DEPARTMENT OF DEFENSE

DEVELOPING CRITICAL TECHNOLOGIES/SCIENCE & TECHNOLOGY (DCT/S&T)

SECTION 12: MANUFACTURING AND FABRICATION TECHNOLOGY

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PREFACE

Developing Critical Technologies/Science & Technology (DCT/S&T) is a product of the Defense Critical Technologies Program (DCTP) process. This process provides a systematic, ongoing assessment and analysis of a wide spectrum of technologies of potential interest to the Department of Defense. DCT/S&T focuses on worldwide government and commercial scientific and technological capabilities that have the potential to significantly enhance or degrade U.S. military capabilities in the future. It includes new and enabling technologies as well as those that can be retrofitted and integrated because of technological advances. It assigns values and parameters to the technologies and covers the worldwide technology spectrum.

DCT/S&T is oriented towards advanced research and development including science and technology. It is developed to be a reference for international cooperative technology programs. A key component is an assessment of worldwide technology capabilities. S&T includes basic research, applied research and advanced technology development.

SECTION 12—MANUFACTURING AND FABRICATION TECHNOLOGY

Scope

Highlights

- The continued development of rapid prototyping and near net-shape manufacturing will result in reduced costs, faster prototyping, and the ability to form a product closer to design (final product tailored to need).
- Higher speed machining capability means less time for the machining operation and, thus, reduced costs.
- The development and implementation of nanotechnology should result in improved military hardware.
- Quieter, longer lasting bearing assemblies will be used in submarines and helicopters.
- As manufactured dimensions become smaller, improved metrology equipment is necessary to maintain quality control and keep costs down.
- As manufactured dimensions become smaller and hardware becomes more expensive, more effective methods of in-process evaluation and non-destructive evaluation (NDE) are necessary to determine the quality of final product.
- Advanced land, sea, and air military robots will extend military capabilities in several areas, including reconnaissance and mine detection.

OVERVIEW

This section describes selected developing critical technologies for the production of U.S. military hardware. Such technology is important if the U.S. military is either to produce increasingly superior military performance or reduce the costs of existing hardware. In most cases, the technologies, the equipment, and the know-how are dual use and impact civil applications, where considerations of costs, agility, flexibility, competitiveness, and so forth have also become major concerns. All technologically advanced countries are pursuing similar programs if only to maintain a commercial advantage.

Several technologies included in subsection 12.1 are rather mature and are included as affordability issues. Affordability usually is considered in the context of a life-cycle allocation of resources. Major considerations for affordability include the following: (1) meets the consumer’s performance parameters; (2) has resources available; (3) is available when the consumer requires it; (4) can be maintained through its life cycle with or without hostilities and without undue shortages at projected budget levels; (5) has importance established compared with other requirements; and (6) reduces cost of operation; and (7) increases reliability, effectiveness, or efficiency.

The technologies addressed in this section either allow prototypes to be produced in a fraction of the time required by conventional methods or, in some cases, actually produce one-of-a kind parts, in a first-time-right concept, without the need of expensive stocks of spare parts. Other technologies (e.g., nanotechnology and several coating technologies) are aimed at effecting significant improvement in military hardware. Bearings (see subsection 12.2) addresses the development of three new types of bearings. In two of the technologies, the new bearings would be critical parts of the improved (high-speed) spindles used in machine tools. The remaining bearing development has potential application in electric power generation.

Developing technologies (see subsections 12.3 and 12.4) address techniques either to inspect dimensionally (metrology) the final product or test the final product for latent failures. Continued development of these technologies will result in more accurately produced and reliable products. Subsection 12.5 addresses production equipment. Technologies listed include both affordability issues (high-speed spindles, machine tool monitoring, and so forth) and technologies that might improve the overall capability of military hardware [hexapods, precision grinders, micromachines/microelectromechanical systems (MEMS), and so forth]. Subsection 12.6 discusses robots that might find increased use in actual battlefield applications.

In short, the items addressed in this section address two critical points: Can we make it better and can we make it more affordable?

BACKGROUND

For years, manufacturing and fabrication equipment has been a mainstay of industrial societies. This equipment was instrumental in bringing about the Industrial Revolution in the 18th century, the continued development of a wider range of machines in the 19th century, and the development of the concept of automation in the early 20th century. The mid-to-late 20th century witnessed a rapid expansion, with the introduction of automatic control of the machining axes and the incorporation of additional axes of motion. Indeed, one can trace the development of our present industrial society, as well as the sophistication of military hardware, to the development of manufacturing and fabrication equipment.

While rudimentary machines have been used throughout history, machines, as we know them today, were first developed in England and the United States. In England in 1775, J. Wilkinson invented a precision horizontal-boring machine to bore out cylinders for the newly invented steam engine. In the United States in 1798, Eli Whitney, invented machinery to produce interchangeable parts for the assembly of army muskets. The 19th century saw the development of milling machines and turning machines (for rifle stocks), gear-cutting machines, sewing machines, harvesters, grinding machines, and automatic screw machines.

The early 20th century witnessed the development of automation. This, coupled with the existing machines, opened the world to mass production. Products could now be manufactured in higher volume and at much lower cost, and the world experienced the mass-market appeal of automobiles and numerous other consumer products. Consumer products became affordable to a much wider range of the populations. At the same time, the military used this capability during World War II to produce tanks, planes, and ships in unprecedented numbers and at costs previously unheard of. Such machines were critical for the manufacture of engine parts and nuclear weapons.

However, automation alone was not sufficient to meet some of the post-World War II military needs, as more sophisticated weapons were developed. Production of these weapons required not only high accuracy, but also high repeatability. From this need came the development, in 1952, of a three-axis machine with the rudiments of numerical control (tape instructions). Development continued, with the introduction of automatic tool changing, four- and five-axes machines, and computer numerical controllers. Most subsequent improvements involved materials, better cutting tools, more accurate raceways, and faster and more stable spindle assemblies.

At the same time that these later developments were being introduced, composite materials were developed. To make best use of these new materials, new machines—tape-laying and filament-winding machines—were developed. This revolutionized the production of a wide range of commercial and military products (e.g., strong and lighter aircraft assemblies and automobile and tank parts).

Along with these continued improvements in manufacturing technology came continued requirements to perform both dimensional inspection and non-destructive inspection (NDI) of the final product.

The technology for coating various substrates has also experienced rapid growth and development during the 20th century. In earlier centuries, coatings were mainly applied for surface protection, and the most common media were paints or similar coatings. The perfection of equipment to produce vacuum environments increased rapidly the range of coating materials and technologies. Technologies moved from simple vacuum evaporation to chemical vapor deposition, plasma spraying, sputter deposition, ion implanting, and so forth. The refinement of these various technologies resulted in faster, more reliable jet aircraft (improved gas turbine engines); improved canopies for aircraft; longer-life bearings for applications in jet engines, machine tools, drive trains of automobiles, trucks, and tanks; specially designed dielectric layers and wear coatings for optical systems and sensors; and coatings to reduce observability of weapon systems.

Other products addressed in this section, bearings and robotics, have experienced similar developments. While bearings, in their simplest concept, have been used for many years, it was not until the 19th century, with the introduction of machine tools, that they were recognized as individual, important components. In the mid 20th century, the development of tapered bearings, high-speed bearings, and miniature bearings were instrumental in improving automotive drive trains; high-speed machine tool spindles; and navigation systems and gyroscopes, respectively. Robots, as they are known today, have developed as a direct result of the invention of computers. They have matured from interesting playthings to important production tools in most state-of-the-art factories, whether as robotic welders or material delivery tools. In more sophisticated applications, they are used in nuclear facilities and are being developed as a battlefield replacement for soldiers in some dangerous environments.

12.1—ADVANCED FABRICATION AND PROCESSING

Highlights

- Rapid prototyping and near net-shape manufacturing will result in reduced cost of producing prototypes and end products.
- More accurate grinding machines will result in reduced cost and improved engine performance.
- Breakthroughs in nanotechnology will result in significant improvements in electronics, chemistry, and materials, with widespread military applications.
- Continued advances in coating technologies will result in improved hardness capability of various military hardware surfaces and improved performance in multiple domains.

OVERVIEW

This subsection covers two groups of technologies. The first includes equipment for fabricating structures using a wide range of different equipment, ranging from various thermal furnaces and equipment for bending, stretching, or rolling material to form-desired shapes to scanning tunneling microscopes (STMs). The second group includes the development, refinement, and production of nonorganic coatings on non-electronic substrates. Such substrates include ceramics, low-thermal-expansion glass, metals, polymers, and so forth. Coating materials include ceramics, metals, dielectric layers, abradable materials, and so forth. The coating procedures include chemical vapor deposition (CVD), various techniques of physical vapor deposition (PVD), sputter deposition, plasma spraying, and ion implantation.

