3.0 Spacecraft Bus Technologies

3.1 Introduction

The continuing development of advanced spacecraft technology is essential in order to increase spacecraft capabilities and reduce costs while lowering weight and volume. Over the last few years, two basic philosophies have emerged. The first philosophy is to integrate many functions in the same spacecraft, thus producing fairly large spacecraft with many capabilities. These complex spacecraft use state-of-practice technologies, have a very small payload mass fraction, tend to be very expensive to develop, and have to be launched on large launch vehicles. The complexity of these multi-function systems is closely related to the number and type of bus technologies required to support the various payload subsystems. The second philosophy uses a different approach to building spacecraft, integrating very few payload instruments and using the most advanced lightweight technologies available (state-of-the-art). These types of spacecraft tend to be relatively small with a much larger payload mass fraction. While these smaller spacecraft have limited capabilities, they are much more affordable than the larger systems due to the basic lower cost of the spacecraft and the use of smaller, much less expensive launch vehicles. With the continuing development of spacecraft technologies, the capabilities of these smaller spacecraft can be enhanced considerably. In the near future, the second design philosophy can be applied to most operational systems.

Spacecraft bus technology in the US has been funded primarily by DoD, NASA, and the commercial sector. Within the DoD, the Air Force continues to be the major developer of satellite technologies. This leadership must continue not only in near term technology evolution, but also in the development of revolutionary technologies that can produce an order of magnitude improvement in capabilities at a reduced cost.

Although spacecraft perform a multitude of functions, every spacecraft, regardless of its function, contains support systems that perform essentially the same tasks. These systems can be divided into:

- Spacecraft structures
- Electrical power systems
- Attitude control systems
- Command and data handling systems
- Thermal control systems
- Propulsion systems

In addition, there is the consideration of the survivability of the spacecraft that determines some of its design. Each of these aspects of spacecraft design is ripe for a significant evolution in the near future.

3.2 Spacecraft Structures

Reducing weight in spacecraft structures has, to date, been a matter of building the structures out of lighter materials while still maintaining the strength, stiffness, and other properties required for the structure. Improvements in materials are likely to occur over the near term; a more radical approach is to integrate different functions of the spacecraft bus into the materials that form its structure.

3.2.1 The State of the Art in Spacecraft Structures

Over the last 25 years, the use of metal matrix, metal resin, and carbon-carbon composite materials as spacecraft materials and structures have reduced the spacecraft weight considerably. The structural weight of an aluminum spacecraft is about 23% of the total spacecraft weight. Composite materials were first introduced in the spacecraft in the mid 70s as secondary structures for reflectors and feed supports. Since then, the use of composites has propagated to the entire spacecraft, to the point that most spacecraft designed today use composites to decrease the structural mass fraction. Figure 3-1 shows that with the integration of composite primary structure and many composite secondary structures, structural weight is currently only about 7% of the total spacecraft weight.

