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CONCEPTUAL DESIGN TOOLS FOR THE NPS SPACECRAFT DESIGN CENTER

by

Michael N. Abreu

September 2001

Thesis Advisor:	Brij N. Agrawal
Second Reader:	Joseph Aguilar
	Christopher Taylor

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CONCEPTUAL DESIGN TOOLS FOR THE NPS SPACECRAFT DESIGN CENTER

Michael N. Abreu
LT, USN
B.S., U.S. Naval Academy, 1992

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Author: ______________________
Michael N. Abreu

Approved by: ______________________
Brij N. Agrawal, Thesis Advisor

____
Joseph Aguilar, Second Reader

____
Christopher Taylor, Second Reader

____
Max Platzer, Chairman
Department of Aeronautics and Astronautics

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The thesis surveys and develops spacecraft design techniques and tools involving the integration of collaborative/concurrent engineering (CE) for spacecraft design, specifically in the areas of spreadsheet and CAD/CAE software, for the NPS Spacecraft Design Center (SDC). The applicability of solid modeling to the spacecraft design process is also explored. A previous class design is modeled using a solid modeling tool and the results compared against the time and effort required for the original. In addition, two CE software tools obtained from commercial and university sources are installed in the SDC, improved, documented if necessary, and evaluated. The capabilities are evaluated with regard to learning curve, CE and their utility to the curriculum. A User's Guide for one of the software tools is written, as no documentation existed for it prior to this thesis. In addition, procedures for spacecraft design utilizing the SDC are developed in order to enhance student design capabilities and further their educational experience.

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DISCLAIMER

The views expressed in this thesis are those of the author and do not reflect the official policy or position of the United States Navy, Department of Defense or the U.S. Government.

While every attempt has been made to thoroughly document the software and its modifications described herein, the author makes no guarantees as to the performance of the software. As with any new software tool, the reader should take precautions to validate all equations, computations, and functional integrity during use.

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I want to thank my wife, Jennifer, for all her support during our two and a half years at NPS. Though I dragged you from your home to a place where you knew no one but me, a tremendously difficult challenge for you, and you handled it magnificently, despite having to put up with me. Through all the difficulties of life, there is no better friend I could ever hope to have. Your spirit, energy, and love carried me through many difficult moments, even if you didn't know it at the time. Though I was trying to become more intelligent with my class work, the smartest thing I did during this tour was to marry you.

I. INTRODUCTION

A. BACKGROUND

The capability to rapidly integrate design ideas and concepts into a formal process for production has come a substantial distance since the advent of Computer-Aided Design (CAD), Computer-Aided Manufacturing (CAM), and Computer-Aided Engineering (CAE) tools. Thirty years ago, drawings throughout the world were produced manually on paper. Changes meant erasing and redrawing, along with the possibility of a brand new drawing being necessary. The process was also dependent on a human being to recognize the need for changes to affected documents and to make those changes when necessary. Collaborative design consisted of weekly meetings at best, with the product design process limited to paper only. [Ref. 1] Since then, CAD has added revolutionary capabilities to the engineering process known as Integrated Collaborative/Concurrent Engineering (ICE/CE), and essentially changed the way product design is conducted.

Collaborative or concurrent engineering is a philosophy that enables product development by a team to be conducted in a real-time, iterative fashion. It is a powerful collection of processes and tools focused on making the team interaction and design extremely efficient, from initial concept to the manufacturing floor. The philosophy entails enabling a design team with the proper tools to successfully complete the design, and a process to guide them through the iterative process. The process uses rules of thumb, experience-based design techniques, analytic equations, and algorithms combined with the use of spreadsheet software to help the team successful complete a design, within a dramatically reduced timeframe as compared to previous spacecraft design processes. This process has been greatly improved with the advent of solid modeling tools for the personal computer (PC) that have improved dramatically in the last five years.

The revolution in CAD/CAE was born in November of 1982: the first CAD program to run on a PC was introduced by Autodesk in the form of AutoCAD. Combined with the production of the first IBM PC that same year, the catalyst for widespread use of PC-based design tools was in place. The introduction and rapid improvement of PC's fueled the competition and capability of CAD systems intensely. In 1987, AutoCAD included Application Program Interfaces (API's) so that programmers could interface the CAD system with other software programs using C code. This provided software programmers to create applications that were considered "add-ons" to the main kernel program. The evolution of CAD/CAM was by this time so feverish that by the end of the 1980's over 600 add-on applications were available for AutoCAD [Ref. 1]. The overwhelming success of AutoCAD was fuel for others to increase their efforts in the area of solid modeling software environment development. The only problem with the increase in capability was the relatively high cost of the software, between $50,000 and $100,000 per seat.

By the early 1990's, the utility and enormous advantage of CAD/CAM/CAE had been proven beyond a doubt, enabled by intense competition, microprocessor speed and Moore's Law, and ever-advancing graphical display capabilities. Commercial products were available with various levels of capabilities at mostly very expensive prices. All of these systems were exceptional in their ability to model physical designs accurately within specified tolerances for transport to electronic drawings and manufacturing facilities. The area where they were lacking, however, was in concurrent/collaborative engineering (CE) capability and its associated tools. This process is critical to successfully take a product through the design and manufacturing process, from concept definition and exploration to initial model development and analysis all the way to product engineering drawings, manufacturing, and assembly. This has led to the CE philosophy creating a fundamental paradigm shift in the product design industry. At a rapid pace, engineers across design disciplines are turning to software tools and facilities where they can pool their collective knowledge all at the same time utilizing a streamlined process. With the combination of further dramatic increases in CPU speed and graphics capability in the late 1990's and the significant reduction in cost and increase of functionality of solid modeling software, product design companies have begun an intense increase in the use of solid modeling software, integrating them into a CE process [Ref. 2].

The creation of powerful, flexible spreadsheet software in the early 1990's paved the way for eventual integration of solid modeling tools for under $10,000 per seat with spreadsheet-based analysis for conceptual product design. Since spacecraft design involves large quantities of relatively straightforward calculations and data manipulation for various spacecraft subsystems, it was inevitable that spreadsheets would become the tool of choice for spacecraft conceptual design. Solid modeling combined with spreadsheet-based analysis offers a way for the design team to rapidly visualize the product, easily modify and improve the model, quickly assess impacts to the whole caused by changes to the parts of the spacecraft, transfer initial models to finite element analysis programs, and continue with the same models directly to the manufacturing floor. This combination has produced nothing short of a revolution in the product design industry. From automobiles to spacecraft, virtually every component in the product will go through a CE/CAD/-CAE/CAM cycle before final assembly. Although each company and research agency has developed different processes for collaborative engineering, one of the most successful being embraced today involves the three aspects of CE: design team, dedicated team facility, and tools and processes that enable and guide the team through the rapid design. [Ref. 5] The Naval Postgraduate School (NPS) Spacecraft Design Center (SDC) aims to provide these three key tenets of CE to space systems engineering students for the very first time.

B. SCOPE

The fundamental processes that make up a design are similar across engineering disciplines. This process, however, is currently undergoing a major shift in focus. Over the recent years, the aerospace industry, along with major commercial and government entities, has developed facilities, processes, and tools to implement the CE philosophy. With the rapid advance in technology having no end in sight, the importance of CE and its integration into the design process has grown into an undeniable force. The methodology used in the engineering process, from concept design to manufacturing, is crucial for a systems engineer to understand properly. A new and increasingly critical part of the integration of technology into the design process is the use of solid modeling tools. Therefore, it is imperative that engineering students at NPS who may go on to serve in space acquisition programs understand the rapidly advancing tools and processes that enable the design, testing, and manufacture of a spacecraft.

The thesis first explores and describes The Aerospace Corporation's Concept Design Center (CDC), a powerful concurrent engineering methodology process. The CDC uses Microsoft Excel to assist in the design of a space system. The spreadsheet tools are used at the focus of their process, serving as the primary source of real-time knowledge sharing for conceptual spacecraft design. The CDC was witnessed firsthand by the author prior to the installation of the tool in the SDC. The background is critical to understanding the full capabilities of this type of approach to spacecraft design and its applicability to the SDC.

The thesis then provides supporting evidence of the revolution in solid modeling as applied to the concurrent engineering process. Across the product design industry and engineering disciplines, solid modeling is being infused into the design process at a rapid pace. This integration, when fueled by the increase of computer processor and graphics capabilities, is changing the fundamental way engineering design takes place. The utility and integration of solid modeling software into the CE process for the CDC spreadsheets at NPS is also evaluated. The Aerospace Corporation utilizes solid modeling capability by including a Configuration seat separately during their design process using SolidWorks™, a powerful, versatile, solid modeling package obtained under an educational license for under $500. In addition, a copy of California Institute of Technology's rapid solid modeling tool, DrawCraft, is used in a concurrent design method to generate conceptual spacecraft. DrawCraft is interfaced with SolidWorks™, and both are installed in the SDC. The utility of integrating DrawCraft/SolidWorks™ into the CDC process is evaluated with respect to learning curve, ease of use, time to generate a solid model, and model modification flexibility. The capabilities of SolidWorks™ with respect to the design process, the use of graphics and animations in presentations and reports, and exporting of solid geometry to finite element analysis (FEA) programs is explored and the results presented. Application to the Space Systems Engineering curriculum is evaluated using a spacecraft design generated in AA4871, the capstone design course, as a test case. The author was involved in the design as a structures engineer. Points of contact for personnel involved in supporting, developing and maintaining all software presented are located in Appendix A.

Thirdly, the thesis details the integration of the CDC spreadsheets into the NPS SDC, part of the Spacecraft Research and Design Center (SRDC). The software was obtained courtesy of The Aerospace Corporation. The tool is the first fully functioning concurrent engineering software to be available in the NPS SDC, and is one of the most powerful conceptual spacecraft design tools available in industry today. The installation and modification of the tool is described and documented, including all pertinent information for proper use in the integrated engineering environment. Since the CDC was seen in use by the author, the firsthand knowledge of witnessing the expert team in action flavors the NPS process as written. Only the systems portion of the tool is considered in depth, as complete documentation of each subsystem is a task that is possibly beyond the reach of a single thesis.

Finally, the CDC spreadsheet data transfer architecture, procedures for future modification of the tool and its Visual Basic code, and a recommended design process for the NPS SDC are discussed. The data transfer architecture is critical to understand in order to add or modify workbooks to the overall system. Modification and description of the software code is undertaken, written in Microsoft Visual Basic for Applications (VBA). The extreme value of this work has been expressed by The Aerospace Company as no user's guide has been written to date. The application of the CDC process and the software it uses toward the NPS curriculum is evaluated primarily based on the following factors: ease of use, maintenance requirements, depth, and ability to reduce spacecraft design time in AA4871. A comparison is undertaken based on the author's experience in the capstone course prior to the software installation. Printouts of worksheets in the Systems workbook are included in the appendix. The completed User's Guide is attached as a separate document.

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II. THE CONCEPT DESIGN CENTER

A. OVERVIEW

The Concept Design Center (CDC) at The Aerospace Corporation consists of a number of teams focusing on different segments of spacecraft mission design, enabled by powerful PC-based spreadsheet tools. At the focus of this exploration is the Space Segment Team, which is responsible for conceptual design of spacecraft. The process methodology is founded on three key tenets:

- A team drawing on a wealth and breadth of engineering expertise.
- A process using design tools that are flexible and work in real-time, enabling design results to be obtained quickly.
- A facility enabling easy and comfortable team and customer interaction. [Ref. 4: p. 3]

The purpose of this methodology is to enable rapid generation of a spacecraft design based on the principles of concurrent engineering. The methodology uses lessons learned, design techniques based on experience, rules of thumb, algorithms, and analytic equations in a data linked system that is very suitable for trade studies, technology insertion assessments, and overall conceptual design [Ref. 4: p. 1].

The design process is intended to be a rapid study into the feasibility and trade space interactions of a spacecraft mission. The high-level insight that is gained from such a study is invaluable in the initial stages of the design. Technology insertion effects may also be evaluated using the process, comparing the benefits versus risk of incorporation of advanced technologies [Ref. 5: p. 1]. The overall goal is to obtain mass, power, and cost estimates for the spacecraft. According to Agrawal [Ref. 7: p. 44],

> The challenge to a spacecraft designer is to select the spacecraft configuration, technologies, and equipment to meet the functional requirements with high reliability and low cost.

B. TEAM, PROCESS, AND FACILITY

The Space Segment Team (SST) consists of engineers specializing in the required subsystems for spacecraft design. These are: propulsion; attitude determination and control (ADACS); power; communications; thermal; structures; command and data handling (CD&H); telemetry, tracking and control (TT&C); astrodynamics; and systems engineer [Ref. 5: p. 4]. The SST focuses on the spacecraft part of space system architectures, performing trade studies on the subsystem level to determine the optimum configuration for a particular mission. The experts retain control over their subsystem spreadsheets, allowing them the flexibility to attack design problems in any way they see fit. Figure 2.1 shows the interaction of the SST with other segments directly involved in the process. The members of the team are not part of the CDC full-time; rather, they are volunteers, carefully picked for their communication and team-building skills, and rotated into studies alternately to avoid burnout.

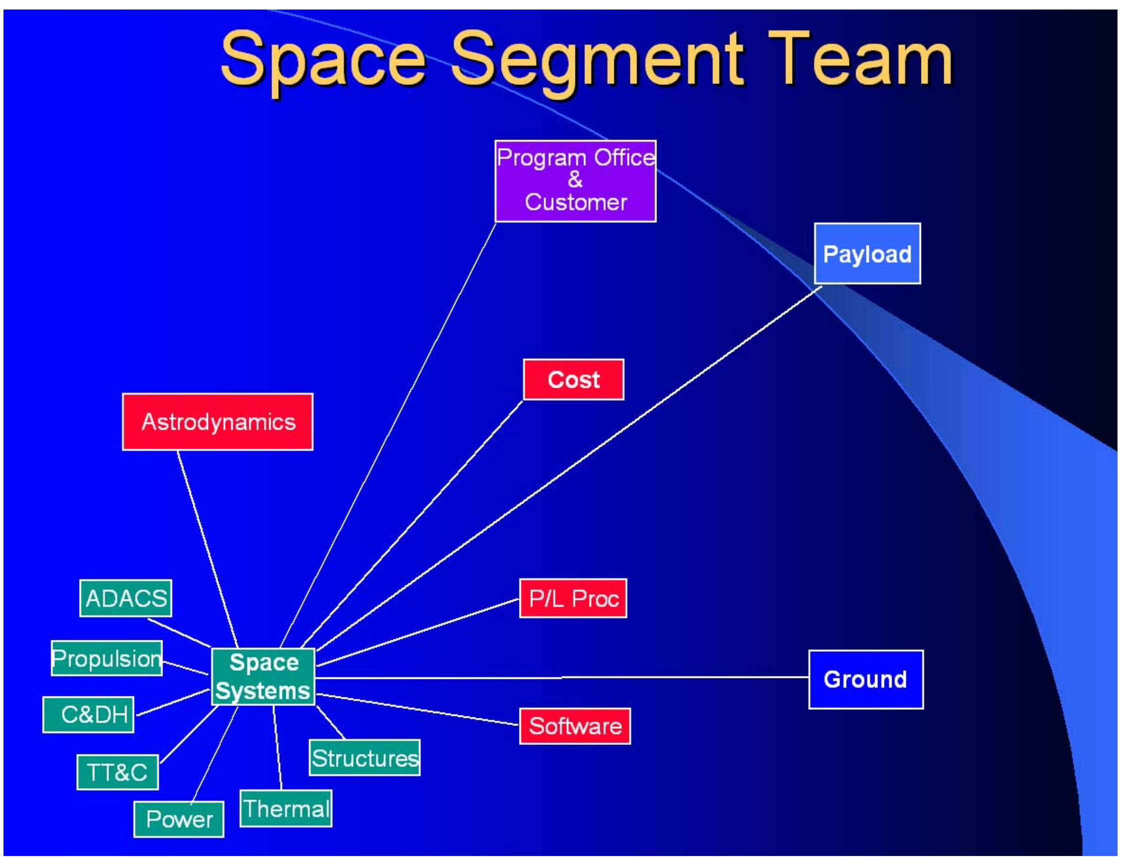

Figure 2.1 The CDC Space Segment Team (courtesy of The Aerospace Corporation).

The integrated design process utilizes three distinct phases. First, the customer reviews requirements with the team members in order to provide enough information to prepare for the actual design session, and to structure the trades that will take place in the sessions [Ref. 5: p. 2]. This takes place in meetings over a period of two to four weeks. The team members prepare software models and conduct research into the intended design. The next phase, the actual design sessions, occur in periods of four hours over a timeframe of a few days. The sessions consist of real-time collaborative interaction between all study participants. The team uses Microsoft Excel to share data between subsystem workbooks by linking parameters between them, allowing for both manual and automatic updating of data. The team discusses design issues amongst each other and with the customer, and iterates the design parameters until a satisfactory configuration is reached. The systems engineer coordinates the efforts of the team and ensures all parameters are kept within study bounds. The documentation phase follows, where customer requests for modifications are taken into consideration when preparing the extensive report on the design session and its results. Team members are responsible for their section of the report, with the process taking three to four weeks to complete.

The teams at The Aerospace Corporation have been equipped with networked design tools since 1997, and opened a new unclassified facility in March 2001. Figure 2.2 depicts the facility, and clearly shows the open, flexible nature of the rooms.

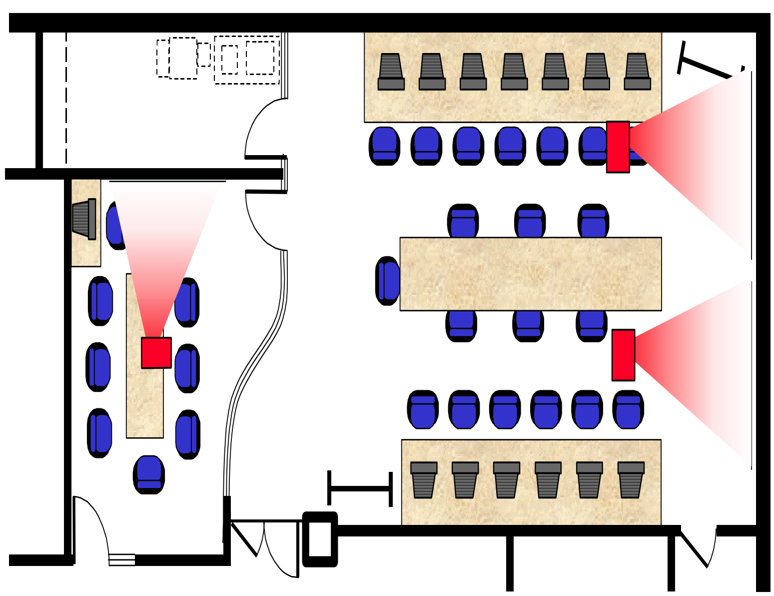

Figure 2.2 CDC facility (courtesy of The Aerospace Corporation).

The PC's share a common network, with pertinent software programs installed on each machine, enabling subsystem engineers to perform real-time analysis. The spreadsheets are linked using Excel's Object Linking and Embedding utility. This enables the real-time linking of parameters between subsystems. Databases are used by each subsystem to choose components for a particular configuration. Visual Basic for Applications (VBA) code enables the systems engineer to control the flow of data during the study. The facility also has two overhead projectors and screens that are controlled by a LCD touch screen interfaced to a video switched control system, allowing any computer monitor to be shown to the study participants. The conference room at the back of the facility is where the study planning takes place. Printers and a copier are located in the adjacent room in order to provide hardcopies of design session information to study participants.

The combination of tools, process, and facility presents a versatile, powerful way to design spacecraft. Each subsystem workbook is maintained by experts, and each study session is choreographed with the data flowing through the central point of the systems engineer. Off-line tool capability adds to the arsenal of design tools so that engineers can run real-time simulations and quickly recover the results into their spreadsheets. The tools available include solid modeling software in the form of SolidWorks™ and PCSOAP, an orbital analysis program. Since the advent of the CDC, The Aerospace Corporation has decreased the time and cost for spacecraft design by up to 70%. This has allowed them to increase the number of design studies significantly while continuing to expand the capabilities of the tool.

The CDC's spreadsheet tool does have limitations. Cost estimation is performed using cost estimating relationships (CER's) as opposed to using component costs and building an estimate from the "ground up". This is being addressed by Aerospace, but the rapidly changing cost of components combined with vendor unwillingness to share cost data severely hampers any bottom up cost estimation effort. The subsystems are also as limited as the equations utilized and the engineers applying them. The engineers must manually optimize their subsystems based on their experience and requirements information rather than utilize a software optimization routine or analytical optimization equations. However, this manual optimization may very well be the lynchpin of the

CDC's software design tools. The component databases also are limited in that they must be rigorously maintained in order to keep the designs based on real-world components.

The CDC software tools are clearly extremely valuable for the rapid design of spacecraft, despite their limitations. The real-time sharing of data and collaboration with customers and team members fosters a healthy environment for discussion of alternatives and allows the design to take place in a minimum amount of time. Performance, risk, and cost assessments of the design can be quickly evaluated, as they never have before. Interdependencies of subsystems are made clear, and comparisons of components in the design may be evaluated. Finally, the systems engineering process may be seen in real-time, further adding to the experience and expertise of all team members. This process and its associated tools are critical for the systems engineer to understand properly. This chapter is fitting to end with an outlook from Wertz [Ref. 8: p. 50].

> … models being developed throughout the aerospace community are attempting to automate this basic design process of evaluating the system-wide implication of changes. In due course, system engineers may become technologically obsolete. Much like modern chess players, the challenge to future systems engineers will be to stay ahead of the computer in being creative and innovative.

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III. SOLID MODELING AND INTEGRATED DESIGN

A. REVOLUTION IN THE DESIGN PROCESS

Michael Davis, founder of Headstuf Product Development [Ref. 2], described the capabilities of solid modeling as follows:

> Young people have no idea how powerful a concept this is. Software at last that can build what you think, the way you think? Amazing. In relative historical terms, this is such a very new concept. [Ref. 2]

The foundation of design and product development used to rely on two separate entities: the designer and the engineer. The introduction of parametric solid modeling tools in the mid-eighties was the herald of a new era in product design. Parametric Technologies released Pro-Engineer, a parametric software design tool. At this point, most companies were still focused on separate design and engineering development processes, not focusing their efforts toward an integrated process. This is partly due to the extreme cost of CAD workstations at the time, which could easily run in excess of $100,000 per seat [Ref. 2]. The market suddenly became flooded with modeling tools that threatened to break the mold of the dedicated CAD workstation.

The fact that solid modeling has come into the design process as a fully recognized major contributing factor only recently is due to the power of the personal computer and the advances in 3-D graphics capabilities that have come with it in the late 1990's. Currently, solid modeling packages are available for reasonably powerful desktop computers for under $10,000, an order of magnitude cost decrease in less than ten years of development. There are many advantages that solid modeling offers the design process, and when combined with continuing decreasing cost and increasing capability, they are the reason the revolution in product design is taking place. Visualization, analysis, revision speed, drawing creation, and data sharing are just some of the benefits of a good solid modeling tool.

Integrated into the process from the beginning, solid modeling can provide for many different options of use. As shown in Table 3.1, the most powerful applicable for use in the SDC are the first three listed: product visualization, analysis, and revision speed. It is critical that engineers as well as the customer have an idea of what the spacecraft will look like as early as possible in the process.

Feature	Benefit
Visualization: Full color rendering of solids, dynamic Rotation, section cutting, hidden line Removal,	Easier visualization of models and assemblies. Eliminate artistic rendering for marketing/presentation purposes. Direct input to animation and design simulation processes.
Analysis: Mass properties output, standard solid Data format, interference checking	Accurate weight, CG, and moment calculations, direct input into FEA, kinematics/dynamics applications, identify interferences, measure clearances.
Revision speed: Parametric dimensions	Dimensions drive solid, changes to dimensions change solid and everywhere it's used.
Drawing generation: Associative 2D drawings from solids	Solids maintain associative link to 2D drawing with dimensions, changes to solid change drawing Automatically, drawings always in sync with solid. View generation easy and accurate.
Manufacturing Input: Direct link to manufacturing	Solids used as input to toolpath generation software, elimination of data redraw.
Rapid Prototyping: Direct link to rapid prototyping	Direct output from solids to RP systems, accurate physical model to review.
Communicating with other 3D software:	As more companies design in solid modeling, you may need to be able to share solid drawings with vendors, contractors and customers.

Table 3.1 Features and benefits of solid modeling [From: Ref. 3].

It is also very important to create an initial configuration quickly, verify that the spacecraft will fit in the launch vehicle fairing in the stowed configuration, and make revisions as necessary. If requirements change often, as experienced by the author in the AA4871 concept design of the *Mithra* spacecraft for the Air Force Research Laboratory, they can be incorporated into the design quickly and easily.

Having a solid model and solid assembly is important for accurate mass property calculations and interference checking, and for transfer of geometry into analysis software. The model is created only once, and revisions automatically update related dimensions within the model. This allows the engineer to spend more time in analysis or trade space studies, where comparisons of various components in the design yield more benefits from the time invested.

Figure 3.1 SolidWorks™ model by Michael Davis [From: Ref. 3].

The ease of use of recent solid modeling packages is astounding, allowing engineers to produce models of complex assemblies without any outside help. This is evidenced by the model in Figure 3.1. It was developed with no outside support and completed in about 15 hours. All the parts are exportable to machine fabrication technology as is [Ref. 3]. The combination of visualization, rapid and easy importation into analysis software and rapid speed of revision make a very strong case for integration of solid modeling into a design process.

B. INTEGRATION INTO SPACECRAFT DESIGN

When applied to the spacecraft design process in AA4871, the advantages of solid modeling become very clear. The process so far at NPS has been limited in its ability to quickly depict an accurate representation of a spacecraft and enable changes to it in a flexible, easy manner. Visualization and analysis of the spacecraft are critical to understanding the component fit relationships, the design evolution and interactions between subsystems, and how the structure will react to launch loads. Solid modeling applies to mission analysis as depicted in Table 3.2.

Analysis Type	Goal	Solid Modeling Applicability
Feasibility Assessment	To establish whether an objective is achievable and its approximate degree of complexity (limited detail)	Yes
Sizing Estimate	To estimate basic parameters such as size, weight, power or cost (limited detail)	Yes
Point Design	To demonstrate feasibility and establish a baseline for comparison of alternatives (limited detail)	Yes
Trade Study	To establish the relative advantages of alternative approaches or options (expanded detail)	Yes
Performance Assessment	To quantify performance parameters (e.g., resolution, timeliness) for a particular approach (expanded detail)	Yes
Utility Assessment	To quantify how well the system can meet overall mission objectives (expanded detail)	Yes

Table 3.2 Mission Analysis Hierarchy [After: Ref. 8: p. 51].

Mission analysis is defined as the process of quantifying the system parameters and the resulting performance [Ref. 8: p. 49]. The ability to conduct each type of analysis is enhanced by the use of models, allowing engineers to make decisions based on fully visualized, easily modifiable configurations. Although the course requirements of AA4871 are geared towards mission analysis to the point of completing a limited performance assessment, the use of solid models when integrated with the CDC spreadsheets will enhance the course scope, enable more trade space to be explored, allow more detail in the performance assessment, and contribute significantly to the utility assessment.

