2 mJ	
Nominal Beam Diameter	~7mm	
TEM (spatial mode)	TEM 00	
Control Interface	RS232	
Power Supply	208 – 240 VAC – 3PH 60 Hz	
Max. Power Consumption	3 kW	

* The SuperPulse is a dual pulse laser system. The output beam is composed internally with 2 independent laser beams referred to as Pulse 1 and 2.

Conclusions for Sub-task 1

The application of the SuperPulse laser to drilling current gas turbine engine components was found to be limited due to: i) its observed lack of reliability and inconsistent performance, ii) too low average power output to produce the range of hole sizes required, and iii) subsequent to i) and ii), too low material removal rates and too low laser reliability and consistency for the overall process to be validated and to be cost effective or timely enough when compared to current production requirements.

Some of the objectives of the Subcontract could not be met due to inconsistent and continually deteriorating performance of the laser.

References

1. ANSI/AWS Standard C7.2, "*Recommended Practices for Laser Beam Welding, Cutting, and Drilling*", AWS, Miami FL, (1998).

Summary of Sub-Task 2: Laser Drilling With Gated High Power Fiber Lasers

Key Players: John Washko (CCAT/NCAL), Paul Denney (CCAT/NCAL);
Salay Stannard (CCAT/NCAL Intern)

Participating Companies: Laser Mechanisms, Preco, IPG, Pratt & Whitney

Period: 01/08-05/08

An alternative to lamp pumped Nd:YAG lasers could be high power fiber lasers. These, while similar to Nd:YAG in wavelength have many capabilities and/or advantages over Nd:YAG lasers presently used for aerospace drilling applications. One characteristic of these continuous wavelength (CW) fiber lasers is that they can be "gated" to very short pulse widths at high repetition rates. The fiber laser also has a uniform power distribution, is fiber delivered, and therefore should have lower maintenance costs than Nd:YAG lasers. While fiber lasers are presently more expensive than and can not reach the same peak powers, there may be some attributes that could justify using the fiber laser for drilling.

The CCAT/NCAL LAL team has been examining the use of a 10 kW fiber laser for drilling. Efforts to date have focused on initial results of drilling and what improvements or modifications may need to be made to the fiber laser if it is to be used for aerospace applications. Further efforts will be conducted under NALI Phase II.

Introduction

Current designs in aerospace turbine engines require a huge number of cooling holes drilled in heat resistant metals to reach maximum performance and reliability. These holes have traditionally been drilled using flashlamp pumped Nd:YAG lasers. Recently developed fiber lasers can now reach continuous wave powers in excess of 10 kilowatts, entering the peak power processing regime of flash lamp pumped lasers for producing these holes.

Flashlamp pumped Nd:YAG lasers have been the primary lasers used in percussion drilling of aerospace turbine engine components for over fifteen years. The justification for using these lasers has been that they can create a Gaussian beam of laser energy with very high peak power. This can then be used to drill through a wide range of materials in differing thicknesses to create a suitable range of hole diameters for thin film cooling of components. However, as engine performance has driven designers to tighter tolerances on holes and increased their number, some short comings have become apparent in the Nd:YAG laser. Pulse-to-pulse power variations, "back strikes", and maintenance costs have pushed Nd:YAG lasers to their limits.

Flashlamp pumped Nd:YAG lasers are a mature technology with well known characteristics and support system requirements. These lasers have approximately 1 – 3% electrical to optical efficiency[1]. Cavity design is complex, typically requiring a directly cooled crystal rod that is sealed with O-rings in an enclosed water jacket. The flash-lamps are also directly cooled and must operate in de-ionized water to avoid electrically short circuiting the lamp power supply. There are many extra-cavity optic elements required to correct for thermal distortion in the Nd:YAG rod. All of these elements must be cooled and kept spotlessly clean and aligned to avoid contributing any optical aberrations to the laser light on its way to the work piece, or physically burning a spot on an optic. The cooling system temperature must be tightly controlled (typically +/- 0.1 degree Celsius) to maintain thermal stability in the cavity, and small variations in temperature stability will result in noticeable differences in beam output characteristics. Beam delivery can be complicated and requires sealed pathways to maintain a dust free environment. Shipping, start-up and alignment are complicated by the adjustable optics necessary to deliver the beam.

High powered fiber lasers are a development of the telecommunications industry. The technology was initially used for low powered, high efficiency, high reliability transmission of data over long distances through optical fibers. Fiber lasers have high electrical to optical efficiencies, typically 25% or greater. Laboratory tests have shown efficiencies as high as 39%[2] . The resonator (or cavity) of a typical fiber laser is totally contained within a single glass fiber, suitably doped to act as an active media. The cavity terminator mirrors are not necessarily “hard optics” as in conventional lasers, but can be Bragg gratings i.e. successive layers of refractive index change, that are directly fused into the fiber and never need cleaning or alignment3. High powers are achieved by combining individual lower powered fiber lasers and fusing them together into a single output fiber. This fiber can range in diameter from 10’s of microns to several hundred’s of microns. This ability to combine multiple low powered lasers into one laser of high power and still maintain high beam quality is unique in the photonics industry.

Fiber lasers, or lasers that have sufficient beam quality to be fiber delivered, also have the ability to be easily re-distributed via multiple fiber relay equipment. A single fiber’s output can be split, re-launched into other fibers, and delivered to multiple workstations. There is typically only (1) mirror and (1) lens per re-launch, and these are housed in a tightly sealed box that rarely needs service. The actual working fiber is metal jacketed, flexible and impervious to the environment. It is impossible to mis-align and never needs cleaning or maintenance once assembled. Final focus assemblies are similar in architecture to conventional Nd:YAG assemblies, and require the same maintenance considerations. One disadvantage of conventional fiber lasers is that if one of the component lasers fails, there is no field repair. The unit must be returned to the manufacturer for refurbishment. Consequently, the laser is supplied with an “extra” laser module as insurance that full output power can still be achieved if one module fails, negating the need to return the unit immediately for repair.

Most high powered fiber lasers are designed for continuous wave (CW) operation, but also can be pulsed to several kilohertz (kHz). Characteristically, they maintain their average power as peak power and reach this in several microseconds. The laser used in these experiments had an average CW power of 10 kilowatts and a rise time of less than 10 microseconds. A local device designer was contracted to develop a method to pulse this laser in many different controlled fashions. The system developed has the capability to pulse the laser open loop, (with a continuously running oscillator), with a single pulse of any shape (triangular, square, or any random shape than can be drawn), or with "structured pulses" where the Pulse Width (PW), frequency, amplitude, and pulse shape can be varied. These pulse "trains" are completely synchronous with the positioning system so it is certain that the complete pulse train is delivered as designed.

One notable difference between conventional lamp pumped lasers and fiber lasers is the ability to deliver short pulses at varying frequencies, with no drop in peak power. This characteristic has the potential to provide some processing advantages in hole drilling. For these reasons there has been an interest in whether high power Yb fiber lasers could be used for aerospace drilling applications. CCAT's NCAL Laser Application Laboratory (LAL) has examined the use of a 10 kW fiber laser for drilling. This paper will present some of the initial results of drilling and discuss what improvements or modifications may be needed to the fiber laser if it is to be used for aerospace applications.

Methods / Procedures

Two sets of tests were performed to investigate whether short pulse width – high frequency processing has any efficiency advantage or microstructure improvement vs. typical lamp pumped Nd:YAG processing. Testing was performed with and without assist gas. The test matrix is shown in Table 8. All material was Inconel 625.

Table 8 PW and Frequency Combinations Used for Drilling Experiments

Pulse Width (μsec)	Frequency (Hz)	Material Thickness mm (in.)
50	10 - 15k	0.63 (0.025)
100	10 - 8k	0.63 (0.025)

All samples were processed at 10 kW peak power. The method used to determine that 10 kW was delivered at each pulse width / frequency combination is as follows: A fast silicon detector (Thorlabs DET 210) was set-up to monitor scattered reflected laser light from a roughened (sandblasted) aluminum plate. The laser was de-focused approximately 50 mm. to avoid material melting. The laser was pulsed at successively longer pulse widths with a commanded power of 10 kW. The magnitude of the detector's output from the reflected light was monitored on an oscilloscope. When the magnitude was seen to be at a maximum the pulse width was recorded. It was seen that above approximately 40 μsec PW the output from the detector did not increase. To further test the peak power, the pulse width was increased to 200μsec. No rise in detector output was seen. A pulse width of 50μsec was chosen as the minimum pulse width to use for these experiments. Figure 91 shows the detector output for a PW of 200 μsec at 1 kHz Vs the detector output for a PW of 50 μsec. The detector voltage can be seen to be identical for both cases.

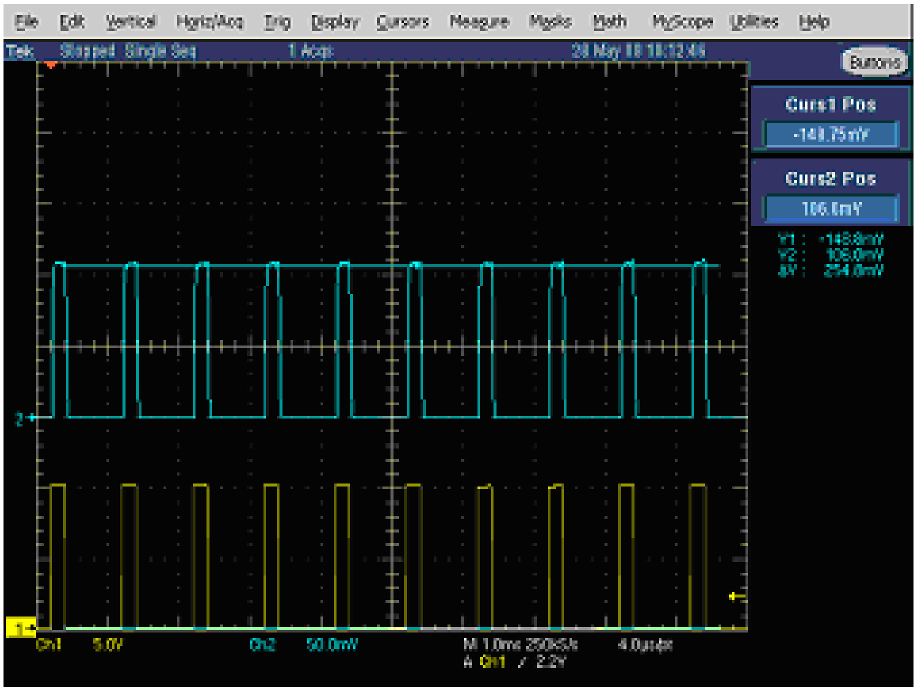


Figure 91 200 µsec PW @ 1 kHz ΔV = 255 mV (X axis msec, Y axis mV DC)