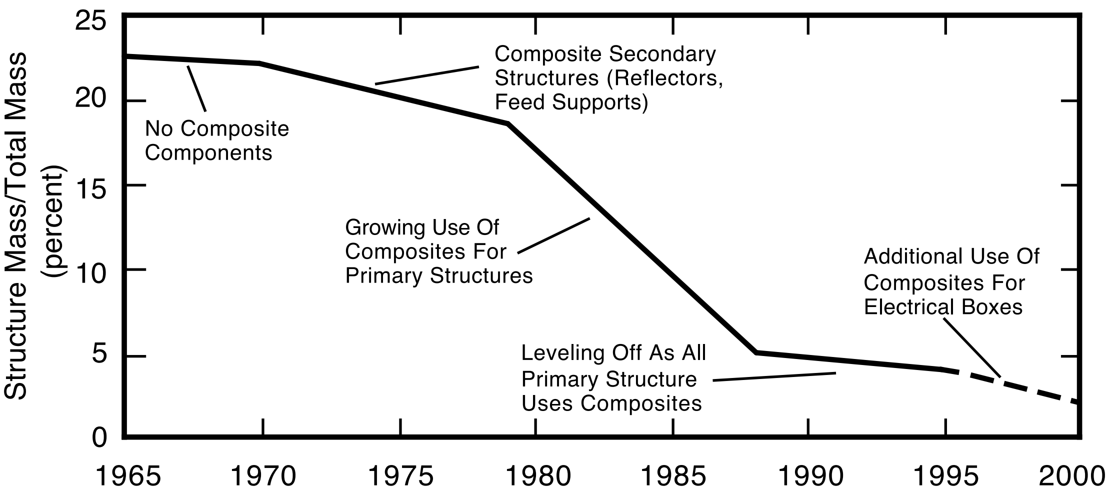

Figure 3-1. Evolution of spacecraft structure as a fraction of spacecraft mass

Spacecraft structures today are being designed predominantly with metal alloys such as 7075 aluminum, organic composites such as graphite lamina, or metallic composites such as silicon carbide on aluminum. Polycynate-ester resin systems (PERS) are now being tested for space applications. PERS have low outgassing and are non-hygroscopic, which prevents potential material condensation onto critical optics. Additionally, significant improvements have been made in the design and manufacturing of materials and structures. Instead of hand machines, workstation computer aided design and precise laser cutting (computer aided manufacturing) are being used almost exclusively today. Current spacecraft designs use structural elements on which electronics boxes and other elements are mounted. Cabling and waveguides are used to interconnect these subsystems.

3.2.2 Technologies for Evolutionary Change in Spacecraft Structures

The spacecraft designed in the early 1990s used trusses and bi-stem beams as deployable structures, with a large ratio of deployed volume to stowed volume. If the present level of funding continues in the development of structures, lightweighting will reduce mass by about 60% over the next ten years. However, the coupling between the displacements of deformable structures and the performance of control systems has led to the development of control/structure interactions. Smart structures using piezoelectric sensors and actuators can provide active damping and jitter suppression, meeting structural requirements such as stiffness and dimensional stability with greatly reduced mass. The Air Force should make the investment required to develop control-structure interactions with active control for vibration suppression.

Most spacecraft have a variety of requirements for electro mechanical devices for precision articulation, separation, appendage release, and so forth. Many of these devices have been pyrotechnically initiated. Innovations in mechanical devices and applications of shape memory and phase change materials are maturing that can not only reduce cost and weight of these devices, but are low-shock, low-vibration, and capable of being activated without use of pyrotechnics. Furthermore, the devices are resettable and completely testable prior to flight use. They are inherently more reliable because of the reduced number of parts. Significant indirect savings are possible by eliminating hazardous operation associated with pyrotechnics. Every effort should be made to avoid debris generation so as not to increase the orbital debris. The Air Force should make the investment necessary to bring this class of devices through qualification and into general use.

Cabling on a spacecraft bus is typically very heavy, and the touch labor in assembling and testing the cabling is significant. Spacecraft bus hardware could be integrated using advanced structures that meet the thermal, electrical, and structural functions. Designing of such multifunctional structure would be made possible by advances in lightweight material development, high density electronics packaging, and advanced computer-aided design tools. In this approach, cabling and interconnects would be replaced by a multilayer network deposited on the structural substrate. Each layer of the multilayer network would perform a specific electronic function: power, ground, control, data transmission, and so on. This innovative approach would also allow electronic subsystems to be mounted directly on the spacecraft structure without the use of enclosures, resulting in unparalleled weight savings. This technology could enable, with the use of standard interfaces, the incorporation of thermal control into the multifunctional structures, and the integration of a satellite subsystems on the structural elements. In addition, it is conceivable to control the multilayer networks on the structural members through software and rerouting algorithms that control the interconnection of various modular subsystems, antenna elements, and microelectromechanical-systems-based devices embedded in the structural elements. To bring this technology to fruition, the Air Force needs to invest in multifunctional structures, microelectromechanical systems (MEMS) technologies, and advanced electronics packaging technologies specifically directed toward space systems.