In order to attempt to understand the true power of solid modeling, it is appropriate to undertake a thorough comparison with the author's previous experience in the AA4871 course. Many hours were spent by the systems engineer in the design class to generate an accurate 2-D drawing of the *Mithra* spacecraft. As the configuration changed, the drawing was revised with much difficulty due to the inherent interrelationships of component placement and sizes as well as the requirement for the spacecraft to fit within the selected launch vehicle fairing. The configuration was to be depicted in 2-D only, due to the steep learning curve associated with solid modeling software perceived by the subsystems engineer. It was assumed that in order to use a solid modeling program, much time and effort would be necessary; therefore the 2-D approach would yield better return on investment for the time spent. Also, the subsystems engineer did not have time to explore both avenues of approach. Figure 3.2 shows the 2-D view of the spacecraft and the launch vehicle fairing.

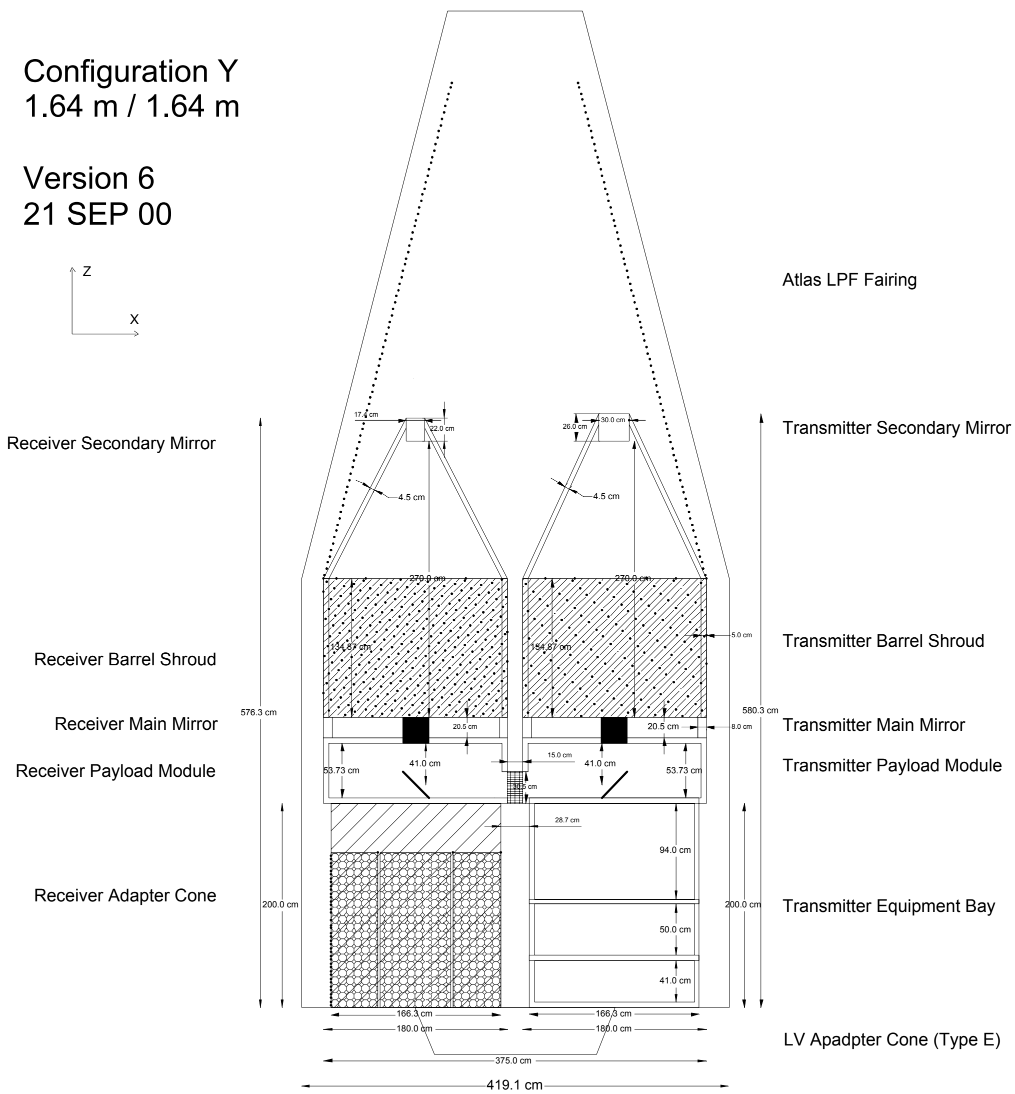

Figure 3.2 *Mithra* spacecraft in the launch vehicle fairing.

The author, as the structures engineer, could not begin to construct a detailed finite element model (FEM) for analysis until the final configuration was set, since the learning curve for the analysis software was exceptionally steep, ascertained after lengthy tutorial sessions. This is the case with many complex FEM packages, since they were initially designed for analysis rather than 3-D modeling.

The final model of the spacecraft, depicted in Figure 3.3, was completed by the electrical power subsystem engineer, since he took the initiative to learn yet another modeling software that the design team was unaware of. The structures engineer was busy creating analytical spreadsheets, completing the FEM, and running the analysis, therefore could not research and assist in the use of a solid modeling tool. The final model of the spacecraft was combined with the 2-D configuration drawings and 3-D analysis results for the coursework presentation and reports. If the team members had access to a capable, easy to use modeling tool, it would have enabled them to more quickly and fully understand the relationships between components and subsystems, see the rationale behind component placements, analyze spacecraft technical parameters, and draft presentations that clearly communicated the design intent and final configuration.

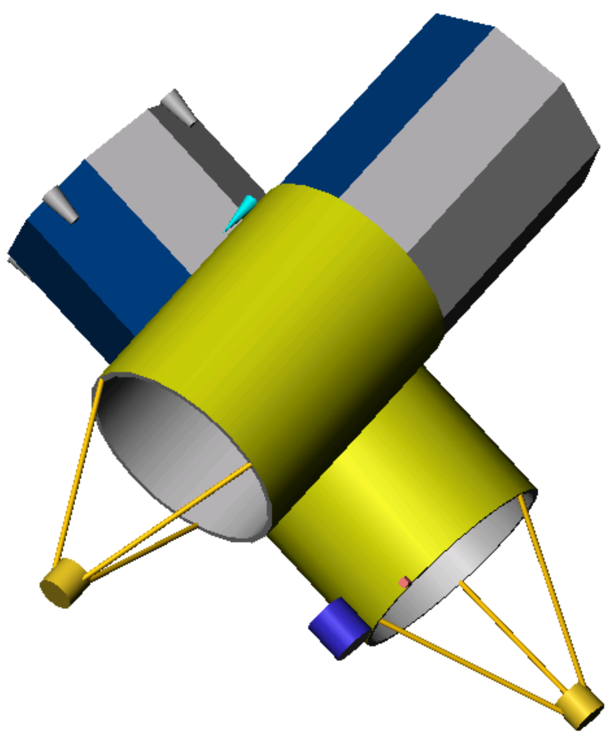

Figure 3.3 *Mithra* Relay Mirror satellite.

Figures 3.4 and 3.5 show the *Mithra* satellite bus and its equipment bays as created by the systems engineer. The models took a great deal of time to create and only 2-D drawings were completed.

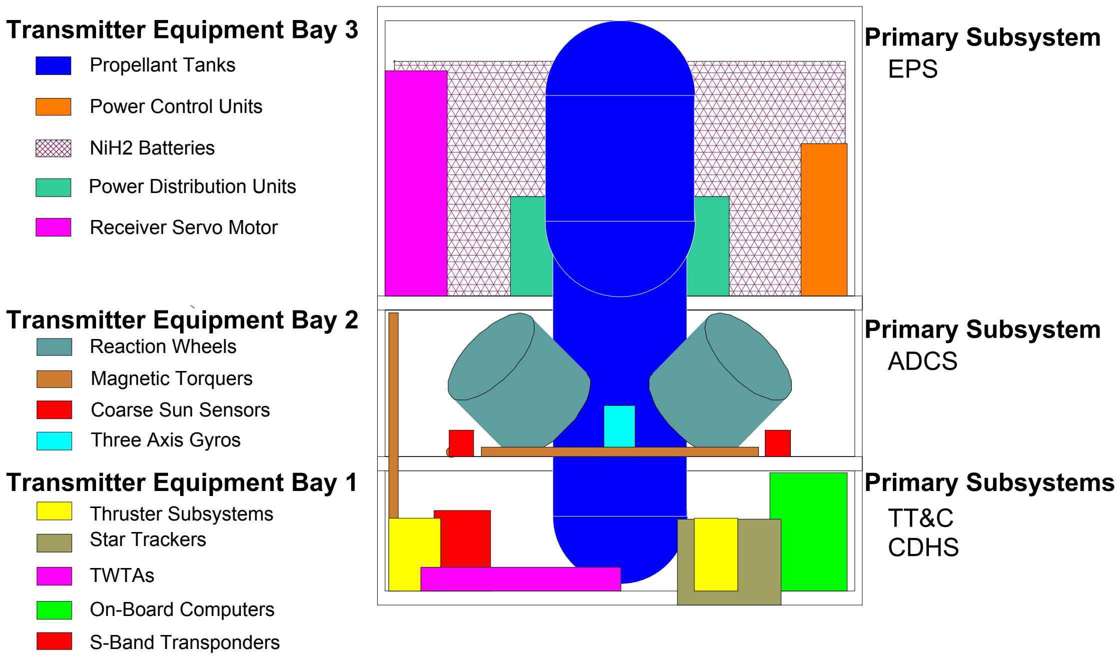

Figure 3.4 *Mithra* bus assembly.

While the use of color enhances Figure 3.4's presentation of the configuration, it still lacks texture and detail, as well as the critical third dimension. Figure 3.5 is difficult to read and does not give the viewer a good impression of the relationships between components within the equipment bays. Although it portrays the 2-D relationships in a satisfactory manner, the information lost because of the lack of 3-D information is significant. The lack of color in Figure 3.5 also hinders their effectiveness.

Now compare this figure to Figure 3.6, where the bus was created with SolidWorks™, a rapid solid modeling software program. The bays are now clearly depicted in a 3-D frame of reference, and the relationships between components as to separation distance and relative size are extremely easy to see. The use of lighting, texture, and color significantly enhance the viewer's comprehension of the spacecraft component layout.

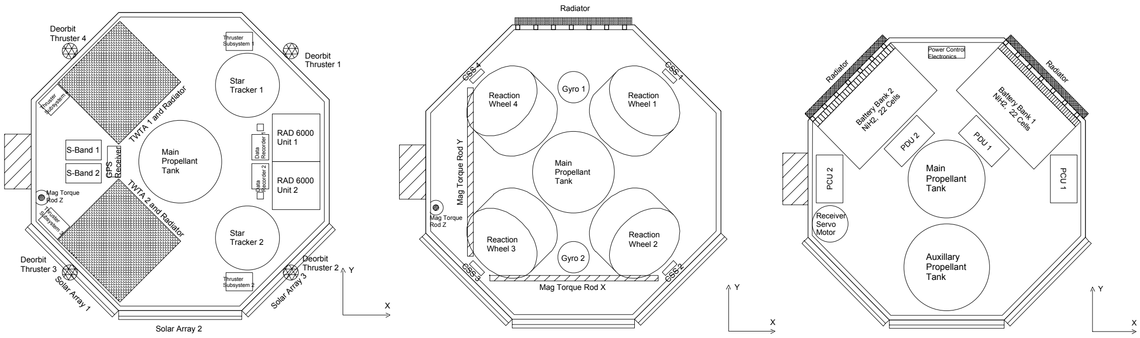

Figure 3.5 *Mithra* equipment bays, AutoCAD.

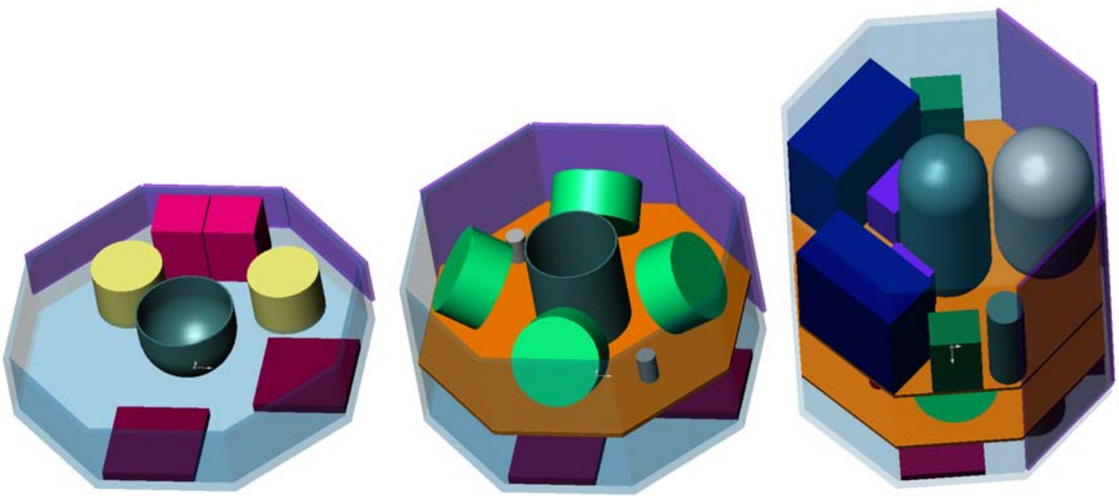

Figure 3.6 *Mithra* bays depicted with SolidWorks™.

The model depicted in Figure 3.6 was created with SolidWorks™ in approximately six to eight hours. The basic familiarization with the software took approximately ten hours, giving a total time to create of about eighteen to twenty hours. If a student is expected to complete one to two hours study for every hour spent in class, this would easily fit within the curriculum's existing time allocation for the AA4871 design course. It is expected that since learning the spacecraft design process is the student's primary reason for enrolling in the curriculum, a significantly greater amount of time would be spent using the tool.

The model dimensions are fully parametric, meaning all assembly dimensions update automatically to accommodate a change in any one dimension. The internal bus components are free to be placed anywhere in the bus using the surface, edge, and point mating tools embedded in the software. Many other relational tools are available. The speed of revision after creating this model is almost instantaneous. Any change in bus side panel length changes the shelf lengths and solar panel lengths, and maintains all relations for the interior bay components. For example, the large batteries are placed against the exterior wall of Bay 3 (rightmost view of Figure 3.6), so if the main bus structure dimension changes in any way, the batteries remain in their proper positions against the wall. In addition, dimensions for any part may be displayed, as well as offsets or reference dimensions, if any. If the relations are chosen carefully and monitored each time a change is made, the model will maintain excellent situational relationships and continue to provide valuable visualization information. All parts are easily moved between bays, enabling the configurations engineer with tremendous flexibility in component placement, enhancing the number of configurations within the equipment bays that can be attempted before deciding on the final one.

SolidWorks™ also allows solid parts to be hidden or set to levels of transparency so that parts within assemblies are easily seen. Figure 3.6 shows the bus outer structure, solar panels, and batteries semi-transparent. This offers another powerful visualization option to the structures/configuration engineer. Features may also be hidden temporarily in order to better see layered components. The model can be rotated easily and different section views can be created quickly, enabling the entire design team to see relationships between components. This especially aids the Thermal subsystem engineer, since it is necessary to determine the relative placement of components before conducting a rough thermal analysis. The model may be exported into a thermal analysis program with the desired components already in place.

Mass properties of each component are available, as well as the overall mass properties of the assembly. Upon creation the individual parts are assigned a density commensurate with their mass and volume, and the software then calculates a rough mass. The mass properties output also includes volume, center of mass, principal axes, surface area, and principal moments of inertia. The properties computed by the software are very close to the spreadsheet calculations and estimates made using parametric equations. Figure 3.8 shows the mass properties as displayed by SolidWorks™. The principal axes are depicted for ease of reference, and the density of any given part may be modified at any time, enabling the structures engineer the flexibility to approximate component masses as necessary.

These mass properties are crucial for the attitude dynamics & control engineers to properly assess the necessary sizes of reaction wheels for the design. The mass and location of components are also critical to the launch vehicle, as the center of mass must be within safe vertical and horizontal operating envelopes of the launch vehicle fairing for stability and control purposes. If any component must be moved, it can be done so readily and the new mass properties calculated immediately. This gives the systems and structures engineer flexibility and speed in revision, which was lacking in the mass property calculations for the original *Mithra* design.

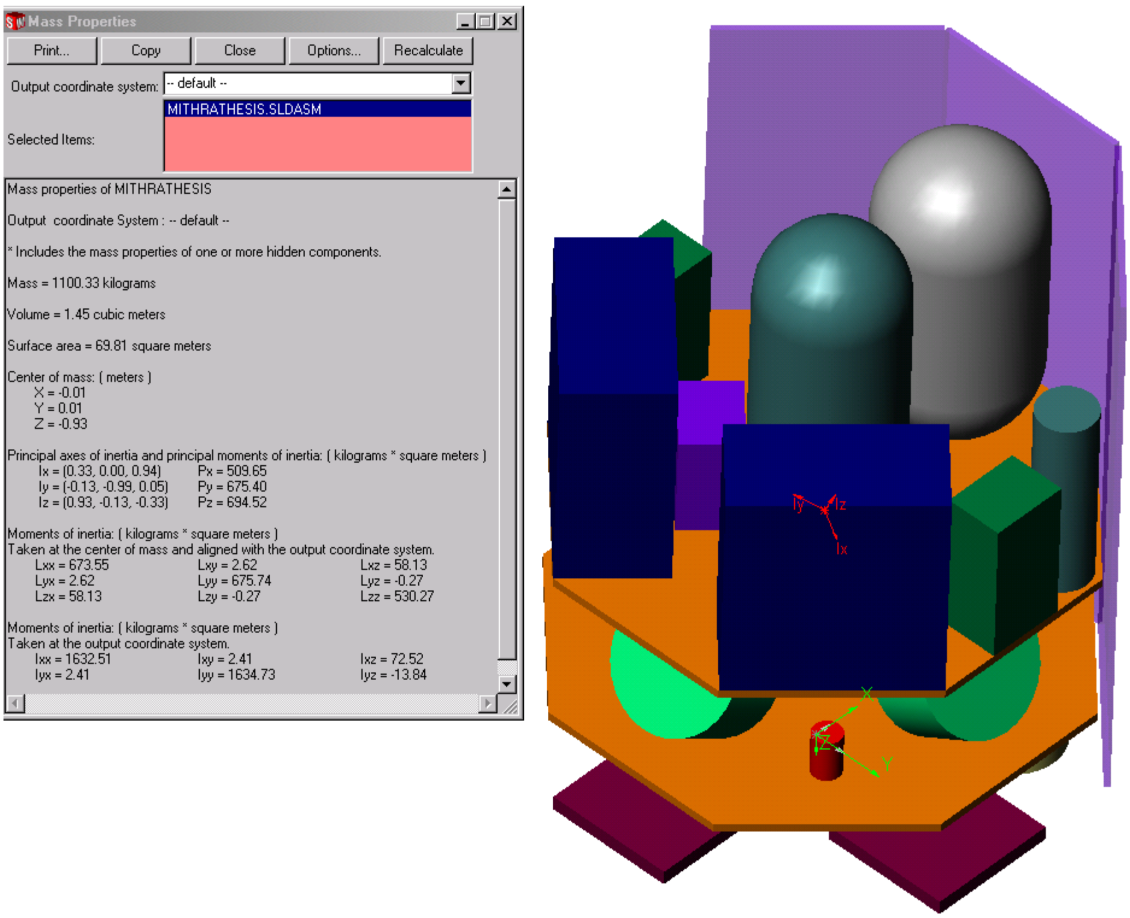

Figure 3.7 Mass properties in SolidWorks™.

In order to determine whether the satellite fit within the launch vehicle fairing, it was necessary to create a drawing. The dimensions of the launch vehicle fairing had to be determined from the launch vehicle user's guide and input into the 2-D design program. As discussed earlier, Figure 3.2 shows the Mithra satellite and the launch vehicle fairing as created by the systems engineer. The figure shows that despite the use of a relatively advanced drafting tool, the basic design intent is not depicted very well. The dimensions are difficult to see, and the 2-D representation is lacking in detail and texture, two key elements of product visualization. Also, many revisions were necessary to ensure that changes made would keep the spacecraft within the desired launch vehicle fairing envelope. A faster, easier way to accomplish this task is depicted in Figure 3.9.

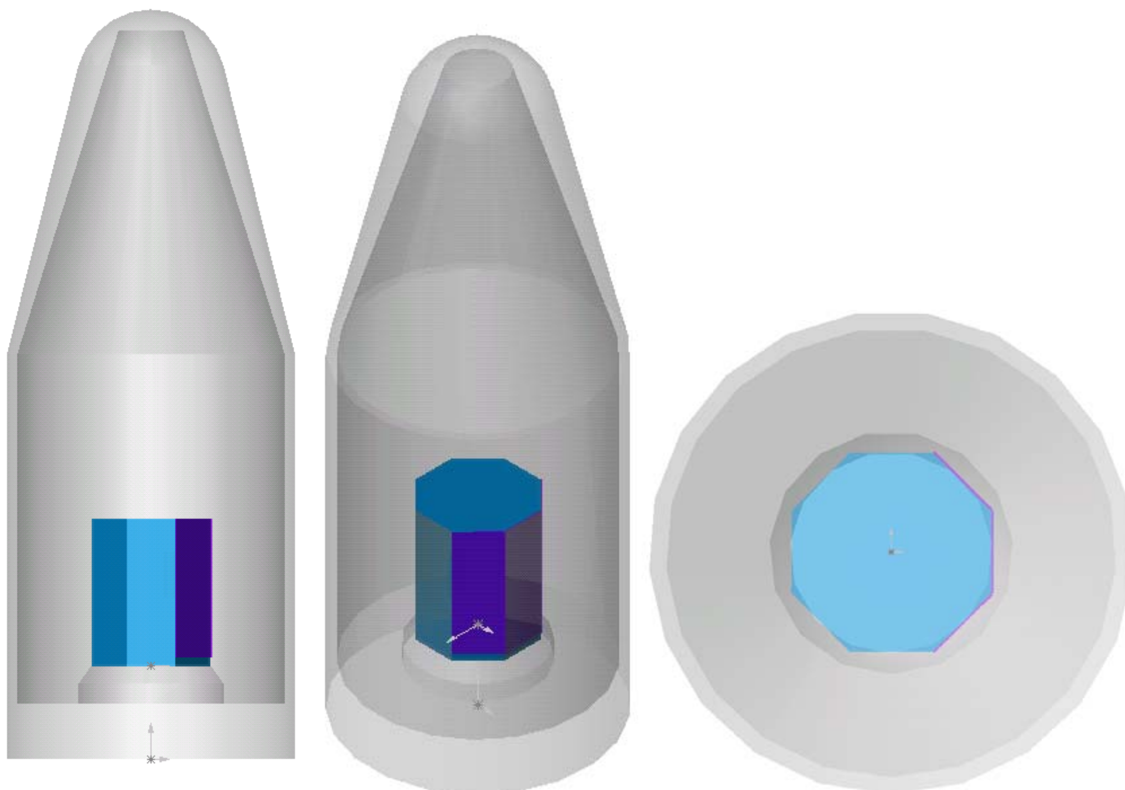

Figure 3.8 SolidWorks™ model of Delta III LV fairing, *Mithra* bus attached.

The Aerospace Corporation utilizes SolidWorks™ extensively in their Concept Design Center. From the author's visit to witness the CDC in action, it was clear that the customer in the study was particularly interested in visualization of the spacecraft being designed, enabled through the solid model. A special seat devoted to the configuration of the spacecraft is used for SolidWorks™. During the design session, it was the most frequently displayed monitor on their large screen.

From their model compilation, The Aerospace Corporation provided over forty launch vehicle fairing solid models, including the STS and Sea Launch systems. The availability of these models, created directly from the launch vehicle user's guides, provides the systems and configurations engineer a clear advantage over 2-D methods when trying to determine whether a complex satellite design will fit within a given fairing in the launch configuration. The engineer simply has to create a new assembly in SolidWorks™, open the satellite and launch vehicle fairing files, and drag and drop the origins of both parts onto the origin of the new assembly. The spacecraft may then be moved and relations put in place or removed to properly orient it with respect to the fairing. Though the three pictures in the figure above do not depict dimensions, they can be easily turned on and off, enlarged or reduced, and placed in any way desired in relation to the model. The model may be rotated to any view desired, shading and transparency modified, and colors changed at any time. This 3-D capability obviously gives a much clearer visual image of the satellite within the launch vehicle.

Figure 3.9 shows a very powerful feature that enables the systems or configuration engineer to determine fit within the launch vehicle fairing. The *Collision Detection* feature is turned on prior to moving an assembly or part, and gives visual and audio alerts when parts are detected as having collided. This process has been done previously using 2-D drafting estimation and revision techniques; now it can be done in 3-D, a much more powerful tool for complex assemblies. The figure shows the *Mithra* bus placed in the Delta III launch vehicle fairing such that an alert is displayed, showing the surfaces that have been detected as having collided. In this case, the outer panel of the spacecraft bus has collided with the inner fairing wall.

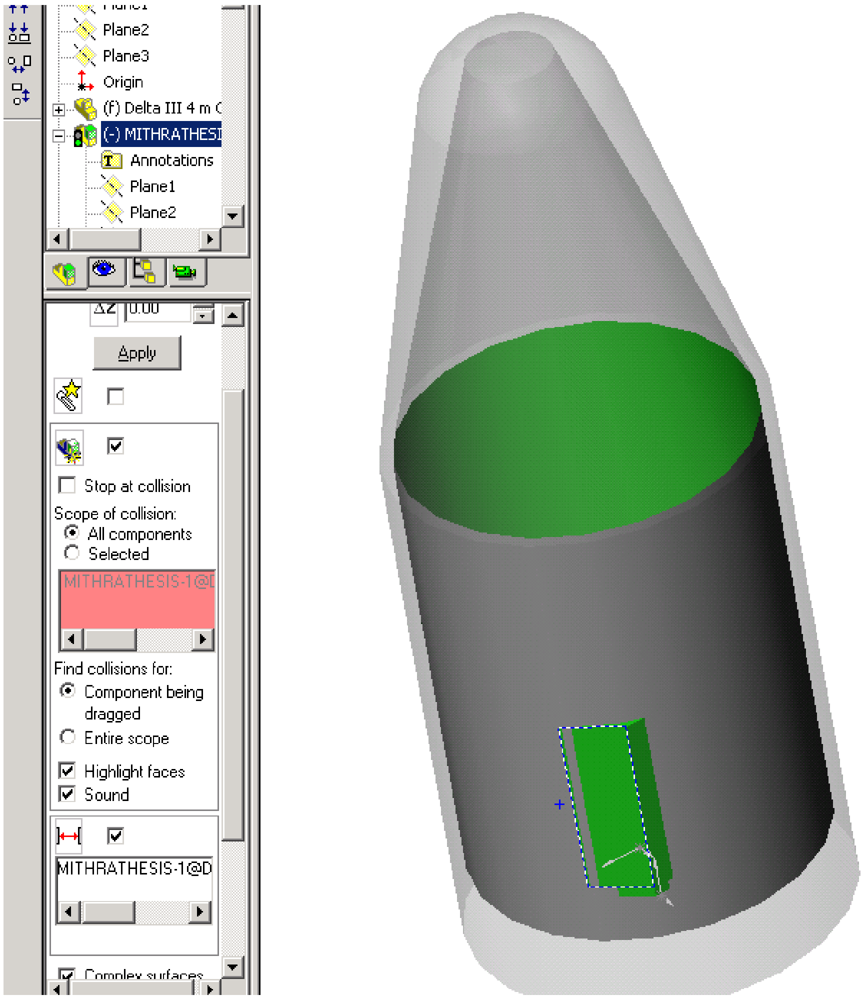

Figure 3.9 Mithra bus moved within Delta III fairing, collision detection on.