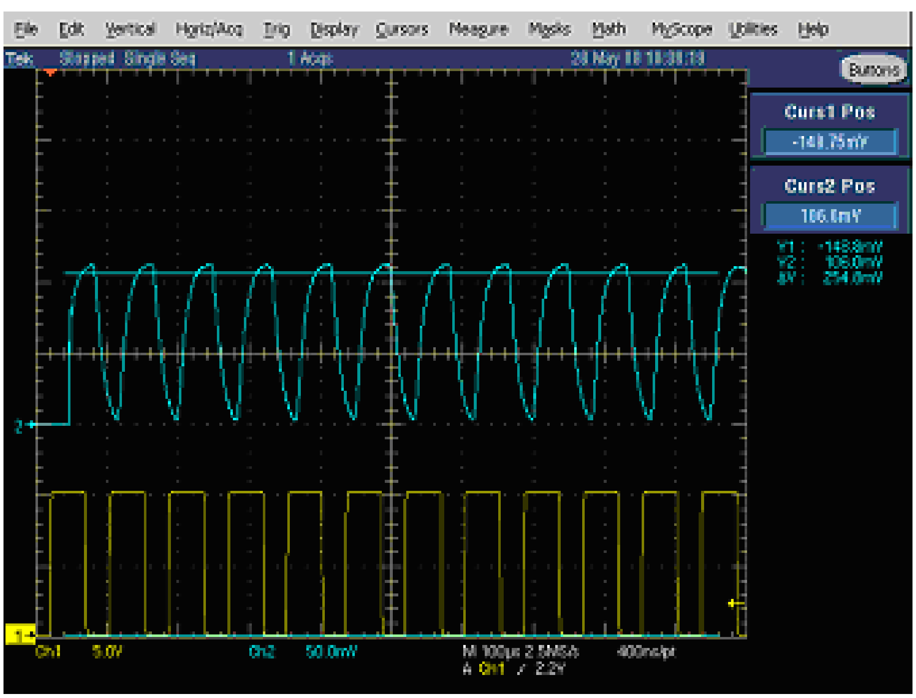


Figure 92 50 µSec @ 12 kHz ΔV = 255 mV (X axis msec, Y axis mV DC)

Figure 93 shows a nearly constant depth per pulse Vs frequency, with the exception of a small dip in the 13 kHz area. Figure 94 shows that assist gas gives marginally deeper depth per pulse as compared to the no assist gas case. Our data shows a more marked dip in efficiency near 14 kHz. Also it should be noted that the curve for pulse 6 is incomplete in some areas. Pulse 6 was the last pulse before breakthrough occurred. In the air assist case, the marginally better drilling performance enabled pulse 6 to sometimes breakthrough and sometimes not. The thickness of the leftover material if the hole was incomplete was on the order of 10 microns. This gives a good indication of the repeatability of the drilling process. Interestingly, the results also show that, for our particular cases, there is little benefit to the drilling process by the use of assist gas. This may or may not be true for holes with different aspect ratios. Our cases were approximately 1:1 aspect ratio (approximately 0.56 mm. (0.022 in) dia. Vs 0.63 mm (0.025 in) thickness).

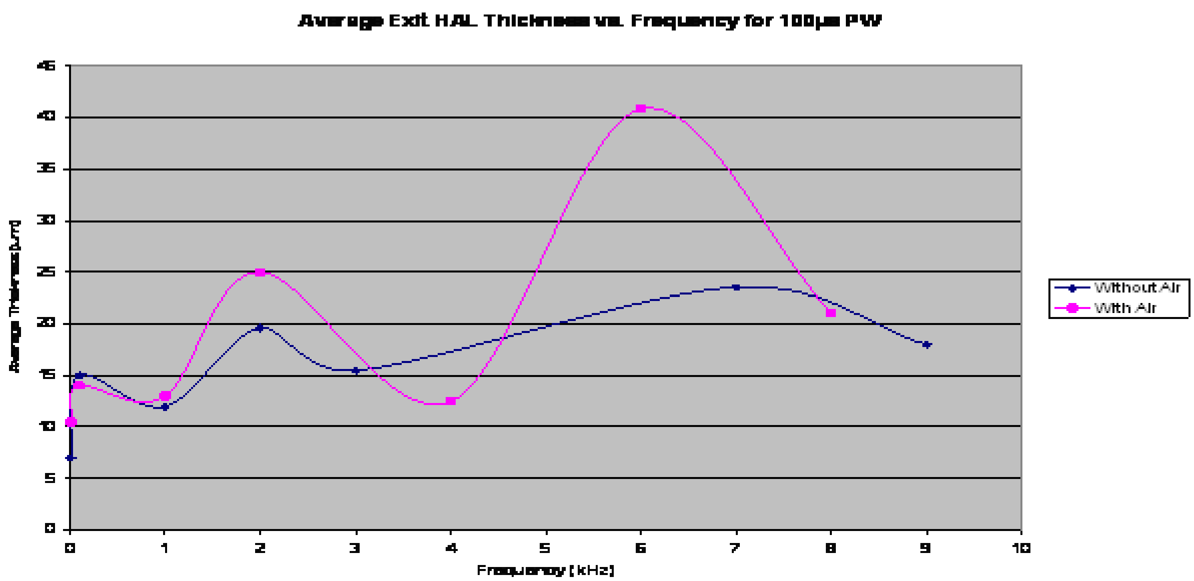


Figure 93 Average Exit HAL Thickness (µm, Y axis) Vs Pulse Frequency (kHz, X-Axis) 100 µsec Pulse Width

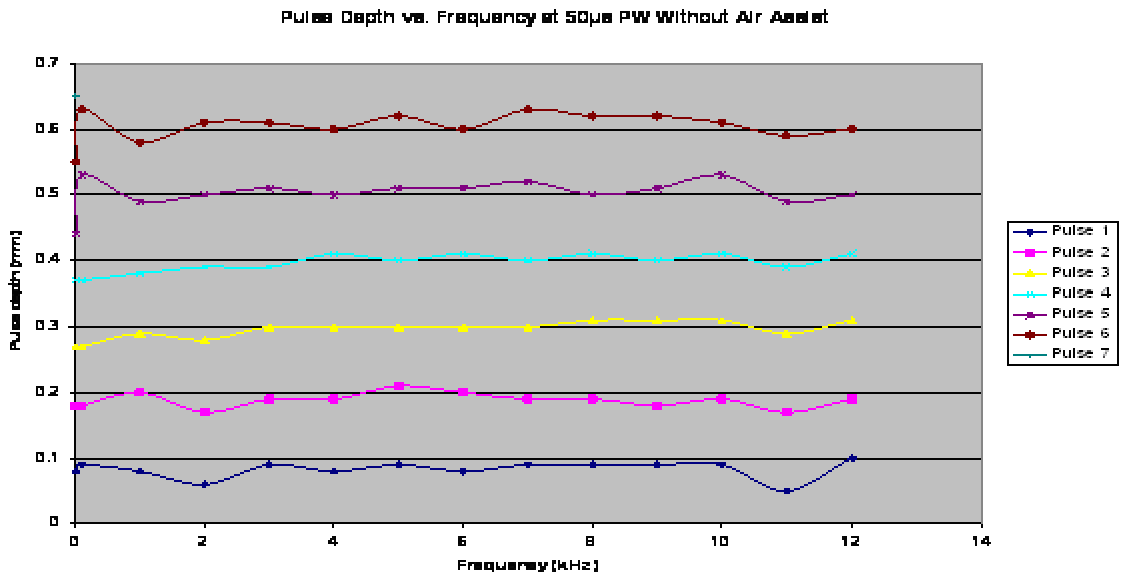


Figure 94 Plot of Pulse Depth (mm, Y Axis) Vs Pulse Frequency (kHz, X Axis), Without Air Assist, for 50 µsec pulse width

Conclusions

The results to date indicate the following:

- It is possible to achieve short pulse durations, high pulse frequencies, and high peak powers with Yb fiber lasers
- Initial results find that the frequency does not play a major role until very high frequencies (>10 kHz at 50 µsec PW) are reached.
- Gas assist does play a role in the HAL noted in the drilling process.
- The holes that were drilled were very uniform and repeatable.

If further research is successful the use of fiber lasers for aerospace drilling may be advantageous for the following reasons:

- Lower maintenance cost due to less alignment and lamp changes
- Single laser feeding two or more cells because of the fiber delivery.
- Possibly better holes and less back strike due to the beam characteristics, shorter pulses, pulse shaping, and pulse train design.

References

[1] www.rp-photonics.com/lamp_pumped _lasers.html
[2] www.ca.sandia.gov/crf/viewArticle.php?cid=104233

2.3.1.9. Shaped Diffuser Drilling

Overall Summary of Task
Key Players: Steve Maynard (CCAT/NCAL), Bobby Wright (CCAT/NCAL)

Participating Companies: Pratt and Whitney (P&W)

Period - 7/07 to 8/08

In July 2007, CCAT' NCAL Laser Applications Laboratory team was approached by Pratt and Whitney to determine if the DMG PowerShape80 is capable of producing the desired diffuser shapes for turbine engine blades after the blades have been treated with a thermal barrier coating.

Introduction
The DMG PowerShape80 is a 5 axis machine tool designed to produce laser machined features in a variety of materials. The machine utilizes the advanced functions of the machine tool combined with a galvo scanner, and three software packages developed and integrated to the machine specifically for this purpose. The machine is equipped with a 100W Q-Switched Nd:YAG laser to produce the laser machined features.

The initial meeting discussed the current method being used to produce these holes and the drawback to that method, which is Electron Discharge Machining (EDM). The disadvantage to EDM is the long cycle time per hole (45 seconds), the cost, and the need to produce the holes before coating which can lead to "coat down", where the coating runs into the hole and causes a detrimental effect to the air flow characteristics of the hole. Example is shown in Figure 95.