Another issue that will affect the design of future spacecraft structures is the requirement to reduce the vulnerability of space assets by making them hard to detect. Low-observable technologies are often considered to be materials issues, but reducing a spacecraft's electromagnetic signature means much more than finding materials that are non-reflective, because each surface of a spacecraft has a function to perform, whether collecting solar energy, radiating thermal energy, collecting or broadcasting radio frequency (RF) energy, or sensing other portions of the electromagnetic spectrum. Systems-level design considerations (for example, placing radiator panels so that they face into space) and overall systems architectures (such as satellites that are passive until they need to perform their particular function) come strongly into play. It is necessary to consider carefully what portion of the spectrum an opponent will be searching (whether RF, visible, or infrared (IR)) to effectively hide a satellite. Technologies for spectrum-selective reflection and absorption is one area that the Air Force should pursue, along with materials that are both stealthy and structural.

3.3 Electrical Power Systems

Presently about 25% of the weight of a spacecraft is used to generate the electricity required to operate the various subsystems. There are three basic elements in the power systems being used by today's spacecraft:

- Energy conversion systems. Most satellites collect solar energy, which the satellite cannot use directly. This energy must be converted into electrical energy to be useful to the satellite.
- Energy storage systems. Solar energy is usually available for only a portion of a satellite's orbit. Therefore, in addition to converting solar energy to electrical energy, a satellite must store energy onboard (usually in a battery) to be used during eclipse times.
- Power conversion systems. Electrical energy taken from storage must be converted into a useful form as required by a satellite's subsystems.

Although a power system consisting of solar cells, batteries, and DC-DC converters is most typical on spacecraft, it is not the only way one can conceive of powering a spacecraft, and innovative technologies for each of these basic functions are possible.

3.3.1 The State of the Art in Electrical Power Systems

Photovoltaic solar cells are used by spacecraft to convert solar energy to electrical energy. Early cells were thick, discrete cells, made out of silicon and laid out on rigid panels. Thin discrete silicon cells were used throughout the 1980s; however, silicon cells have been limited to about 14% efficiency. In the early 1990s, smaller Gallium Arsenide (GaAs) cells were developed and integrated on flexible panels with a cell efficiency over 18%. Now, in 1995, dual junction Gallium Indium Phosphide/Gallium Arsenide ($GaInP_2$/GaAs) cells on a germanium substrate have shown 23% efficiency. With continuing funding, triple junction thin-film cells will be built and manufactured in the near future, obtaining roughly 30% efficiency.

Nickel hydrogen batteries have replaced nickel cadmium batteries in most of today's spacecraft. Recently, the nickel hydrogen common pressure vessel battery with a specific energy of 55 Watt-hours per kilogram (Wh/kg) has produced twice as much energy density than a design using individual pressure vessels. Additionally, nickel hydrogen batteries can tolerate a much larger depth of discharge than nickel cadmium batteries without degradation.

The energy stored in the battery has to be converted efficiently for use by the various spacecraft subsystems. Early spacecraft obtained about 50% power conversion efficiency using discrete components. The present state of practice uses linear integrated circuits with bipolar transistors to achieve about 65% efficiency. However, the present state of the art is to use hybrid application-specific integrated circuits based on metal oxide semiconductor (MOS) transistors to obtain about 80% efficiency.