SolidWorks™ also allows animation and photo-realistic rendering by parts, enabling engineers to create detailed movies of antennas unfolding, the spacecraft repositioning, or range of movement of a particular appendage. This capability, when combined with the ability to export the model directly to FEA programs, underscores the importance of incorporation of solid modeling into spacecraft design. The examples shown also verify the powerful capability of solid modeling as applied to a spacecraft design at NPS. It is for these reasons that the effort was undertaken to develop the capability of solid modeling for the NPS SDC and integrate it to the fullest extent possible into the CDC process.

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IV. CDC AND THE NPS SPACECRAFT DESIGN CENTER

A. OVERVIEW

The Aerospace Corporation provided the Excel architecture used in the CDC to the NPS SDC in calendar year 2000. This was done because there was no iterative, real-time design capability within the NPS Space Systems Engineering curriculum, leaving students at a disadvantage when it comes to understanding the real-world process that space systems engineers must go through in order to design a spacecraft. The software was then modified and installed by the author for test and evaluation, with consideration towards future use in the Space Systems Engineering curriculum. The effort was undertaken to provide the capstone design course, AA4871, a better way to conduct spacecraft design while furthering the educational experience of the class. In addition, the long-term goal of a student-designed and NPS-built small satellite would be furthered by the addition of a rapid conceptual design tool. Another reason for the effort is the fact that a User's Guide to the CDC did not exist prior to this thesis, despite the overwhelming success of the tool at Aerospace and other organizations, including the Jet Propulsion Laboratory in Pasadena, California. Currently, Aerospace systems engineers must train new personnel by having them witness the design process firsthand and allowing them to access the subsystem spreadsheets, with no preparation or manual available for study or guidance.

The CDC suite consists of linked spreadsheets within Microsoft Excel with macros controlling key data transfer functions. It should be noted that real-time verbal and written interaction between subsystems is an essential part of a successful CDC process. The overall graphic representation of the CDC software was extensively modified prior to full installation in order to enhance the user interface experience and to reflect the cooperation, professionalism, and outstanding relationship existing between The Aerospace Corporation, the NPS SDC, and the Aeronautics and Astronautics Department.

The NPS SDC lab manager and Professor Brij Agrawal control the original, properly functioning copy of the CDC software. Dual backups of the spreadsheets were deposited with the lab manager in case reinstallation is necessary, since he is responsible for all hardware and software installed in the lab. When discussing VBA code in this and subsequent chapters, the terms "macro" and "subroutine" are used interchangeably.

In order to provide for security and proper use of the tool, it is important to note the role of NPS network administrators. They retain overall authority and responsibility for the use and maintenance of the workstations/network associated with the SDC in accordance with NPS computer use policies. It is imperative that they are consulted on all network issues, in addition to the lab manager. This enables controlled points of access to the software, thereby allowing proper use and development of the tool.

The User's Guide approaches the CDC software from a systems perspective, concentrating on the Systems workbook and it's inherent control of the data flow and overall guidance of the design process. A detailed description of the Systems workbook is presented followed by the overall data transfer architecture, specifics on link structure, and the associated Visual Basic for Applications (VBA) code. A section on modification to the link system, workbooks and code is also included. Details of each subsystem are left to the user for investigation, since proper documentation and understanding of each one is a task beyond the scope of one thesis.

The CDC User's Guide is not intended to be an authoritative, all-encompassing or restrictive manual on the software and its setup. The NPS SDC users are free to modify workbooks and add functions wherever improvement is warranted upon the approval of Professor Brij Agrawal. Modifications should take place with the full understanding of the implications as delineated in this thesis.

B. SYSTEMS WORKBOOK

The systems workbook contains seven sheets: *Inputs, Outputs, Guidelines, Summary, Audit, TRL,* and *Calculations*. The primary sheets used for data transfer control are Inputs, Outputs, Summary, and Audit. The Guidelines, TRL and Calculations sheets are for reference only. Comments were inserted for many of the cells in each worksheet to serve as an in-use guide for the workbook. This section details the Systems workbook in order to enable systems engineers to realize the proper use and functionality of this crucial part of the CDC tool.

1. Inputs

The two columns of each subsystem's Output sheet are linked directly to their corresponding sections here, up to approximately 300 rows. Activating any cell on the sheet and observing the editor location to the right of the equal sign shows the link path. Figure 4.1 shows cell C3 highlighted and the corresponding linked cell (in the ADACS workbook) appearing in the editor location.

C3 = ='C:\Documents and Settings\Administrator\My Documents\Thesis\Aerospace Tools\NPS Files\SDC on OMEGA\Models\[ADACS.xls]Outputs'!C3

	A	B	C	D	E
1	Ref ID	ADACS	Value		ASTRO
2	1	ADACS Mass [kg]	102.74		Mission Orbit Perigee Altitude [km]
3	2	ADACS Power [W] -- Mode 1	252.676		Mission Orbit Apogee Altitude [km]
4	3	ADACS TRL	5		Mission Orbit Inclination [deg]
5	4	Attitude Knowledge [deg]	0.03		Mission Orbit Period [min]
6	5	Pointing Accuracy [deg]	0.05		Mission North-South ΔV [m/s]
7	6	Sun Sensor Quantity	5		Mission East-West ΔV [m/s]

Figure 4.1 Systems workbook, Inputs worksheet.

The Ref ID column is included as a reference for finding specific data related to each subsystem, and is not currently used. It may be useful in the future upon integration of other software tools. The subsystem data is linked in two columns: the parameter name and the actual value. Units are included in the parameter name to ensure mistakes between English and SI units are minmized. Each subsystem is separated for ease of visual reference with a blue demarcation line, and the columns associated with the separation lines are not linked. Each subsystem save time and interface check time stamp are included near the end of their columns. Any parameter on the Outputs sheet may be linked to the proper column here in order to pass systems data such as total spacecraft mass, power, and requirements information to the subsystems with each update.

2. Outputs

The Outputs sheet is linked to its appropriate column on the Inputs sheet. Discretion is left to the systems engineer as to what data to include here. Possible outputs relevant to the subsystems are study number, requirements from the Guidelines sheet, and total system mass and power figures. The cells on the Outputs sheet can be directly linked to any other sheet in the workbook using the *Copy* and *Paste Special-Paste Link* operations. Figure 4.2 shows cell C3 linked to the Summary sheet.

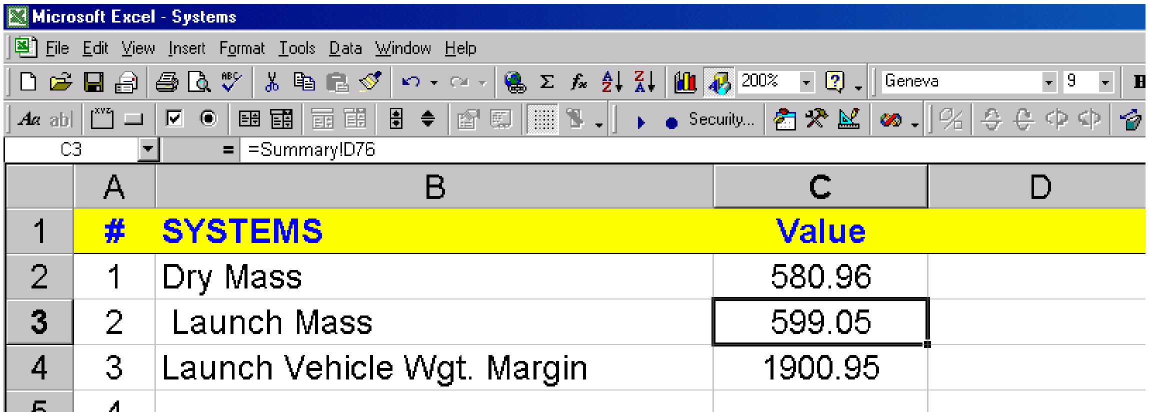


Figure 4.2 Systems Outputs sheet linked to the Summary sheet.

3. Guidelines

The Guidelines sheet is the starting information for the design. It includes general information such as lifetime, orbit, and constellation size, as well as the specific spacecraft requirements such as repositioning requirements and pointing accuracy. Also included is the overall cost target and a listing of participating subsystem engineers. The cost model software is not included in the guide, since the workbook is not directly linked to the real-time flow of information between subsystem engineers.

This sheet enables initial calculations to be made by each subsystem and thereby begins the study process. The Aerospace logo at the top right contains the software credit and date of modification information. The approximate date of any modifications to the software should be appended to the macro in Visual Basic to maintain a basic change history. The proper format for this procedure is described in the macro comments.

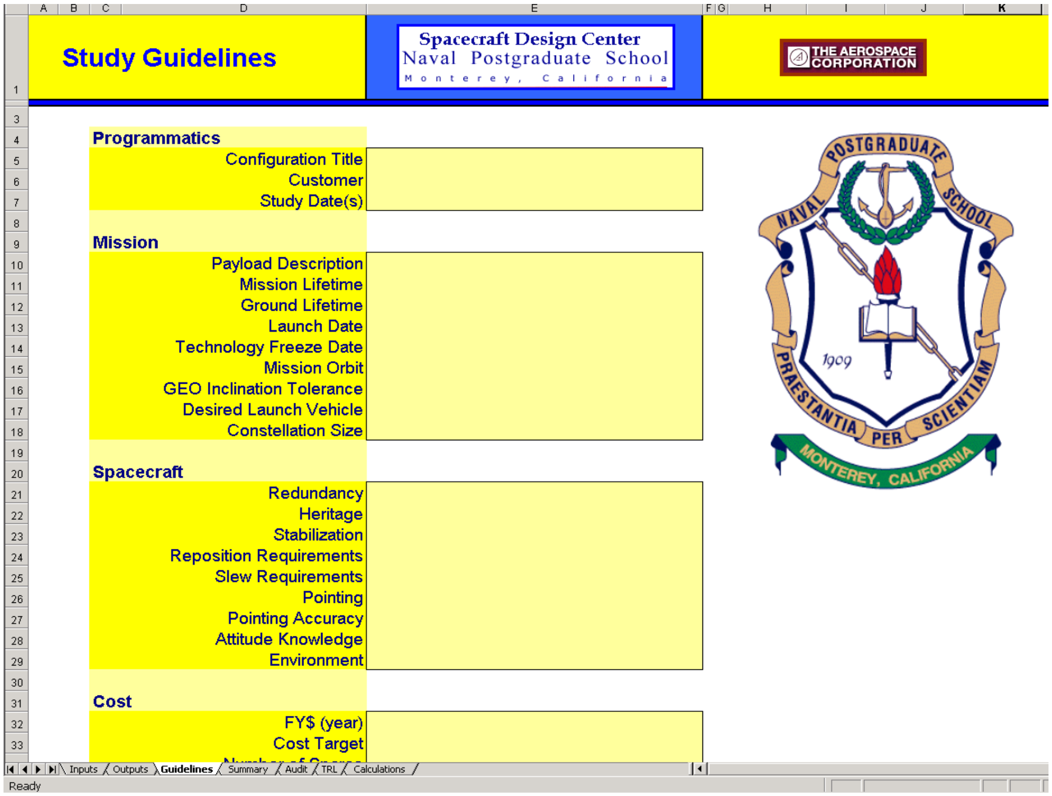


Figure 4.3 Guidelines sheet.

4. Summary

The Summary sheet is the focal point of the Systems workbook. Included on this sheet are linked values from the Inputs sheet and check calculations to ensure that values are correct and within a reasonable range for the design. The sheet serves as the Systems engineer's quality control mechanism. The sheet may be added to in any manner with calculations, graphs, charts, or pictures in order to facilitate the Systems engineer's situational awareness of the design. While the sheet is best viewed at 60-90% zoom factor, with 75% being used for optimum display quality, splitting the screen view by using the split box at the top of the vertical scrollbar greatly facilitates simultaneous monitoring of two or more sheet sections. Much of the functions and formatting of the original spreadsheet were modified in order to improve functionality and graphical presentation of the data. While most changes are addressed in the text of this chapter, the additions and changes are documented in detail in the VBA code, Appendix C. Figure 4.4 shows the first row containing buttons that control the data flow and provide workbook information. These subroutines were modified and improved by the author, explained in more detail in Appendix C.

Figure 4.4 Summary sheet data transfer control section.

Update Button

Runs the *Update* subroutine. This automatically updates the workbook links for every link on the Audit sheet that has been saved since the last update. It brings the most recently saved information from the subsystem Output sheets into their appropriate columns on the Systems Inputs sheet with all links to the Inputs sheet updating accordingly. It also contains subroutines for automatic calculations and parameter manipulation on the Systems Summary sheet. See the comments in the code for more details.

Output Button

Runs the S*aveData* subroutine. This deletes the current data.xls file, copies the Systems Inputs sheet, and saves it as a new data.xls file. The file is then used by the subsystems to update their Inputs sheets via their *Update External Data* button or the *Edit-Links…Update Now* operation.

Display Links Button

Runs the *DisplayLinks* subroutine. This displays all links associated with the Systems workbook for easy reference. It serves as a check to ensure all intended links are properly attached to the workbook. The Aerospace Corporation logo displays information about the CDC software as installed in the SDC when pressed.

The ***Inputs (Quicklook)*** and ***Spacecraft Summary (Quicklook)*** sections of the summary sheet display parameters that the Systems engineer wishes to keep track of during the design process. This section can be thought of as a "quick look" for the design's critical parameters and is shown in Figure 3.5. Many of these values are used later in the sheet for calculation checks for various subsystems. This section can be modified to include other data by linking cells directly to the desired parameter on the Inputs sheet. The values will then automatically change with each update cycle. The systems engineer retains the option to directly enter a value in a cell to override the subsystem inputs. If this is done, the link to the inputs sheet must be reestablished before the next update, otherwise the cell must continue to be updated manually. Note that the *Communications* subsystem is divided into *TT&C* and *C&DH*. These two subsystems may be under the purview of one engineer, but frequently are considered separate in their functions. If it is necessary to model a specific communications payload, the mass and power estimates may be entered manually in the *Payload* area of the *Mass and Power* section. Any other subsystem created by a design team may have its inputs inserted here, but care must be taken with the cell references as written in the VBA code.

INPUTS (Quicklook)	CURRENT	PREVIOUS
Solar Array BOL Power	2000.0	2000.0
Orbit Insertion Propellant (kg)	0.0	0.0
On-Orbit Propellant (kg)	0.2	0.2
Pressurant (kg)	0.0	0.0
Launch Vehicle Cost [$M]	6043.0	6043.0
Launch Vehicle Adapter Mass (kg)	17.9	17.9
Mission Orbit Perigee Altitude (km)	300.0	300.0
Mission Orbit Apogee Altitude (km)	300.0	300.0
Mission Orbit Inclination (deg)	45.0	45.0
Mission Orbit Period (min)	90.5	90.5
North-South Delta-V (m/s)	0.0	0.0
East-West Delta-V (m/s)	0.0	0.0
Maneuver Delta-V (m/s)	0.0	0.0
Drag Makeup Delta-V (m/s)	3.1	3.1
ADACS Delta-V (m/s)	2.8	2.8
Disposal Delta-V (m/s)	132.7	132.7
Number of Satellites	1.0	1.0
Mission Orbit Period [min]	90.5	90.5
Maximum Eclipse Duration [min]	36.6	36.6

Spacecraft Summary (Quicklook)				Power	W			
CURRENT	Mass	Tot. Daylight	Tot. Eclipse	Mode 1	Mode 2	Mode 3	Mode 4	TRL
Propulsion	10.1	100.0	33.0	30.0	0.0	0.0	0.0	6
ADACS	105.1	180.1	180.1	100.0	180.1	180.1	0.0	5
TT&C	14.7	20.0	14.5	0.0	2.0	0.0	0.0	6
C&DH	19.5	50.0	26.3	23.0	1.0	0.0	0.0	6
Thermal	25.0	10.0	42.2	42.2	0.0	0.0	0.0	9
Power	198.7	0.0	1.0	0.0	2.0	0.0	0.0	5
Structure	26.3							6
TOTAL	399.5	360.1	297.1	195.2	185.1	180.1	0.0	
	kg			Power	W			
PREVIOUS	Mass	Tot. Daylight	Tot. Eclipse	Mode 1	Mode 2	Mode 3	Mode 4	TRL
Propulsion	10.1	100.0	33.0	30.0	0.0	0.0	0.0	6
ADACS	105.1	180.1	180.1	100.0	180.1	180.1	0.0	5
TT&C	14.7	20.0	14.5	0.0	2.0	0.0	0.0	6
C&DH	19.5	50.0	26.3	23.0	1.0	0.0	0.0	6
Thermal	25.0	10.0	42.2	42.2	0.0	0.0	0.0	9
Power	198.7	0.0	1.0	0.0	2.0	0.0	0.0	5
Structure	26.3							6
TOTAL	399.5	360.1	297.1	195.2	185.1	180.1	0.0	

LEGEND
Subsystem Inputs
Last Update
Subsystem Totals
Calculated
Manually Entered
Worksheet Links

Figure 4.5 Inputs section of the Systems Summary sheet.

The *drag and drop* operation can be used to highlight all of the section below which it is desired to insert the new row and move it down one row, then adjusting the dividers between the sections if necessary. Since the *Current* area is copied into the *Previous* area when an update is performed, it will be necessary to record a new macro and put it in place of the previous macro in order to perform the operation correctly. Details of the proper subroutine operation are included in Appendix C.

The *Previous* area was created using the current value cells as the source and copying them to the previous cells when an update is performed. This area serves as a quick reference to identify changes that might exceed the study bounds, as well as providing verification of units and other important parameters. It also keeps the Systems engineer, as well as all subsystems, aware of the effect their changes are causing over the design iteration. A macro was recorded when creating the areas highlighted in Figure 4.5. The *Copy* and *Paste Special-Values* operation was used on the *Current* areas and the values placed in the *Previous* cells. The macros were then included at the beginning of the update subroutine, as detailed in Appendix C. This has the effect of transferring the current values to the previous values whenever the *Update* button is depressed, prior to retrieving the new values from the subsystems. Any other parameters of interest can be added to the *Current* and *Previous* areas by minimal additions to the code. The comments in the VBA code detail this procedure.

The ***Spacecraft Summary*** area of the Summary worksheet contains orbital parameters and mass/power information. Shown in Figure 4.6, the ***Orbital Parameters*** section uses analytical equations to calculate parameters for both quality assurance and quick reference.

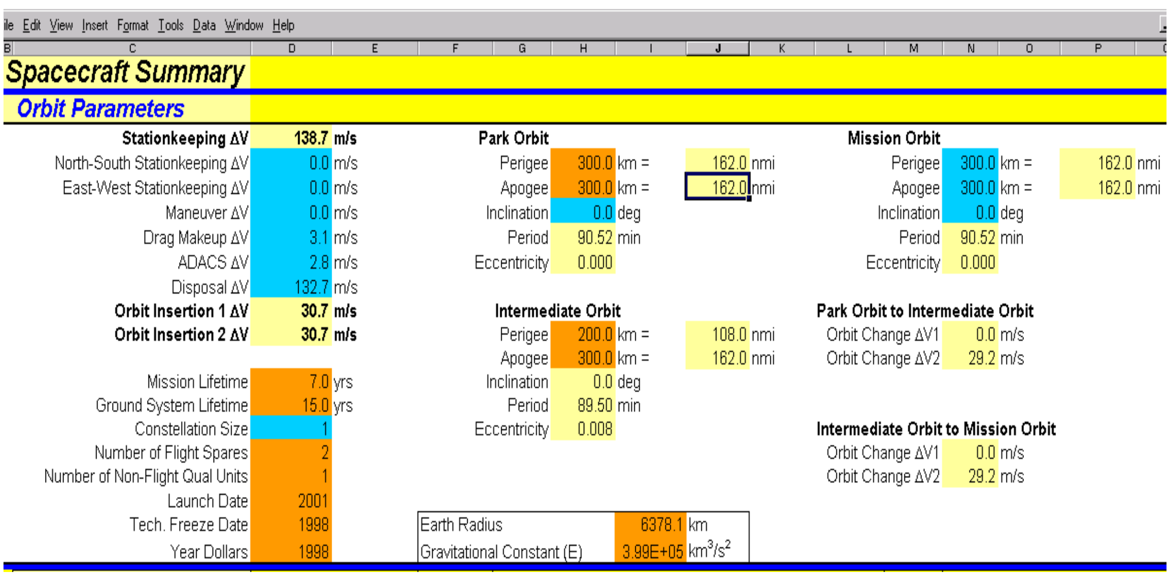


Figure 4.6 The Orbit Parameters section of the Systems Summary sheet.

Since the orbital parameters can greatly influence a payload and its performance, this section can be extremely useful. The basic mission characteristics are also summarized here with information such as mission lifetime, launch date, and technology freeze date. The manually entered values give the Systems engineer freedom to include parameter data that may have contingencies associated with them or are related to the study in an indirect manner. For example, the *Orbit Insertion 1 ΔV* and *Orbit Insertion 2 ΔV* cells have a contingency of 5% added to the sum of the cells above them.

The ***Mass and Power*** section is used to break down the mass and power of each subsystem and includes design margins and percentage of dry mass calculations. The *Mass* column takes inputs in SI units and converts them to English units in the adjacent column. The percentage of dry mass is included in order to ensure the values are within a reasonable range and to track the effects of subsystem changes on the design. A very important parameter, launch vehicle mass margin, is calculated in the *Launch Vehicle* section by subtracting the total spacecraft mass from the launch vehicle throw mass.

Mass & Power	Mass		%Dry Mass	Power [W]							Comments
	[kg]	[lbs]		Daylight	Eclipse	Mode 1	Mode 2	Mode 3	Mode 4		
		Time (min)		80.0	10.5	10.5	30.0	40.0	10.0	NASA	Tot. Daylight Time should be 53.9 minutes
						Eclipse	Daylight	Daylight	Daylight	TRL	Tot. Eclipse Time should be 36.6 minutes
Payload	83.8	184.7	14%	262.5	168.8	6.3	0.0	0.0	0.0	4	MODES: None / Daylight / Eclipse
Payload	12.0	26.5		100.0	50.0	5.0	0.0	0.0	0.0	5	
Payload Processing	5.0	11.0		10.0	5.0	0.0	0.0	0.0	0.0	5	
Payload Communications	50.0	110.3		100.0	80.0	0.0	0.0	0.0	0.0	5	Contingency Percentages (Margin):
Payload Contingency	16.8	36.9		52.5	33.8	1.3	0.0	0.0	0.0	4	25% Mass 25% Power
Spacecraft	499.4	1101.2		450.1	371.4	244.1	231.4	225.1	0.0	5	Save Times
Propulsion	10.1	22.4	2%	100.0	33.0	30.0	0.0	0.0	0.0	6	
ADACS	105.1	231.8	23%	180.1	180.1	100.0	180.1	180.1	0.0	5	
TT&C	14.7	32.5	3%	20.0	14.5	0.0	2.0	0.0	0.0	6	
Command & Data Handling	19.5	43.0	4%	50.0	26.3	23.0	1.0	0.0	0.0	6	
Thermal	25.0	55.1	5%	10.0	42.2	42.2	0.0	0.0	0.0	9	
Power	198.7	438.2	43%	0.0	1.0	0.0	2.0	0.0	0.0	5	
Structure	26.3	58.0	6%	0.0	0.0	0.0	0.0	0.0	0.0	6	Contingency Percentages (Margin):
Spacecraft Contingency	99.9	220.2		90.0	74.3	48.8	46.3	45.0	0.0		25% Mass 25% Power
Satellite Summary											
EOL Power				1252.7	540.1	250.3	231.4	225.1	0.0		
BOL Power				2000.0							
Dry Mass	583.2	1285.9									Dry Mass w/o Contingency = 466.5 kg
Orbit Insertion Propellant	0.0	0.0									
On-Orbit Propellant	0.2	0.4									
Pressurant	0.0	0.0									
Wet Mass	583.4	1286.3									
Adapter	17.9	39.5									On-orbit mass = 583.4 kg
Launch Mass	601.3	1325.8									1286.3 lb
# of s/c per launch	1										3.1% of Wet Mass
Launch Vehicle											
Performance	2500.0	5512.5									
Launch Vehicle Wgt. Margin	1898.7	4186.7									
Launch Vehicle % Margin			75.9%								

Figure 4.7 Mass and Power section of the Summary sheet.

The first rows of the *Payload* and *Spacecraft* sections calculate the total mass and power appropriately. Manual values are used for the payload mass and power entries to allow the design team flexibility, since the specifications for many payloads are not available in the initial design stages. If a communications payload is being designed, its parameters may be entered here, separate from the *TT&C/CD&H* subsystems. The mass and power inputs for the spacecraft are linked to those in the *Inputs* section of the sheet. Both the *Payload* and *Spacecraft* sections include design margins, or contingencies, as annotated in the *Comments* area. Margins are calculated for the spacecraft mass and power, broken down between payload and other subsystems, and clearly listed in each section. The margins are always manually entered values, allowing the Systems engineer flexibility to adjust them appropriately depending on the margins used by the subsystems.

Typical values of preliminary design margins range from 25% for new equipment to 5% for known hardware [Ref. 8:p. 317]. According to Joseph Aguilar of The Aerospace Corporation, the margins for conceptual design, which takes place in the CDC, should not fall below 25%. The decision must be made early in the design process as to the use of margins by the subsystems in order to ensure proper use of this critical design factor. In the SDC, the subsystem component lists may be used for general design guidance where available. However, the design team should take into consideration that The Aerospace Corporation generally does not specify hardware at the component level.