Many of the developing technologies associated with the fabrication equipment involve new and continuing procedures to produce what is needed accurately and affordably. While manufacturing most products, prototypes have to be produced. An ongoing program, rapid (virtual) prototyping allows for a quick three-dimensional (3–D) fabrication of the prototype so that a design can be evaluated before production is initiated. This technology consists of:

- A computer-aided design (CAD)-generated virtual-reality model of the design, which can be analyzed and altered, as necessary
- The ability to perform virtual machining (manufacturing) of the virtual part, followed by a computer comparison of the virtual part with the original digital design
- The capability to produce a model from the pattern in a fraction of the time required to produce a model using conventional model-shop procedures.

Additional effort is being aimed toward extending this procedure to produce not only prototypes, but also final products, thus significantly reducing the time/cost of production.

Rapid prototyping is an integral part of the product realization cycle. It permits the fabrication of complex parts in a fraction of the time required by traditional prototyping techniques and, thus, will play a significant role in making products more affordable. Rapid prototyping can be categorized into two areas: virtual and physical. In the former, the computer system (CAD) is used to generate a 3–D image that can be analyzed before final manufacture. In the latter, the CAD program is fed directly to the manufacturing tool that produces either a final product (most often made of ceramic, wax, or plastic) or a mold to produce a metal object. Much effort is being expended to produce high-quality metal objects without the need of a mold.

Another ongoing developing technology included in this subsection is near net-shape. Near net-shape is an ongoing program with the goal of lowering the costs of manufactured products by reducing the amount of raw material used (less waste) and by producing a product so close to the design shape that only a minimum amount of subsequent machining is required to achieve the desired final shape. Casting is an example of a technology in which much effort is being expended in near net-shape. The traditional trial-and-error approach of selecting an optimum combination of design and process parameters results in long lead times and excessive material waste. To circumvent this approach, computer simulation of the casting process is being used and evaluated as a means to ensure that defect-free castings are produced in the first attempt.

Generally, items manufactured using techniques such as casting, injection molding, hot isostatic pressing, and so forth result in a final shape different from the shape of the container. As a result, historically, many products were manufactured using several steps until the proper shape of the container could be determined. Near net-shape technology uses CAD programs to calculate the resultant changes in shape that occur during cooling of the product so that the final product is “near the designed shape.” This is of particular importance when fabricating ceramic parts because such items are very hard and subsequent finishing steps can be quite time consuming and expensive. Near net-shape is an approach similar to the philosophy of “first-time-right” manufacturing.

Ausforming is another developing near net-shape technology to manufacture superior spur and helical gears at less cost. It involves contour austenization of case-hardened gear teeth and quenching to metastable austenite, followed by plastic deformation of the gear tooth surface layers to final dimensions and then quenching to marstenite. The potential advantage of this procedure is that it forms the final shape of the gear without damaging the hard surface. It eliminates the need for gear tooth grinding while improving surface durability and fatigue behavior and reducing overall processing time and costs. The objective of the research program is to produce gears of better than 12 American Gear Manufacturing Association (AGMA) quality.

Semi-solid metalworking (SSM) is another example of near net-shape manufacturing, incorporating elements of casting and forming. In this process, the raw material is melted and allowed to cool to form a “mush” of liquid/solid material. This slush is then forced into a die, forming a final product that has higher structural integrity than castings but can be produced at lower cost than forgings.

Parts produced with SSM enjoy several advantages:

- Have higher structural integrity than castings, yet can be produced at lower cost than forgings
- Are less porous than parts produced with conventional high-pressure die casting
- Have equivalent properties to parts produced by either forging or conventional machining but require fewer steps.

To date, SSM has been demonstrated with aluminum, titanium, and copper; however, its implementation in either civil or military applications has been hindered by lack of process specifications, process models, training, and experience.

The most radical technology in this subsection deals with nanotechnology, defined as an anticipated manufacturing technology giving thorough, inexpensive control of the structure of matter (i.e., the ability to design and manufacture devices that are only tens or hundreds of atoms across). Nanotechnology is still an emerging technology. Significant advances have been made (e.g., buckyballs and fullerenes), but there has been little commercial activity. The development of “supersensitive coating to improve detection of dangerous materials” has been evaporated. Some use has been made of conducting fullerton as a filler material in plastics to make the plastic conductive. However, nanotechnology holds promise of an industrial revolution, as witnessed by the organizations—both government and industry—that are active in research.

Most of the research technology areas include materials, electronics, and medical devices. In materials, the bulk behavior of materials can be dramatically altered when constituted from nanoscale building blocks, the hardness and strength of nanophase metals can be greatly increased, and nanophase fillers in composite materials yield unique properties. Buckyballs and fullerenes (sometimes called buckytubes) are examples of nanophase materials. They are specific forms of carbon that are one-fourth the weight of steel and greater than 100 times stronger. Such capabilities hold great promise not only for use as improved cables, but as filler material for composite materials. Other potential applications include metal-doped buckytubes that theoretically would be 50 times more conductive than copper. Such tubes would bring about a revolution in power transmission.

Such a capability holds great promise in biology, electronics, chemical catalysis, and materials. This technology requires the capability to manipulate microscopic atoms, molecules, and so forth to form the desired structures. The procedures used in nanobiotechnology might be significantly different from those used in nonbiological applications. In the former, researchers are studying the molecular behavior of nucleic acids and proteins. In the latter, researchers are actively studying ways to use “buckyballs” and “buckytubes” (nanotubes) to produce usable end-items. Some military applications of this technology include biosensors, stronger ceramics and composites, superior coatings, abrasion-resistant materials, and so forth.

Buckyball structures are extremely malleable, can be compressed to less than half their original volume, and can be joined readily to other atoms, creating new capabilities. Although there have been no practical applications, as yet, for buckyballs, possible applications include superior armor, superconductor applications, ferromagnetic applications, superior lubricants, and medical applications.

Another fallout from buckyballs, and possibly more promising, are buckytubes (or nanotubes). These nanotubes are similar to buckyballs, but, instead of a sphere, the carbon atoms are linked together in a chicken-wire pattern. In certain cases (controllable), the carbon sheets roll together, and the edges join seamlessly, forming a nanotube. In some arrangements, the tube is a conductor. In other arrangements, the tube is a semiconductor. If two such tubes are joined to form a single molecule, the junction acts like a diode. Other possibilities for nanotubes include use as ultrastrong, thin cable and as a means of delivering medicine internally. Presently, conductive nanotubes are used in plastics to make the plastic conductive.

Coating technologies include several programs of developing technologies. Research has been conducted for several years on the technology for the deposition of diamond coatings. While some success has been achieved, the widespread application of the technology is still 5–10 years away. Nanophase coatings and cubic boron nitride coatings are more recent research programs, and both offer potential in the same technology area as diamond coatings—extremely hard, durable coatings. All these technologies have wide potential applications in military and civil applications. Of the three, nanophase coatings (related to nanophase materials) is probably the most esoteric.

Items fabricated from nanophase materials have superior characteristics. For example, nanophase copper and palladium have hardness and yield strengths 500 percent greater than conventionally produced metal, and nanophase ceramic material can be manufactured with much greater ductility than conventionally manufactured ceramics. These same bulk-nanophase characteristics result in similar improvements in the characteristics of nanophase coatings, particularly in applications requiring improved wear-resistant surfaces and increased thermal protection.

More recent studies have focused on the use of multilaser sources to heat the surface of a substrate selectively—resulting in extremely hard, graded surfaces. The technology can be modified by adding specific constituents to the plasma around the surface, altering the surface layer of the substrate and resulting in an extremely hard surface alloy.

LIST OF TECHNOLOGY DATA SHEETS
12.1. ADVANCED FABRICATION AND PROCESSING

DATA SHEET 12.1. RAPID PROTOTYPING MANUFACTURING (RPM)

Developing Critical Technology Parameter	Some early users of this technology report time reductions of 5–1 and cost reductions of 10–1. This is an ongoing program in a wide range of civil and military facilities.
Critical Materials	The materials depends on the RPM procedure used, including materials such as photopolymer epoxy resins, acrylates, polycarbonates, nylon, elastomers, certain metals, thermoplastics, polyester, ceramic powder, and so forth.
Unique Test, Production, Inspection Equipment	Laser stereolithography, laser sintering equipment, polymer extrusion equipment, and computers (for CAD).
Unique Software	CAD programs.
Major Commercial Applications	Aerospace products that are produced in small volume and molds for items produced in large volume (e.g., automotive).
Affordability	1. Allows quick fabrication of 3–D prototypes to evaluate of the design before beginning production. 2. Allows rapid production of small-volume products, spare parts, and so forth.