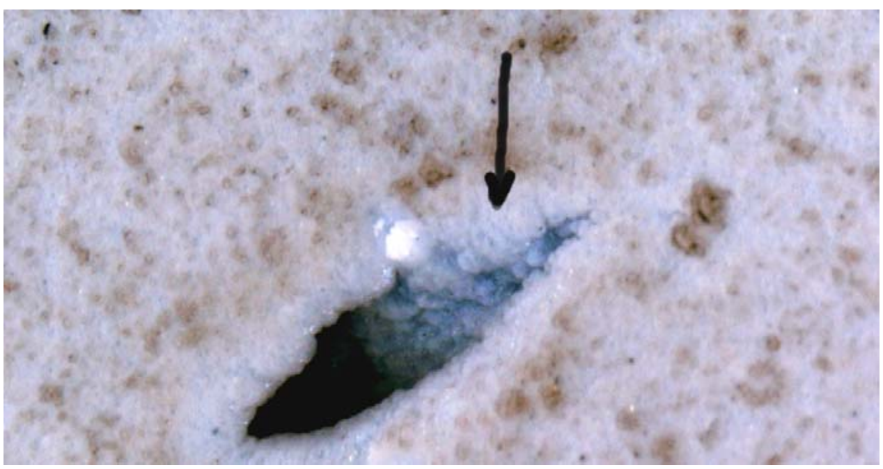


Figure 95 "Coat Down" into EDM hole

It was decided that CCAT/NCAL LAL personnel would first produce 5 sample shapes on the platform of the blade for metallurgical evaluation. Note: The 5 shapes were produced on 10/02/07, delivered to P&W the same day but to date no results have been disclosed to CCAT/NCAL LAL staff. From these results it was determined that the CCAT/NCAL LAL team would continue with the development of shapes for the entire blade.

Methods / Procedures

The PowerShape 80 machine is one of the newest most advanced machines in the world, with less than 3 installed in facilities throughout the world at the start of this program. The machine is programmed from the same CAD data files which are used to design the parts. This presented a few obstacles in completion of this project as the part and its associated files are under ITAR control and the machine manufacturer (DMG) is a German company. This prevented us from utilizing them as a resource during the development process and the part, and the diffuser holes needed, are beyond anything which had been accomplished on the machine at that time.

To produce diffuser shaped holes on the PowerShape80 machine, a number of CAD files are needed. The first is a CAD model of the actual part, the second is a CAD model of the material to be removed, for each hole be machined, the last is a text file with the coordinates of the hole location on the part and the value of the directional vector which represents the center axis of each hole.

These files, combined with the software packages developed for the machine are used to produce the laser tracks which will perform the laser machining operation used to produce the shaped holes.

The part designed had 217 individual shaped holes, with near vertical side walls, and all of different size and orientation. The main software program used to produce these shapes is called "LPSWin" and is able to "slice" the CAD model into layers for laser machining. This software was initially developed for larger sized shapes, without vertical side walls making laser machining from one angular direction simple, but incapable of producing the vertical side walls which were desired for these shaped holes. After discussing the need for vertical side walls with the machine manufacturer they produced a beta version of the software which enabled the ability to program the shape in two sections, and the ability to process from two different angles to obtain vertical side walls. This was done by utilizing the "C" axis of rotation (rotation about the Z-axis of the hole) and produced better results but was still not enough to produce all the desired vertical side walls, it was determined that "B" axis rotation (rotation about the Y-axis of the hole) would be needed to correctly produce the desired shapes. After some time the DMG was able to provide CCAT with a second beta software version of LPSWin with an option to program shapes from 4 different orientations and produce the vertical sidewalls desired. Note: These two software revisions are Beta releases and to our knowledge, specifically generated for the CCAT/NCAL LAL team.

The second obstacle was to generate the required text file needed for hole location and axis orientation as the hole definition convention used by P&W is different from the necessary convention for the PowerShape80 machine. After learning how to read the hole definition file from P&W it was determined that the file included enough information to produce the text file required for programming. This is critically important because if the hole axis is programmed incorrectly, the shapes will not only be produced incorrectly on the part, but a risk of machine crash is possible during 5 Axis interpolation.

The next step in the process development was to determine the correct laser parameters needed to produce the shapes. It became quickly apparent that parameters which worked well for the TBC material, would not work well on the substrate alloy, and vice versa so a set of parameters which could produce acceptable results on both materials would have to be developed. The laser parameters are also not associated with each hole; they are associated to the part program. If different holes must be processed with different laser parameters (this is a definite possibility due to angle of incidence and coupling efficiency of the beam with the material) the final part program will need to be done in segments.

The Rofin 100D laser, in its configuration shipped from the manufacturer, had a focused spot size which was too large for many of the small shapes on this particular part, but by using different (smaller) apertures in the resonator, we were able to decreased the spot size. This does however result in a 70% reduction in laser power, which will slow the processing rate per hole.

Conclusions

The DMG PowerShape80, with its software and programming methods although complex, are an extremely powerful package which can successfully produce shaped diffuser holes in the correct location and orientation on parts using laser machining. Two other blades of different materials and coatings have also successfully been programmed and laser machined using the same method to date.

The laser machining method of producing shaped diffuser holes is a two step process. First the metering section of the hole must be drilled using a different machine, and then the shaped diffuser portion can be laser machined on top of this hole. This part with P&W did not have the metering portions drilled making it difficult to determine the best laser parameters to produce the diffuser shapes, it is clear that the metering portion must be drilled before the shaped diffuser is laser machined.

The laser machining method is a viable alternative to the EDM process and it can compete in cycle time per shape without the additional cost of producing an electrode.

References

None

2.3.1.10. Laser Drilling Process Parameter Study to Optimize Hole Quality

Overall Summary of Task
Key Players: Robert Wright (CCAT/NCAL)

Participating Companies: Pratt & Whitney

Period: 08/06-12/07

Introduction
In gas turbine engines, increased turbine inlet air temperatures result in a more efficient turbine. This increases the net work of the engine, and ultimately reduces specific fuel consumption. This has increased the operating temperatures beyond the melting point of the nickel-based alloys used in combustor and turbine components and forced the development of cooling methods to prevent the parts from overheating, the most successful of which is boundary layer cooling where high pressure cooling air is bled from the compression stages, or low pressure bypass air is directed internally through the components and out over its surface wrapping the parts with cooling air to protect them from the high temperature combustion gases. Gas turbine engine cooling holes are typically produced either using EDM (electrical discharge machining) or by laser. The Nd:YAG laser has emerged as the current laser of choice for drilling purposes due to its coupling ability at 1.06 μm, high pulse energy and peak power, and its ability to produce high aspect ratio holes quickly and with minimal tooling complexity.

This paper investigates percussion laser drilling using two flash-lamp pumped Nd:YAG lasers having different resonator designs; one with a single rod the other with a twin rod design. Holes were drilled over a range of laser parameters using each laser, respectively, on a nickel-based alloy (i.e., waspalloy) to observe how the laser beam characteristics of pulse shape, pulse to pulse stability, pulse power variations and influence impact hole geometry and the location and amount of resultant surface debris.

Methods / Procedures:
Drilling trials were conducted by transmitting the output beams through the same path for each laser to eliminate inconsistencies from the machine tool to the work piece. The drilling trials were performed using the same parameters from each laser to produce percussion drilled holes and to compare the effects of differences in laser design. This study used both a single rod resonator design, and a twin rod resonator design whose specifications are shown in Table 9. Pulse widths were varied from 0.3 ms to 1.3 ms, and frequencies from 10 to 30 Hz. Each laser was tuned to these parameters to have equal output of average and peak powers. In Table 10, additional processing parameters that were held constant for all trials are listed.

Table 9 Laser Specifications

	Single Rod	Twin Rod
Max Average Power (W)	250	230
Pulse Energy (J)	50	60
Pulse Width (ms)	0.25 - 9.99	0.3 - 20
Frequency (Hz)	1- 200	4 - 100

Table 10 Processing Constants

Material Thickness	1.25 mm
Nozzle Diameter	2.5 mm
Nozzle Standoff	15 mm
Focus Position	@ Workpiece
Assist gas	Air, 620.5 kPascal
Incidence angle	20 degress to surface

The single rod laser uses a conventional resonator design with one single rod excited by two flash lamps, to adjust the laser cavity a compensating telescope is used to re-collimate the beam inside the cavity, changing its effective length to compensate for thermal lensing (thermal cycling) at varying power levels. The dual rod design utilizes two smaller rods in the same cavity excited with two flash lamps. This design should reduce thermal lensing from the rod or in this case rods, due to the ability to produce more cooling to the core of the rod compared to the single rod design. This does however make it a much more complex cavity requiring both rods be aligned not only with each other, but also the rear mirror and output coupler.

The laser pulse shapes were monitored using a silicon biased photodiode and a high speed oscilloscope through out the entire beam path. Starting with a view from behind the rear mirror of the laser, through a turning mirror in the delivery path, and finally after breakthrough. The laser pulses remained unchanged through out the beam delivery. A 30 hole array (i.e., 5 holes x 6 holes) was drilled for each set of laser parameters at 20 degrees to the sample surface as shown in Figure 96, Figure 97, and Figure 98.