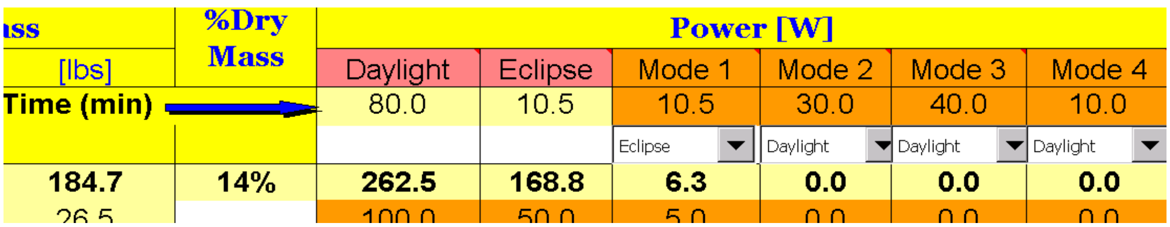
The ***Satellite Summary*** section calculates the End of Life (EOL) power for each mode based on the subsystem inputs and lists the Beginning of Life (BOL) power from the Power subsystem. EOL power is the power required for proper mission performance at the end of the spacecraft design life, and is the average power that determines the size of the power source [Ref. 8:p. 407]. BOL power is the amount necessary to reach EOL power taking into account degradation effects over the design life of the spacecraft. Degradation effects can reduce BOL power over the life of the satellite by up to 30% [Ref. 8:p. 315]. The section also calculates the dry mass of the entire satellite (spacecraft plus payload), the wet mass using input from the *Propulsion* subsystem, and the launch mass including the adapter mass obtained from the *Structures* subsystem. Useful calculations are made in the comments section, including dry mass without contingencies and on-orbit mass as a percentage of wet mass.

Satellite Summary					
EOL Power				**1252.7**	**540.1**
BOL Power				**2000.0**	
Dry Mass	**583.2**	**1285.9**			
Orbit Insertion Propellant	0.0	0.0			
On-Orbit Propellant	0.2	0.4			
Pressurant	0.0	0.0			
Wet Mass	**583.4**	**1286.3**			
Adapter	17.9	39.5			
Launch Mass	**601.3**	**1325.8**			
# of s/c per launch	1				
Launch Vehicle					
Performance	**2500.0**	**5512.5**			
Launch Vehicle Wgt. Margin	**1898.7**	**4186.7**			
Launch Vehicle % Margin			**75.9%**		

Figure 4.8 Satellite Summary section.

The drop down box below launch mass will adjust the mass according to the number of s/c that will be launched simultaneously. This assumes each spacecraft is identical across subsystem masses.

The *Power* section was modified to calculate the total time spent in daylight and eclipse from the Mode 1-4 columns, whose titles may be modified to more accurately reflect the power states of the spacecraft. The time in minutes spent in each mode is manually entered in the orange cells directly below the Mode 1-4 cells, with the appropriate titles selected from the dropdown boxes.



ass	%Dry Mass	Power [W]					
[lbs]		Daylight	Eclipse	Mode 1	Mode 2	Mode 3	Mode 4
Time (min)		80.0	10.5	10.5	30.0	40.0	10.0
				Eclipse	Daylight	Daylight	Daylight
184.7	14%	262.5	168.8	6.3	0.0	0.0	0.0
26.5		100.0	50.0	5.0	0.0	0.0	0.0

Figure 4.9 Total time spent in daylight and eclipse.

The dropdown boxes are linked to the highlighted area in the comments section. The *Daylight* and *Eclipse Time* cells sum those modes that are daylight or eclipse, respectively, across the *Power* section according to the status of the drop down boxes. This effectively creates a referenced association between the orbital power requirements and the times they will be needed. The orbital period must completely be accounted for when entering values in the time cells. For example, four possible modes consist of *standby*, *tracking*, *downloading*, and *recording*. The *standby* mode may be used as a "catch-all" which includes time not specifically accounted for in the other modes. With a ninety-minute orbital period, thirty may be spent in tracking and recording, and thirty in downloading. This would leave thirty minutes for the standby mode, regardless of whether the time spent in it was in daylight or eclipse. The total time that the spacecraft spends in daylight and eclipse is compared against a backup calculation at the top of the comments section based on the maximum eclipse and orbital period times from the *Astrodynamics/Orbit* subsystem, ensuring the entire orbital cycle is accounted for. The average eclipse times are assumed to be near maximum during the spacecraft life, giving the appropriate scenario for design analysis [Ref. 8:p. 107]. It is important to note that the subsystem power and mode outputs must match the format of the Summary worksheet. This must be monitored by the Systems engineer and coordinated prior to the design session.

The *NASA TRL* column lists each of the payload or subsystem Technology Readiness Levels (TRL's), with the TRL associated with the *Payload* and *Spacecraft* totals rows as the minimum of their respective sections. This gives the subsystems engineer a quick reference towards reliability and risk, as it is not explicitly considered in the CDC software. With the lowest subsystem TRL taken as definitive for the design, this feature leans towards the conservative. As seen in Figure 4.14, as TRL number increases, so does technology readiness. This also allows the team to assess the impact of technology insertion on their design, both in capability of the spacecraft and inherent risk. The TRL's estimate the cost risk due to technical difficulties inherent in development. Categories 1 and 2 are high risk, 3 through 5 moderate, and 6 through 8 low [Ref. 8:p. 804]. TRL's as applied to the CDC process are explained in more detail later in this chapter.

The ***Convergence*** section was added to the base CDC software by the author since The Aerospace Corporation expressed interest in this capability. It allows the design team to track mass and power as the design is iterated, as well as graphically witness the affect of subsystem changes. The mass and power history are critical sources of information for the systems engineer as the design will begin to converge around an optimum launch mass for a particular configuration. This will in turn signal the systems engineer that the design may be near completion for the configuration chosen. Controls for calculation of the percentage change of mass and power values from one update to the next were added by the author in order to realize design convergence more quickly. The Update button is simply a copy of the same button at the top of the sheet, placed strategically to allow an update from this section. All of the buttons may be rearranged on the sheet by right-clicking on them and moving them to a different location if the systems engineer decides to do so.

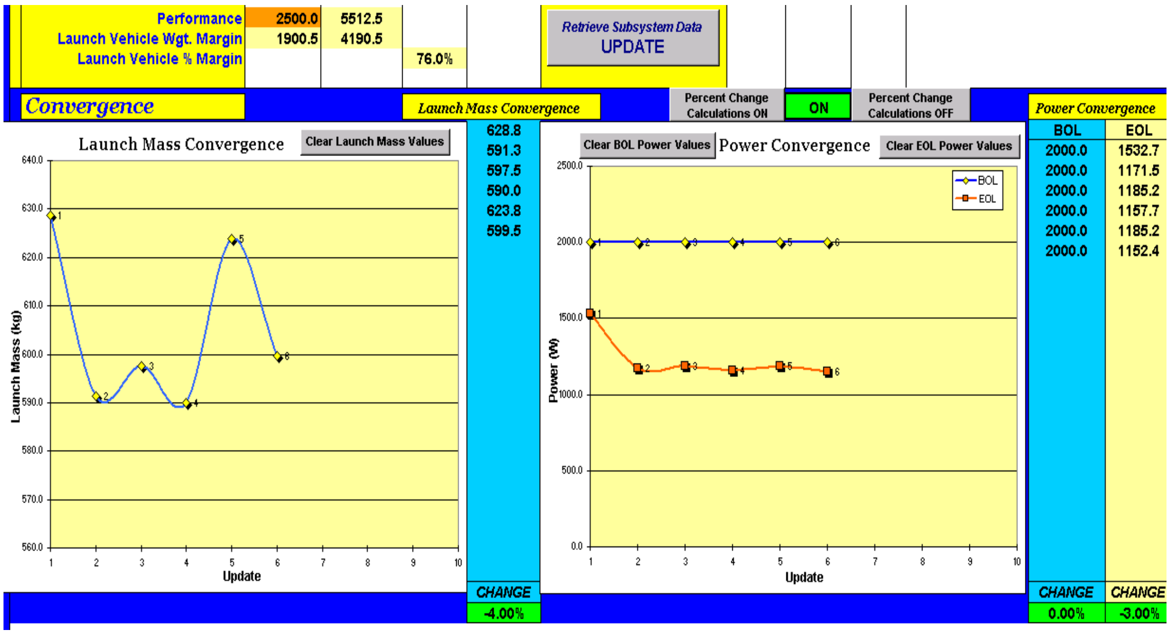


Figure 4.10 Convergence section.

As the CDC Systems subsystem exists today at The Aerospace Corporation, no analytical capability is included to determine quantitatively that the design iteration may be stopped. Instead, systems engineers rely on handwritten tracking of mass values and use only their experience to guide them towards moving on to another configuration. In order to enhance the systems engineer's knowledge and situational awareness of the design during the process, the charts graphically show the trends in mass and power as they change with iteration. The controls allow values to be cleared from the columns, percentage calculations to be turned on and off, and an update to be performed directly from this section of the sheet. This also provides a powerful educational tool for the Space Systems Engineering curriculum, as students may receive immediate feedback on the impact of subsystem changes on the overall design.

Studies of convergence may lead to a significant decrease in design time if they reveal that a certain percentage change between designs is found to be optimum. Studies may also be done on the relationship between mass and power convergences in order to reveal their effects on each other during the conceptual design stage. In addition, any other parameters of interest may be monitored during the design in this fashion by a relatively simple copying of the section cells, charts, VBA code and push buttons if desired, and ensuring that they are referenced properly. The previously working section of the worksheet and the associated code would act as the guide to proper arrangement and function. The data gathered from this section over a design or multiple designs may be extremely useful for analysis of trade study impacts, use in presentations and reports, and as a subject for studies on the effectiveness and design capability of the NPS SDC.

The *Percentage Change Calculation ON* and *OFF* buttons operate by enabling the calculation of percentage change differences between the current and previous values of mass and power. When the *ON* button is depressed, the adjacent cell, which acts as a status indicator, changes to green and displays "ON".

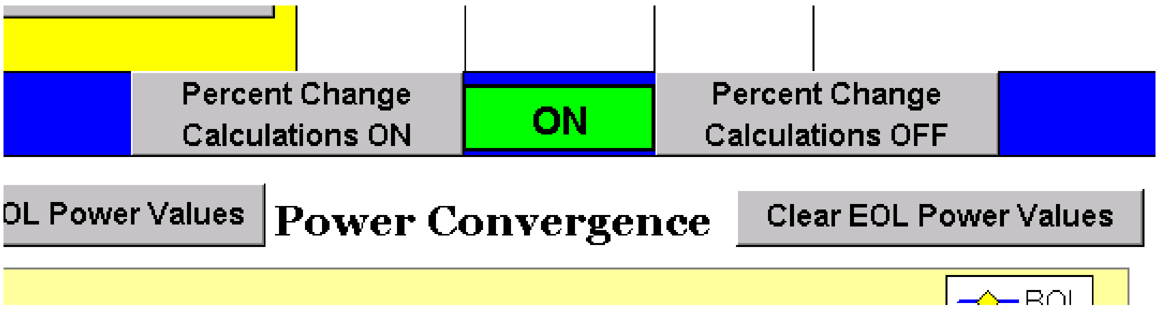


Figure 4.11 Percent Change Calculation controls.

The color of the *CHANGE* data display cell is also set to green and "ON" displayed. The *OFF* button acts in a similar manner, with the color of the cells changing to red to indicate the function has been disabled.

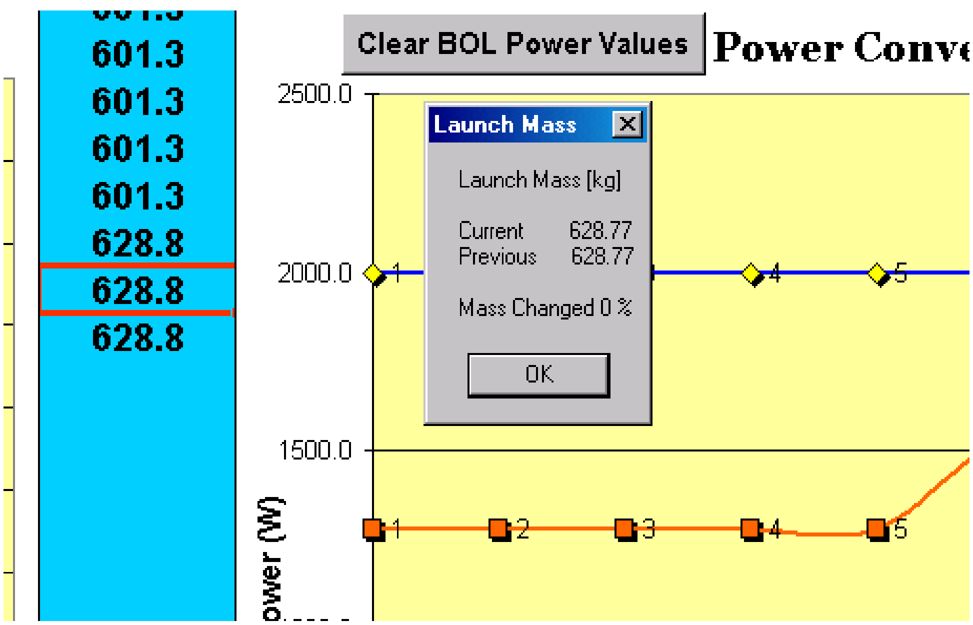


Figure 4.12 Percent change alert.

The code performs the calculation when an update is performed if it is enabled, evidenced by the green "ON" in the status cell. It finds the last two values in each column and displays the difference as a percentage relative to the previous value using the general formula ***(Current-Previous)/Previous***. The values and percentage change are then displayed using message boxes in order to quickly and clearly alert the Systems engineer to the changes and are then placed in the appropriate *CHANGE* data display cell. The *CHANGE* data display cell is manually formatted to display the value as a percentage, while the formatting for the message box alerts is done in the VBA code. The *OFF* button inhibits the performance of the calculations. When the *ON* button is depressed during the iterative process, the last calculated value of percent change is replaced with "ON" in the data display cell beneath the respective columns. The raw code and associated comments may be found within the VBA code section of this document.

Since the functionality is embedded in the update macro, each time the Update button is pressed the new value of launch mass and EOL/BOL power are taken from the Launch Mass cell and the EOL/BOL Power cells and written to the appropriate columns. The columns are linked as the data source for the charts, thus updating the chart automatically. When a new study begins or it becomes necessary to clear the charts at any time, the *Launch Mass Convergence* and *Power Convergence* columns (chart source columns) can be cleared of data by depressing the *Clear* button corresponding to the column of interest. The function may also be performed by activating the cells of interest, right clicking, and using the *Clear Contents* operation. If the button is used to clear the data, it cannot be recovered, while using the *Clear Contents* operation enables recovery using the *Undo* button.

The source data range may be changed by activating the chart of interest, right clicking, selecting *Source Data…*, and modifying the *Data Range* field as appropriate. The source data range is outlined in blue when the chart area is activated. Initially, the source data range is kept relatively small in order for the chart to present the information effectively. As the design is iterated, the source data range may be increased as necessary by activating the chart and dragging the range outlined in blue to the appropriate size. The clear buttons are not available when the chart is active.

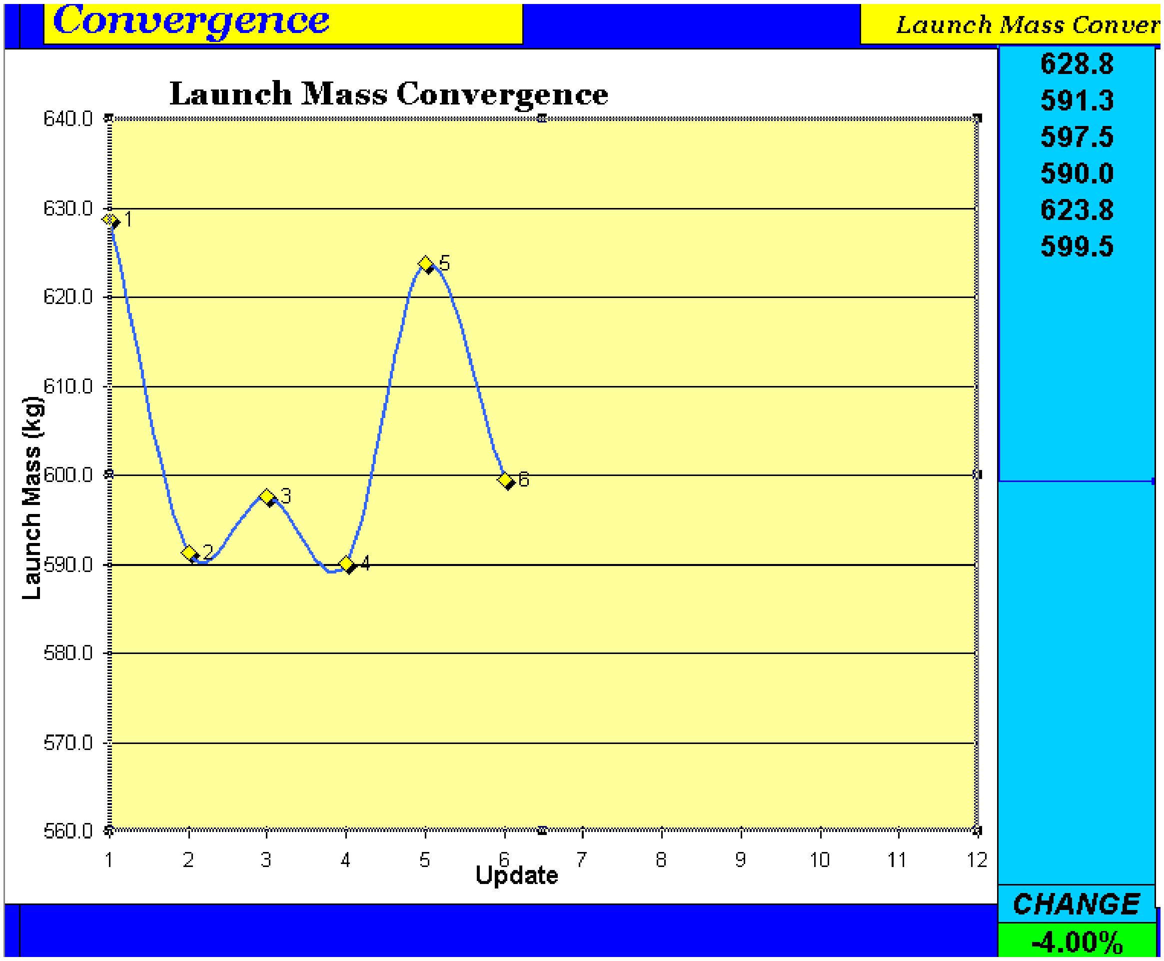


Figure 4.13 Activated Launch Mass Convergence chart.

As the design progresses, the source data range or the plot area should be modified so that the chart displays the data in the most useful manner possible according to the Systems engineer's judgment. For instance, it may be necessary for large fluctuations in values at the outset of a design to maintain the source data range equal to the update number plus one or two. As the variations begin to decrease, the range can be increased to enable the chart to depict the convergence more clearly. This is shown more clearly in Figures 4.14 and 4.15. With the source data range set to update times two, the range affects the chart graphics by appearing to show a relatively large fluctuation, even though the launch mass percent change between updates 5 and 6 is only a decrease of 4% from the previous value.

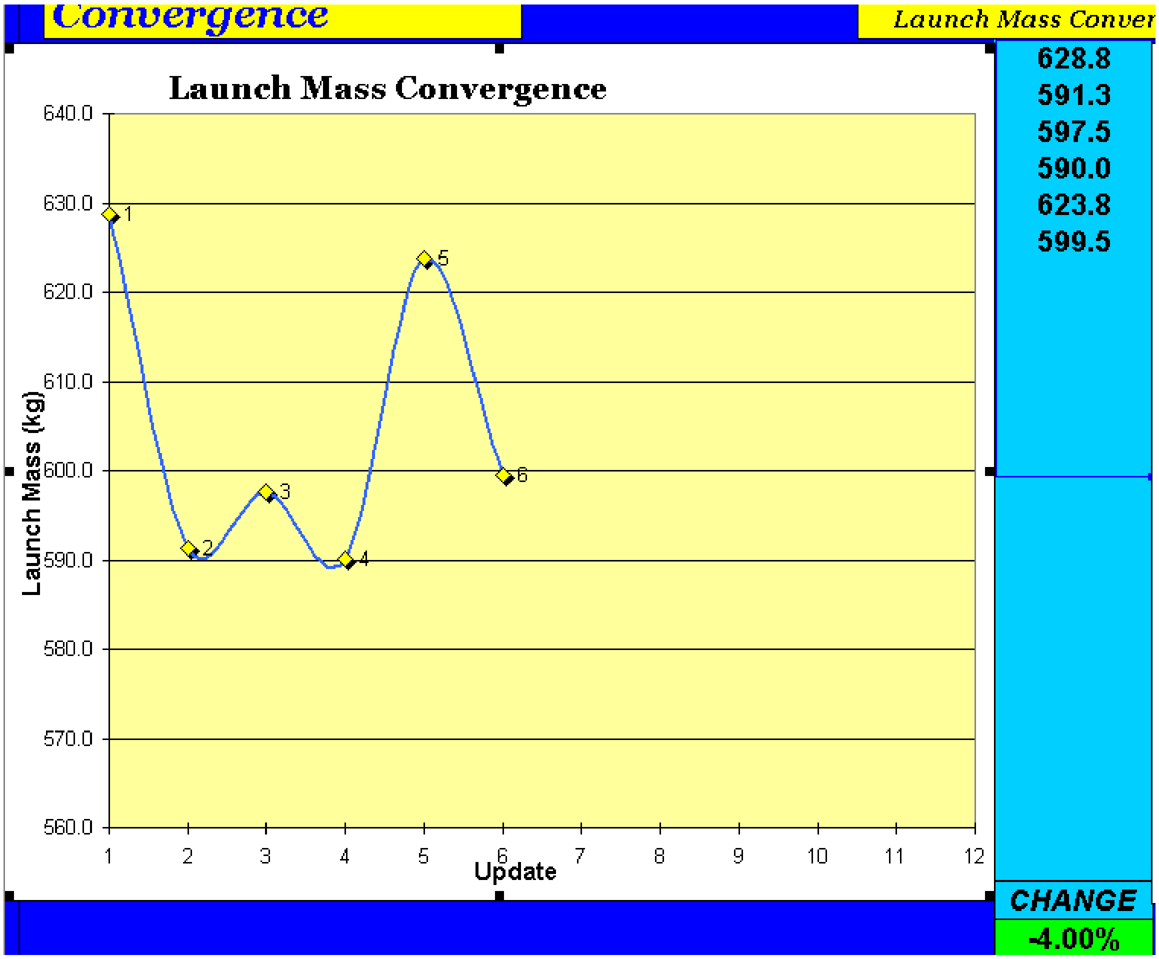


Figure 4.14 Launch Mass Convergence, source range set to update times two.

When the range is changed to a setting of update number times three, the graphic appears to show a much greater variation. This is seen in Figure 4.15, where the data is simply being compressed into a much larger x-axis range. This is evidence that the appearance of the chart is very important and the functionality of the percent change calculations is extremely valuable to quantify the change between iterations. The appearance can also be modified by resizing the plot area. One possible guideline for convergence might be considering the iteration complete when the values stabilize to within 5% or less. For example, a 1000 kg spacecraft may satisfactorily converge if the change in value is within 50 kg for three or four iterations. Long-term experience with adjusting the plot area and proper use of the percent change feature may help to establish a confident rule of thumb to follow. The use of design margins and their values should also be considered when assessing the convergence of a design.

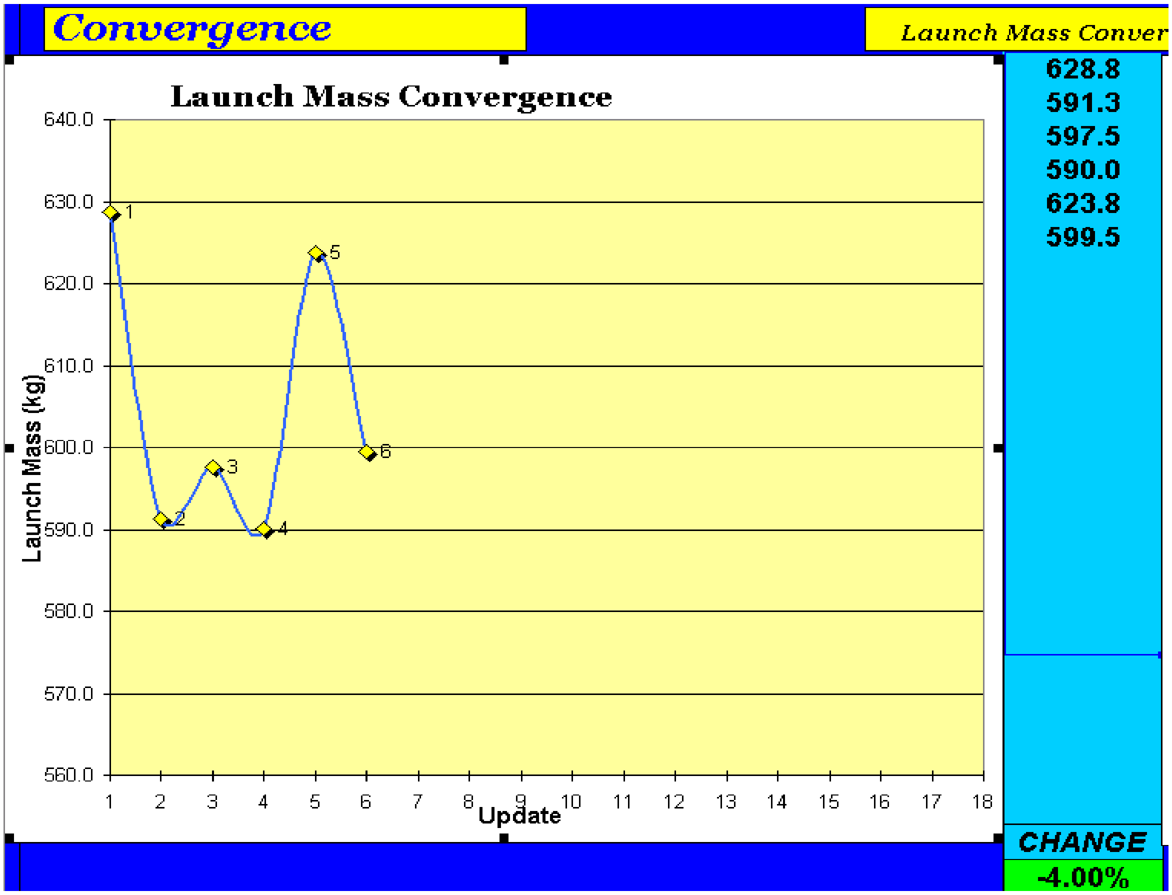
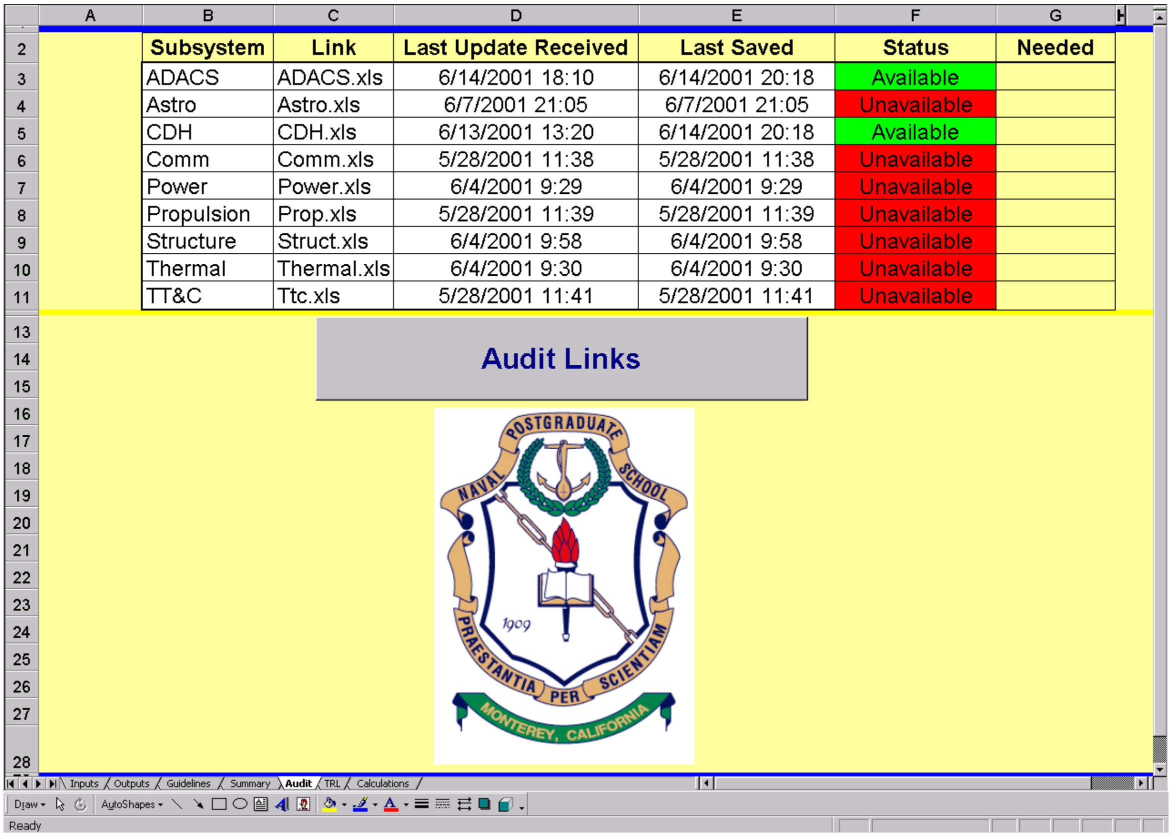


Figure 4.15 Launch Mass Convergence, source range set to update times three.