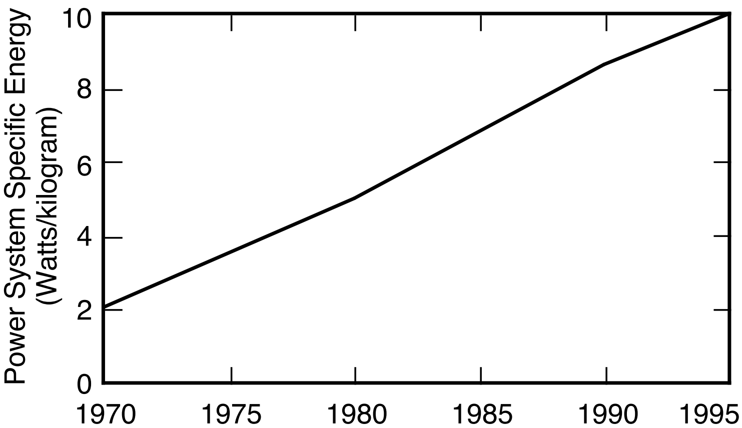

Figure 3-2. Evolution of power system specific energy

Overall, the efficiency of the entire electrical power system is measured by calculating the power system specific energy. The present state of the art is 10 Watts per kilogram (W/kg). Figure 3-2 shows the trend in the development of the electrical power system over the last 25 years. The results are very striking. For example, to produce 1 kiloWatt (kW) of power in 1970, about 460 kg was required. Now, in 1995, the same power can be provided with about 92 kg.

3.3.2 Technologies for Evolutionary Change in Electrical Power Systems

Over the last ten years, most spacecraft have moved to the 18% efficiency GaAs cells. GaAs cells are more radiation-tolerant and have lower loss of power with temperature than silicon cells. However, silicon panels continue to be at least 20% cheaper than GaAs panels. Instead of debating the advantages of today's cells, it would be better to leave both of these technologies behind and to begin to fund the development of wideband cells with expected efficiencies between 21-30%. The Air Force should assist the commercial sector to develop dual junction $GaInP_2$/GaAs cell manufacturing technologies, to build large-area arrays, and to increase the yields to levels comparable to GaAs cells. At the same time, the Air Force should proceed to fund the development of triple junction cells and quadruple junction cells to continue to optimize the yield from the sun. With a well-managed effort and increased funding, 30%-efficient triple junction cells should be able to be manufactured in large scale at the beginning of the 21st century. Other energy conversion alternatives should also be funded. The Air Force should fund the development of Fresnel concentrator arrays as the main source of spacecraft energy conversion. Preliminary tests (in sample sizes) of GaAs/GaSb concentrator arrays have already yielded 30% efficiency with optimum solar pointing. These high-efficiency solar arrays would have a major impact on the design of spacecraft. This work should continue, not only to push the theoretical limits of these concentrator arrays, but also to examine manufacturing techniques and the impact on spacecraft operations of using such cells.

An alternative technology to high efficiency cells is in thin film photovoltaic materials such as Copper Indium Diselenide (CIS) or Cadmium Telluride (CdTe). Cells could be monolithically integrated by scribing the circuits directly on to the thin film, which could be produced in large area on flexible substrates to achieve an order of magnitude improvement in cost and weight metrics ($100/Watt, 300W/kg for arrays). Because efficiency is only predicted to be in the 10-15% range, relatively large surfaces would be required, but this is acceptable for many applications due to the small storage volume of the thin flexible material.

Even though the Nickel-Hydrogen (NiH_2) common pressure vessel batteries have shown energy density of about 60 Wh/kg, they appear to be reaching their theoretical limit. Lightweight lithium ion batteries are expected to increase energy densities to approximately 80 Wh/kg. However, there are currently severe limitations in the number of cycles that lithium ion batteries can withstand. These limitations have to be overcome to produce a reliable lightweight battery with an energy density of 110 Wh/kg or more. The coordinated Air Force and NASA programs to develop lithium batteries will be aided by commercial terrestrial development for computers, cellular telephones, and cameras; however, the funding to develop the large capacity cells required for spacecraft energy storage is not being planned. The Air Force has plans to build and flight test a sodium sulfur battery in the next few years, but a significant financial and managerial effort is required to take advantage of the potential benefits expected from sodium sulfur batteries.