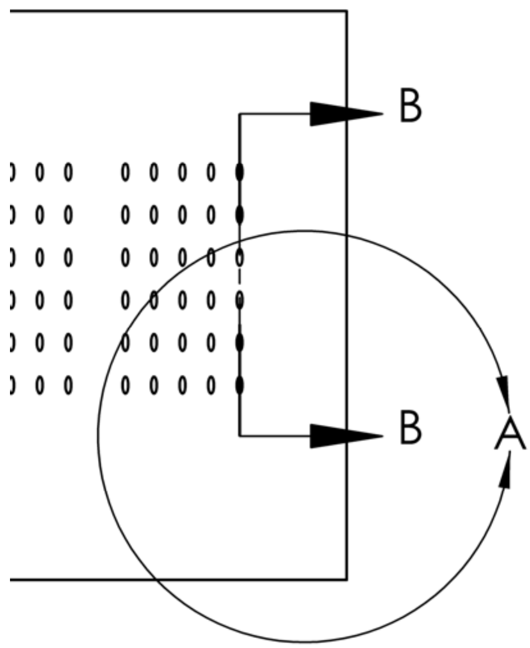


Figure 96 Standard Test Array

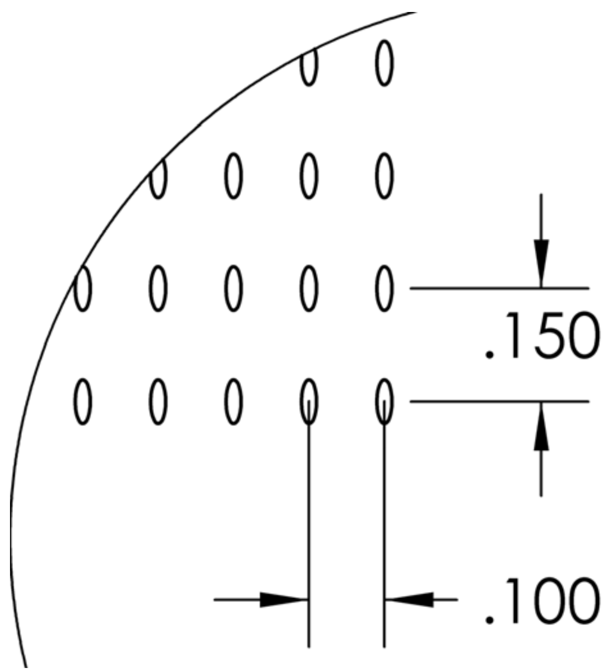


Figure 97 Array spacing -Detail A, Dimensions in inches

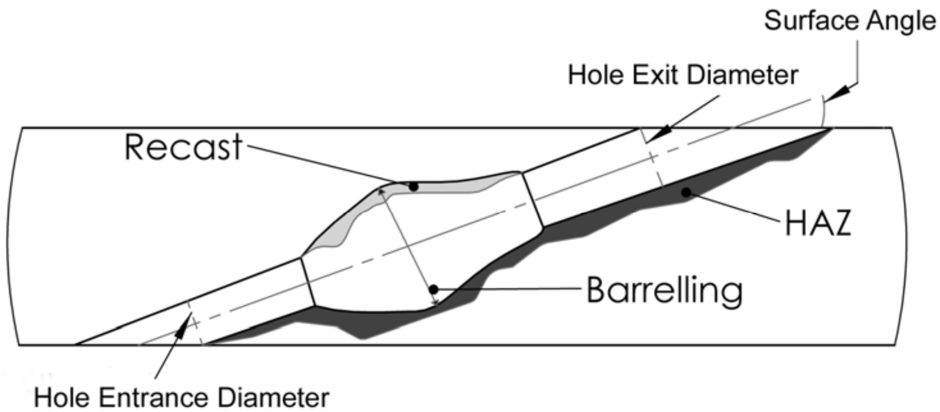


Figure 98 Hole characteristics – Section B

Each hole was studied for amount and location of debris on the work piece. Entry and exit hole diameters were measured using both pin gauging and a dental impression material. Each array was airflow tested to determine its pressure ratio. Each method of evaluation offers different advantages and disadvantages. Pin gauging of each individual hole provides:

- Entrance and exit effective (not exact) hole diameters
- Ability to measure each hole individually
- A baseline for determining airflow testing parameters

Pin gauging however is a subjective, time consuming, non-value-added operation, and each persons interpretation of which pin is the correct size does vary. Polyvinylsiloxane, a dental impression material provides:

- A measure of hole geometry in a non-destructive manner for determination of:
  - Taper
  - Barreling
  - Recast (i.e., detached will stick to the dental impression material)
- Verification of pin gauging

Impression materials however must be carefully removed to avoid tearing and leaving the slug of the impression material inside the hole. Reflected light microscopy provides detailed results of internal dimensions and material characteristics such as:

- Heat affected zone (HAZ)
- Recast layer thickness
- Macro and Micro-cracking

Metallographic processing is a destructive process and it is extremely critical that the holes be sectioned to the center for accurate measurement results; it should be noted that optical measurements are also subject to variation according to operator.

Conclusions

Two Nd: YAG lasers utilizing the same beam delivery optics were used to percussion drill a range of holes at varying pulse parameters and beam power densities. The following conclusions can be drawn:

- The laser design will significantly affect process parameter selection because of repeatability
    - The twin rod laser had fewer settings allowing for a simpler, more predictable process
    - The single rod laser could be "adjusted" (i.e., tuning the CT) to give a more consistent air entrance hole diameter but additional variables made air exit hole diameter less predictable
- Pulse decay rate impacts location and amount of resultant surface spatter

2.3.1.11. VSM of Laser Hole Drilling Process

Overall Summary of Task
Key Players: Elizabeth Gounaris (CCAT/NCAL)

Participating Companies: Pratt & Whitney East Hartford
Pratt & Whitney North Berwick
Bolton Works

Period – 06/07-12/07

***Note: Due to ITAR restrictions all sensitive information has been removed from this write-up.*

CCAT's NCAL Laser Applications Laboratory staff teamed with Pratt & Whitney North Berwick to assess its F135 Combustor Panel Liner Drilling Process from Casting through Final Inspection.

Value Stream Mapping is a graphical lean practice used to analyze the flow of materials and information from "door to door" (Rother, 2003). It aids in recognizing and identifying sources of waste. This report is supported by discussing related principles and the application of the selected tools. By analyzing and mapping the Current State of the process, proposed methods and improvements have been identified.

Pratt and Whitney's North Berwick (PW NB) facility has reported variations in hole diameters while laser drilling with Prima Industries P50 laser systems. They requested assistance to determine if there was pulse-to-pulse or time of operation variations in the laser. To accomplish this the LAL team brought equipment to PW NB that could monitor the pulse shape. The two lasers monitored demonstrated pulse shape and peak power variations similar to those observed in the laser applications lab but the NB machine 1, performed with less variation pulse to pulse than the second NB machine. It was not conclusive that these variations were sufficient to result in the variations in hole quality.

CCAT Subcontracted Pratt & Whitney to provide services and a knowledge base to further manufacturing technology.

From the Mini-SAVE Event held at Pratt & Whitney North Berwick, the LAL team was tasked to provide:

I. Value Stream Assessment and Mapping to be used in the improvement of the F135 Combustor Panel Liner Drilling Process from Casting through Inspection.
II. Collect data with a high speed photo-detector to evaluate the consistency of the pulse energy to 1) determine if there was a change in the pulse energy and 2) to determine if it was a short term (pulse-to-pulse) or long term (time of operation) variation.
III. Work with Bolton Works a tenant of CCAT to perform white light inspection to determine sources and magnitudes of part dimension variations.

Introduction
On February 9, 2007 Pratt & Whitney North Berwick held a Mini-SAVE Event, Laser Drilling of F135 Combustor Panel Liners which Terri Marsico, Paul Denney, and Bob Murray from the Connecticut Center for Advanced Technology (CCAT), Laser Applications Laboratory (LAL) attended.

The current F135 Combustor Panel Liner Process has 5 part numbers of interest and go through a series of 5 individual processes in the laser drilling sequence. Seen in Figure 99 is an example of a section of a laser drilled combustor panel liner.

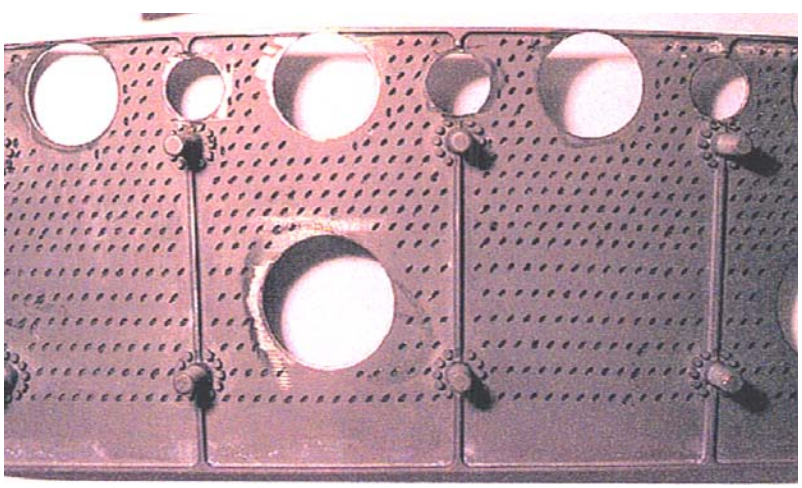


Figure 99 Example of a Laser Drilled Combustor Panel Liner

P&W North Berwick is currently evaluating Laser Drilling systems that can carry the capacity and needs of both the laser drilling for Combustor Panel Liners and BOAS.

There are many issues with the current process. Some of the common problems are: failing airflow requirements, intersecting holes, blocked cooling holes, laser wall strikes, casting imperfections, and casting panel thickness variation along the gating.

P&W North Berwick has concerns of hole variability during the drilling of F135 combustor panels on their two Gemini aerospace drilling workstations equipped with Prima Industries P50 lasers. One possible source for the variation in the hole diameters is in variations in the pulse energy of the laser. The variation in pulse energy can occur in a "pulse-to-pulse" or in a "time of operation" mode. In the pulse-to-pulse mode, the energy of each pulse may vary due to a number of factors such as variations in the power from the power supplies and variables in the cavity. The result would be that the energy of pulses would differ (have a mean and a standard deviation). Variations due to time of operation would mean that the energy of the pulses is changing over time. This could be due to "aging" of the lamps, thermal heating of the optics or cavity, or other factors that would change with time. Pulse energy variations would also occur for this change but there would be a trend with time so the mean (and possibly the standard deviation) would change over time. The CCAT/NCAL LAL team was requested to collect data with a high speed photo-detector to evaluate the consistency of the pulse energy to 1) determine if there was a change in the pulse energy and 2) to determine if it was a short term (pulse-to-pulse) or long term (time of operation) variation.

Methods / Procedures- Objective I

Value Stream Mapping is a graphical technique to visualize and understand the relationship between material flow & information flow in the system, identify sources of waste, and target improvement opportunities to leverage the system. Wastes identified are those that do not add value to the process or product. There are 8 wastes. Wastes 1-7 were first established by Taiichi Ohno from the Toyota Motor Corporation in the 1980's (Sukaski, 1987) and the 8th waste was coined by Bob Emiliani (Emiliani, 1998).

Table 11 Waste Sources used in the Value Stream Mapping Procedure

	Waste	Description
1.	Overproduction	Making Parts Earlier, Faster, or in More Qty than Required
2.	Inventory	Excess Supply
3.	Transportation	Parts Movement & Handling
4.	Defects	Scrap, Rework, Repair
5.	Motion	Unnecessary Motion
6.	Processing	Excess Processing Steps
7.	Waiting	Unnecessary Idle Time
8.	Behavioral	Behaviors That Add No Value and Can Be Eliminated

Ohno believes that by improving productivity, waste will be identified and quality problems will start to sort themselves out.

Taking on a value stream point of view means taking on the overall picture rather than individual processes. By not focusing on the individual processes it allows to optimize as a whole. (Rother, 2003) The procedure includes mapping the current state and focusing on where that particular value stream wants to be to assist in the future state mapping. The current state includes all value added and non-value added activities to bring the product through the entire value stream. The process of mapping a future state includes identifying improvement areas.

Current State

In order to create a current state value stream map it is important to identify the appropriate product family to analyze. The current state map is a reflection of the process categories rather than each processing step.

As the objective stated we are to analyze the Drilling Process from Casting through Inspection. Two site visits to "walk the flow" of just the laser drilling process category provided much of the current state information.

Ted Bernier of North Berwick also assisted in answering time and cost information on the overall value stream. The value stream map was mapped in eVSM software. This allows us to keep our maps electronic and contain the key data required for any future Factory Floor Simulations. The eVSM software interfaces with Excel and Visio for ease of use and quick calculations.

<u>Metrics Used</u>

Several metrics were used in gather data on the current state value stream map. Below is a list of the common metrics assessed through each individual process.