DATA SHEET 12.1. IMPROVED NEAR NET-SHAPE

Developing Critical Technology Parameter	This is a continuing, ongoing program, encompassing several different manufacturing technologies. Near net-shape manufacturing is a manufacturing process aimed at producing a final product that closely approximates the final design shape. Advanced simulation software is an important element is most of the processes. As an example, “Ausforming,” a technique being developed for gear manufacture, minimizes manufacturing steps, preserves the hard surface of the gear, and imparts compressive residual stress into the gear. The technical objective is to produce gears of that are greater than 12 AGMA quality. The goals of near net-shape manufacturing are cost reduction (less final machining to reach the final design shape and less waste) and improved technical characteristics of the final product.
Critical Materials	Depends on the process used. Fine powder technologies (metal and ceramic).
Unique Test, Production, Inspection Equipment	Hot isostatic press, powder press, casting equipment, injection molding equipment, X-ray machines, electron microscopes, metallography, forming press, and so forth.
Unique Software	CAD for process simulations. To incorporate algorithms to initiate changes in component form because of compensation for shrinkage, warpage, or other process and material conditions.
Major Commercial Applications	Aerospace engines; automotive transmission cases and engine blocks; marine engine blocks and motor mounts; bearings made from powder metallurgy; home appliances (e.g., washers, dryers, and mixers); and office equipment (e.g., printer heads and disc drives); and so forth.
Affordability	If items can be cast, or prepared, closer to their final shape, fewer machining operations are required to reach the design shape, thus reducing cost.

DATA SHEET 12.1. SEMI-SOLID METALWORKING (SSM)

Developing Critical Technology Parameter	Initial studies indicate that parts manufactured using SSM have higher structural integrity than castings and are less expensive than forgings.
Critical Materials	The base materials used in the manufacture of end product.
Unique Test, Production, Inspection Equipment	Casting and forming equipment, X-ray machines, electron microscopes, metallography, and so forth.
Unique Software	CAD and process simulation software.
Major Commercial Applications	Aerospace engines; automotive transmission cases and engine blocks; marine engine blocks and motor mounts; home appliances (e.g., washers, dryers, and mixers); and office equipment (e.g., printer heads and disc drives); and so forth.
Affordability	Estimates from pilot work indicate that cost savings per valve will be in the $1K–$10K range. If this technology allows conversion to titanium valves, savings could reach $13,000,000 per ship, over a 40-year life.

BACKGROUND

SSM technology is a near net-shape approach to manufacturing wherein the metal, in a semi-solid state (i.e., at a temperature between its solid and liquid states) is formed, using pressure, in dies. This combination of slush and pressure results in a final product with less voids. More conventional processing uses either molten metal (casting) or solid metal (forming). Parts produced by SSM have higher structural integrity than castings and can be produced at lower costs than forgings. The process is capable of producing parts that are essentially free of the porosity associated with conventional high-pressure die casting. At the present time, SSM is being used with titanium and aluminum.

DATA SHEET 12.1. TECHNOLOGY FOR MOLECULAR MANUFACTURING (NANOTECHNOLOGY)

Developing Critical Technology Parameter	The manufacture of items using extremely small and/or extremely strong building materials [e.g., buckyballs (fullerenes), buckytubes (nanotubes), and so forth]. Nanophase materials and nanocomposites are characterized by ultra-fine grain size (< 50 nm).
Critical Materials	The base materials used in the manufacture of end product. Buckyballs and nanotubes are made of carbon. Many potential applications of buckyballs and nanotubes would require the addition of other elements to the carbon structure. This could include hydrogen or fluorine atoms to form "fuzzy" balls, potassium to form a superconducting material, and so forth.
Unique Test, Production, Inspection Equipment	Scanning tunneling microscopes (STMs) for the manipulation of atoms and furnaces to form buckyballs and nanotubes.
Unique Software	None identified.
Major Commercial Applications	Applications could include very small, highly sophisticated, low-power electronic systems; stronger, lighter structural members; multifunctional surfaces; small, accurate antennas; and so forth.
Affordability	Not an issue.

BACKGROUND

Nanotechnology was defined by Drexler as "the knowledge and means for designing, fabricating, and employing molecular scale devices by the manipulation and placement of individual atoms and molecules with precision on the atomic scale." This so-called "bottom-up" approach to manufacture contrasts sharply with the conventional "top-down" approach, where a bulk material is machined down to meet the designed shape.

Research on specific characteristics of buckyballs and nanotubes have demonstrated that:

- They are unaffected by collisions at speeds of up to 15,000 mph.
- When compressed, they are harder than diamonds.
- Their internal cavity is large enough to hold any known element, thus having the possibility of being a carrier for medicines or radioactive materials.
- The addition of hydrogen or fluorine atoms to each of the carbon atoms ("fuzzy balls") should result in films with very low coefficient of friction.
- The addition of potassium atoms can result in either a superconducting material or an insulator, depending on the number of potassium atoms.
- Nanotubes could be used as fibers in composite materials, resulting in materials superior to carbon-carbon composite materials.

Figures 12.1-1 and 12.1-2 are computer representations of a buckyball (fullerene) and a nanotube.

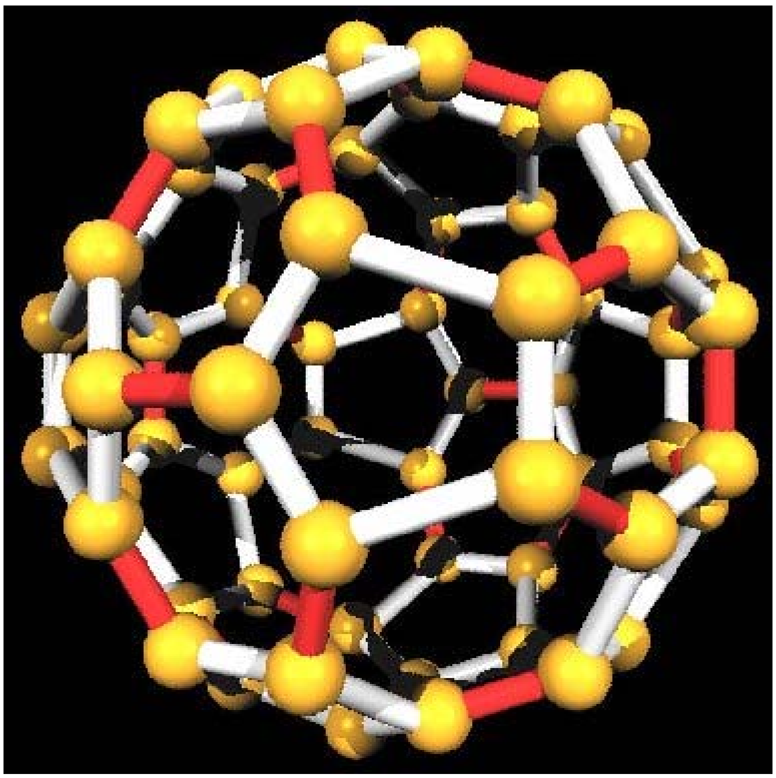


Figure 12.1-1. Buckyball (Fullerene)

Note for Figure 12.1-1: *This figure shows the C_{60} structure of the 60 symmetrically arranged carbon atoms.*

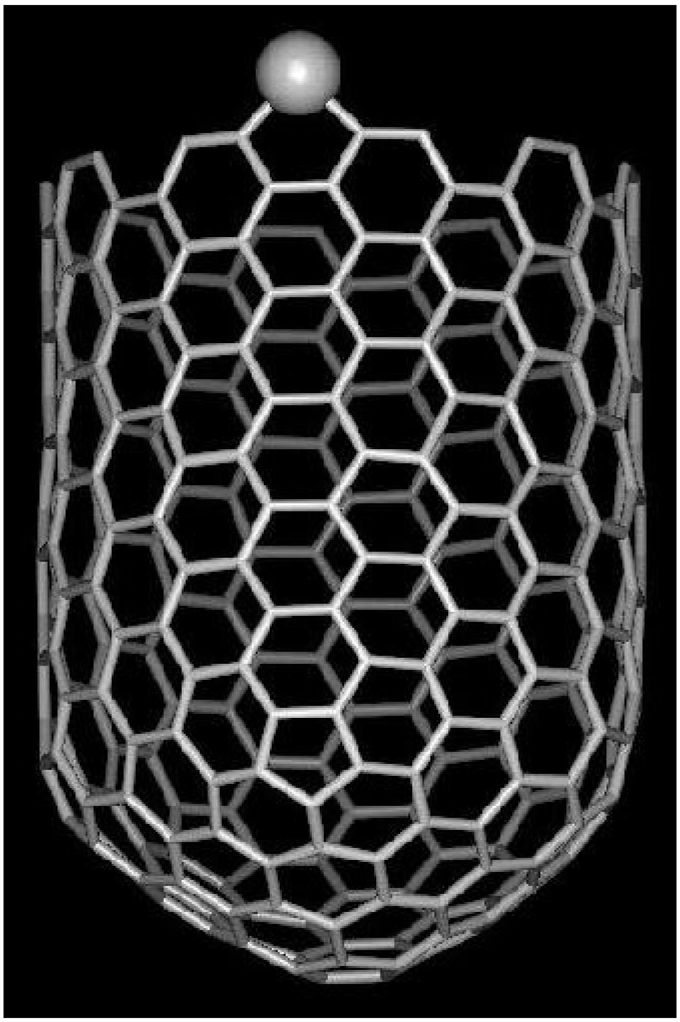


Figure 12.1-2. Nanotube

Note for Figure 12.1-2: *Computer simulation demonstrates the nanotube structure, a thin hollow cylinder of carbon capped at each end.*