Another energy storage device that appears to have a tremendous potential is the electro-mechanical flywheel battery (EMFB). Recently developed EMFBs have shown over 60 Whr/kg, 90% depth of discharge, and long life (on the order 15 years). EMFBs can also be used as energy momentum wheels, providing both the energy storage capability and the capability to perform small spacecraft movements. For efficient flywheel energy storage and conversion, the bearing must be extremely low friction. A hybrid superconducting magnetic bearing has recently been designed and tested. A flywheel energy storage prototype has been constructed for testing bearing friction loss and characterizing the dynamics of the rotor. The hybrid bearing design uses magnetic forces from permanent magnets for levitation (for ground-based application) and high temperature superconductor YBCO in between the magnets for stabilization. A 42 lb flywheel currently can rotate up to 6000 RPM with stored kinetic energy of 8 Watt-hours (Whr). The result from the recent rotor spin-down experiment indicates an average frictional energy loss of less than 2% per hour in a vacuum of 10^{-5} Torr, with imperfect system alignment and rotor balance. System dynamics studies have been conducted to improve upon the energy loss and rotor-bearing modeling. Projections are for the next generation flywheel to have losses less than 0.1% per hour. The energy storage for such devices should scale as the square of mass. The Air Force should invest in the development of this promising EMFB technology to be used not only for energy storage but also as momentum wheels.

Evolutionary improvements in power conversion should continue from the present state of the art of 80% conversion to over 90% in the next ten years without any increase in the funding of this technology. Power conversion today is being accomplished by applying high frequency conversion using metal oxide semiconductors field effect transistors (MOSFETs) and high-frequency, high-voltage Schottky diodes. The commercial sector will continue to integrate the latest electrical devices.

Solar thermal-to-electric power conversion began in the 1950s with the introduction of the solar cell. In the 1980’s, solar thermal propulsion combined forces with electric power conversion, becoming known as solar bi-modal power and propulsion. Solar bi-modal power and propulsion systems are similar to solar thermal propulsion systems in that they use the same concentrators and have a heat exchange medium as an absorber. There is one major difference: solar thermal propulsion systems have a separate, conventional electrical power conversion system while solar bi-modal schemes include the electric conversion system as part of the propulsion system, using the enormous amount of thermal energy available from the heat absorber to supply heat for thermionic diodes or thermoelectrics.

3.3.3 Technologies for Revolutionary Change in Electrical Power Systems

All current spacecraft are either power limited or restricted in some measure by inadequate electrical power. Power limitations impose restrictions on the communications and propulsion subsystems and currently make large space-based radars and space-based weapons relatively unfeasible. A revolutionary change in capabilities will result from power technologies capable of providing large amounts of power onboard satellites. Large amounts of power will be enabling on spacecraft in the same sense that large amounts of random access memory have been enabling in personal computers. If power is not an issue, then previously hard applications become easy and new applications become possible. Evolutionary development of solar-array-based power technologies will see improvements to tens of kilowatts on satellites over the next decades. However, all solar collection systems in Earth orbit are limited by the solar constant of 1.4 kiloWatts per square meter. Large powers from solar collectors require large collection areas. For substantially larger powers (> 100 kW), several different types of technologies will have to be explored. Powers of this level will make large space-based radars, space-based directed energy weapons, and the use of high-performance electrically driven maneuvering technologies possible. A natural technology to enable high power is nuclear power in space; however, this technology has to date been considered unacceptable due to political and environmental limitations. Thus it is desirable to develop other technologies that may provide large power levels in space. In addition to continued development of safe nuclear systems, two other sources of continuous power in space that should be explored are the concepts of electrodynamic power-generating tethers and power beaming from one location to another (e.g., from space to space). The development of these and other technologies for high continuous power will have a revolutionary effect and the Air Force should invest in these areas as well as continuing to invest in solar collection technologies.

Over the years, there have been several programs in nuclear powered spacecraft. NASA has been using Radioisotope Thermoelectric Generators (RTGs) for the interplanetary missions that generate a few tens of watts of power. Russia has flown nuclear reactors in space and BMDO has a joint program with the Russians (TOPAZ), under which the Defense department bought three of the reactors to do laboratory experiments. DoE had a program (SP 100) to use nuclear power in space and the Air Force had a nuclear propulsion program; these programs have been canceled. Nuclear power, however, remains one of the attractive alternatives in generating large amounts of power in space. To build a reactor for space applications has many challenging technical aspects including development of high-temperature lightweight materials, active cooling technologies, extremely radiation-hard and high-temperature electronics, and fail-safe system architectures. Setting the emotional issues of nuclear power aside, this technology offers a viable alternative for large amount of power in space. The Air Force should continue efforts towards making a safe nuclear reactor in space a viable option. Existing joint programs with Russia offer a low cost alternative and should be pursued.