5. Audit

The *Audit* worksheet is used to monitor the status of the subsystems during the design. When the *Audit Links* button is pressed, the latest save time/date stamp for each subsystem is compared to the previous and the Status column is updated appropriately. The list used in the code loop is defined as "linklist" using the Excel capability to assign a name to ranges and manipulate them in various ways. This is currently set to the list of workbooks as shown in the Link column of Figure 4.16 and may be viewed using the

Insert-Name-Define operation from the toolbar and selecting the name to see the cell range in the *Refers To* message box. If another workbook is added to the CDC software the list must be modified and the new workbook incorporated into the data flow. A row may be inserted and the range updated to include the new workbook, necessitating the graphic formatting of the new cells to be updated to match the rest of the sheet. The VBA code in the *AuditLinks* macro must then be modified to ensure the ranges are referenced correctly and effect proper operation. See the Appendix C for details on proper functioning.



Subsystem	Link	Last Update Received	Last Saved	Status	Needed
ADACS	ADACS.xls	6/14/2001 18:10	6/14/2001 20:18	Available	
Astro	Astro.xls	6/7/2001 21:05	6/7/2001 21:05	Unavailable	
CDH	CDH.xls	6/13/2001 13:20	6/14/2001 20:18	Available	
Comm	Comm.xls	5/28/2001 11:38	5/28/2001 11:38	Unavailable	
Power	Power.xls	6/4/2001 9:29	6/4/2001 9:29	Unavailable	
Propulsion	Prop.xls	5/28/2001 11:39	5/28/2001 11:39	Unavailable	
Structure	Struct.xls	6/4/2001 9:58	6/4/2001 9:58	Unavailable	
Thermal	Thermal.xls	6/4/2001 9:30	6/4/2001 9:30	Unavailable	
TT&C	Ttc.xls	5/28/2001 11:41	5/28/2001 11:41	Unavailable	

Figure 4.16 Audit sheet.

6. TRL

The Technology Readiness Level sheet provides a quick reference to the NASA guidelines for technology readiness, as shown in Figure 4.17.

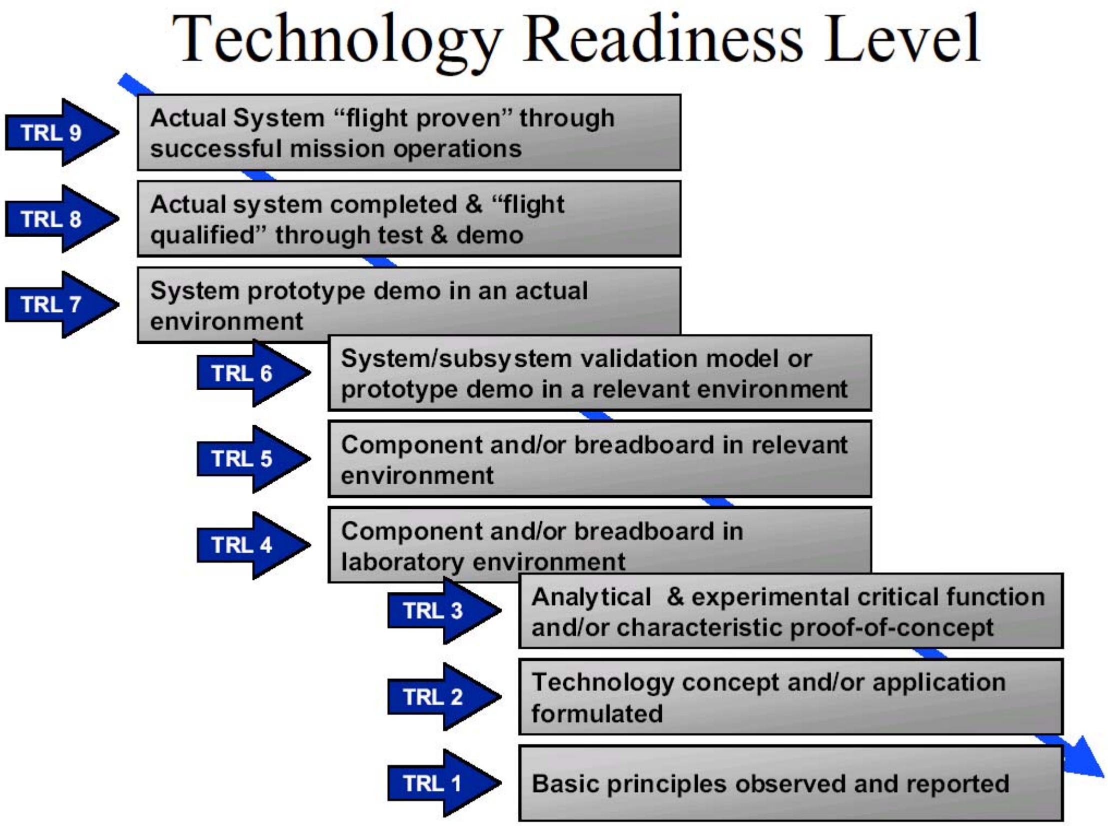


Figure 4.17 NASA TRL Levels (From: Ref. 4). Arrow denotes increasing risk.

This is used as a guide by each subsystem throughout the design process. The TRL's offer a reference to risk and reliability, since they quantify the level of development of the spacecraft components. Each subsystem engineer is responsible for applying the TRL's appropriately within their workbooks and ensuring their outputs accurately reflect the design. For the systems engineer's reference, a white paper explaining TRL's in detail, in picture format, is included in the TRL sheet [Ref. 4].

7. Calculations

The Calculations sheet is intended to be a scratch sheet for miscellaneous calculations that the systems engineer wishes to conduct separately from the other sheets. This sheet can also be used to link values to the summary sheet for drop-down boxes, formulas, or other uses.

C. SOLIDWORKS™ AND DRAWCRAFT INTEGRATION

The capabilities of the solid modeling tools installed in the SDC are significant in their impact on the design process. SolidWorks™ is a solid modeling tool used to create 3-D models that is integrated into the SDC along with DrawCraft, a software tool that interfaces with SolidWorks™, and which was obtained by the author courtesy of the California Institute of Technology.

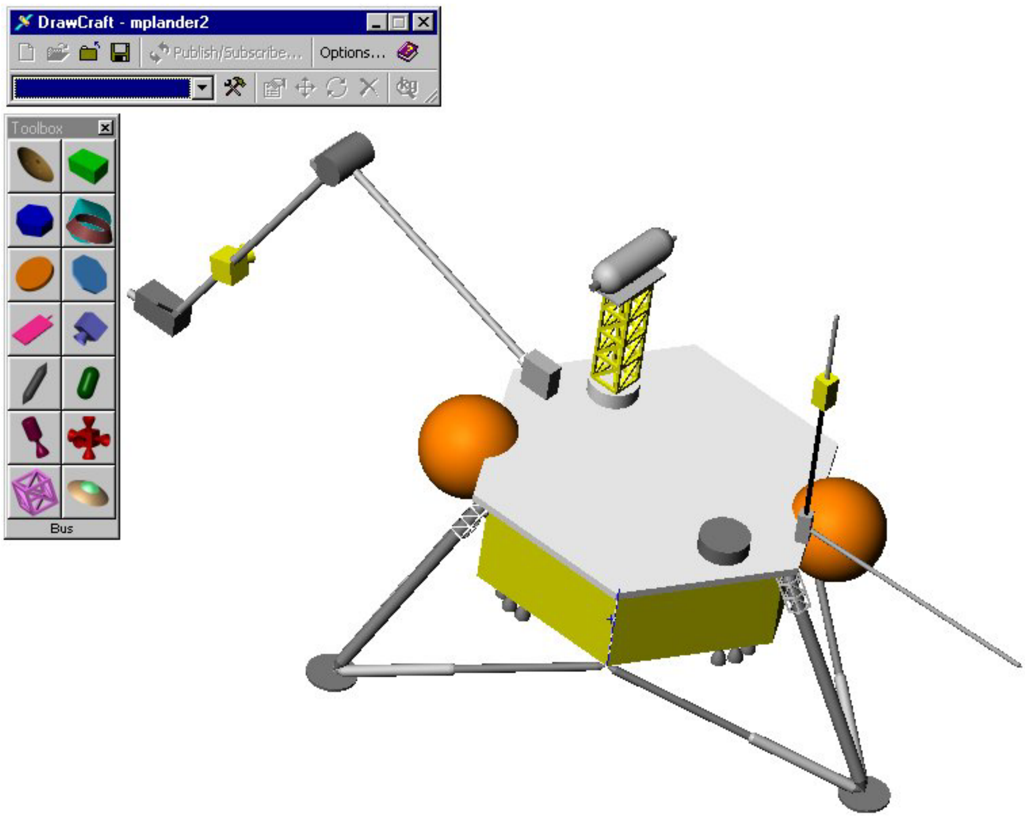


Figure 4.18 Mars Polar Lander model created by Caltech.

The DrawCraft software can be used to rapidly create a basic spacecraft from a toolbar of definable simple parts. The Aerospace Corporation has also provided SolidWorks™ models for use in the SDC, consisting of launch vehicle fairings and basic spacecraft components, which can be used alone or via the DrawCraft software. The software comes with a basic User's Guide that enables the Structures/Configuration engineer to quickly learn to use the tool. The software interfaces with SolidWorks™ through the Application Programming Interface (API) included with the SolidWorks™ program. After the basic spacecraft parts and assembly are created, they may be added to or modified using either the normal SolidWorks™ software interface or the DrawCraft interface. The DrawCraft interface allows the addition of custom objects, which would include The Aerospace Corporation components. Custom objects are parts that have been previously created within SolidWorks™. The DrawCraft User's Guide provides adequate guidance on how to use the tool, and the SolidWorks™ help resource is considerable in scope and application. The basic components that come with the DrawCraft software are also directly accessible via the SolidWorks™ software itself.

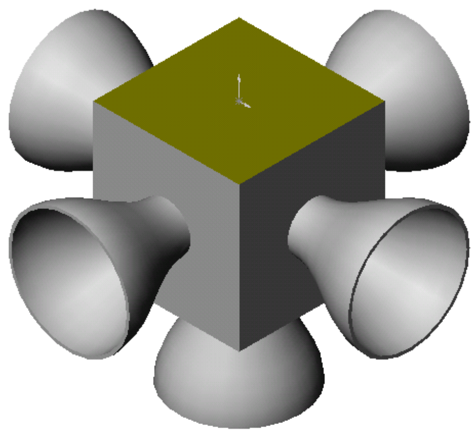


Figure 4.19 Thruster cluster created in SolidWorks™ with DrawCraft.

One of the most powerful aspects of using SolidWorks™ is that upon modification of a part dimension, the assembly is able to automatically update based on the change. The Structures/Configuration engineer must ensure the proper relationships exist between the parts of the assembly. The DrawCraft tool offers an interface that will automatically mate the parts properly to the main bus when initially created and allow the addition of a custom object, or part, that has previously been created in SolidWorks™.

In SolidWorks™, modification of a generic DrawCraft part is accomplished by double-clicking on the part of interest and changing its dimensions, then performing a rebuild by pressing the *Rebuild* icon on the SolidWorks™ toolbar. There may be parts created by the DrawCraft tool that are based on equations to size the parameters of the object. If it is necessary to modify these in SolidWorks™, the *Equations* label in the part property area of the screen may be used to access the equations in order to determine which dimension is driving the part. Once this is determined, the side or face of the part containing that dimension may be double-clicked, modified, and rebuilt, with all other dimensions of the part updating as necessary. If any part being modified is set to read-only, the program will not allow modifications. In this case, the part must be activated, its properties accessed by right-clicking, and the read-only check box deactivated. The dimensions can then be modified and the program will maintain the relationships between parts in the assembly.

Though it contains minor technical errors, the DrawCraft tutorial enables rapid learning for the tool, allowing a simple spacecraft to be built using the tool in only a few hours. The thruster cluster depicted in Figure 4.19 is one example of parts that are available to be automatically dimensioned and mated within an assembly. Also included are antennas, trusses, propellant tanks, and solar arrays. The tutorial allows the creation of a basic spacecraft in just a few hours, providing a very powerful tool for the SDC and the spacecraft design team when added to the capabilities of SolidWorks™ itself.

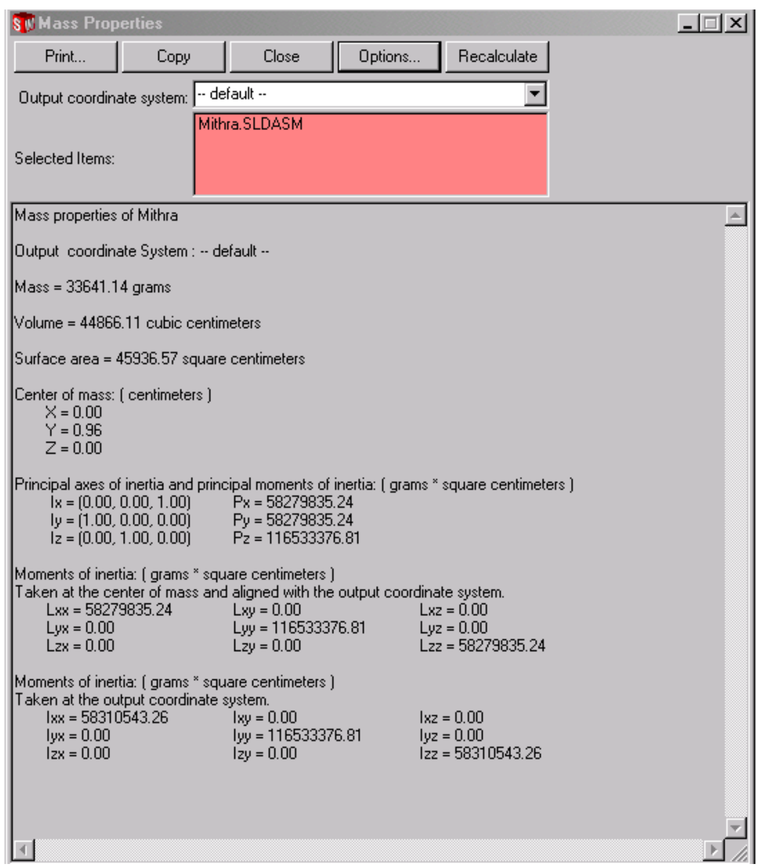


Figure 4.20 SolidWorks™ Mass Properties.

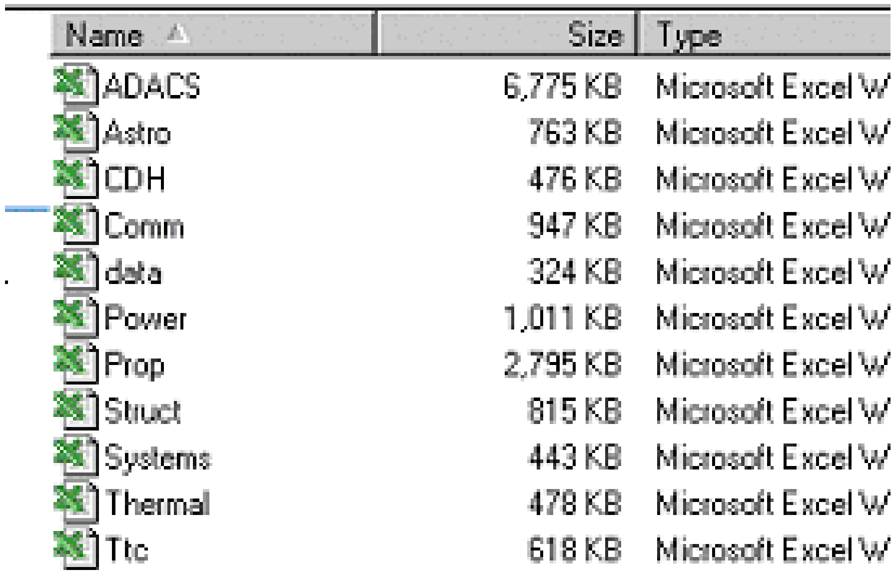
Mass properties may be accessed using the *Tools* command from the SolidWorks™ toolbar. It is important to remember that SolidWorks™ provides for a generic density to be entered for each part in the assembly and the mass properties of each part to be viewed independently. When the mass properties for the entire assembly are calculated, they will be displayed with the density option disabled. Care must be taken to identify the coordinate system for the data in order to properly interface and crosscheck with the Attitude Determination and Control subsystem.

The DrawCraft interface allows a mass to be entered for each part, which in turn is used as input into the mass properties calculations. The solid model created may be saved in a file format compatible with Finite Element Analysis (FEA) programs at any stage in the process. This enables rapid availability of the model for FEA where in previous design classes the FEA could not take place until the final configuration was set. As the configuration changes, the Structures/Configuration engineer can save a new copy of the model in either of the most popular formats, International Graphics Exchange System (IGES) or Standard Exchange Protocol (STEP). These may then be imported for analysis into programs such as SDRC's I-DEAS, available on the NPS network from the Mechanical Engineering department server.

D. CDC DATA TRANSFER AND CONTROL ARCHITECTURE

1. File and Link Structure

The file structure of the CDC software tool as installed in the SDC consists of all Excel workbooks that make up the suite residing in the same folder. This folder must be accessible by all team members in order to facilitate ease of maintenance and control of design configuration archiving. The shared path for all links in the tool's system is *D:\\Aerospace Tools\CDC* on the computer *Endeavor*. Only the base systems and subsystem workbooks should be included in this folder.



Name	Size	Type
ADACS	6,775 KB	Microsoft Excel W
Astro	763 KB	Microsoft Excel W
CDH	476 KB	Microsoft Excel W
Comm	947 KB	Microsoft Excel W
data	324 KB	Microsoft Excel W
Power	1,011 KB	Microsoft Excel W
Prop	2,795 KB	Microsoft Excel W
Struct	815 KB	Microsoft Excel W
Systems	443 KB	Microsoft Excel W
Thermal	478 KB	Microsoft Excel W
Ttc	618 KB	Microsoft Excel W

Figure 4.21 Workbooks in D:\\Aerospace Tools\CDC.

All other links to workbooks or programs should reside somewhere other than within the CDC software folder. The folder may be located anywhere on the network as long as it can be accessed by all team members easily and the links in each subsystem are pointed to the correct folder. All team members should be responsible for ensuring that all links to their workbook are functioning as necessary, including those links to workbooks other than included in the workbook folder. Archiving designs is accomplished by creating a new folder under Aerospace Tools with the design title or other identifying information, copying all workbooks in the base CDC workbook folder, and pasting them to the new archive folder. The base CDC workbooks may then continue to reside in the same folder and to be used with little concern over corruption by removal of workbooks. Additional subsystem workbooks may be added to this folder if necessary.

The link structure is simple, but affords a great deal of capability. Each subsystem workbook's Outputs sheet is linked, to a row depth of approximately 300 rows, directly to the Systems Inputs sheet in the appropriate areas. This was accomplished using the *Copy* and *Paste Special-Paste Links* operation.

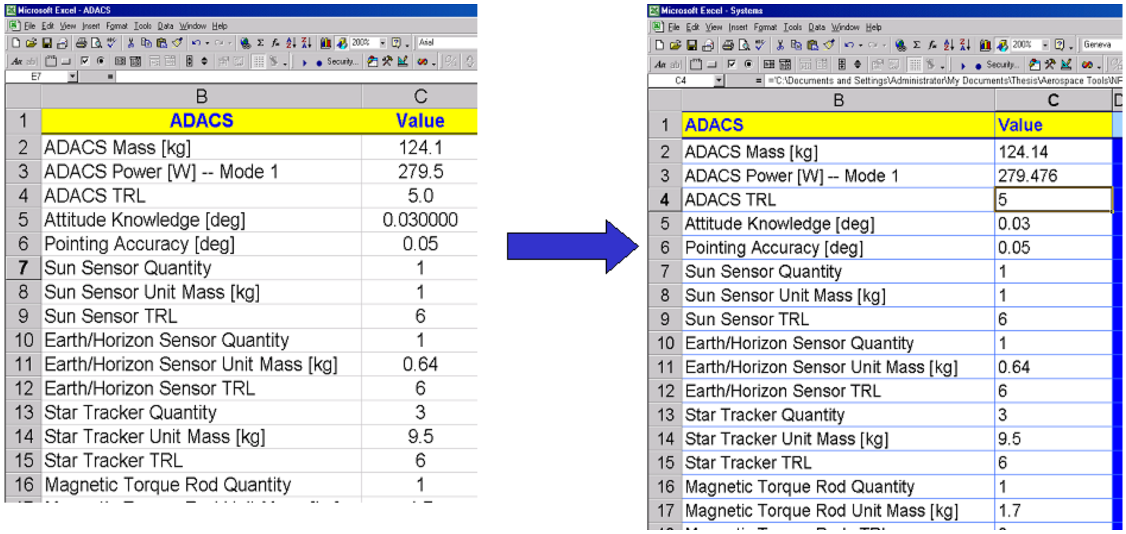


Figure 4.22 Subsystem Output sheet to Systems Input sheet.

The number of rows was chosen by the author by taking into consideration the longest output sheet of all subsystems included in the original CDC tool, Communications, adding a small margin, and assuming all other subsystems would not grow greater than 300 rows in any design taking place within the NPS SDC. As the number of linked rows increases, the time to execute the updates increases as well. The local formatting of each workbook applies to the linked data.

2. Data Flow Architecture

The CDC data control architecture consists of cells within worksheets, as well as entire worksheets, which utilize the linking properties included in the Microsoft Excel spreadsheet software. The control over most of the executable code rests in the Systems workbook, with the Summary sheet containing the majority of the functions. The actions that control the data transfer rely on a synergistic, coordinated set of commands executed at flexible time intervals that are promulgated by the Systems engineer. The *Audit* or *Save* actions may be used at any time without negative effects, since they do not affect the majority of executable code.

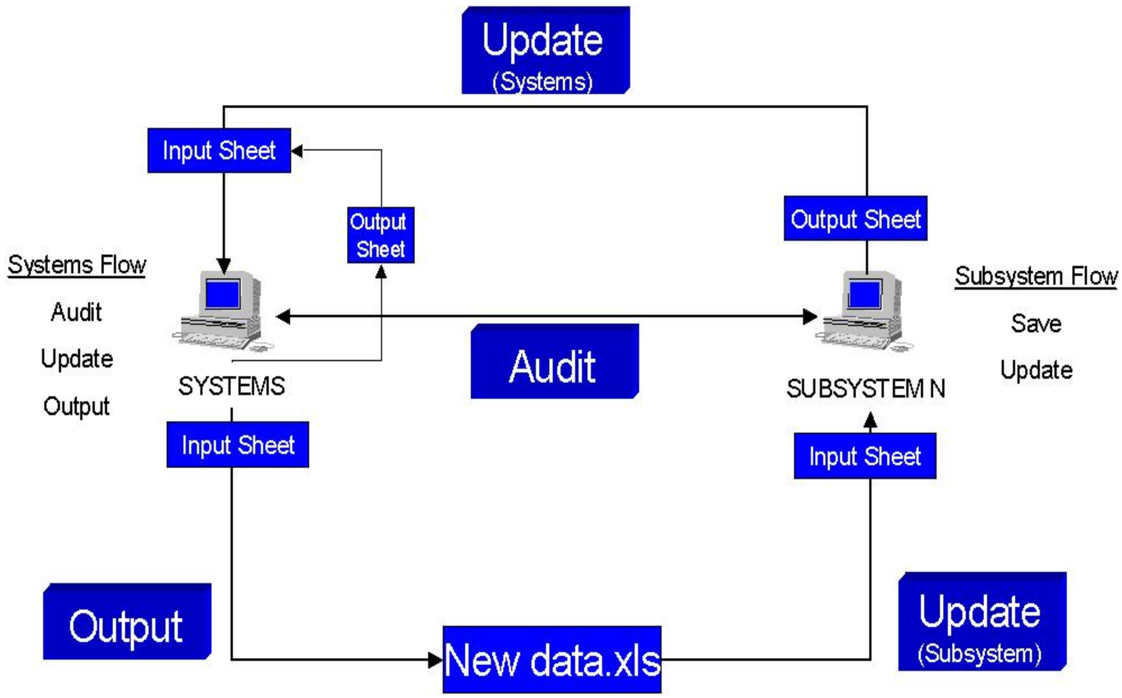


Figure 4.23 CDC Data Transfer and Control Architecture

The Audit button is used to determine when the subsystems of interest have completed a save, signaling to the Systems engineer that an update may be warranted. When the *UPDATE* button is pressed, the update macro is executed. All subsystem links to the input sheet are updated, including the Output sheet of the Systems workbook. The code then modifies the Systems Summary sheet as described earlier.

The *OUTPUT* button is depressed when the Systems engineer has examined the data and is prepared to send it to the subsystems. This deletes the data workbook and copies the *Systems Inputs* sheet into a new one. This is done in order to allow subsystems the flexibility, since an automatic transfer directly to them could interrupt their current calculations. When the subsystems are ready to receive the new data, the *Update External Data* button on their sheets is used to place it in their own Inputs sheet.