Table 12 Common Metrics Assessed Through Each Process

Cycle Time	value	Mins
Uptime (%)	value	%
Maint. Downtime	value	Mins
Rework (%)	value	%
Yield (%)	value	%
Batch Size	value	Pcs
Operators	value	Staff
Time Avail.	value	Hrs
Available Stations	value	#
Cost/resource hr	value	$

A set of questions was submitted to Ted Bernier of P&W North Berwick who was able to gather the answers to better understand the current state laser drilling value stream.

Techniques used to Eliminate Non-Value Added Activities

There were several techniques implemented to eliminate non-value added activities:

- Determine Available working time. Available working time is the time based on a standard work period minus any standard breaks, clean-up, and meetings.
- Determine Takt Time. Takt time is the demand frequency to meet the customers' needs.
- Eliminate bottlenecks and waste through process kaizen to bring the work content under the takt time. This may be causing overproduction waste, work in process (WIP), and extra processing time.
- Can inventories be reduced or supermarkets used? This can increase the flow of paperwork and reduce expensive inventory and finished goods areas.
- Can you improve the flow? A first-in-first-out (FIFO) lane might be appropriate.
- Process Improvements highlighted by Kaizen bursts.
- Layout of working cell.

Table 13 lists several tools used to study the process.

Table 13 Tools Used to Study the Process

Tools	Study
Value Stream Map	Analyze the flow of material & information
TAKT Time	"Pace" of Production
Floor Layout & 3D Model	Floor Layout, capacity, and real time view of the value stream in motion
KAIZEN: Brainstorm, Identify & Eliminate Waste	8 Wastes & Areas for Improvement

The current state value stream map was reviewed and kaizen bursts were added to areas for potential improvement. A list was produced with identified areas for improvement that may be contributing to waste in the overall system. The resulting kaizen bursts helped to determine a potential future state value stream map.

Conclusions- Objective I

Due to funding a complete analysis of the casting through inspection process of drilling combustor panel liners was limited. We had planned on a trip to look at all other processes other than the specific laser hole drilling and how it affects the overall value stream. Unfortunately due to time constraints and funding we were not able to visit Pratt & Whitney North Berwick again for this project. On that same trip we hoped to obtain a floor layout to construct a spaghetti chart of the value stream, collect any additional information needed to for the CCAT/NCAL Modeling & Simulation team to run a Discrete Event Simulation in DELMIA Quest software program. Our Modeling & Simulation team has developed a macro that interfaces with eVSM and it's excel functionality to convert eVSM data into a Quest Factory Floor Simulation. Quest would then allow us to evaluate kaizen opportunities and make use of "what if" scenarios before executing it on the floor.

As noted in the kaizen value stream map, we recommend looking into those areas to reduce unnecessary waster in the evaluated value stream. Major topic areas include: casting/grinding process, how the part is fixtured, breakthrough detection, and eliminating queues/finished good inventory locations where parts sit for long periods of time and inventory accumulates. In Objective III we were able to take a closer look at mainly the casting/grinding process and also how the part is being held in the fixture through a white light scan inspection.

Methods / Procedures- Objective II

The CCAT/NCAL LAL team has conducted similar tests on the P50 laser at the LAL using the Tektronix TDS5032B high speed oscilloscope and Thor labs battery biased high-speed silicon detector, Model DET 210 to study pulse shape consistency, and peak power pulse variations. This method also allows numerous lasers to be compared in the same manner. Tests are conducted by defocusing the beam onto a diffuse reflection plate at a spot size that will not couple into the material. This allow for the true pulse shape to be observed with a strong signal. Pulse parameters of 2.2 ms width and 10 Hz (typical parameters for PW NB) were observed on both Prima Industries P50 Gemini aerospace drilling workstations.

Conclusions- Objective II

The laser pulse shapes observed on both of the P&W North Berwick machines were very similar to those reported on the CCAT system. The observed "decay" seen in both sets of data from NB may have been a result of oscilloscope settings.

There was a difference in all three machines with NB 2 having a higher percent variation (almost twice) that of NB 1, when observing the 1st ten, and last 10 pulses. The laser had even a larger percent variation than both NB machines. This is most likely due to the lamps and how they pump the rod. Each lamp is manufactured individually, (not as a matched pair) and each lamp has its own impedance, and internal gas pressure (manufacturing tolerance unknown). This will give each laser its own stability characteristics of pulse to pulse variations.

Because both NB lasers seem to be equal to or superior to the data collected from the CCAT P-50, the pulse to pulse variations effecting energy per pulse do not appear significant enough to make a large impact on resulting hole diameter. Other potential factors that may be related to a gradual hole variability may be:

- Degradation of the cover/protective window
- Heating of the focusing optics
- Cooling water changes that alter the divergence of the laser beam out of the Nd:YAG rod

Methods / Procedures- Objective III

Pratt & Whitney requested that the CCAT/NCAL LAL team work with a tenant at the CCAT Innovation Center to use white light inspection method to evaluate the casting/grinding process performed at Hitchiner Manufacturing Co., Inc.

Four sets of different combustor panel part numbers were laser hole drilled. Numbers were assigned to each panel for tracking of the panels once they were returned to North Berwick for processing. The panels and fixtures, along with a diagram on how to install the panels into the fixtures were handed off to Bolton Works for inspection. After the panels were scanned in the fixtures everything was sent back to Pratt & Whitney, North Berwick. The panels were then plasma coated and laser hole drilled. The same panels and fixtures were sent back to the LAL for additional scanning.

Bolton Works observed the panels were very difficult to put in the fixtures the same way twice. An edge of the panel is lined up along a ledge of the fixture and then screwed down with clamps various points around the entire panel. Aligning the edge is difficult as there are no specific points or stops along the panel or fixture. Also, the clamps can be tightened to different torques based on the person. The different torques applied with any degree of pressure was noticed in the scans.

Conclusions – Objective III

Bolton Works provided of one of the panel part numbers scanned. It is noticeable that there is variation due to the manual grinding along the gates. One the scans the gates and the areas where they were manually grinded past tolerance are highlighted.

A trip to Hitchiner Manufacturing Co., Inc. was made shortly after the scans were completed and reviewed with Phil Kirsopp (PW EH), Ted Bernier (PW NB), and Carlo Dabbs (PW NB). The scans were presented to Hitchiner as a problem area. Hitchiner stated several reasons why they could be out of tolerance, some of which include: cross training employees at the moment due to lean implementation, F135 panels have a different tolerance than the F119 and the operator may have ignored the operations sheet, and the inspection method of each panel is supposed to be random but the operators tend to measure around the same points. Pratt & Whitney asked them to put through a batch of the F135 combustor panel liners, mark them that they were a special batch and manually grind them flush to the gates. These panels will be inspected at Pratt & Whitney at a further date.

We sent Pratt & Whitney a list of different companies with inspection systems that Hitchiner or Pratt may want to implement to catch issues such as this. The list was generated by Brian Kindilien of the CCAT/NCAL M&S team.

References

Emiliani, M.L. (1998). Lean Behaviors. *Management Decision*, 39 (9), 615-631.

Ohno, Taiichi. (1988). *Toyota Production System: Beyond Large-Scale Production*. New York, NY: Productivity Press.

Patel, Delish. (2007, November). *Electronic Value Stream Mapping Workshop*. eVSM.

Rother, M., Shook, J. (2003). *Learning to See: Value- Stream Mapping to Create Value and Eliminate Muda.* Cambridge, MA: The Lean Enterprise Institute, Inc.

Stec, Dave. (2007, Fall). *Applications of Lean Principles*. IT 561: Central Connecticut State University.

Suzaki, Kiyoshi. (1987). *The New Manufacturing Challenge: Techniques for Continuous Improvement*. New York, NY: The Free Press.

2.3.1.12. University of Hartford

Overall Summary of Task

Key Players: Terri Marsico (CCAT/NCAL), Paul Denney (CCAT/NCAL)

Participating Companies: University of Hartford; College of Engineering

Period: 09/05- 12/07

Introduction

It was recognized that to support the use of lasers in the aerospace industry in regional and nationally, there needed to be the development of academic programs, both teaching and in research, to support this technical area. To foster the development of such an effort, the CCAT/NCAL LAL team worked with the University of Hartford. The goal of this effort was to establish a Laser Manufacturing and Photonics program that enabled faculty and students to engage in research and share expertise leading to partnerships with regional industries and educational institutions. The two year program was designed to helped the University to establish academic programs and research initiatives in Laser Applications in the College of Engineering, Technology and Architecture, and to promote entrepreneurial activities in the Barney School of Business.

Specific objectives were:

- Working with the CCAT/NCAL LAL team, conduct research activity on advanced laser-based technologies of critical importance to the air force and the aerospace supply chain, especially in the areas of: laser drilling; laser marking; laser based joining processes, laser cladding, laser diagnostics with applications in sensing.
- Create an academic program in Lasers and Photonics.
- Create tools and techniques to improve quality, productivity, in a cost effective manner in aerospace manufacturing and to serve as center of excellence for research and development, and demonstration of advanced manufacturing processes.
- Disseminate the results through education, training and participation in national conferences

The following is a short summary of some of the research “activities” that were accomplished under this effort:

- Drilling Routine for Estimating, Analyzing and Modeling (DREAM)
- Laser Drilling Process Characterization Using Neural Networks
- Acoustic Monitoring and Control
- Mixed-mode Laser Ablation for Augmenter-Liner Cooling Holes
- Optimization of Parameters Influencing Laser Drilling – Design of Experiments
- Instrument & Methodology to Inspect Laser Drilled Holes
- Laser Vibrometer and breakthrough detection
- Optimization of Parameters for Effective Welding of Aerospace Components
- Laser Marking Investigation of Glass Frit Deposition
- Laser Cladding & Metallurgical Analysis
- Leak Testing of Fuel Cell Sub Components
- Research on melt ejection during laser drilling process
- Geometric inspection, cost and quality analysis of micro laser drilling of cooling Holes.
- Experimental investigation of precision shaped holes, optimization of parameters to reduce back wall problems
- Optimization of laser machining parameters in laser machining using Taguchi methods.
- Laser Design Characteristics and Pulse Parameters and Their Impact on Percussion Hole Quality
- Inspection Instrument for Broach Tools for Aero Industry
- Back-strike Damage - Research was conducted for eliminating/reducing laser back-strike damage in blind cavities while drilling hot side cooling holes in coated hardware by way of Nd: YAG laser. (In progress)
- Using fringe projection, white light and fiber optics, design an inspection probe for internal features of Pratt & Whitney component (In progress)
- Portable Surface Roughness Inspection Instrument
- Dynamic Measuring of the Robot Motion (In progress)

The University was also able to establish a Master's program with the following:

- The program was able to "support" 6 undergraduate and 13 graduate student
- Many of the graduate students were part time students that worked for OEM's or suppliers in the Hartford area
- Some of the research activities were conducted at the CCAT/NCAL LAL and took advantage of the equipment there
- Research topics were often selected through discussions with the CCAT/NCAL LAL or industrial representatives and in many cases included activities at company sites

Conclusions
The effort was successful in that:

- A Laser Manufacturing and Photonics program has been started in the Hartford area to support the OEM's and suppliers
- Interactions have been established between the University of Hartford and the CCAT/NCAL LAL and efforts outside the NALI program are active in the area of optics and photonics including efforts with incubator companies and also support of the NASA Space Grant effort at the University
- Research efforts, begun as part of this effort, are transitioning to the next level of implementation including laser drilling with fiber lasers and the use of acoustics to determine break through in laser drilling

References
The University of Hartford has also undertaken several Master's level graduate students' thesis topics focused on addressing key issues identified by the CCAT/NCAL LAL team. The topics of each are listed below:

2.3.1.13. Webcast on Laser Drilling

Overall Summary of Task:
Key Players: Terri Marsico (CCAT/NCAL)

Period: 09/07 -12/07

CCAT's NCAL Laser Applications Laboratory team was asked by Industrial Laser Solutions (ILS) magazine to present an overview of laser hole drilling with respect to gas turbine engines. The webcast presentation would cover the history of laser hole drilling, its importance in producing gas turbine engine components, the characteristics of the holes which are produced, and the keys understanding the laser drilling process.