DATA SHEET 12.1. TECHNOLOGY FOR DIAMOND COATINGS

Developing Critical Technology Parameter	Extremely hard, durable coatings. Characteristics should approach the following properties of diamond: • Hardness of 80–90 GPa • Coefficient of thermal expansion (at room temperature) of 0.8×10^{-6} K • Coefficients of 0.005 • Thermal conductivity (at room temperature) of 2×10^{3} W/m/K • Very resistant to chemical corrosion • Biologically compatible.
Critical Materials	Carbon deposition source.
Unique Test, Production, Inspection Equipment	Chemical vapor-deposition equipment, sputtering, ion beam and direct current (DC) plasma deposition equipment, multi-laser system. Scanning electron microscopes (SEMs) and various optical equipment to analyze the surface.
Unique Software	None identified.
Major Commercial Applications	Wide application in materials requiring surface protection from erosion.
Affordability	Not an issue.

BACKGROUND

Diamond coatings offer extremely hard, durable, transparent coatings for a wide variety of applications. Extensive research is being conducted worldwide, and progress is continuing. Some applications have entered the commercial marketplace [e.g., coating of cutting tools (not applicable for machining ferrous materials) and heat sinks].

DATA SHEET 12.1. TECHNOLOGY FOR NANOPHASE COATINGS

Developing Critical Technology Parameter	Extremely hard, durable coatings and thermal barrier coatings produced from the deposition of particles whose size is in the nanometer range (10^{-9} m).
Critical Materials	Many different materials are being studied (e.g., n-WC/Co, MnO_2, yttria-stabilized zirconia, SiC, BN, and so forth).
Unique Test, Production, Inspection Equipment	Thermal spray equipment, CVD equipment, DC plasma deposition equipment, PVD equipment, and equipment to analyze the surface coating.
Unique Software	None identified.
Major Commercial Applications	Wide application in materials requiring surface protection from erosion or high temperatures. Applications would extend to cutting tools, engines, sensor windows, and so forth.
Affordability	Not an issue.

DATA SHEET 12.1. TECHNOLOGY FOR MULTI-LASER SURFACE MODIFICATION/COATING

Developing Critical Technology Parameter	Produces either a super-hard outer layer of the base material or a super-hard graded coating made up of the base material and an added constituent.
Critical Materials	Dependent on the coating to be deposited. The technique has had success with diamond, diamond-like carbon, and titanium carbide, among other sources.
Unique Test, Production, Inspection Equipment	Excimer, yttrium-aluminum garnet, and carbon-dioxide lasers. Other laser types might be substituted for these lasers.
Unique Software	Programs to control the multiplexing of the three lasers, the furnace temperature, and the gas mixtures.
Major Commercial Applications	Wide application in materials requiring an extremely hard surface layer. Preliminary results on steel punches, golf club heads, and fuel-injector nozzles.
Affordability	Not an issue.

BACKGROUND

Surface modification/coating offers extremely hard coatings for a wide range of applications and does so with only surface heating. At the present time, the patented procedure can deposit diamond, diamond-like carbon, and titanium carbide films.

DATA SHEET 12.1. TECHNOLOGY FOR CUBIC BORON NITRIDE COATINGS

Developing Critical Technology Parameter	Extremely hard, durable coatings, with a hardness of 5,000 knoop (second only to diamond), a thermal conductivity of 13 (W/cm)(K) and a heat resistance of 1,000 °C. "Knoop" hardness is a method of measuring a material's hardness by its resistance to indentation
Critical Materials	Boron and nitrogen compounds
Unique Test, Production, Inspection Equipment	CVD equipment, sputter equipment, PVD equipment for deposition, and IR spectroscopy to characterize films.
Unique Software	None identified.
Major Commercial Applications	Wide application in materials requiring surface protection from erosion. Also, should have wide application in the production of superior cutting tools, dies, and molds.
Affordability	Not an issue.

12.2—BEARINGS

Highlights

- Development of magnetic bearings using high-temperature superconductors will result in
  - Improved compressors for space cryocoolers
  - Frictionless bearings for use in high-speed machining
  - Magnetic bearings for use in electric vehicles and magnetic guns.

OVERVIEW

Bearings are not only key elements in military equipment that use rotating elements, but they are essential for the operation of precision machine tools and metrology equipment used to manufacture military equipment. For many years, steel roller and tapered bearings were used almost exclusively in advanced military hardware and precision machine tools. In recent years, considerable effort has been expended in developing self-lubricating ceramic bearings. These bearings have longer life, less friction, and lower density than similar steel bearings.

More recent effort has been focused on aerostatic and hydrostatic bearings. These bearings use air and liquid to maintain a separation between the surfaces during their sliding or rotating motion. Their potential in high-/low-speed, high-precision equipment is unquestioned. They also operate quietly, thus offering the possibility of improved quiet propellers. Aerostatic and hydrostatic bearings approaches possess the following advantages:

- No wear of either surface
- High precision
- Operation at both very low and very high speeds
- High stiffness (hydrostatic bearings only).

Research on high-temperature superconductor, magnetic bearings is still in an early stage. Much of this program's success is related to continued research on high-temperature superconductors. Several potential applications have been discussed. The use of these bearings in space cryocoolers would avoid the problem of heat generation that occurs with the present gas bearings. Other possible applications include the support for the shaft of high-speed motors, the levitation force for high-speed locomotives, and energy storage. The concept of energy storage involves using the bearings with flywheels, where the flywheels rotate at very high speeds. The flywheel concept holds great promise for both off-peak energy storage of power plants and use a power source for vehicles, whether civil or military. A major problem has been related to concerns of flywheel breakage and the requirements to surround the system with heavy production shrouds. Another possibility is application in high-energy weapons.

LIST OF TECHNOLOGY DATA SHEETS
12.2 BEARINGS

DATA SHEET 12.2. TECHNOLOGY FOR SUPERCONDUCTING MAGNETIC BEARINGS

Developing Critical Technology Parameter	Offer promise for the mounting frame of flywheel energy storage systems (with application in electric vehicles and electric utilities) and spacecraft gyroscopes.
Critical Materials	High critical temperature superconductive material.
Unique Test, Production, Inspection Equipment	Standard machine tools.
Unique Software	CAD programs for design of structure.
Major Commercial Applications	Electric automobiles, electric utility companies, superior coolers, and the superconductive magnetic levitated (MAGLEV) railway systems.
Affordability	Not an issue.

BACKGROUND

Superconducting magnetic bearings are directly dependent on the advances in the development of superconducting materials. Materials have been developed with transition temperatures (T_c) in the 135 K range, considerably higher than the temperature of liquid nitrogen (77 K). Research on superconducting bearings is proceeding at a rapid pace throughout the world.

12.3—METROLOGY

Highlights
• As critical dimensions of hardware become smaller, the positioning of the machining tool and the ability to measure that position become more important.
• The accuracy to which gears can be machined has a direct bearing on the noise and heat generated by the gears. Efforts to extend the metrology capability of gears to the 100-nm range should result in quieter and more efficient gear trains.
• The ability to operate high-quality coordinate measuring machines (CMMs) in the shop environment would result in a cost saving because the necessity of taking the part to a centrally located measuring room for high-precision dimensional measurements is very time consuming.

OVERVIEW

Metrology, in some form, has been used since the beginning of civilization. It took on additional importance during the Industrial Revolution when parts were no longer manufactured as one-of-a-kind. During the intervening years, metrology has advanced from measuring angles and lengths in inches and degrees to measurements in fractions of microns and arc-seconds. Modern metrology equipment includes gauge blocks, surface profilers, angular measuring equipment, laser-based measuring systems, coordinate measuring machines, and so forth.

Present developing technology can be separated into two parts: increased measurement capability and the use of advanced equipment in the shop working area (as opposed to operation only in controlled environments). This subsection addresses two technologies in the first part and one in the second. The following programs to increase measurement capability are listed: (1) to produce gear-measuring equipment that is not only faster than conventional equipment but will have measurement accuracies less than 1 µm and (2) to improve the capability of more accurately measuring the position of the spindle of a machine tool. Work is also being carried out to produce high-quality coordinate measuring machines that can withstand the environment of the shop floor and, thus, carry out inspections next to the production machines.