3. Modifying Links, Adding Workbooks and Sheets

The links are controlled by the *Edit-Links…* operation as used from the command bar. The *Links* message box shows all links to the current workbook and gives the user options to execute on them. If it is desired to add another workbook to the inputs sheet, it must first reside in the Models folder wherever the CDC software is being run from.

Modification may then be accomplished by opening both workbooks simultaneously and using the *Copy-Paste Special-Paste Links* operation using the right-click method. When pasting, activate only the upper left cell of the range desired to paste into, and the program will automatically paste to the proper range. Care must be taken to paste only the exact ranges necessary for proper linking, full row, column, or sheet linking can exceed the system memory. Once this is accomplished, the new link will appear in the in the *Links* box when it is next checked. The *Audit* sheet linklist must also be modified, as noted earlier in this guide in the sheet description, to include the new link for automatic update when the update is performed. For more information on using the Links controls, use the MS Excel help documentation.

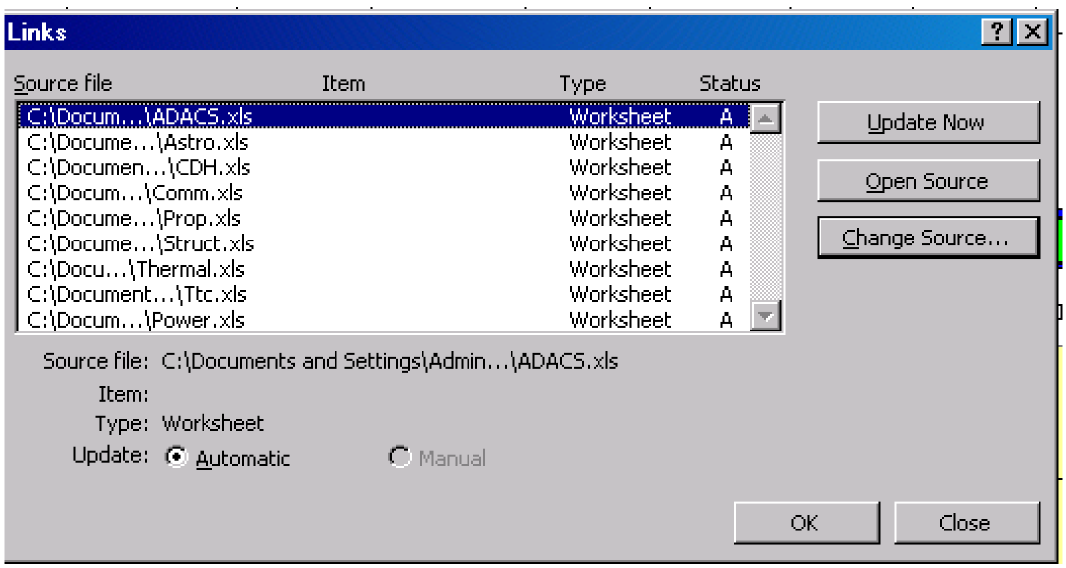


Figure 4.24 Links control box.

When checking proper operation of the links by executing code (using any of the control button in the CDC), ensure only the workbook that is executing the code is open. Any other open workbook that is linked to the active workbook will cause an error in the link update procedure.

If changes are made to any workbook in the CDC with regard to Excel link sources, such as graphing or database workbooks, those links may be updated separate from the data.xls workbook using the *Edit-Links…Update Now* operation on the link of interest. Sheets may be added to any workbook in the CDC, and any cells may be linked to the Outputs sheet, which will then be automatically included in the Systems Inputs sheets upon the next update. This is the easiest way to include parameters which other subsystems may find useful. If it is necessary to remove output parameters, ensure the entire row is deleted so no gaps in parameters or values remain.

4. Cautions

The proper operation of the CDC relies on control of modifications to links and their sources for all workbooks, as well as control of modification to the VBA code. The links are affected when adding or deleting linked ranges or modifying existing ones. The code is affected when recording new macros to perform an operation, or by manual changes. New macros are stored in a new subroutine module that can be viewed on the left side of the screen when using the Visual Basic Editor, which is available directly from the command bar or by using the *Tools-Macro-Visual Basic Editor* operation. The editor contains an extensive help resource that is extremely valuable when adding to or modifying the code. If any modifications are made, it is suggested that the entire *Models* folder be copied to another folder and revised therein, leaving the original CDC software in place and operational until replacement is warranted, only after extensive testing of the new code.

The subsystems require diligence in learning their powerful features and functions before use. Any modifications to the workbooks themselves, especially any VBA code within them, must be done with a backup copy. NPS SDC users may add sheets as necessary to the original CDC workbooks in order to improve their functionality, as long as the existing functionality of all other sheets is not corrupted.

E. VISUAL BASIC FOR APPLICATIONS (VBA) CODE

1. Overview

VBA is a productivity-oriented tool development program that is included in all MS Office applications. Its flexibility and powerful functionality allow engineers to rapidly develop powerful GUI's, which are crucial to the presentation and conveyance of data in the concurrent engineering process. The following sections provide a brief description of each section, with the details of its operation found in the code comments, as attached to this document.

The original code was documented and modified extensively over a period of two months in order to enhance the functionality of the overall CDC software and the Systems workbook. The overall intent is to allow control of data flow to reside within the Systems workbook and provide a means for flexible, rapid, and clear data presentation and manipulation in order to enhance the Systems engineer's, as well as each team member's, overall situational awareness of the design. The code was in serious need of documentation, as well as functionality enhancement. The original code provided little documentation on program flow, necessitating the addition of extensive comments to the code as changes and additions were made.

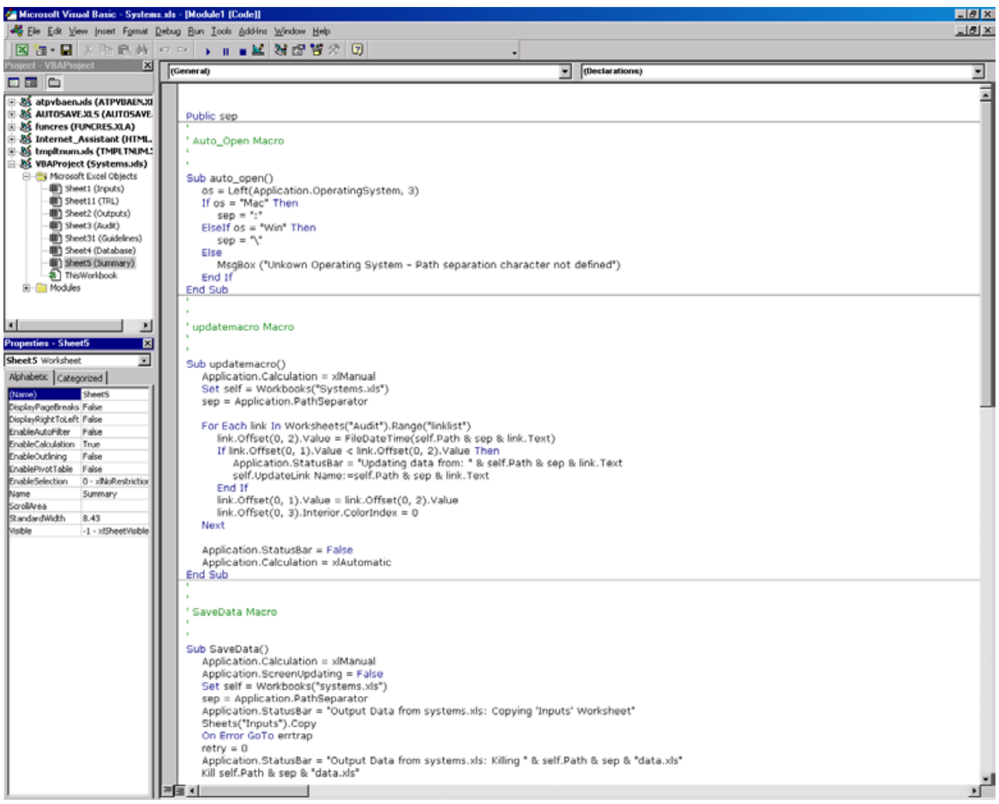


Figure 4.25 First section of VBA code before modification.

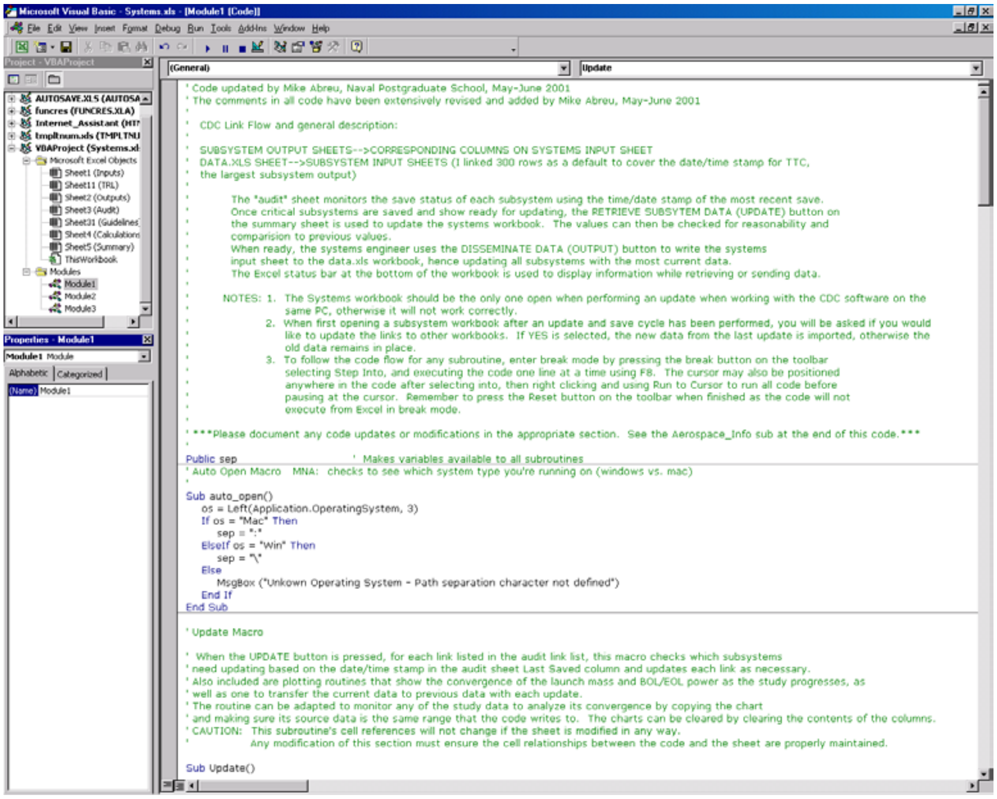


Figure 4.26 First section of code after modification.

The main source of control flows from the *Update* subroutine, which calls other subroutines as it executes and contains most of the executable code for the Systems workbook. The preamble to the code provides notes and general operation information for quick reference when studying the code. Figures 4.25 and 4.26 compare the first few sections of the code before and after modification.

2. Auto Open Macro

The CDC tool can be run on Mac workstations. Upon opening of the Systems workbook, this subroutine checks to see which operating system is in use. It then sets the directory path separator as the "\" symbol for Windows, which is used in the SDC. The *Pub* declaration makes the path separator available to all modules for delineation of file paths within the code.

```
Public sep                    ' Makes variables available to all subroutines
' Auto Open Macro   MNA:  checks to see which system type you're running on (windows vs. mac)
'
Sub auto_open()
    os = Left(Application.OperatingSystem, 3)
    If os = "Mac" Then
        sep = ":"
    ElseIf os = "Win" Then
        sep = "\"
    Else
        MsgBox ("Unkown Operating System - Path separation character not defined")
    End If
End Sub
```

Figure 4.27 Auto Open macro.

3. Update Macro

An update is performed when the Systems engineer presses the *Update* button on the Summary spreadsheet. This causes the execution of the subroutine, which in turn calls subroutines while executing.

```
' Update Macro

'  When the UPDATE button is pressed, for each link listed in the audit link list, this macro checks which subsystems
' need updating based on the date/time stamp in the audit sheet Last Saved column and updates each link as necessary.
' Also included are plotting routines that show the convergence of the launch mass and BOL/EOL power as the study progresses, as
' well as one to transfer the current data to previous data with each update.
' The routine can be adapted to monitor any of the study data to analyze its convergence by copying the chart
' and making sure its source data is the same range that the code writes to.  The charts can be cleared by clearing the contents of the column
' CAUTION:  This subroutine's cell references will not change if the sheet is modified in any way.
'              Any modification of this section must ensure the cell relationships between the code and the sheet are properly maintained.

Sub Update()

    ' Initially sets variables to the current values since they will be the previous values when the new values come
    ' into the workbook.  It then calls a subroutine to transfer current values to the previous areas.  The previous varables
    ' are used later for percent change calculations.
    ' The "application.calculation=xlAutomatic" enables auto updates all the linked values within the Summary sheet.
    ' It is included to ensure all fields in the Summary sheet are automatically updated when the new data arrives.

Set self = Workbooks("Systems.xls")
    sep = Application.PathSeparator
    Application.Calculation = xlCalculationManual
    Worksheets("Summary").Activate
    LM = ActiveSheet.Range("D76").Value       ' Sets the current values for use later as the previous values after update has taken place.
    EOL = ActiveSheet.Range("G68").Value
    BOL = ActiveSheet.Range("G69").Value
    Current_to_Previous1                         ' Copies the values from the current areas of the input section of the summary sheet
    Application.Calculation = xlAutomatic        ' to the previous areas and allows any values that change to be updated automatically
                                                 ' throughout the workbook.
    ' Check date/time stamps from the Audit sheet and update links from subsystems if necessary.
    For Each link In Worksheets("Audit").Range("linklist")
        link.Offset(0, 2).Value = FileDateTime(self.Path & sep & link.Text)
            If link.Offset(0, 1).Value < link.Offset(0, 2).Value Then
                Application.StatusBar = "Updating data from: " & self.Path & sep & link.Text
                self.UpdateLink Name:=self.Path & sep & link.Text
            End If
        link.Offset(0, 1).Value = link.Offset(0, 2).Value     ' Replaces the old last update received with the last saved date/time stamp.
        link.Offset(0, 3).Interior.ColorIndex = 3             ' The value will be the last time the update button was pressed.
        link.Offset(0, 3).Value = "Unavailable"
    Next
```

Figure 4.28 Update subroutine, beginning section.

When the code is executed, it sets the path separator for Windows, activates the Summary sheet, and assigns the current values of launch mass and BOL/EOL power to variables for use after insertion of the new data, at which point they will be considered the previous values. In order to prevent any cell automatic updating to occur, the automatic calculation property of the worksheet is disabled. The *Current_to_Previous* subroutine is called to copy the current data for all subsystems to the proper cells, with automatic calculation then re-enabled so that when the links are updated the new values propagate throughout the sheet.

```
 ' Adds current values to the convergence section by finding the first empty cell in each convergence column and copying the appropriate value to it.
 With Worksheets("Summary").Range("G84:G115")
 Set mass = .Find("", LookIn:=xlValues)
 End With
 mass.Value = ActiveSheet.Range("D76").Value
 'self.Worksheets("Summary").Cells(76, 4)   ' MNA: Writes the updated launch mass to the first empty cell found, hence updating the plot.

 With Worksheets("Summary").Range("P84:P115")
 Set BOLPower = .Find("", LookIn:=xlValues)
 End With
 BOLPower.Value = ActiveSheet.Range("G69").Value
 ' MNA: Writes the updated BOL power to the first empty cell found, hence updating the plot.

 With Worksheets("Summary").Range("Q84:Q115")     ' Specifies range of the EOL power convergence column to look in and finds the first empy cell.
 Set EOLPower = .Find("", LookIn:=xlValues)
 End With
 EOLPower.Value = ActiveSheet.Range("G68").Value

 ' This section copies the updated values, calculates the percent change from the previous values, and places the values in the appropriate cells.
 ' It will not execute if the Percent Chance Calculations has been turned off.  It finds the first empty cell in the same manner as above.

'Range("L84") = "ON" Then
 With Worksheets("Summary").Range("G84:G115")
     Set mass1 = .Find("", LookIn:=xlValues)
 End With
 c = mass1.Address                                  ' Selects first empty cell, hops one cell up, and assigns the value to the current variable.
 Range(c).Select
 ActiveCell.Offset(rowoffset:=-1, columnoffset:=0).Activate
 CurrentMass1 = ActiveCell.Value

 If ActiveCell.Address = "$G$85" Then
   LM = "None"
   MPercentChange = 0                               ' Makes sure a division by zero does not occur by checking if the current value is in the first cell of
   GoTo MassFix                                     ' the convergence columns.  This case occurs any time there is not a value in the first cell of the co
 Else
   ActiveCell.Offset(rowoffset:=-1, columnoffset:=0).Activate
   LM = ActiveCell.Value
   MPercentChange = CurrentMass1 - LM               ' If all is well, LM is already set to the previous value.
   MPercentChange = MPercentChange / LM             ' Calculates percentage change from previous value.
   LM = Round(LM, [2])
 End If
assFix:
     CurrentMass1 = Round(CurrentMass1, [2])                   ' Rounds the number to two decimal places.
     MPercentChange = Round(MPercentChange, [2])
     title = "Launch Mass"                                                       ' Displays the alert box.
     msg = "Launch Mass [kg]" & vbCrLf & vbCrLf & "Current       " & CurrentMass1 & vbCrLf & _
     "Previous      " & LM & vbCrLf & vbCrLf & "Mass Changed " & MPercentChange * 100 & " %"
     Response = MsgBox(msg, vbOKOnly, title)

The other two convergence columns work in the same way as above.
 With Worksheets("Summary").Range("P85:P115")    ' Specifies the range of the BOL convergence column to look in and finds the first empy cell.
     Set BOL1 = .Find("", LookIn:=xlValues)
 End With
 d = BOL1.Address
 Range(d).Select
 ActiveCell.Offset(rowoffset:=-1, columnoffset:=0).Activate
```

Figure 4.29 Update macro code.

The links are updated according to their save status as indicated in the Audit worksheet. Each link is updated if the last save time is more recent than the last updated time, and the "Unavailable" alert with its proper color is reset in the status column.

The Convergence section is then modified by the code. The new launch mass and power values are placed in the first empty cell of their convergence columns using the *Find* method, which returns the cell address of the first empty cell. If the percentage calculations are enabled as indicated by the green "ON" status indicator, the code then executes the calculation of mass and power percentage change relative to the previous values. The last entry in the column is assigned as the current value, and the address of that value is checked to determine if it is the address of the first entry. If this is determined, then it is assumed the current update is either the first of the design or the first after the column values have all been cleared. Therefore, the previous values are not considered and variables are set accordingly, with the calculations of percent change bypassed by the *GoTo* command. The code then displays the message boxes appropriate for that situation. If it is determined that the address of the last entry is not the first of the column, then calculations are enabled and the percent change is displayed, along with the current and previous values. This gives the Systems engineer a clear alert to the changes taking place due to the last iteration. The last percentage change values are then placed at the end of the columns for ease of reference. If calculations are not enabled, "OFF" is placed in the change cell and its color changed to red.

Since the chart source data is set to the convergence columns, the charts automatically update. This gives a graphic representation of the data and enables the Systems engineer to assess the impact of design changes during the study. When the columns are cleared using the appropriate buttons, the charts also clear.

4. Save Data Macro

When the *Output* button is pressed, the Systems Input sheet is written to a file called "data.xls". This file is then accessed by the subsystems when they are ready to import the new data by pressing their own *Update* buttons or using the *Update Now* function under the *Edit* command on the toolbar. The operation of the code is fairly easy to discern.

```
' Save Data Macro

' This macro sets the active workbook to Systems, copies the systems input sheet, deletes the previous
' data.xls workbook and saves the systems input sheet to a new data.xls, updating all subsystem input sheets.
' The macro is assigned to the OUTPUT button.
'
Sub SaveData()
    Application.Calculation = xlManual
    Application.ScreenUpdating = False
    Set self = Workbooks("systems.xls")
    sep = Application.PathSeparator
    Application.StatusBar = "Output Data from systems.xls: Copying 'Inputs' and 'Summary' Worksheet"
    Sheets(Array("Inputs", "Summary")).Copy
    On Error GoTo errtrap
    retry = 0
    Application.StatusBar = "Output Data from systems.xls: Killing " & self.Path & sep & "data.xls"
    Kill self.Path & sep & "data.xls"
    Application.StatusBar = "Output Data from systems.xls: Saving new data.xls"
    ActiveWorkbook.SaveAs FileName:=self.Path & sep & "data.xls"
    On Error GoTo 0
    ActiveWorkbook.Close
    Application.StatusBar = False
    Application.Calculation = xlAutomatic
    Application.ScreenUpdating = True
    End

errtrap:
    retry = retry + 1
    Application.StatusBar = "Output Data from systems.xls: " & self.Path & ":data.xls was busy. Retry: " & retry
    Resume
End Sub
```

Figure 4.30 SaveData subroutine.

5. Audit Links Macro

The Systems engineer monitors the save status of the subsystems by running the AuditLinks macro. For each link defined in the link list on the Audit sheet, the code checks the save status to determine if updating is necessary and does so as appropriate. The subroutine was modified from the original by adding text and color displays to indicate the save status of each subsystem in a more easily readable manner.

```vb
' Audit Links Macro

' When the AUDIT button is pressed, the most recent subsytem save date/time stamps are transferred to the Last Saved
' column.  This macro checks that stamp against the last update time stamp (generated when the UPDATE button is pressed)
' and alerts the systems engineer that the subsystem is ready to update if the update stamp is older.
' Link offset 0,1 is Last Update Received and link offset 0,2 is Last Saved.

Sub AuditLinks()
   Dim msg1, msg2 As String
   msg1 = "Available"
   msg2 = "Unavailable"
   Application.Calculation = xlManual
   Application.ScreenUpdating = False
   Application.StatusBar = "Auditing Link Status"
   Set self = Workbooks("systems.xls")
   sep = Application.PathSeparator

   For Each link In Worksheets("audit").Range("linklist")
      link.Offset(0, 2).Value = FileDateTime(self.Path & sep & link.Text)

      If link.Offset(0, 1).Value < link.Offset(0, 2).Value Then         ' Compares latest save time to last save time and
         link.Offset(0, 3).Interior.ColorIndex = 4                      ' sets messages and colors to display in the link status column.
         link.Offset(0, 3) = (msg1)
         link.Offset(0, 3).Font.color = 6
      End If
      If link.Offset(0, 1).Value > link.Offset(0, 2).Value Then
         link.Offset(0, 3).Interior.ColorIndex = 3
         link.Offset(0, 3) = (msg2)
         link.Offset(0, 3).Interior.ColorIndex = 3
      End If
   Next

   Application.StatusBar = False
   Application.ScreenUpdating = True
   Application.Calculation = xlAutomatic
   Worksheets("audit").Select
End Sub
```

Figure 4.31 Audit Links macro.

6. Display Links and Software Information Macros

These simple subroutines add minor, but very useful capabilities to the CDC tool. The *Display Links* button is used to activate the *DisplayLinks* macro, where a *for* loop is used to show a message box for every link to the Systems workbook. This enables the Systems engineer to quickly verify link status if in question. The *Aerospace_Info* macro gives proper credit to the source of the software tool, and offers a way to track modifications to the software, specifically the Systems workbook, by adding dates of modification. The current design class must be aware of the last modifications made to the software in order to determine if updates to capabilities may be in order.

```
' Display Links macro

' MNA:  This macro checks all the links in the active workbooks and displays them for quick reference from the systems summary sheet.
' The links can also be checked using the "Edit-Links" operation from the Edit toolbar.

Sub DisplayLinks()
  alinks = ActiveWorkbook.LinkSources
  If Not IsEmpty(alinks) Then
    For I = 1 To UBound(alinks)
        MsgBox "Link " & I & ":" & Chr(13) & alinks(I)
    Next I
  End If
 End Sub
```

```
' Software Information Macro

' MNA:  This macro displays CDC software information.  If modifications are made to any part of the code, a quick reference to
' the latest month and year of update can be made by adding a msg3 to the Dim statement, specifying the text of msg3,
' then adding "vbCrLf & msg3" to the msg line.

Sub Aerospace_Info()
    Dim msg, msg1, msg2, title, Response As String
    title = "Naval Postgraduate School Spacecraft Design Center - May 2001"
    msg1 = "This Concept Design Center software was provided by The Aerospace Corporation"
    msg2 = "Modifications made May 2001 by Mike Abreu at the Naval Postgraduate School, Monterey, CA"
    msg = msg1 & vbCrLf & vbCrLf & msg2
    Response = MsgBox(msg, vbInformation, title)
End Sub
```

Figure 4.32 Display Links and Software Information macros.

7. Modifications, Additions, and Cautions

Any modifications or additions to the VBA code should be done in a backup copy of the Models folder with all the subsystems contained therein. The workbooks as installed should be left operational until new code and its capabilities are thoroughly tested, commented, and documented, with the additional documentation added to this guide. Most cell references in the code are fixed, therefore changes in operating ranges in the Systems Summary sheet must be guided by the code in order to ensure continued proper operation. Any cells outside those already in operation may be modified without restriction.

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V. SPACECRAFT DESIGN AT THE NPS SDC

A. SDC DESCRIPTION

The SDC consists of nine Pentium workstations, plus a laptop computer, of varying processor speeds, ranging from 450 MHz to 733 MHz, with large screens, on a common network. The workstations are arranged in order to maximize benefit of real-time interactions between subsystems that need frequent access to each other. The systems engineer or project manager may choose between the Pentium 850 MHz laptop computer attached to the network and projector, or the *Endeavor* computer station where the CDC software files reside.