Introduction:
Today's advanced military engines require over 1 million cooling holes, many of which are laser drilled. Cooling holes are important to allow these engines to meet the performance expectations needed to complete the desired mission specifications for the engine. In addition, the laser allows for creation of flared holes in rotor and guide blades of high pressure turbines. The advantage is an improved airflow over the component's surface. The corresponding increase in cooling allows for turbine inlet temperatures and thus improves its efficiency.

Methods / Procedures:
The CCAT/NCAL LAL team worked to compile an overview of the importance and methods of laser hole drilling drawing from the numerous years of experience possessed by its staff. The presentation was broadcast live by Industrial Laser Solutions on December 13th, 2007 through their website with a visual power point presentation accompanied by audio. ILS has since stored the webcast in its archives for future reference.

Conclusions:
At the request of Industrial Laser Solutions, CCAT/NCAL presented a webcast that demonstrated the abilities and capabilities of the LAL and how it is being recognized by the industry. It also gave the organization the opportunity to further disseminate its knowledge and to increase our recognition through the laser community. The webcast presented to the listeners a background on laser hole drilling from the different methods used to produce holes with a laser and its competing processes while showing the advantages and disadvantages of each. The presentation also covered the physics of the laser hole drilling process, the characteristics of a laser drilled hole, the key process input and outputs, while also presenting the quality and manufacturing challenges to the process.

References
Opportunities in Laser Technology Careers, *Bone, Jan* (2000)
CCAT/NCAL Hole Drilling Workshop, *W. Gostic* (2006)
Physics Today, *Breinan, Kear and Bana* (1976)

2.3.1.14. CCAT/NCAL Laser Workshops and Hosted Events

Laser Hole Drilling Conferences

As part of the NALI program objective to be a leader in advanced propulsion and power systems that are critical to Department of Defense current and future needs, the CCAT/NCAL Laser Application Laboratory team was tasked to develop and conduct a "laser hole drilling conference". The conference was planned to as method to accelerate the transition and application of research and development. The hope that conducting such conferences was to have an event that would bring together academia/researchers, educators, and industry representatives to exchange ideas and needs.

Laser Hole Drilling Conference 2005

On November 7 & 8, 2005, the first annual Laser Applications Hole Drilling Conference 2005 was held at the Connecticut Convention Center and Rensselaer Hartford. The objective of the conference was to clarify and address the many challenges surrounding laser hole drilling for gas turbine engine applications. It was sponsored by the U.S. National Aerospace Leadership Initiative and hosted by the Connecticut Center for Advanced Technology. The event was a success bringing in 120 of the world leaders in advanced gas turbine engine technology including representatives of the U.S. Air Force, Army, Pratt & Whitney, GE, participants from England and Germany and a strong contingent from the Connecticut region.

To briefly recap, during the conference we heard from 15 speakers on industrial perspectives and the history and state of the art in laser hole drilling; from Pratt & Whitney and GE on their critical needs; and from Tom Farmer, President of Military Engines at Pratt & Whitney, who wrapped up the first day speaking on the future of high performance engines and their reliance on advanced hole drilling concepts. The second day was divided into Feature Specific and System Specific groups. Participants had an opportunity to discuss common issues such as laser process control, further clarification of laser-material interactions, the need for additional standards and protocols for comparison of results, optimization of highly integrated, complex machine tool designs, and process control/monitoring vs. inspection.


Figure 100 Participants at the Laser Hole Drilling Conference 2005

The growing interest in these challenges has prompted another meeting the following next year to continue such discussions with the hope of sharing a common knowledge base.

Laser Hole Drilling Conference 2006

On October 26 & 27, 2006, the Laser Hole Drilling Conference 2006 was held at the Connecticut Convention Center in Hartford, Connecticut. The event was hosted by the Connecticut Center for Advanced Technology. This event was a huge success with the participation of the world leaders in advanced gas turbine engine technology. Participants joined us from the United Kingdom, Netherlands, Canada and Germany as well as a strong contingent from the Connecticut region.

The objective of the conference was to continue the dialog from the Laser Hole Drilling Conference 2005 to address the challenges surrounding laser hole drilling for gas turbine engine applications. During the conference we heard from 15 different speakers and their perspectives from the job shop, integrator, fabricator and OEM. The highlight presentation was the keynote speech by Mr. William Gostic, Vice President, Military Engines Program Manager, F135 Engine, Joint Strike Fighter United Technologies Corporation, Pratt & Whitney Division. Mr. Gostic wrapped up the first day speaking on the future of the F135 JSF high performance engine and their reliance on advanced hole drilling concepts.

The second day we heard four different topics relating to laser hole drilling and laser marking. As in the 1st Hole Drilling Conference the attendees had an opportunity to address and discuss the common issues surrounding laser process control, laser-material interactions, the need for additional standards and protocols for comparison of results, optimization of highly integrated, complex machine tool designs, and process control/monitoring vs. inspection.


Figure 101 Participants at the Laser Hole Drilling Conference 2006

The interest in these challenges as well as other laser applications such as welding, cutting, marking, additive and subtractive manufacturing has prompted another conference to continue this important information and technology exchange. The Symposium of Aerospace Laser Applications "SALA" was planned and carried out in April 2008.

Symposium For Aerospace Laser Applications (SALA 2008)

While the earlier two conferences were focused on laser drilling for aerospace applications, it was recognized that there were or could be other uses for lasers in aerospace manufacturing. This was based on the fact that lasers are presently used for a wide range of applications in other industries. The justification has been to address high production rates, improved performance, and to lower costs. While many other industries have accepted and benefited from a wide range of laser processes, the aerospace industry has really only implemented laser drilling. There was clearly a need to be served.

The third CCAT/NCAL laser drilling conference was designed to expand beyond drilling and examine other potential applications. The symposium brought together over 160 industry, academia, and government representatives at Rentschler Field in East Hartford, CT, on April 2-3, 2008, to exchange information and perspectives on implementing laser processing. While most of the representatives were from the New England, there were also attendees from California, Washington, Canada, Germany, France, and the Netherlands.

As in the previous two symposiums, there were a number of presentations on laser hole drilling. These presentations ranged from basic understanding of the drilling process by French researchers, to papers on laser drilling efforts and needs by Pratt & Whitney and General Electric engineers. There were also presentations on the use of the next generation of high brightness lasers for trepan drilling as well as monitoring of the drilling operation by acoustic monitoring.

But unlike the previous symposium, SALA 2008 expanded into other laser processes. This included presentations on welding, cutting, additive manufacturing, marking, and paint removal all for the aerospace industry. Michael Urban presented Sikorsky's need for an "aerospace" laser cutting specifications for aluminum. Recent improvements in lasers may finally allow cutting of aerospace materials without an impact on fatigue. If a specification could be developed that took advantage of these improvements it could decrease manufacturing cost while increasing the number of potential qualified suppliers. Dr. Ingomar Kelbassa of Fraunhofer Germany presented their efforts with Rolls Royce to develop an additive manufacturing system for the repair/refurbishment of engine components. The ability to repair/refurbish parts will critical to decrease the operating cost of jet engines and will be needed for aging aircraft in the future. The status of lasers for paint removal by the U.S. Air Force was presented by Gerard Mongelli of Concurrent Technologies Corporations. He explained that the primary goal of this effort has been to go "green" by eliminating toxic chemicals and waste while at the same time decreasing processing time. This program is now examining ways to take the laser to the aircraft in the field by using the latest in laser technology.

While the technical focus of the symposium was on laser processing, there were presentations on other areas that could be useful to the attendees. Presentations were made on the Small Business Innovative Research (SBIR) program, becoming a qualified supplier, and the use of advanced manufacturing "tools" to be more productive.

Figure 102 Example of 1 of 20 Vender Tables at SALA 2008

In addition to the technical presentations, 20 venders were present to discuss their capabilities and network with attendees during breaks. The venders ranged from laser manufacturers and optics companies to job shops.

There were also featured speakers between of the technical sessions. During the first day's lunch, Kristin Muschett, President of HABCO, an innovative Connecticut small business, presented on how a small, family owned business met the ever changing needs of the aerospace industry. During lunch on Thursday, David Belforte, Editor of *Industrial Laser Solutions*, presented an overview of the potential needs for laser processing and systems to meet the commercial jet industry for the next ten years. The highlight presentation was the dinner presentation on Wednesday evening. William Gigliotti, F-35 Test Pilot for Lockheed Martin Aeronautics Company in Fort Worth, TX, and former U.S. Naval aviator, gave an exciting and entertaining overview of the technology and capabilities of the F-35 Lightning II, Joint Strike Fighter (JSF).

Figure 103 Attendees at the SALA 2008
From Left to Right: Keynote Speaker-William Gigliotti,
Connecticut Corsair- Craig McBurney, CCAT CEO- Elliot Ginsberg,
SALA Organizer- Bob Murray, NCAL Director- Brig. Gen. Bob Mansfield (Ret.)

The symposium concluded on Thursday afternoon with a tour of the CCAT/NCAL Laser Applications Laboratory. The tour included a demonstration of CCAT/NCAL LAL's acoustic monitoring development project, and a demonstration of air flow testing by HABCO. The CCAT/NCAL LAL team also demonstrated its capabilities in optimized laser marking and validation. Also demonstrated and discussed was the use of high power fiber lasers for drilling rather than the Nd:YAG lasers presently more commonly in use.