LIST OF TECHNOLOGY DATA SHEETS
12.3. METROLOGY

DATA SHEET 12.3. MACHINE TOOL METROLOGY

Developing Critical Technology Parameter	There are no quantitative parameters for this technology. Studies are being conducted on techniques to measure the position of the spindle more accurately. Techniques include laser triangulation and IR technology. Time frame: 5–10 years.
Critical Materials	Sensors to measure displacement, velocity, acceleration and deceleration, force and strain, pressure, or temperature.
Unique Test, Production, Inspection Equipment	Standard machine tools.
Unique Software	Software algorithm to analyze input from sensors.
Major Commercial Applications	Broad application in most machining operations used in the manufacture of commercial hardware.
Affordability	Increased metrology capability and reduced time for measurements reduces overall costs for gears.

DATA SHEET 12.3. GEAR METROLOGY

Developing Critical Technology Parameter	Measure gear parameters 10^2 to 10^3 times faster than CMMs (3–4 gears per second), with submicrometer accuracies.
Critical Materials	Sensors.
Unique Test, Production, Inspection Equipment	Standard machine tools.
Unique Software	Software algorithm to analyze input from sensors.
Major Commercial Applications	Application in the manufacture of a range of gears that require very accurate tolerances (e.g., helicopter gear sets and jet engines).
Affordability	Increased metrology capability and reduced time for measurements reduces overall costs for gears.

DATA SHEET 12.3. FACTORY-FLOOR-CAPABLE COORDINATE MEASURING MACHINES (CMMs)

Developing Critical Technology Parameter	The design and manufacture of CMMs so that the critical operating parts are not affected by the shop environment. The goal is to produce CMMs with accuracies in the 3.5 µm = L/200, where L is the linear distance being measured, in a temperature from 10–35 °C. Time frame: 5–10 years.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	Standard machine tools.
Unique Software	Software algorithm to analyze input from sensors.
Major Commercial Applications	Broad application in most machining operations used in the manufacture of commercial hardware.
Affordability	Having the CMMs on the shop floor, near the machining centers, would result in reduced costs of performing product inspections.

12.4—NON-DESTRUCTIVE INSPECTION AND EVALUATION

Highlights

- The use of shearographic techniques should increase the technical capabilities for the detection of flaws.
- Smart materials could revolutionize the inspection and evaluation of hardware by incorporating within the hardware sensors that could detect flaws.
- The application of data fusion technology to NDE should reduce the time/cost to perform more advanced analyses.

OVERVIEW

NDE encompasses a wide range of disciplines, including eddy current, magnetic testing, penetrant testing, radiographic testing, and ultrasonic testing. Each of these techniques is used in several different applications; however, they all have one thing in common: They are used for the detection of defects after an item or structure has been manufactured and requires periodic inspection. All these techniques have been used for quite a few years, and only minor changes have been incorporated into the procedures. Most changes have resulted from improvements in detection equipment. In this subsection, we describe three new NDE techniques: digital shearography, the use of smart materials, and data fusion.

Shearography is more traditional. It is a technique that is used to analyze finished product. In its simpler sense, shearography is an existing technology; however, it has several drawbacks. Digital shearography is an approach aimed at improving the technique. In short, shearography is a nonscanning, laser-based interferometry system used to detect areas of stress concentration caused by anomalies in materials. Digital shearography combines these techniques with charged-coupled device (CCD) cameras and computers to improve the image and allow analyses of the results. Digital shearography can examine substances as large as one ft square and is portable so inspection need not to be place in a laboratory.

Shearography has a major advantage over conventional non-destructive test (NDT) techniques (e.g., dye penetrant, magnetic particles, and radiography) used to detect flaws. The conventional techniques detect all visible flaws, but shearography, by examining not the flaws but the flaw-induced strain, provides more information on the criticality of the flaw. Potential military applications include the detection of subsurface flaws in aircraft panels and the detection of voids in composite materials.

The use of smart materials is a more radical approach because the sensors used to detect flaws in the structure are built into the structure and can be used to monitor quality/reliability either during manufacture or after the product is completed. The concept of smart materials is also an emerging technology in materials technology. In that application, the sensors detect some “designed-for” parameter and respond with a counteraction (e.g., damping engine vibrations, silencing refrigerators and aircraft cabin noise, and so forth).

Smart materials include technologies such as piezoelectric materials, shape memory alloys, and magneto-strictive fluids. The field of piezoelectric materials is the most advanced, and some commercial applications have been developed. However, widespread use of these technologies is still in the future. Potential civil and military applications abound, with civil applications including sensor determination of aging in building, bridges, and so forth; determination of maintenance requirements for engines, aircraft, and so forth; and chromogenic applications (e.g., self-dimming rear-view mirrors, architectural windows, and so forth).

Data fusion is a technique that uses data from a group of NDE sensors rather than using data from a single sensor. It has potential application in a wide range of disciplines. In essence, data fusion is a technique in which data from multiple—and perhaps diverse—sensors are correlated into digitally formatted products. These products provide a user with complex information in a user-friendly format so that decisions can be made quickly and accurately.

LIST OF TECHNOLOGY DATA SHEETS
12.4. NON-DESTRUCTIVE INSPECTION AND EVALUATION

DATA SHEET 12.4. DIGITAL SHEAROGRAPHY

Developing Critical Technology Parameter	Provides a large-area, quantitative analysis of stress concentrations resulting from either the vibration of a structure or existing in composite materials in aging aircraft. Inspection speed of an order of magnitude higher than conventional ultrasonic techniques. Time frame: 5–10 years.
Critical Materials	Lasers, CCD cameras, and so forth.
Unique Test, Production, Inspection Equipment	Laser system, CCD camera, and image processor.
Unique Software	Software algorithm to process information.
Major Commercial Applications	Useful in a wide range of commercial hardware, particularly aging aircraft.
Affordability	Improved shearography would result in reduced costs for performing some NDI tests.

DATA SHEET 12.4. NDE USING SMART MATERIALS

Developing Critical Technology Parameter	Theoretically, can sense (and often take corrective action) of a wide range of developing problems (e.g., local stress, corrosion, fatigue, vibration, noise, and so forth).
Critical Materials	Piezoelectric materials, shape memory alloys, magnetostrictive fluids, fiber optic material, and thermoplastics. Many of these are incorporated into MEMS structures.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	Software algorithms to process information.
Major Commercial Applications	Useful for the NDE of a wide range of commercial hardware, including items such as launch vehicles, aircraft, heavy equipment, trains, and so forth.
Affordability	The reduction of rejected hardware, the reduction of built-in latent failures, and the capability of detecting operationally induced failure mechanisms should lead to an overall reduction of costs.

DATA SHEET 12.4. NDE DATA FUSION

Developing Critical Technology Parameter	Improves NDE data collection and assessment by using the input from multisensors (rather than from a single sensor). Processing data and providing an integrated analysis of the item under test.
Critical Materials	Sensors.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	Software algorithms to process information from multisensors.
Major Commercial Applications	Machine tool monitoring, aircraft, automotive, and medical applications.
Affordability	Improved NDE data fusion could reduce the overall costs by reducing waste and improving reliability.

12.5—PRODUCTION EQUIPMENT

Highlights

- The development of spindles capable of operating at higher speeds and power would reduce the cost of machining.
- Improved grinding machines would result in more powerful jet and diesel engines and more accurate guidance systems.
- The continued development of parallel kinematic machine tools may result in improved machining capabilities and reduced cost of the machining operation.
- The use of MEMS technologies to improve military hardware and to reduce costs may be one of the most significant advances in developing superior and less expensive military hardware.
- Improved monitoring of machines and tools should reduce the cost of military hardware.

OVERVIEW

This subsection addresses various developing production technologies including the following:

- Improved grinding machines
- Machine tools based on the parallel kinematic concept (e.g., Stewart platform or hexapod)
- Extremely small machine tools (micromachines)
- MEMS, a revolutionary technology or manufacturing miniature hardware that combines both electronic and mechanical on a monolithic substrate.

Hexapods are based on the Stewart platform. Companies in numerous countries are investigating the use of hexapods as machine tools. Indeed, initial designs have been manufactured and are in the process of being evaluated. While some limited use has been found for the equipment, sufficient problems still limit their use at the present time. The main problem is that the positioning accuracies are on the order of five times worse than that of the best milling machines (although comparable to many existing machines). Such equipment might find a niche in the manufacture of micro- or nano-scale products.

Tetrahedral tripods are a third class of parallel kinematic machines. Efforts are still in the research stage, but such equipment may avoid some of the problems inherent in Stewart-platform-based equipment.