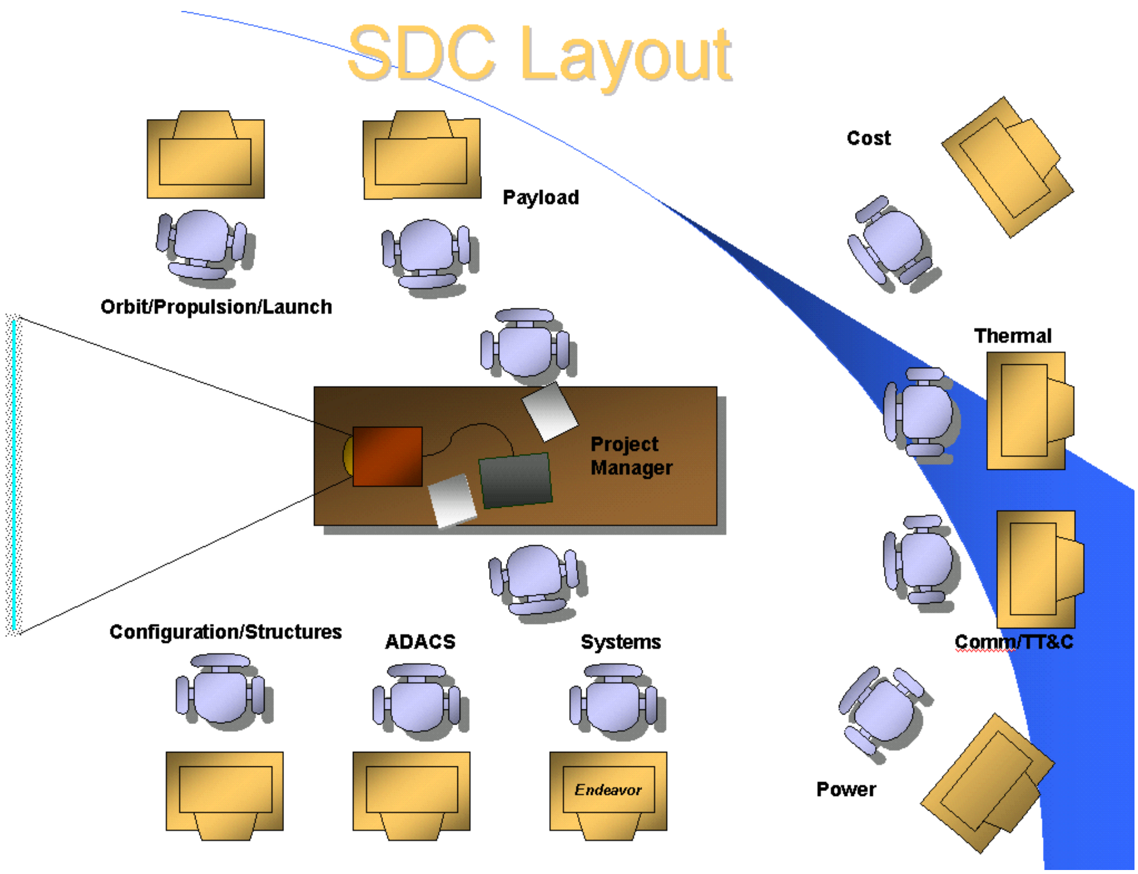

Figure 5.1 Spacecraft Design Center layout.

All workstations have access to a common network, and the projector resides in the laboratory, set up for design sessions.

B. SYSTEM/SUBSYSTEM SETUP

All workstations prepare for the session by logging on to the network and opening their respective subsystem Excel files. When the Systems engineer has opened his workbook, the subsystems can also open the Systems workbook as a read-only file, thereby enabling them access to real-time system information. This is a powerful feature of the CDC tool. In previous design classes, the subsystem engineers did not have the ability to monitor the overall spacecraft status in real time, nor were they able to immediately assess the impacts of their changes on the spacecraft as a whole.

The subsystems can commence work if requirements information has been disseminated, and save their subsystems as necessary. Another powerful feature for use

Figure 5.2 The NPS Spacecraft Design Center.

at NPS is that their work may be carried out independently of a session since the data control is not dependent on the physical presence of the subsystem engineers or whether or not their workbooks are open. This gives subsystem engineers freedom to work on their subsystem as time permits, and use the design sessions to assess the latest changes all team members have made through data exchange. The disadvantage to this is that data from other subsystems will not be available immediately, leaving the subsystem engineer to work on his workbook alone. During a regular session with all team members present, all data is available under control of the Subsystem engineer.

Preparation for sessions is necessary, since trade studies encompass various possible configurations of the spacecraft. It is the project manager's responsibility, along with the Systems engineer, to ensure that bounds and requirements for each configuration are distributed to team members well prior to a session. For instance, it may be required to assess the effect of different orbits on payload performance. The number of orbits to be evaluated and their parameters, as well as any other subsystem requirements that may flow from them, should be identified beforehand so that all members can prepare properly for the session. In addition, the impact of technology insertion on a design may be assessed; with one configuration utilizing flight-proven, reliable components while another is significantly more advanced. The associated risk with advanced technology should be taken into account for both cost estimates and impact on the component assembly and testing schedule.

It is important to note that adequate time for a design class will not be available to complete a design in one day. It should be the project manager's responsibility to stop the session when necessary and continue work later whenever it is possible.

C. DESIGN

The major challenge is to obtain the initial design for the spacecraft. Subsequent iterations will be modifications to the original. The design begins by the Systems engineer initializing the system parameters in his Guidelines and Outputs sheets, then running an output, so that each team member's subsystem model may then access the initial study parameters. He then uses the *Audit Links* button on the Audit sheet to determine if the subsystems have been saved as team members work on their workbooks. The subsystems manually enter or link cells for the requirements information as it applies to them, and begin configuring their worksheets as necessary. The Systems engineer monitors the progress of the subsystems and coordinates the flow of data among the team. He also periodically updates the master list of design requirements parameters. As team members work on their subsystems, they exchange ideas about design issues with their teammates.

When the Systems engineer is satisfied that an update is warranted, he announces that an update is about to be performed. Upon receipt of the new data, the Systems engineer analyzes any changes and the quality of parameters, ensuring they are within study bounds. If any parameters are out of bounds, the subsystems should be notified and an investigation made into the source of the inconsistency. When the Systems engineer is ready to send the data to the subsystems, he performs the output and announces to the team that an update is available. The subsystems may then import the data using their Update buttons, as well as check their read-only copies of the Systems workbook to assess the spacecraft status. Team members at any time may explain subsystem design issues to the entire team so that everyone understands how the design is evolving. This understanding is critical to the education of a Space Systems engineer; therefore, the subsystem explanations must be given a chance to take place.

During the design, the configuration/structures engineer may be utilizing both Excel and SolidWorks™ to perform his analysis. The solid modeling is an addition to the CDC software. Although it is not fully integrated into the process, it performs a valuable role in visualizing the spacecraft design and ensuring that the stowed configuration is appropriate for the launch vehicle selected. In previous spacecraft designs at NPS, this capability was not available, leading to much delay in structural analysis and attitude control calculations since modifications to the configuration could not be assessed completely on a real-time basis.

D. DOCUMENTATION/DESIGN ARCHIVING

When the study has been completed, the design must be archived for future reference for documentation or class presentation purposes by copying the Models folder to the Archive folder and renaming it to the design title, with the date completed included if so desired. This allows one archive folder to maintain the continuity of design produced in the SDC. It is important to note that design iterations may be run from the archive folder if so desired, but the intent is to maintain one operational source rather than create multiple ones. This is done in order to avoid problems with links or the data transfer and control structure.

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VI. SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

A. SUMMARY

This thesis explored and described The Aerospace Corporation's Concept Design Center and its associated Excel-based software tool as witnessed firsthand by the author prior to the installation of the tool in the SDC. It then provided supporting evidence of the revolution in solid modeling as applied to the concurrent engineering process. The utility and integration of solid modeling software into the CE process for the CDC software tool at NPS was also evaluated. This was done based on The Aerospace Corporation's utilization of a solid modeling capability in their design process by including a specific Configuration engineering seat in their facility.

California Institute of Technology's rapid solid modeling tool DrawCraft, which is integrated with SolidWorks™, was used in a concurrent design method to generate conceptual spacecraft. The utility of integrating DrawCraft/SolidWorks™ into the CDC process was evaluated with respect to learning curve, ease of use, time to generate a solid model, and model modification flexibility. The capabilities of SolidWorks™ with respect to the design process, the use of graphics and animations in presentations and reports, and exporting of solid geometry to finite element analysis (FEA) programs was explored as well and found to be robust. Application to the Space Systems Engineering curriculum was evaluated using a spacecraft design generated in AA4871, the capstone design course, as a test case.

The CDC software tool was integrated into the NPS SDC, and is the first fully functioning concurrent engineering software to be available for the curriculum's use. The installation and modification of the tool was described and documented, including all pertinent information for proper use in the integrated engineering environment. Specifically, improvements were made to the Systems workbook by the addition of current and previous parameter display areas, as well as the addition of a launch mass and power convergence section, in order to facilitate design situational awareness by the team. Since the CDC was seen in use by the author, the firsthand knowledge of witnessing the expert team in action flavored the NPS modifications and process as written.

The CDC software data transfer architecture, procedures for future modification of the tool and its Visual Basic for Applications code, and a recommended design process for the NPS SDC were developed and discussed. The software's data transfer architecture is critical to understand in order to add or modify workbooks to the spreadsheet software structure. Modification and description of the software code were undertaken in order to improve the functionality, ease of use, and graphical display of systems data for the design team. The extreme value of this work has been expressed by The Aerospace Corporation as no user's guide for the CDC Excel software has been written to date. The application of the CDC software toward the NPS curriculum was evaluated relative to the spacecraft design in AA4871. A comparison was undertaken based on the author's experience as a structures engineer in the course, prior to the software installation.

B. CONCLUSIONS

The Concept Design Center process and software combined with solid modeling tools is a very powerful team for spacecraft design at NPS. Along with the facility, these things all work to benefit the design team. The tools provide a design capability to the NPS SDC that did not exist prior to their modification and installation. The abilities of the CDC software in particular extend beyond what is necessary for the curriculum, yet it provides a solid foundation for students to understand the complex interactions of a real-world spacecraft conceptual design. The modifications to the Systems workbook increase the level of team awareness of the design by allowing them to track specific changes in mass and power between iterations. The convergence section, in particular, is provides the team with a percentage change calculation warning between iterations and a graphical tracking mechanism for mass and power of the spacecraft, two of the three most important parameters of spacecraft design. The documentation serves to guide the NPS space systems engineering curriculum in their future modification of the tool, provide a detailed description of the inner workings of the CDC processes and tools, and enable a capability that did not previously exist formally in the SDC.

Solid modeling tools provide an extremely powerful visualization capability and are a critical integrative facet of the process. SolidWorks™ and DrawCraft provide the design team the ability to rapidly create a model, make changes to it, visualize the spacecraft in 3-D, extract and verify critical design information such as total mass and moments of inertia, and export the model to a finite element analysis program. These parameters may then be compared against spreadsheet or analytical calculations in order to assess their equivalency. This is done in a relatively easy manner compared to the author's experience in AA4871, and in a considerably shorter time. The additions of launch vehicle fairing models provided by The Aerospace Corporation and easily modifiable generic spacecraft components available through the DrawCraft software are significant contributions towards solid modeling capability at the SDC. In addition, curriculum students now have a vehicle to enhance their understanding of the revolution in solid modeling and product design taking place in both government and commercial endeavors, adding a critical facet to their education as space systems engineers.

C. RECOMMENDATIONS

The CDC software can be modified by student design teams and brought to a level of complexity, either more or less than exists today, that more accurately contributes to the education and class design needs of the curriculum and AA4871. The data control structure and code documentation has been verified by The Aerospace Corporation as being valuable to their systems engineers, as no formal training methodology is in place and a user's guide was nonexistent prior to this thesis. The documentation serves to guide the NPS space systems engineering curriculum in their future modification of the tool, and provides a detailed description of the inner workings of the CDC. This documentation should be updated further as the details of the software functionality become more evident with its use.

Studies may be conducted into the utility of the added convergence section of the Systems workbook Summary sheet. Since the evaluation of an iterated design is currently done manually by estimation based on experience, the studies may shed more light on the correlation between specific subsystem changes and total mass and power fluctuations, and their cumulative effects on the overall design. Studies may also show if these fluctuations can be determined quantitatively as being sufficient to stop design iteration. If this were the case, a reduction in the number of iterations to design stoppage would result in reduced total iteration time, thus decreasing the cost of the design in a commercial setting.

The integration of concurrent engineering methodology and integrated collaborative engineering principles into the design process at NPS has potential for significantly enhancing the level of quality, comprehension, depth, and scope of future spacecraft designs. Student knowledge of the real-world design process is now available, serving to enhance their space systems engineering education. Though the process is necessarily different from that of The Aerospace Corporation, it still provides the design team a versatile, flexible approach to maintaining their situational awareness of the design throughout its iteration. Improvements to the process are inevitably necessary, since this marks the first true implementation of the integrated concurrent engineering process into the SDC. All NPS users of the tools should strive to incorporate and document such changes with the consent of the curriculum manager. It will be necessary to judge the true impact of the process on spacecraft design at NPS. This may be accomplished by the solicitation of feedback from design teams, assessing the real-time effects of the process and tools using previous designs and experience as benchmarks, and conducting comparisons of the product of designs; namely the final design report.

APPENDIX A. POINTS OF CONTACT

The Aerospace Corporation	Stephen Presley	(310) 336-2448
2350 El Segundo Blvd.	Stephen.p.presley@aero.org	
El Segundo, CA 90245-4691	Joseph Aguilar	(310) 336-2179
www.aero.org	Joseph.a.aguilar@aero.org	
	Christopher Taylor	(310) 336-1423
	Christopher.s.taylor@aero.org	
California Institute of Technology	Dr. Joel Sercel	(818) 354-4044
4800 Oak Grove Drive	sercel@earthlink.net	
Pasadena, CA 91109-8099		
www.caltech.com		
NPS SDC	Professor Brij Agrawal	(831) 656-3338
www.nps.navy.mil	Dr. Hong-Jen Chen	(831) 656-2716

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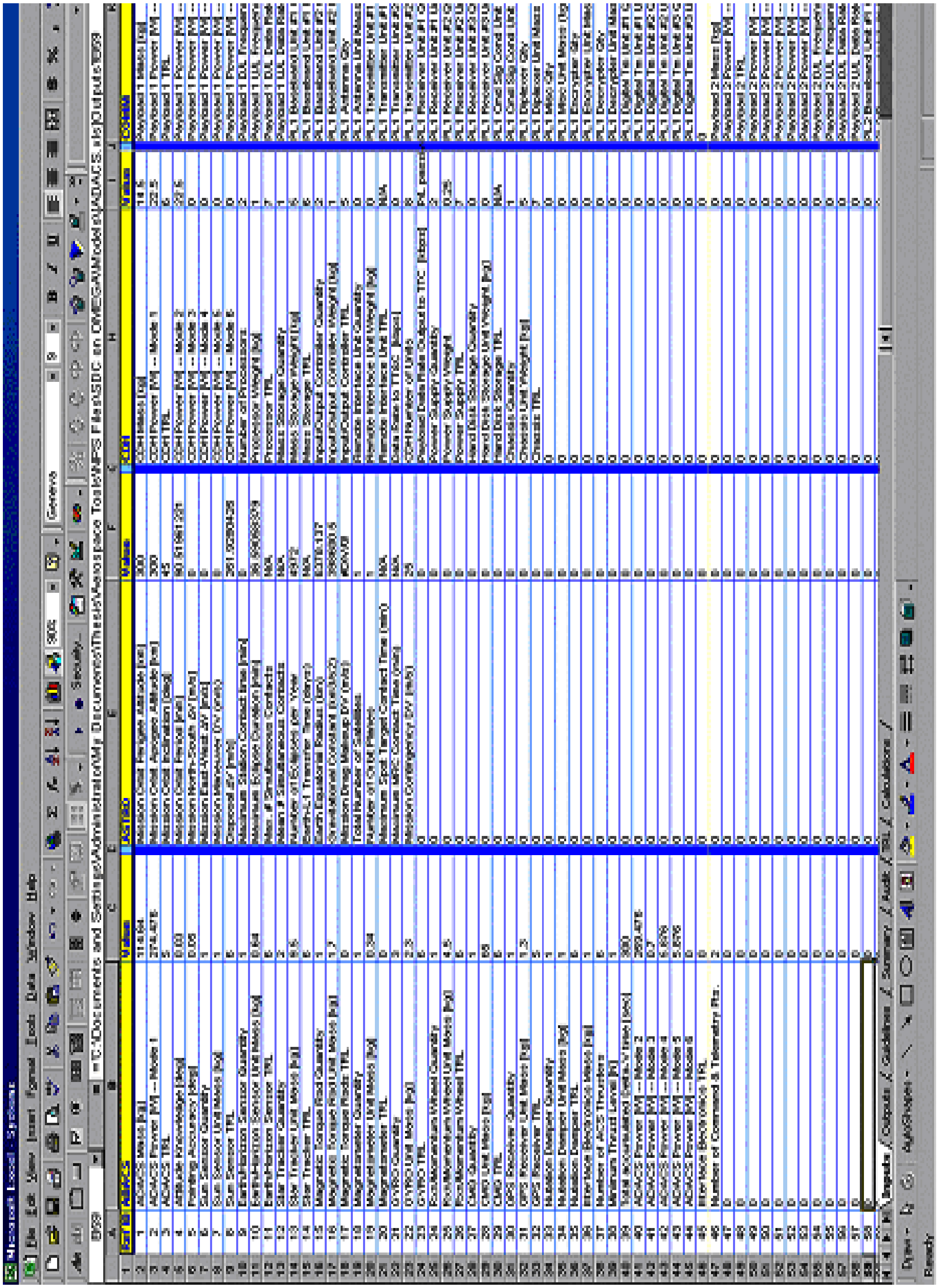
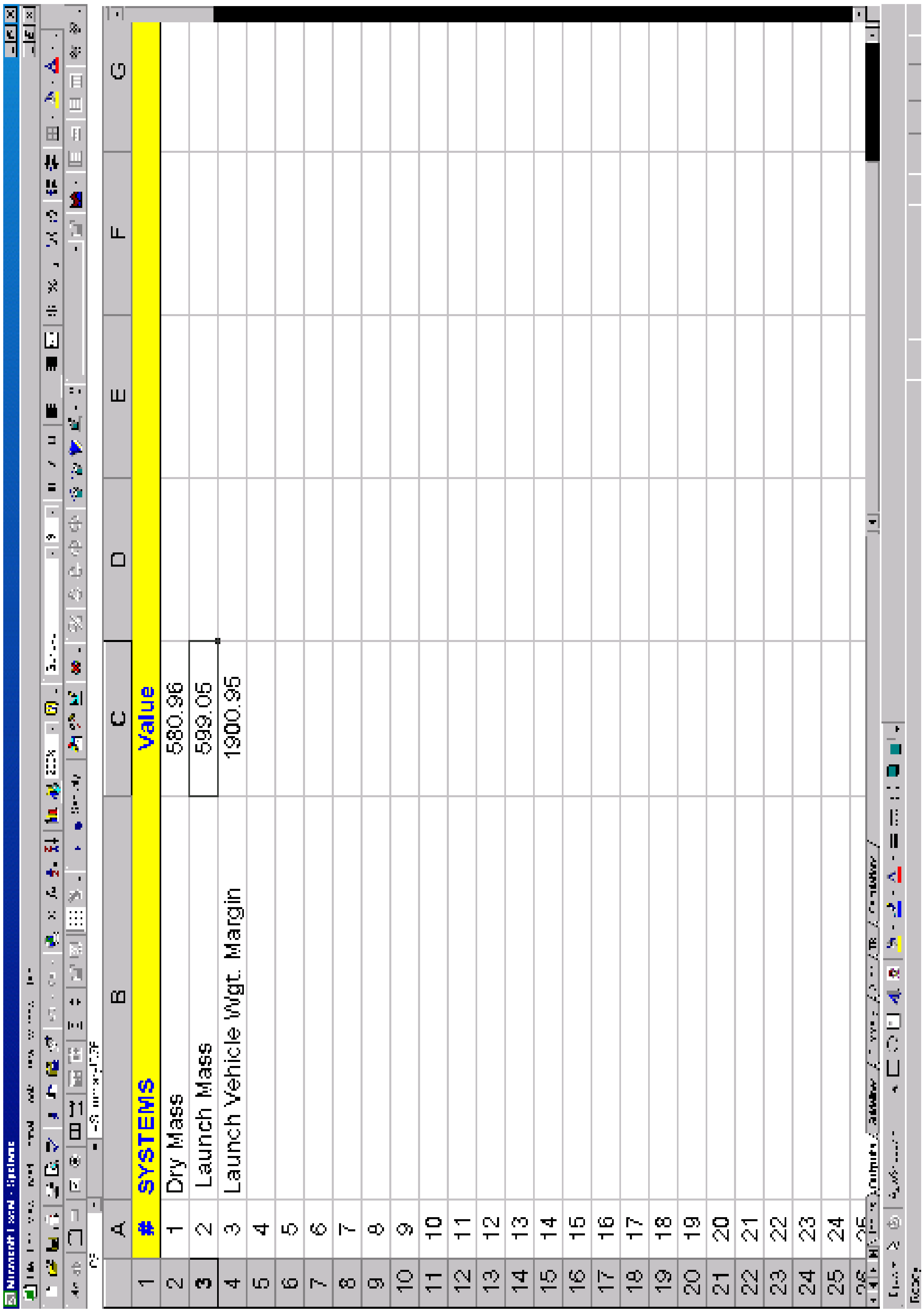
APPENDIX B. CDC SYSTEMS WORKBOOK SHEETS



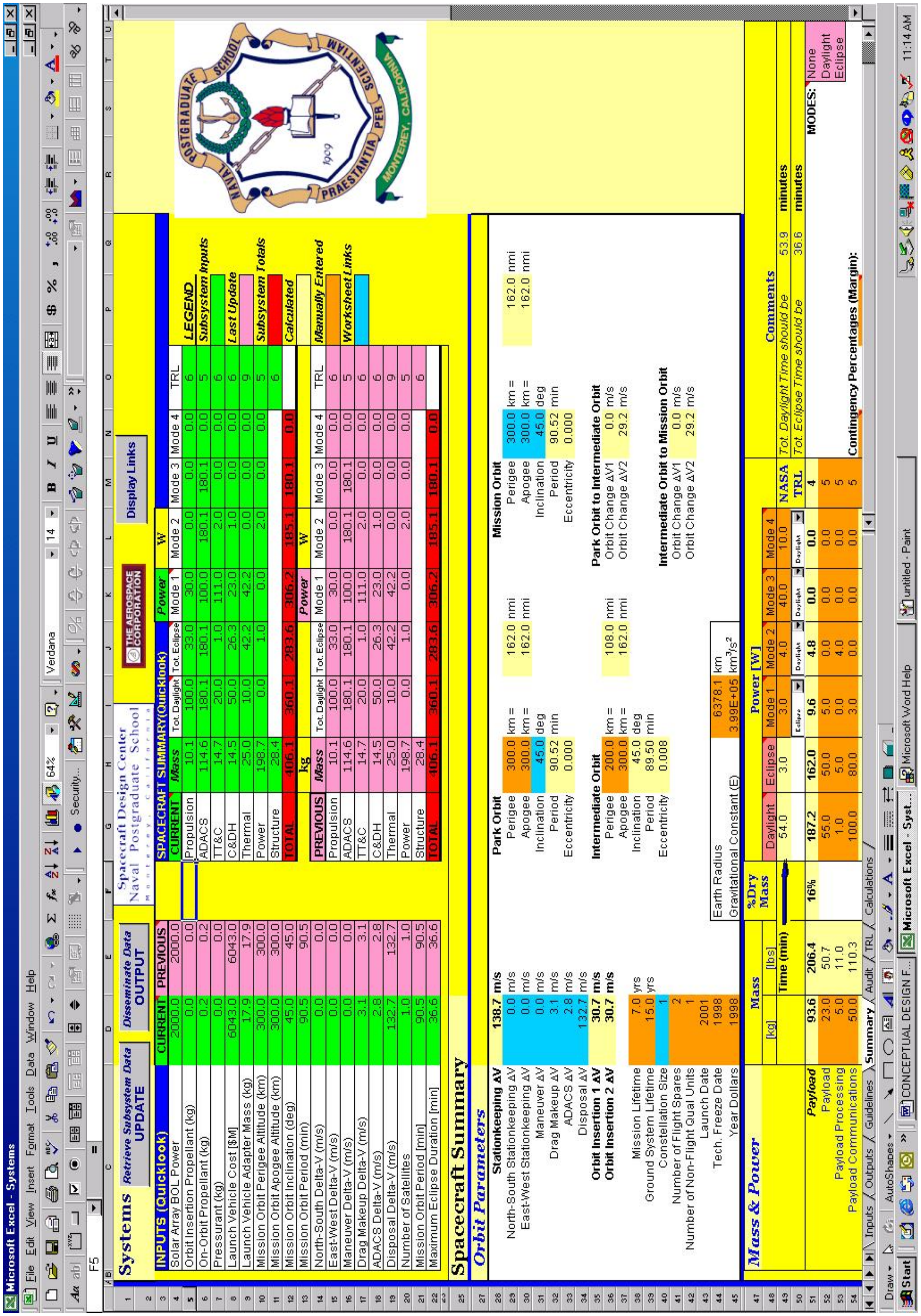
Inputs Sheet



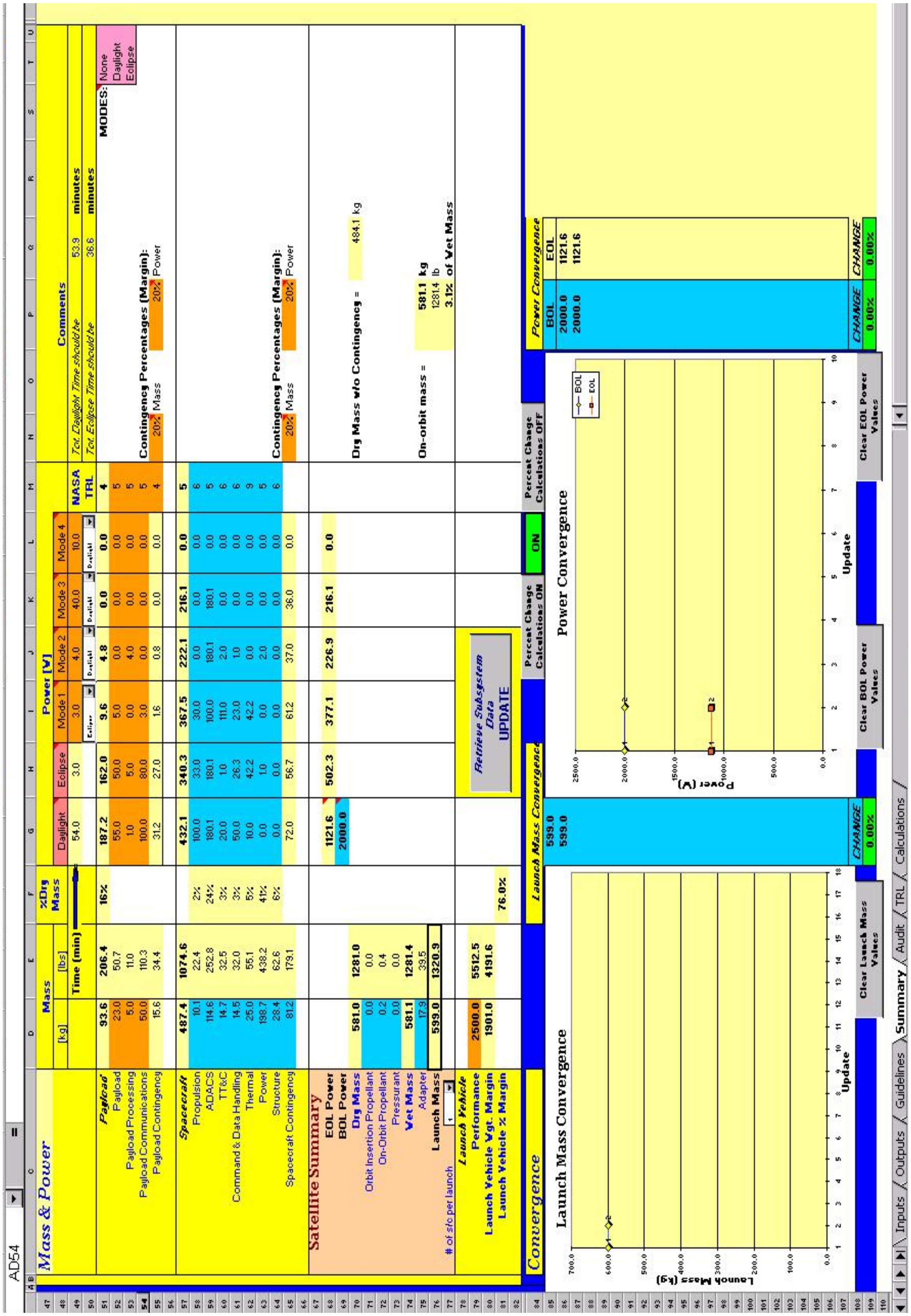
#	SYSTEMS	Value
1	Dry Mass	580.96
2	Launch Mass	599.05
3	Launch Vehicle Wgt. Margin	1900.95