The conference was very well received as both an informative exchange as well as a great networking opportunity. Most every returned comment card was very positive. The CCAT/NCAL LAL team is already planning for SALA 2009 (04/01/09-04/02/09).

<u>Other Hosted Events</u>

To develop and disseminate technology that meets the mission of CCAT's NCAL LAL for the U.S. Air Force and the aerospace industry, the CCAT/NCAL LAL staff participated in and/or hosted a number of meetings, training sessions, and symposiums.

The following is a short description of some of the major events with a table that documents all of the events that the LAL staff participated in.

<u>Laser Institute of America (LIA) ICALEO 2006 and 2007</u>

CCAT/NCAL LAL staff members participated in both the LIA ICALEO 2006 (Tucson, AZ) and 2007 (Orlando, FL) events. The Laser Institute of America's (LIA's) International Congress on Applications of Laser and Electro-Optics (ICALEO) is the leading technical conference held annually on the applications of lasers in materials processing. The conference attendees include academia, industry, and venders.

At the ICALEO 2006 conference, the CCAT/NCAL LAL staff presented some of its initial results on laser shaped hole processing and efforts accomplished to date with the DMG 80 Shaper. Also at this conference were presentations made by University of Hartford on drilling parameter prediction software (DREAM).

The Laser Materials Processing Conference within the ICALEO 2007 was chaired by CCAT/NCAL LAL staff member Paul Denney. This conference also had two sessions on lasers and aerospace applications (including laser drilling). Bobby Wright (CCAT/NCAL) presented a paper on laser hole quality while papers were also presented by Prof. Eppes from University of Hartford on further development of the DREAM program while Paul Jacobs of LFI presented initial results on acoustic monitoring as a method for break through on laser drilling.

Laser Institute of America Regional Chapter Meeting

On September 26, 2006 the Connecticut Center for Advanced Technology (CCAT) hosted the Laser Institute of America (LIA) Northeast Quarterly Chapter Meeting in East Hartford, CT. The evening started with a tour of the CCAT/NCAL Laser Applications Laboratory given by Steven Maynard and Scott Davis. An overview of the lasers and a demo provided by the CCAT Modeling & Simulation Initiative gave guests an educational and informative experience.

The group then moved to the Sheraton Hartford for a social hour and dinner followed by a series of presentations. Merrie London of CCAT's SBIR (Small Business Innovation Research) program presented "*The SBIR Program- The Best Kept R&D Funding Secret*." London best summarizes the SBIR program by stating: "*the award is not a loan – you get to keep the money and not pay it back, and you retain all of your intellectual property;, the government pays for your R&D, and you can win more than one award per year for subsequent years."*

Bob Torrani then presented "Responding to evolving demands of Aerospace & Defense OEMs". Bob Torrani is the Director of CCAT's Center for Manufacturing Supply Chain Integration (CMSCI). In Torrani's presentation, he discussed how manufacturers can step-up by providing lower cost, improved quality, and higher levels of integration with shorter lead times. Torrani implied that when a supply chain link is broken, it has lost all its connections. As a result, the term "network" would be a better model and approach to use.

Lastly, the keynote speaker was Professor Susan Coleman from the University of Hartford's Barney School of Business. She delivered a captivating presentation, "*Economic Trends, Key Issues for the Manufacturing Sector and A Role for Education*." Susan presented an overview of the U.S. economy, and how it impacts the manufacturing industry in general and more specifically its impact on laser suppliers (job shops). Coleman also addressed how education can be used to develop and provide future resources to help meet the needs of the manufacturing industry and the nation as a whole.

Overall, approximately 40 people attended the meeting, thus making it a huge success!

Figure 104 Participants at the LIA Chapter Meeting Hosted by CCAT

Table 14 Events & Training Attended by CCAT/NCAL LAL Team

Event / Training	Location	Start/End Dates	
UTC-2005 Defense Manufacturing Conference	Orlando, FL	11/28/05	12/1/05
UTC-2006 Defense Manufacturing Conference	Nashville, TN	11/27/06	11/30/06
UTC-2007 Defense Manufacturing Conference	Las Vegas, NV	12/3/07	12/6/07
SME-EASTEC 2005 Exposition	West Springfield, MA	6/24/05	6/26/05
SME-EASTEC 2006 Exposition	West Springfield, MA	6/23/06	6/25/06
SME-EASTEC 2007 Exposition	West Springfield, MA	5/22/07	5/24/07
AWS Aerospace Welding Conference	Dayton, OH	09/19/06	09/20/06
CCAT- SBIR Conference	East Hartford, CT	06/19/07	06/21/07
CCAT/NCAL- Laser Hole Drilling Conference 2005	Hartford, CT	11/7/05	11/8/05
CCAT/NCAL- Laser Hole Drilling Conference 2006	Hartford, CT	10/26/06	10/27/06
CCAT/NCAL- M&S Future of Machining Event	East Hartford, CT	03/07/07	03/07/07
CCAT/NCAL- Symposium for Aerospace Laser Applications (SALA) 2008	Hartford, CT	03/02/08	03/03/08
CONNSTEP Symposium @ Trumpf	Farmington, CT	9/20/07	9/20/07
Fabtech	Atlanta, GA	10/31/06	11/02/06
Handling Difficult and Demanding Customers – taught by Rockhurst University Continuing Education Center	Hartford, CT	07/26/06	07/26/06
IMTS 2006	Chicago, IL	09/09/06	09/13/06
Laser 2007	Munich, Germany	06/18/07	06/21/07

Event / Training	Location	Start/End Dates	
LIA/FMA- ALAW Automotive Laser Application Workshop	Plymouth, MI	04/17/07	04/19/07
LIA- Hosted Regional Chapter Meeting	East Hartford, CT	09/26/06	09/26/06
LIA- ICALEO 2006	Scottsdale, AZ	10/30/06	11/02/07
LIA- ICALEO 2007	Orlando, FL	10/29/07	11/01/07
LIA- Laser Safety Officer (LSO) Training	St. Louis, MO	03/27/06	03/31/06
Manufacturer's Excellence Conf- TPM Workshop	Hartford, CT	10/24/07	10/24/07
Mastercam– taught by MACDAC	Enfield, CT	01/10/06	01/12/06
MEDI Conference 2005	Hartford, CT	10/26/05	10/27/05
NASA-PLAN Academy 2007	East Hartford, CT	08/01/07	08/01/07
Pratt & Whitney- Casting Technologies: Foundry School – taught by the PW Rapid Prototype Casting Lab (RPCL)	East Hartford, CT	08/21/06	08/25/06
Pratt & Whitney- F119-PW100 (Military) Engine Familiarization – taught by the PW Customer Training Center	East Hartford, CT	08/15/06	08/17/06
SolidWorks taught by CADDedge	Farmington, CT	03/06/06	03/08/06
Trumpf - VMC Operation & Programming with Quickflow Training	Farmington, CT	04/23/07	04/27/07
Trumpf Workshop – UID Laser Marking	Farmington, CT	01/18/07	01/18/07
UTC- Turbine Engine Technology Symposium	Dayton, OH	09/11/06	09/14/06
UTC-Aging Aircraft 2007	Palm Springs, CA	4/16/07	4/19/07

2.4. Task IV - Total Supply Chain Enterprise Effectiveness

2.4.1. Introduction and Scope of CTC's Efforts

Concurrent Technologies Corporation's (*CTC*) period of performance for this phase is 15 May 2005 – 30 Jun 2006. *CTC's* extensive logistics optimization knowledge and experience with researching, developing, and implementing advanced technologies and enhanced business processes have enabled visualization and decision support tool prototypes development. This development facilitates the management of complex associative relationships in play within the supply chain that have streamlined processes, improved military effectiveness and reduced costs. *CTC* has performed research and development and project management efforts through the National Aerospace Leadership Initiative (NALI) to enhance supply chain effectiveness for the United States Air Force (USAF).

2.4.2. Methods & Procedures

CTC is dedicated to continuous improvement and technical leadership to implement mature systems and software development practices that support NALI's efforts to achieve world class agility and competitiveness as a national resource to the commercial and military/industrial base.

2.4.3. Results & Discussions

CTC conducted research within the USAF and recognized the need for USAF organizations to achieve total asset visibility of items within the supply chain from war fighter to manufacturer. *CTC* analyzed these specific needs and determined the lack of supply chain visibility. *CTC* is in the development stages of a visualization support tool prototype that may provide optimal supply chain management directed toward streamlined business processes, improved effectiveness, and reduced costs. This tool is designed utilizing an open architecture that will provide total asset visibility of the supply chain from war fighter to manufacturer that can be synchronized and integrated with emerging Air Force systems. *CTC* has discussed and demonstrated this prototype at the Air Force Transformation office, (A4ID) in the Pentagon. Those attending the demonstration included Lieutenant Commander (LTC) Muramoto, A4ID, Dr. Joan Fuller, Air Force Office of Scientific Research, Dr. Rollie Dutton, Air Force Research Laboratory, Dr. Karl Prewo, CCAT and Rob Evans Miller, Advanced Virtual Engine Test Cell. At the conclusion of the presentation, it was apparent that the demonstration of the visualization support tool prototype generated interest especially on the part of LTC Muramoto. LTC Muramoto's interest focused on the tool having the ability to view the supply chain from warfighter to the manufacturer.