Micromachines are being pursued to manufacture minute items, such as invasive medical micromachines and maintenance systems for power plants. The technology, although different from MEMs, has the same general goals as the MEMS concept.

MEMS uses the techniques developed for the manufacture of integrated circuits to fabricate devices that incorporate, on a semiconductor substrate, not only integrated circuits, but also mechanical structures that can be used for a range of applications. MEMS technology includes three important characteristics: miniaturization, multiplicity, and microelectronics. By using semiconductor device manufacturing technology, these packaged MEMS-based systems are very small (ranging from 1 mm to 2 cm in size), can be manufactured in quantity using conventional pholithographic techniques, and incorporate complex electronic circuitry.

Until the advent of MEMS, miniaturization was a concept most often associated with electronics. The continual miniaturization of electronic systems has been one of the pillars of the advanced technologies used in military and civil hardware. The decrease in size, coupled with the increase in processing power, of computers is a prime example of the advances in electronic technology. In MEMS technology, actuators, sensors, and medical devices incorporating mechanical structures (e.g., levers, springs, motion sensors, and so forth) and integrated circuits are manufactured on semiconductor substrates, thus using the miniaturization capabilities of integrated circuit technology. The use of semiconductor manufacturing technology also results in the batch processing inherent in photolithographic-based semiconductor processing and makes it possible to fabricate thousands of components as easily as a single component. As a result, the cost of the components is reduced significantly, thus extending the use of the products to a wider range of applications. The incorporation of these mechanical structures either into microcircuit chips or on associated substrates (hybrid device) provides the intelligence to the devices that allow their use without the cumbersome external components that were often required to interconnect discrete components.

Technologies that may result in decreased costs include:

- Tool monitoring and sensing, which may result in more cost effective technique for determining tool life
- Machine degradation monitoring, which may result in a more cost-effective technique for determining machine tool maintenance
- High-speed spindles, which will decrease the time required to machine many parts, thus reducing the final cost
- First-part-correct programs, which would reduce the cost of having to make two or three items before the design/manufacturing process was corrected to produce a product that met design specifications.

LIST OF TECHNOLOGY DATA SHEETS
12.5. PRODUCTION EQUIPMENT

DATA SHEET 12.5. HIGH-SPEED, HIGH-POWER SPINDLES WITH HIGH-FEED RATE

Developing Critical Technology Parameter	The requirement is to obtain spindles that have not only high-speed capability, but can operate at that speed with both high force and feed rates. The overall goal is to develop spindles with the following capabilities: 100,000 rpm @ 100 kW and with a feed rate of 3,000 in. per minute.
Critical Materials	Bearings, motors, seals, cooling, and lubrication.
Unique Test, Production, Inspection Equipment	Standard machine tools.
Unique Software	Software algorithms to handle high-speed machining/grinding.
Major Commercial Applications	Large-scale manufacturing: aerospace, automotive.
Affordability	The use of higher speed spindles would allow the fabrication of many critical parts in much less time.

DATA SHEET 12.5. CUBIC BORON NITRIDE (cBN) GRINDING WHEELS FOR HARDENED STEEL GEARS AND BEARINGS

Developing Critical Technology Parameter	Important for grinding steel gears (diamond-coated wheels are of limited value in grinding hardened steel) to improve power density of gearbox.
Critical Materials	cBN.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	None identified.
Major Commercial Applications	Helicopters, engines, and so forth.
Affordability	cBN-coated wheels will last much longer than conventional wheels.

DATA SHEET 12.5. PRECISION PROFILE GRINDERS

Developing Critical Technology Parameter	A work head run-out <0.1 microns and a wheel surface speed >100 m/second @ 50 kW grinding power help achieve 6-sigma quality for ground parts.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	Standard machine tools.
Unique Software	None identified.
Major Commercial Applications	Large-scale manufacturing: aerospace, automotive.
Affordability	Not an issue.

DATA SHEET 12.5. PARALLEL KINEMATIC MACHINE TOOLS (STEWART PLATFORM, HEXAPOD, PARALLEL LINKAGE STRUCTURES, AND SO FORTH)

Developing Critical Technology Parameter	Parallel kinematic machine tools are a new concept in machine tool design. Existing developmental models have several drawbacks, and considerable research is being done to overcome these problems. If such machines can be improved to possess positioning accuracies of < 10 microns, velocity of 1 m/second, and spindle speeds in the 50,000-rpm range, they would find a definite niche among machine tools.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	Standard machine tools.
Unique Software	Unique algorithms to control six axes (for the Stewart platform and hexapod) and three axes (for the tetrahedral tripod).
Major Commercial Applications	Applications would include machining of small, complex parts or for use in pick-and-place systems.
Affordability	Not an issue.

RATIONALE

Figures 12.5-1 and 12.5-2 are pictures of a hexapod and a Stewart platform, respectively.