Outputs Sheet

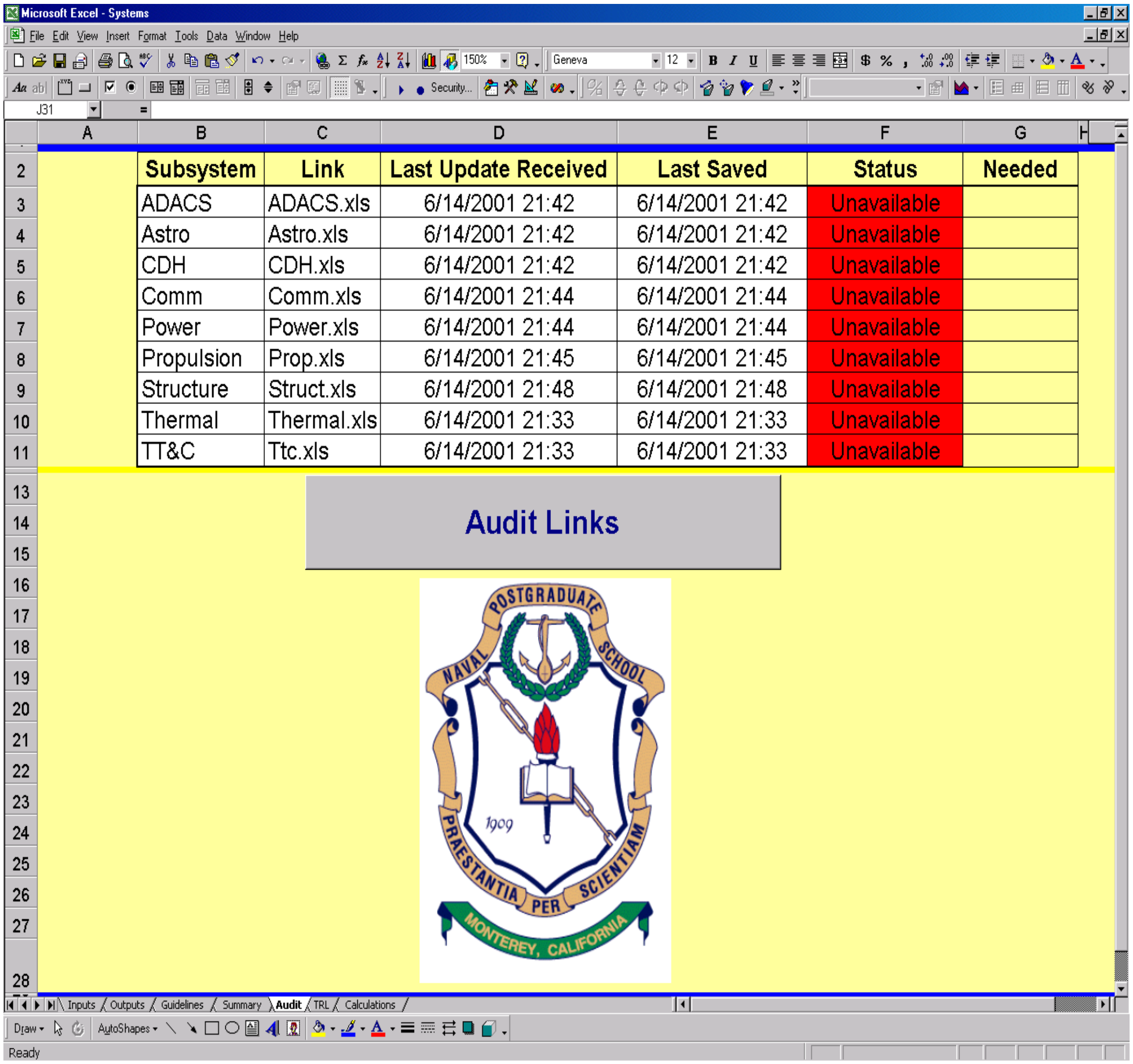
Guidelines Sheet



Summary Sheet

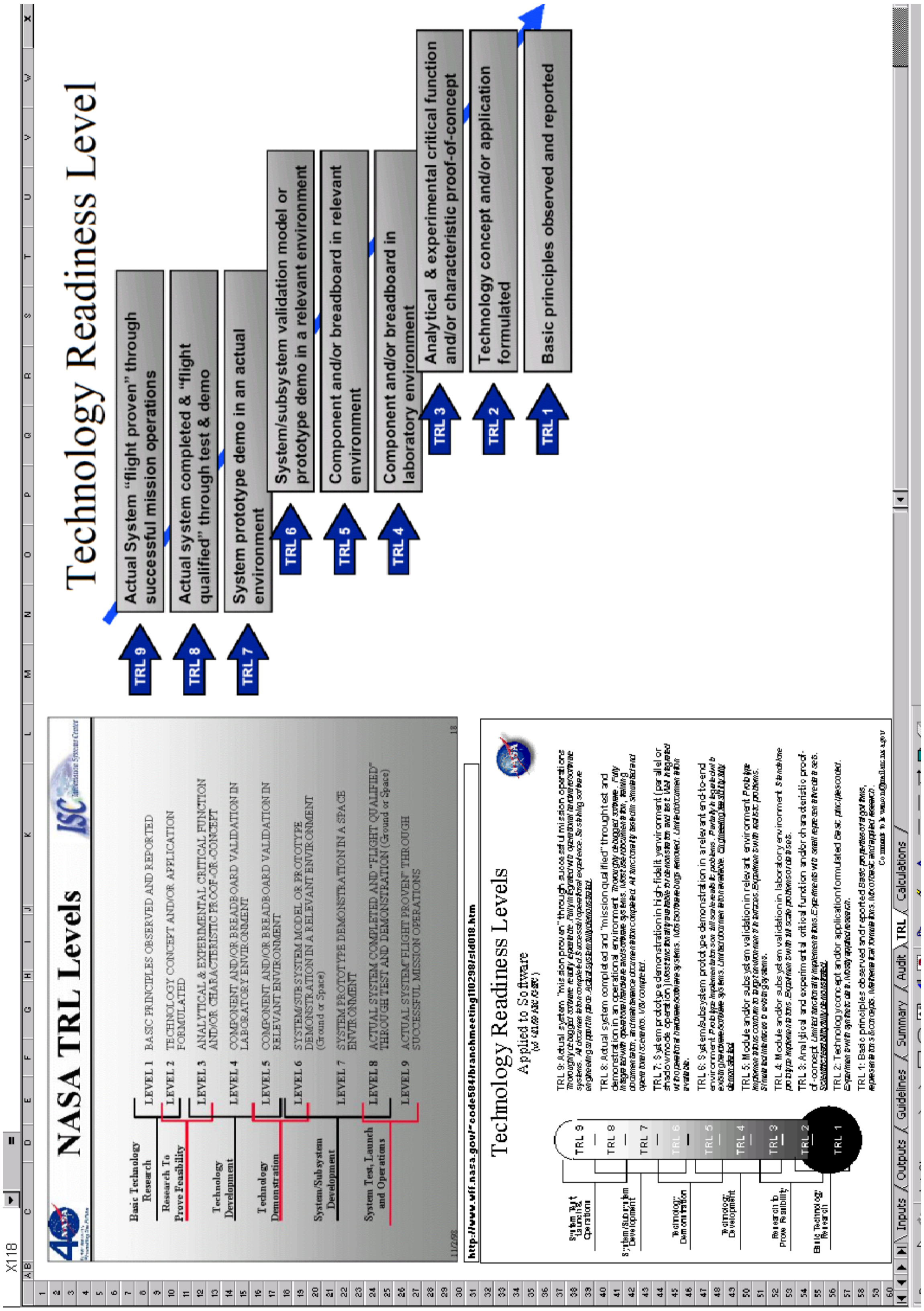


Summary Sheet, continued



Subsystem	Link	Last Update Received	Last Saved	Status	Needed
ADACS	ADACS.xls	6/14/2001 21:42	6/14/2001 21:42	Unavailable	
Astro	Astro.xls	6/14/2001 21:42	6/14/2001 21:42	Unavailable	
CDH	CDH.xls	6/14/2001 21:42	6/14/2001 21:42	Unavailable	
Comm	Comm.xls	6/14/2001 21:44	6/14/2001 21:44	Unavailable	
Power	Power.xls	6/14/2001 21:44	6/14/2001 21:44	Unavailable	
Propulsion	Prop.xls	6/14/2001 21:45	6/14/2001 21:45	Unavailable	
Structure	Struct.xls	6/14/2001 21:48	6/14/2001 21:48	Unavailable	
Thermal	Thermal.xls	6/14/2001 21:33	6/14/2001 21:33	Unavailable	
TT&C	Ttc.xls	6/14/2001 21:33	6/14/2001 21:33	Unavailable	

Audit Links Sheet



Technology Readiness Level
TRL 9
Actual System “flight proven” through successful mission operations
TRL 8
Actual system completed & “flight qualified” through test & demo
TRL 7
System prototype demo in an actual environment
TRL 6
System/subsystem validation model or prototype demo in a relevant environment
TRL 5
Component and/or breadboard in relevant environment
TRL 4
Component and/or breadboard in laboratory environment
TRL 3
Analytical & experimental critical function and/or characteristic proof-of-concept
TRL 2
Technology concept and/or application formulated
TRL 1
Basic principles observed and reported
NASA TRL Levels
Technology Readiness Levels
Applied to Software
Inputs
Outputs
Guidelines
Summary
Audit
TRL
Calculations

TRL Sheet

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APPENDIX C. SYSTEMS WORKBOOK VBA CODE

```
' CDC Code updated by Mike Abreu, Naval Postgraduate School, May-June 2001
' The comments in all code have been extensively revised and added to by Mike Abreu, May-June 2001
'
'   CDC Link Flow and general description:
'
'   SUBSYSTEM OUTPUT SHEETS-->CORRESPONDING COLUMNS ON SYSTEMS INPUT SHEET
'   DATA.XLS SHEET-->SUBSYSTEM INPUT SHEETS (I linked 300 rows as a default to cover the date/time stamp for TTC,
'   the largest subsystem output)
'
'         The "audit" sheet monitors the save status of each subsystem using the time/date stamp of the most recent save.
'         Once critical subsystems are saved and show ready for updating, the RETRIEVE SUBSYTEM DATA (UPDATE) button on
'         the summary sheet is used to update the systems workbook.  The values can then be checked for reasonability and
'         comparision to previous values.
'         When ready, the systems engineer uses the DISSEMINATE DATA (OUTPUT) button to write the systems
'         input sheet to the data.xls workbook, hence updating all subsystems with the most current data.
'         The Excel status bar at the bottom of the workbook is used to display information while retrieving or sending data.
'
'        NOTES: 1.  The Systems workbook should be the only one open when performing an update when working with the CDC
software on the
'                   same PC, otherwise it will not work correctly.
'                2.  When first opening a subsystem workbook after an update and save cycle has been performed, you will be asked if
you would
'                   like to update the links to other workbooks.  If YES is selected, the new data from the last update is imported,
otherwise the
'                   old data remains in place.
'                3.  To follow the code flow for any subroutine, enter break mode by pressing the break button on the toolbar
'                   selecting Step Into, and executing the code one line at a time using F8.  The cursor may also be positioned
'                   anywhere in the code after selecting into, then right clicking and using Run to Cursor to run all code before
'                   pausing at the cursor.  Remember to press the Reset button on the toolbar when finished as the code will not
'                   execute from Excel in break mode.
'
' ***Please document any code updates or modifications in the appropriate section.  See the Aerospace_Info sub at the end of this
code.***
'
Public sep                    '  Makes variables available to all subroutines
' Auto Open macro, checks to see which system type you're running on (windows vs. mac), and assigns the directory path separator
' appropriately.
'
Sub auto_open()
   os = Left(Application.OperatingSystem, 3)
   If os = "Mac" Then
```

```
        sep = ":"
    ElseIf os = "Win" Then
        sep = "\"
    Else
        MsgBox ("Unkown Operating System - Path separation character not defined")
    End If
End Sub

' Update macro

'  When the UPDATE button is pressed, for each link listed in the audit link list, this macro checks which subsystems
' need updating based on the date/time stamp in the audit sheet Last Saved column and updates each link as necessary.
' Also included are plotting routines that show the convergence of the launch mass and BOL/EOL power as the study progresses, as
' well as one to transfer the current data to previous data with each update.
' The routine can be adapted to monitor any of the study data to analyze its convergence by copying the chart
' and making sure its source data is the same range that the code writes to.  The charts can be cleared by clearing the contents of the
columns.
' CAUTION:  This subroutine's cell references will not change if the sheet is modified in any way.
'           Any modification of this section must ensure the cell relationships between the code and the sheet are properly maintained.

Sub Update()

    ' Initially sets variables to the current values since they will be the previous values when the new values come
    ' into the workbook.  It then calls a subroutine to transfer current values to the previous areas.  The previous varables
    ' are used later for percent change calculations.
    ' The "application.calculation=xlAutomatic" enables auto updates all the linked values within the Summary sheet.
    ' It is included to ensure all fields in the Summary sheet are automatically updated when the new data arrives.

Set self = Workbooks("Systems.xls")
    sep = Application.PathSeparator
    Application.Calculation = xlCalculationManual
    Worksheets("Summary").Activate
    LM = ActiveSheet.Range("D76").Value        ' Sets the current values for use later as the previous values after update has taken
place.
    EOL = ActiveSheet.Range("G68").Value
    BOL = ActiveSheet.Range("G69").Value
    Current_to_Previous1                       ' Copies the values from the current areas of the input section of the summary
sheet
    Application.Calculation = xlAutomatic      ' to the previous areas and allows any values that change to be updated
automatically
                                               ' throughout the workbook.
    ' Check date/time stamps from the Audit sheet and update links from subsystems if necessary.
    For Each link In Worksheets("Audit").Range("linklist")
        link.Offset(0, 2).Value = FileDateTime(self.Path & sep & link.Text)
```

```
        If link.Offset(0, 1).Value < link.Offset(0, 2).Value Then
            Application.StatusBar = "Updating data from: " & self.Path & sep & link.Text
            self.UpdateLink Name:=self.Path & sep & link.Text
         End If
      link.Offset(0, 1).Value = link.Offset(0, 2).Value      ' Replaces the old last update received with the last saved date/time stamp.
      link.Offset(0, 3).Interior.ColorIndex = 3               ' The value will be the last time the update button was pressed.
      link.Offset(0, 3).Value = "Unavailable"
   Next


   ' Adds current values to the convergence section by finding the first empty cell in each convergence column and copying the
appropriate value to it.
   With Worksheets("Summary").Range("G84:G115")
   Set mass = .Find("", LookIn:=xlValues)
   End With
   mass.Value = ActiveSheet.Range("D76").Value
   'self.Worksheets("Summary").Cells(76, 4)   ' MNA: Writes the updated launch mass to the first empty cell found, hence updating
the plot.


   With Worksheets("Summary").Range("P84:P115")
   Set BOLPower = .Find("", LookIn:=xlValues)
   End With
   BOLPower.Value = ActiveSheet.Range("G69").Value
   ' MNA: Writes the updated BOL power to the first empty cell found, hence updating the plot.


   With Worksheets("Summary").Range("Q84:Q115")     ' Specifies range of the EOL power convergence column to look in and finds
the first empy cell.
   Set EOLPower = .Find("", LookIn:=xlValues)
   End With
   EOLPower.Value = ActiveSheet.Range("G68").Value


   ' This section copies the updated values, calculates the percent change from the previous values, and places the values in the
appropriate cells.
   ' It will not execute if the Percent Chance Calculations has been turned off.  It finds the first empty cell in the same manner as
above.


If Range("L84") = "ON" Then
   With Worksheets("Summary").Range("G84:G115")
       Set mass1 = .Find("", LookIn:=xlValues)
   End With
   c = mass1.Address                                   ' Selects first empty cell, hops one cell up, and assigns the value to the current
variable.
   Range(c).Select
   ActiveCell.Offset(rowoffset:=-1, columnoffset:=0).Activate
   CurrentMass1 = ActiveCell.Value
```

```
    If ActiveCell.Address = "$G$85" Then
      LM = "None"
      MPercentChange = 0                              ' Makes sure a division by zero does not occur by checking if the current value is in
the first cell of
      GoTo MassFix                                    ' the convergence columns.  This case occurs any time there is not a value in the first
cell of the column.
    Else
      ActiveCell.Offset(rowoffset:=-1, columnoffset:=0).Activate
      LM = ActiveCell.Value
      MPercentChange = CurrentMass1 - LM          ' If all is well, LM is already set to the previous value.
      MPercentChange = MPercentChange / LM        ' Calculates percentage change from previous value.
      LM = Round(LM, [2])
    End If
MassFix:
        CurrentMass1 = Round(CurrentMass1, [2])                  ' Rounds the number to two decimal places.
        MPercentChange = Round(MPercentChange, [2])
        title = "Launch Mass"                                                         ' Displays the alert box.
        msg = "Launch Mass [kg]" & vbCrLf & vbCrLf & "Current       " & CurrentMass1 & vbCrLf & _
        "Previous      " & LM & vbCrLf & vbCrLf & "Mass Changed " & MPercentChange * 100 & " %"
        Response = MsgBox(msg, vbOKOnly, title)


' The other two convergence columns work in the same way as above.
    With Worksheets("Summary").Range("P85:P115")    ' Specifies the range of the BOL convergence column to look in and finds the
first empy cell.
         Set BOL1 = .Find("", LookIn:=xlValues)
    End With
    d = BOL1.Address
    Range(d).Select
    ActiveCell.Offset(rowoffset:=-1, columnoffset:=0).Activate
    CurrentBOLPower = ActiveCell.Value


    If ActiveCell.Address = "$P$86" Then
        BPowerPercentChange = 0
        BOL = "None"
        GoTo BOLPowerFix
    Else
        ActiveCell.Offset(rowoffset:=-1, columnoffset:=0).Activate
        BOL = ActiveCell.Value
        BPowerPercentChange = CurrentBOLPower - BOL
        BPowerPercentChange = BPowerPercentChange / BOL
        BOL = Round(BOL, [2])
BOLPowerFix:
        CurrentBOLPower = Round(CurrentBOLPower, [2])
        BPowerPercentChange = Round(BPowerPercentChange, [2])
```

```
        title = "Beginning of Life Power"
        msg = "BOL Power [W]" & vbCrLf & vbCrLf & "Current       " & CurrentBOLPower & vbCrLf & "Previous    " & _
        BOL & vbCrLf & vbCrLf & "BOL Power Changed " & BPowerPercentChange * 100 & " %"
        Response = MsgBox(msg, vbOKOnly, title)
    End If

    With Worksheets("Summary").Range("Q85:Q115")       ' Specifies the range of the EOL convergence column to look in and finds
the first empy cell.
         Set EOL1 = .Find("", LookIn:=xlValues)
    End With
    e = EOL1.Address
    Range(e).Select
    ActiveCell.Offset(rowoffset:=-1, columnoffset:=0).Activate
    CurrentEOLPower = ActiveCell.Value
    If ActiveCell.Address = "$Q$86" Then
        EPowerPercentChange = 0
        EOL = "None"
        GoTo EOLPowerFix
    Else
        ActiveCell.Offset(rowoffset:=-1, columnoffset:=0).Activate
        EOL = ActiveCell.Value
        EPowerPercentChange = CurrentEOLPower - EOL
        EPowerPercentChange = EPowerPercentChange / EOL
        EOL = Round(EOL, [2])
EOLPowerFix:
        CurrentEOLPower = Round(CurrentEOLPower, [2])
        EPowerPercentChange = Round(EPowerPercentChange, [2])
        title = "End of Life Power"
        msg = "EOL Power [W]" & vbCrLf & vbCrLf & "Current       " & CurrentEOLPower & vbCrLf & "Previous    " & EOL _
        & vbCrLf & vbCrLf & "EOL Power Changed " & EPowerPercentChange * 100 & " %"
        Response = MsgBox(msg, vbOKOnly, title)
     End If

' Write appropriate values to the percent change tracking cells.
    If Range("L84") = "OFF" Then
      Range("G109") = "OFF"
      Range("P109") = "OFF"
      Range("Q109") = "OFF"
      Range("C84").Select
    Else
        Range("G109").Value = MPercentChange
        Range("P109").Value = BPowerPercentChange
        Range("Q109").Value = EPowerPercentChange
```

```
        Range("C84").Select
    End If
End If

    Application.StatusBar = False
    Application.Calculation = xlAutomatic

End Sub

' Save Data Macro

' This macro sets the active workbook to Systems, copies the systems input sheet, deletes the previous
' data.xls workbook and saves the systems input sheet to a new data.xls, updating all subsystem input sheets.
' The macro is assigned to the OUTPUT button.
'
Sub SaveData()
    Application.Calculation = xlManual
    Application.ScreenUpdating = False
    Set self = Workbooks("systems.xls")
    sep = Application.PathSeparator
    Application.StatusBar = "Output Data from systems.xls: Copying 'Inputs' and 'Summary' Worksheet"
    Sheets(Array("Inputs", "Summary")).Copy
    On Error GoTo errtrap
    retry = 0
    Application.StatusBar = "Output Data from systems.xls: Killing " & self.Path & sep & "data.xls"
    Kill self.Path & sep & "data.xls"
    Application.StatusBar = "Output Data from systems.xls: Saving new data.xls"
    ActiveWorkbook.SaveAs FileName:=self.Path & sep & "data.xls"
    On Error GoTo 0
    ActiveWorkbook.Close
    Application.StatusBar = False
    Application.Calculation = xlAutomatic
    Application.ScreenUpdating = True
    End

errtrap:
    retry = retry + 1
    Application.StatusBar = "Output Data from systems.xls: " & self.Path & ":data.xls was busy. Retry: " & retry
    Resume
End Sub

' Audit Links macro
```

```
' When the AUDIT button is pressed, the most recent subsytem save date/time stamps are transferred to the Last Saved
' column.  This macro checks that stamp against the last update time stamp (generated when the UPDATE button is pressed)
' and alerts the systems engineer that the subsystem is ready to update if the update stamp is older.
' Link offset 0,1 is Last Update Received and link offset 0,2 is Last Saved.

Sub AuditLinks()
   Dim msg1, msg2 As String
   msg1 = "Available"
   msg2 = "Unavailable"
   Application.Calculation = xlManual
   Application.ScreenUpdating = False
   Application.StatusBar = "Auditing Link Status"
   Set self = Workbooks("systems.xls")
   sep = Application.PathSeparator

   For Each link In Worksheets("audit").Range("linklist")
      link.Offset(0, 2).Value = FileDateTime(self.Path & sep & link.Text)

      If link.Offset(0, 1).Value < link.Offset(0, 2).Value Then          ' Compares latest save time to last save time and
        link.Offset(0, 3).Interior.ColorIndex = 4                         ' sets messages and colors to display in the link status column.
        link.Offset(0, 3) = (msg1)
        link.Offset(0, 3).Font.color = 6
      End If
      If link.Offset(0, 1).Value > link.Offset(0, 2).Value Then
        link.Offset(0, 3).Interior.ColorIndex = 3
        link.Offset(0, 3) = (msg2)
        link.Offset(0, 3).Interior.ColorIndex = 3
      End If
   Next

   Application.StatusBar = False
   Application.ScreenUpdating = True
   Application.Calculation = xlAutomatic
   Worksheets("audit").Select
End Sub


' Remove Hidden Names macro

' Module to remove all hidden names on active workbook.

' Excel allows names to be given to ranges within sheets.  These names can then be used to manipulate the ranges
' more easily.  This macro is not currently linked to a button.  All names in the active workbook may be viewed by either
```

```
' running this macro manually from the command bar above or using the Insert-Names-Define operation from Excel to
' view and/or modify names and ranges.  See VBA Help on Names for more information.

Sub Remove_Hidden_Names()

' Dimension variables.
Dim xName As Variant
Dim Result As Variant
Dim Vis As Variant

'Loop once for each name in the workbook.
For Each xName In ActiveWorkbook.Names

   'If a name is not visible (it is hidden)...
   If xName.Visible = True Then
      Vis = "Visible"
   Else
      Vis = "Hidden"
   End If

   '...ask whether or not to delete the name.
   Result = MsgBox(prompt:="Delete " & Vis & " Name " & _
      Chr(10) & xName.Name & "?" & Chr(10) & _
      "Which refers to: " & Chr(10) & xName.RefersTo, _
      Buttons:=vbYesNo)

   'If the result is true, then delete the name.
   If Result = vbYes Then xName.Delete

   'Loop to the next name.
Next xName
End Sub

' Display Links macro

' MNA:  This macro checks all the links in the active workbooks and displays them for quick reference from the systems summary sheet.
' The links can also be checked using the "Edit-Links" operation from the Edit toolbar.

Sub DisplayLinks()
  alinks = ActiveWorkbook.LinkSources
  If Not IsEmpty(alinks) Then
   For I = 1 To UBound(alinks)
```

```
      MsgBox "Link " & I & ":" & Chr(13) & alinks(I)
    Next I
  End If
 End Sub

' Software Information Macro

' MNA:  This macro displays CDC software information.  If modifications are made to any part of the code, a quick reference to
' the latest month and year of update can be made by adding a msg3 to the Dim statement, specifying the text of msg3,
' then adding "vbCrLf & msg3" to the msg line.

Sub Aerospace_Info()
    Dim msg, msg1, msg2, title, Response As String
    title = "Naval Postgraduate School Spacecraft Design Center - May 2001"
    msg1 = "This Concept Design Center software was provided by The Aerospace Corporation"
    msg2 = "Modifications made May 2001 by Mike Abreu at the Naval Postgraduate School, Monterey, CA"
    msg = msg1 & vbCrLf & vbCrLf & msg2
    Response = MsgBox(msg, vbInformation, title)
End Sub
```

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   Monterey, CA
   platzer@nps.navy.mil

4. Prof. Brij N. Agrawal
   Naval Postgraduate School
   Monterey, CA
   agrawal@nps.navy.mil

5. Mr. Joseph Aguilar
   The Aerospace Corporation
   El Segundo, CA
   Joseph.a.aguilar@aero.org

6. Mr. Christopher Taylor
   The Aerospace Corporation
   El Segundo, CA
   Christopher.s.taylor@aero.org

7. Mr. Stephen Presley
   The Aerospace Corporation
   El Segundo, CA
   Stephen.p.presley@aero.org

8. Dr. Joel Sercel
   California Institute of Technology
   Pasadena, CA
   sercel@caltech.edu