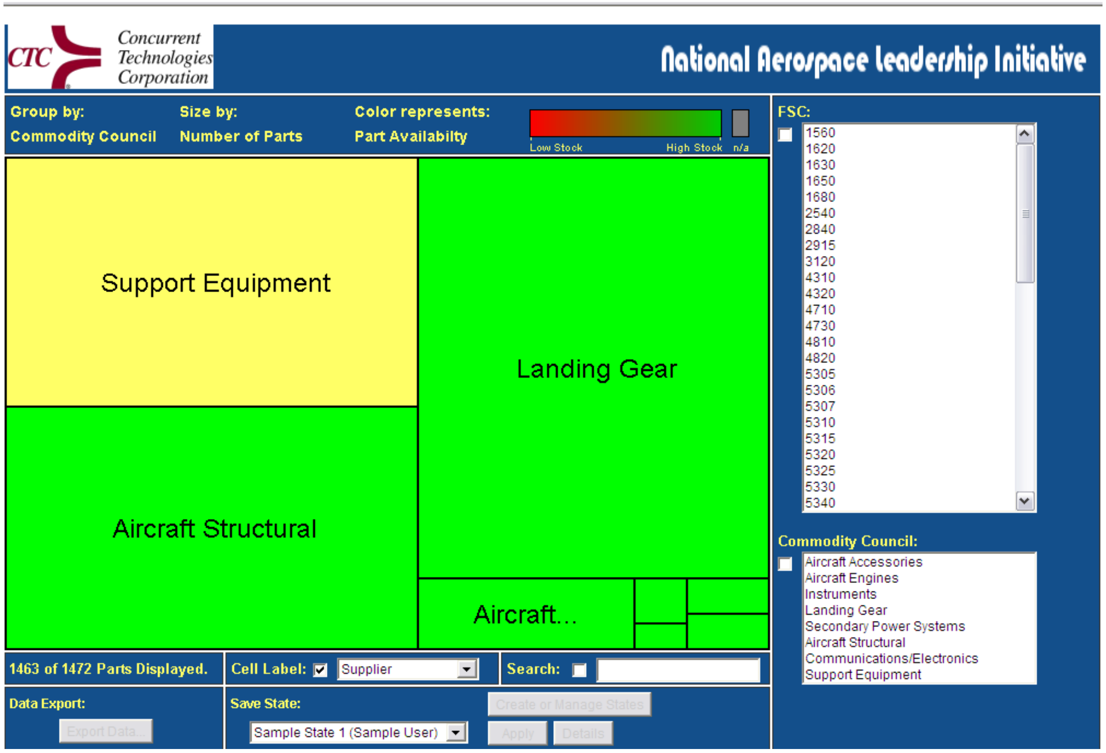
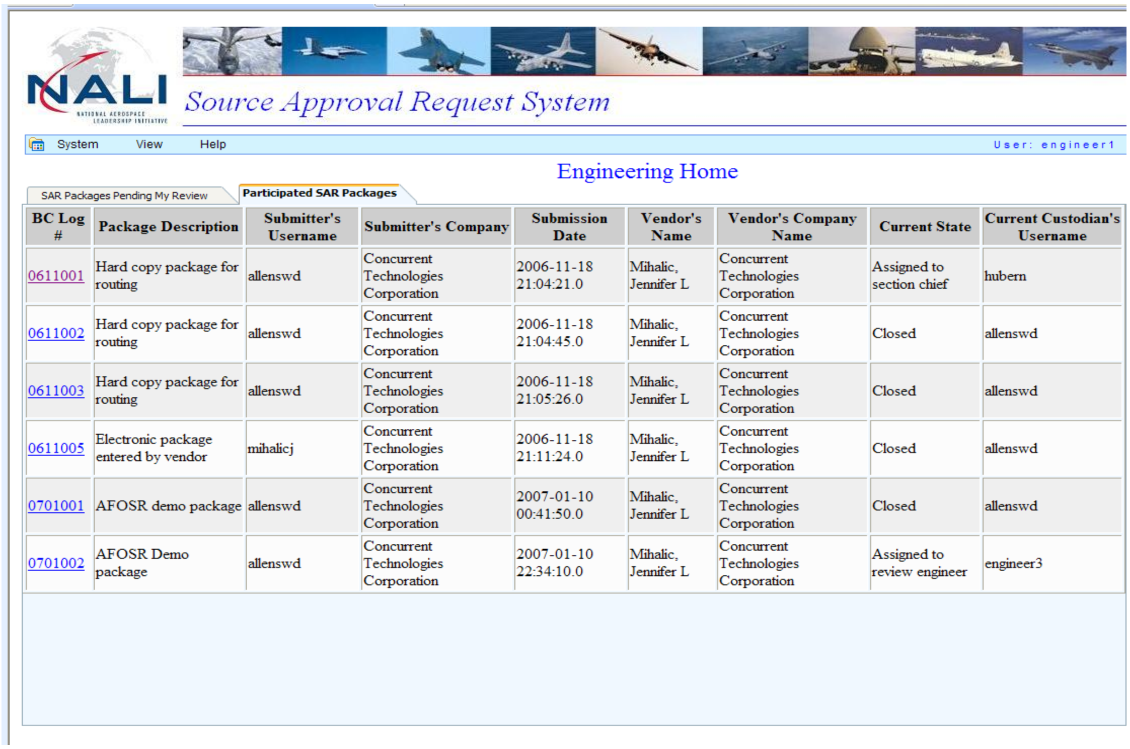


Figure 105 Visualization Tool Prototype

CTC attended the Propulsion-Safety and Affordable Readiness Conference, March 2006. *CTC* personnel attended the conference to identify Air Force organizations with propulsion supply chain needs. During the conference *CTC* attendees spoke with Mr. Ted Fecke, Senior Leader for Propulsion, Aeronautical Systems Center, Engineering Directorate. After an explanation of *CTC*'s tasking under the NALI program, Mr. Fecke organized a meeting between *CTC* and the two Propulsion Sustainment Groups at Oklahoma City Air Logistics Center (OC-ALC), 448th Combat Sustainment Wing, Tinker AFB. Personnel attending the meeting included Mr. John Over, Executive Director, and Dr. Wayne Jones, Chief Engineer, OC-ALC. The result of the meeting was the decision to automate the Source Approval Reporting (SAR) process. The SARS process is a manual approval process for for the certification of manufacturers aircraft parts. *CTC*'s proposed SARS prototype provides a Web enabled collaboration system for vendor product management. OC-ALC Chief Scientist identified the current manual SAR process improvement due to the process time involved in acceptance manufactures packages. *CTC* rapidly developed an initial concept to demonstrate benefits of web based process flow tracker. *CTC* development team met with OC-ALC Small Business Office (SBO) and OC-ALC Lean Specialist to fully understand SAR process and issues. *CTC* rapidly developed and demonstrated the prototype to OC-ALC in November 2006. SARS implementation can eliminate processing days from the existing manual process increasing aircraft readiness.



BC Log #	Package Description	Submitter's Username	Submitter's Company	Submission Date	Vendor's Name	Vendor's Company Name	Current State	Current Custodian's Username
0611001	Hard copy package for routing	allenswd	Concurrent Technologies Corporation	2006-11-18 21:04:21.0	Mihalic, Jennifer L	Concurrent Technologies Corporation	Assigned to section chief	hubern
0611002	Hard copy package for routing	allenswd	Concurrent Technologies Corporation	2006-11-18 21:04:45.0	Mihalic, Jennifer L	Concurrent Technologies Corporation	Closed	allenswd
0611003	Hard copy package for routing	allenswd	Concurrent Technologies Corporation	2006-11-18 21:05:26.0	Mihalic, Jennifer L	Concurrent Technologies Corporation	Closed	allenswd
0611005	Electronic package entered by vendor	mihalicj	Concurrent Technologies Corporation	2006-11-18 21:11:24.0	Mihalic, Jennifer L	Concurrent Technologies Corporation	Closed	allenswd
0701001	AFOSR demo package	allenswd	Concurrent Technologies Corporation	2007-01-10 00:41:50.0	Mihalic, Jennifer L	Concurrent Technologies Corporation	Closed	allenswd
0701002	AFOSR Demo package	allenswd	Concurrent Technologies Corporation	2007-01-10 22:34:10.0	Mihalic, Jennifer L	Concurrent Technologies Corporation	Assigned to review engineer	engineer3

Figure 106 SARS Prototype

Recruited two Johnstown area schools to participate in the LaunchQuest Program. Through this involvement, *CTC* sponsored on-hands training for CCAT's CyberAct™ software program which supported the LaunchQuest Program. Six instructors from the participating Johnstown area schools attended. The training was conducted by Sue Palisano, CCAT. In September, 2006, a *CTC* staff member, traveled to New Mexico to observe the inaugural launch of the unmanned SpaceLoft™ XL vehicle.

2.4.4. Summary

- Further development of the visualization support tool will incorporate a more enhanced view of the Commodity Councils utilizing representative data.
- Completed prototype development of a web-based decision support tool, SAR provided it to OC-ALC for evaluation and determination of future use. The SAR enables accurate tracking of and decisions for proposals, and allows for efficient expansion of the supply chain enabling an automated process.
- Continue investigation into the USAF enterprise supply chain and possible resources that can be provided to enhance its effectiveness.

3. Closing Remarks

In Phase I of the NALI program, excellent progress has been made in each of the four tasks towards establishing capability to meet the three top level objectives: strengthen the aerospace manufacturing supply chain by providing next generation technology applications and create a workforce capable of using that technology.

The program has shown innovation in a broad range of Modeling and Simulation research and developing applications for transition into the supply base. The Laser Applications Laboratory has been a leader in hole drilling and marking. Progress has been made in supply chain visibility.

Creative approaches have been taken to engage students at all levels to become more familiar with STEM curriculum and the value of manufacturing. Partnerships have been created with colleges, particularly with the community college network, to make available the latest in manufacturing and engineering software tools.

Under the NALI program, the federal government's Small Business Innovation Research (SBIR) program has been embraced. By supporting the "Future of Manufacturing in Innovation" initiative, new potential opportunities for creating new capabilities and solving problems in aerospace manufacturing processes have been uncovered.

The NALI program has gotten off to a strong start in Phase I, making substantial contributions toward achieving its mission. The follow-on NALI Phase II, III, and IV activities build upon the achievements made in this first phase.

4. Glossary/Acronyms

ADE	Aerospace & Defense Initiative
AFRL	Air Force Research Laboratory
AMPI	Advanced Manufacturing Propulsion Initiative
APLC	Advanced Programmable Logic Control
BRI	Blade Row Interaction
C2E2	Common Collaborative Engineering Environment
CARL	Compressor Aero Research Laboratory
CBIA	Connecticut Business & Industry Association
CBM	Condition Based Maintenance
CCAT	Connecticut Center for Advanced Technology
CCSU	Central Connecticut State University
CFD	Computational Fluid Dynamics
CMSCI	Connecticut Manufacturing Supply Chain Integration
COTS	Commercial-off-the-shelf
CTC	Concurrent Technologies Corporation
DICE	Data Intensive Computing Environment
DMC	Defense Manufacturing Conference
DSCR	Defense Supply Center
EDM	Electrical Discharge Machining
EHMS	Engine Health Management System
eVSM	Electronic Value Stream Mapping
GLSC	Global Logistics Support Center
HPC	High Performance Computing
IGTI	International Gas Turbine Institute
LAL	Laser Applications Laboratory
M&S	Modeling and Simulation
MAI	Metals Affordability Initiative
MRSO	Multiple Response Statistical Optimization
MSRC	Major Shared Resource Center
NACFAM	National Council for Advanced Manufacturing
NALI	National Aerospace Leadership Initiative
NCAL	National Center for Aerospace Leadership
NDIA	National Defense Industries Association
NGRMS	Next Generation Regional Manufacturing Center
OC-ALC	Oklahoma City Air Logistics Center
PLC	Programmable Logic Controller
SAR	Source Approval Reporting
SBIR	Small Business Innovation Research
STEM	Science, Technology, Engineering, and Mathematics
TECT	Turbine Engine Components Technologies
TMAC	Tool Monitor Adaptive Control System
VSA	Value Stream Analysis
VSM	Value Stream Map or Value Stream Mapping