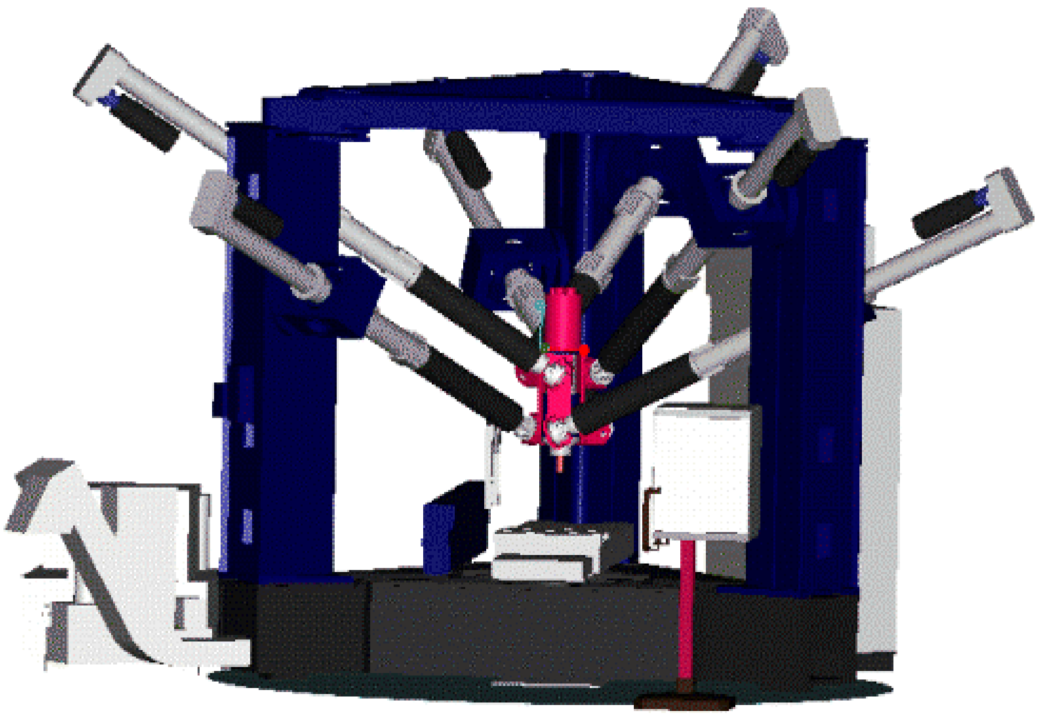


Figure 12.5-1. Hexapod

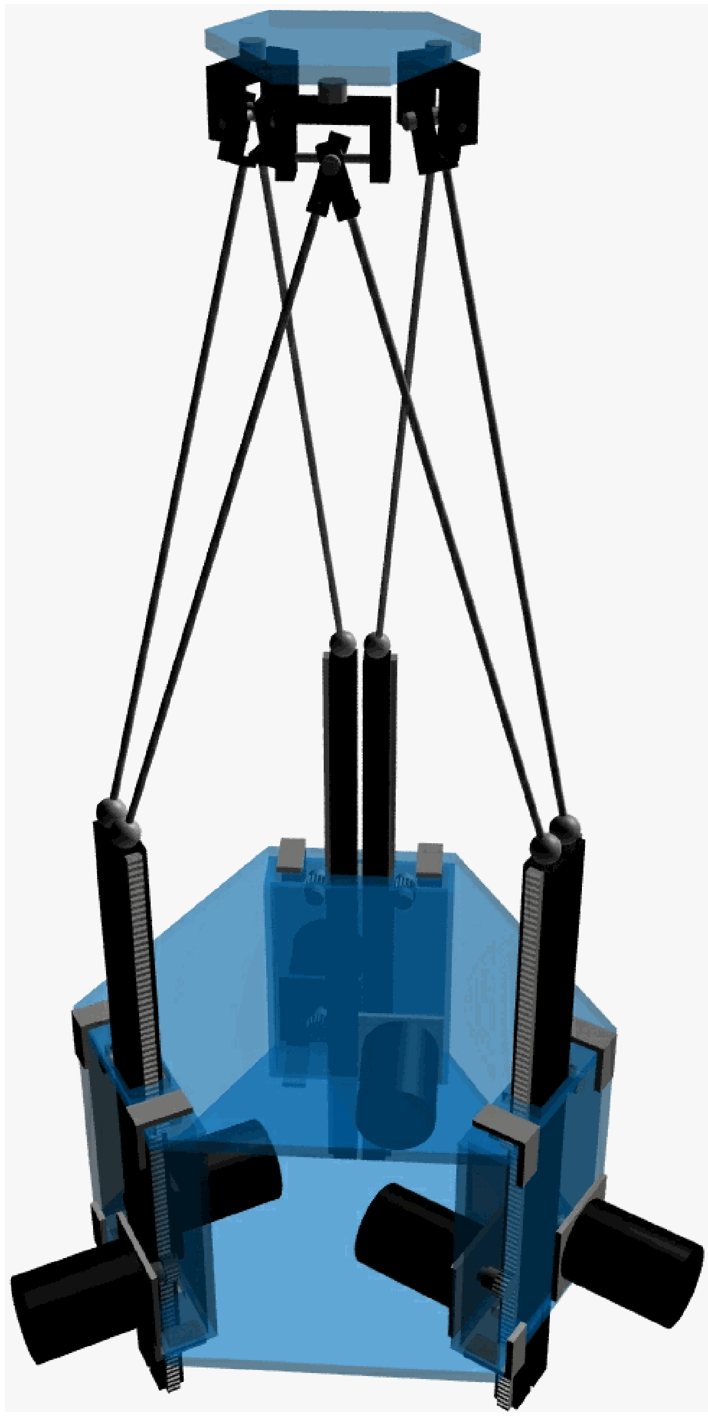


Figure 12.5-2. Stewart Platform

DATA SHEET 12.5. MONITORING AND SENSING OF CUTTING TOOLS AND MACHINE TOOLS

Developing Critical Technology Parameter	No quantitative parameters are available; a continuing, ongoing program. Thin film sensors (coated with a hard protective layer) can be deposited onto the cutting tool and used to measure the condition of the tool. In machine tools, the sensors are mounted within the mass of the machine tool and measure parameters such as temperature, vibration, and so forth.
Critical Materials	Capacitance gauging, lasers, sensors, and so forth.
Unique Test, Production, Inspection Equipment	Computers and sensors.
Unique Software	Unique algorithms to monitor cutting tool or machine tool condition.
Major Commercial Applications	General machine tool operation.
Affordability	Cutting time is the criterion used by most manufacturers for tool life. With sensors mounted on, or in, the tools to measure parameters such as force (radial and thrust) and torque, a more accurate determination of tool life and condition is possible.

BACKGROUND

The normal operation of a machine tool generates heat and vibration within the mass of the machine tool. Both can affect the positioning accuracy and cut of the tool. Accurate monitoring of these parameters, coupled with a feedback mechanism, can minimize most of the heat and vibration effects.

DATA SHEET 12.5. MICROMACHINES

Developing Critical Technology Parameter	No quantitative parameters are available. However, the general concept is to build extremely small machines (using miniaturized machine tools) that can perform the same tasks, albeit on a miniature scale, as conventional machines.
Critical Materials	Material of end product.
Unique Test, Production, Inspection Equipment	Machine tools or lasers capable of producing the micromachines.
Unique Software	None identified.
Major Commercial Applications	Overall applications are unknown. Initial interest includes invasive medical devices and very small items, such as mini-gyroscopes, micromotors, pumps, and robots.
Affordability	Not an issue.

BACKGROUND

Micromachines are extremely small and comprise minute (millimeter range) functional elements that are highly sophisticated and are capable of performing complicated tasks. The concept of micromachines is similar to that of MEMS technology (i.e., manufacture devices that are extremely small, allowing continued miniaturization of hardware, with the many benefits associated with miniaturization).

DATA SHEET 12.5. MICROELECTROMECHNICAL SYSTEMS (MEMS)

Developing Critical Technology Parameter	No quantitative parameters are available. However, the general concept is to build extremely small machines (devices) that can perform the same tasks, albeit on a miniature scale, as conventional machines. In short, MEMS devices should be smaller, less expensive, and more reliable than more conventional devices.
Critical Materials	Silicon wafers; other materials used in microelectronics fabrication industry.
Unique Test, Production, Inspection Equipment	Standard semiconductor manufacturing equipment, including photolithographic equipment, dry etchers, deposition equipment, and systems for reactive ion etching, LIGA, wafer-to-wafer bonding, and so forth.
Unique Software	None identified.
Major Commercial Applications	Unlimited applications. Present uses include accelerometers for airbag deployment in automobiles; micropressure sensors, medical microfluidic systems; micromirrors for projectors; nozzles for inkjet printers; and fluid flow sensors.
Affordability	MEMS fabrication is less costly than the fabrication of traditional components. MEMS-based systems often have improved performance or reduced size and weight, which leads to further savings.

BACKGROUND

MEMS are micron-scale devices that integrate novel sensing and actuation functions with traditional micro-electronics-based data processing and control systems. MEMS are unique because they combine mechanical or structural elements, such as accelerometers and micromirrors, with electronic elements, such as microprocessors and radio frequency transmitters. Figures 12.5-3 and 12.5-4 are representative of the structures being fabricated.

DATA SHEET 12.5. FIRST PART CORRECT (OR VALID)

Developing Critical Technology Parameter	Ability to take complicated engineering designs from design to manufacturing and have the end product meet all specifications the first time.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	Computers and normal manufacturing equipment.
Unique Software	Computer-aided design/computer-aided manufacturing/computer-aided engineering (CAD/CAM/CAE) programs.
Major Commercial Applications	All manufacturing operations; however, the most important area would be for items manufactured in small volumes.
Affordability	In small-volume applications, each part that does not meet specification is a significant part of the overall cost.

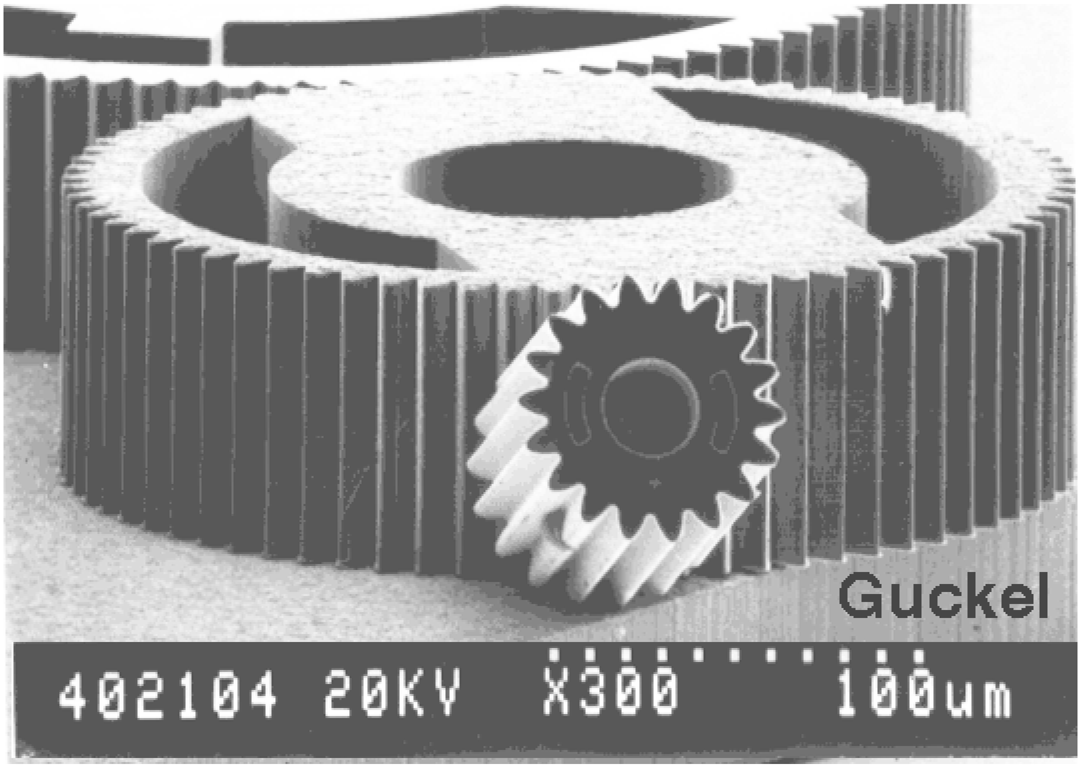


Figure 12.5-3. MEMS Gear

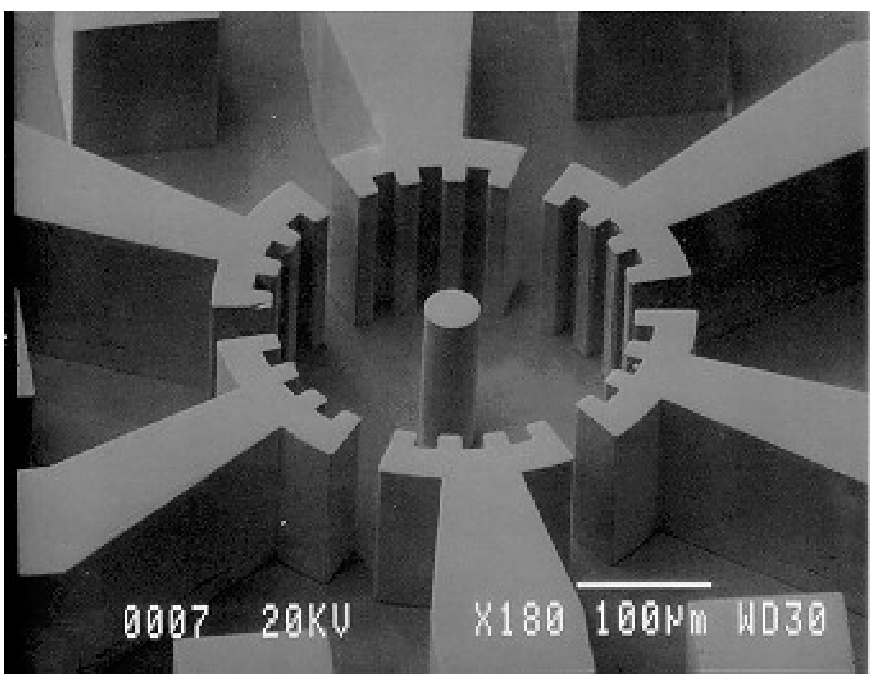


Figure 12.5-4. MEMS Motor

12.6—ROBOTICS

Highlights

- Advanced sea, air, and land robots will carry out a wide range of military operations, ranging from chemical and biological warfare (CBW) detection and reconnaissance to mine detection.
- The development of fractal, self-duplicating, self-repairing robots would be a significant breakthrough in the design of military hardware.

OVERVIEW

This subsection covers the developing technology for advanced battlefield robots, encompassing robots for land, sea, and air. Possible robots include:

- **Ground robots.** Although these robots could be designed for many different applications, early planning has addressed the fields of cameras, sensors, or equipment for gathering and disseminating information.
- **Seaborne robots that resemble jet skis.** These robots can be equipped with a various types of equipment, including underwater cameras, laser scanners, night vision equipment, radar, and so forth.
- **Micro and mini air vehicles (MAVs).** Proposed designs of these pilotless machines vary from micro (smaller than 6 in.) to extremely small (8- to 10-in. size) to moderate (on the order of 3- to 5-ft size). Initial plans would be for the craft to carry some type of sensor, although they could also carry small amounts of explosives.
- **Fractal shape-changing robots.** These robots can, theoretically, change shape, replicate, self-repair, and perform a wide variety of military tasks.

The fractal shape-changing robots are a form of nanotechnology and are still in the conceptual stage. However, interest has been increasing since the inventor was awarded the 1996 European Invention Competition of Monaco. The concept of replication is a basic tenet of nanotechnology, whether one considers classic nanotechnology or molecular nanotechnology. The goals of nanotechnology are low cost, molecular precision, and flexibility. Some authors believe these can only be reached with the development of self-replicating objects.

LIST OF TECHNOLOGY DATA SHEETS
12.6. ROBOTICS

DATA SHEET 12.6. BATTLEFIELD ROBOTS

Developing Critical Technology Parameter	Perform reconnaissance, mine clearing, material handling, target identification, and CBW detection.
Critical Materials	Sensors.
Unique Test, Production, Inspection Equipment	Standard machine tools, computers, and so forth.
Unique Software	Software algorithms to control action of the robot.
Major Commercial Applications	Law enforcement.
Affordability	Not an affordability issue in dollars and cents matters but definitely an affordability issue in human life and safety matters.

BACKGROUND

Figure 12.6-1 shows a robot developed for reconnaissance.

Figure 12.6-1. Reconnaissance Land Robot

DATA SHEET 12.6. UNDERSEA ROBOTS

Developing Critical Technology Parameter	Perform reconnaissance, on water surface and underwater, including cameras (visual), laser scanning, night vision, and so forth.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	Standard machine tools, computers, and so forth.
Unique Software	Software algorithms to control action of the robot.
Major Commercial Applications	Underwater research, shipwreck investigations, oil and mineral exploration.
Affordability	Not an issue.

BACKGROUND

Figure 12.6-2 shows a robot developed for underwater reconnaissance.

Figure 12.6-2. Underwater Robot

DATA SHEET 12.6. MICRO AIR VEHICLES (MAVs)

Developing Critical Technology Parameter	Perform reconnaissance, target identification, and CBW detection.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	Standard machine tools, computers, and so forth.
Unique Software	Software algorithms to control the robot's action.
Major Commercial Applications	Possible application in agriculture (crop studies), archeology (study of terrain), crowd control, and search and rescue.
Affordability	MAV should be considerably less expensive than conventional drones. In addition, the use of MAVs would minimize the danger to personnel.

BACKGROUND

Figure 12.6-3 shows a reconnaissance and an extremely small MAV being developed for a wide range of potential applications. Figure 12.6-4 is an example of a less conventional approach to MAVs, one using the concept of "flapping wings."

(a) Reconnaissance UAV

Figure 12.6-3. UAVs

(b) Less Conventional MAV

Figure 12.6-3. UAVs

Figure 12.6-4. UAV "Flapping Wings" Approach, as Researched at Georgia Tech

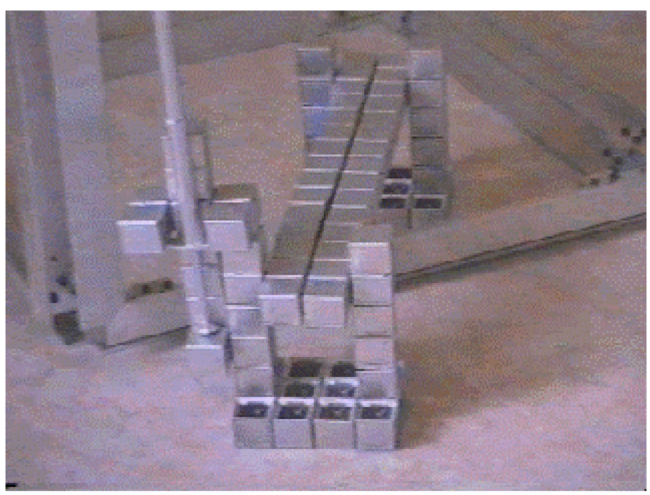
DATA SHEET 12.6. FRACTAL SELF-SHAPING ROBOTS

Developing Critical Technology Parameter	Extremely small (nanotechnology approach), shape-changing, self-repairing cubes.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	Computers.
Unique Software	Software algorithms to control action of the robot.
Major Commercial Applications	Potential applications include medical technology, bridge building, space technology, and so forth.
Affordability	Not an issue.

BACKGROUND

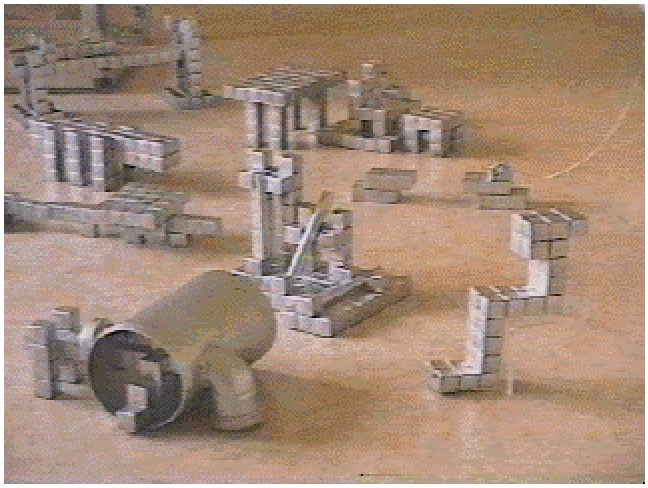
A fractal is a shape that, when one looks at a small part of it, has similar (but not necessarily identical) appearance to the full shape.

Fractal shape-changing robots presently make use of large numbers of small cubes, each containing a computer chip, programmed to perform specific functions. These functions can include movement, laterally or vertically, and can effect a change in the shape of the final structure. Figure 12.6-5 shows examples of fractal robots.



(a) Robotic Demonstration of Bridge Building

Figure 12.6-5. Fractal Robots



(b) Various Examples of Fractal Robot Structures

Figure 12.6-5. Fractal Robots