Electrodynamic tethers are essentially long wires that are drawn across the Earth's magnetic field. Just as in an electrical generator, the motion of a conductor across a magnetic field causes a voltage to be generated. If a current can be made to flow from the ionosphere through the tether and close back in the ionosphere, power can be generated. This power comes at the expense of orbital energy since the tether feels a drag force. Thus the tether effectively changes orbital kinetic energy to electrical energy and thus a continuous power system would be composed of a tether and a thruster to reboost the orbit. Alternatively, a system can be designed that uses a tether to extract energy during part of an orbit and then reboosts during another part of the orbit. Electrodynamic tethers can also be used as thrusters by reversing the current flow through the tether with an onboard power supply. In addition, electrodynamic tethers can also be used for momentum exchange between two tethered spacecraft. Since electrodynamic tethers work by using the voltage drop that comes from moving across the Earth's magnetic field, they are limited for effective use to orbits where the field is strong enough to give reasonable voltage drops. This limits tethers to orbits below a thousand kilometers from the Earth's surface. There are many technical issues to be resolved with high power electrodynamic tethers. These include the extraction of large currents from the ionosphere (tens of amperes), the emission of such large currents back into the ionosphere, and the dynamic stability of such large unidimensional conductors in orbit. This technology offers one high-risk, high-payoff way to achieve high powers in space and should be pursued.

Power beaming to a spacecraft using high power lasers offers another option for obtaining large quantities of power in space. In one concept, a high-power ground-based laser would be used to form a collimated beam onto the spacecraft. Solar arrays on the spacecraft would convert the laser power into onboard electricity for the spacecraft. In another concept, a space-based laser driven by a large solar array or a nuclear reactor could be used to beam power to another spacecraft. The Directed Energy Panel has identified many of the technologies that are needed for these concepts. In order for the receiving spacecraft to have small arrays, the arrays much be capable of processing equivalent power densities greater than 100 suns (140 kW per square meter). This would enable hundreds of kilowatts to be received by an array on the order of a few square meters in size. The limitation on such arrays is the availability of semiconductor materials that can convert such large power densities to electricity without large heat losses or without suffering permanent damage. The Air Force should invest in the basic research necessary to develop such materials as well as in pointing, tracking, and continuous high power generation in a laser device. As these technologies mature, the power beaming concept may become feasible for transmitting high powers to spacecraft; research will reveal where the limitations to this concept lie.

3.4 Attitude Control System (ACS)

A significant portion of the weight and volume of most spacecraft today is required to point the spacecraft. Precise pointing is required to execute controlled maneuvers, fulfill mission requirements (e.g., imaging specific areas of the Earth), and to maintain communications. Even though there have been significant advances in the development of this technology over the last few years, continued funding and a well-planned management strategy will be required to make additional progress. The ACS is divided into three categories:

- Sensors used to compute position, velocity, attitude, and attitude rate
- Algorithms (usually implemented in software) to perform guidance, attitude determination, pointing control, momentum management, and associated functions
- Control actuators to maintain the orbit, attitude, and appendage/payload pointing

3.4.1 The State of the Art in Attitude Control Systems

To control the attitude of a spacecraft, it is necessary to establish a frame of reference. A stellar reference system is usually required to obtain an absolute attitude reference. Star sensors, sun sensors, magnetometers, horizontal scanners, and wide-field-of-view star cameras have been used for attitude determination. In the 1970s, the single star tracker was used with photomultipliers; by the 1980s intensified image tubes were built to produce slit scanners on narrow-field-of-view cameras. In the 1990s, wide-field-of-view star cameras using charged coupled device have produced a high precision stellar reference.

Gyroscopes are required to provide an inertial reference by measuring pitch, roll, and yaw attitude changes. The size of the gyro is closely related to its accuracy, which is normally determined by the drift rate. Over the last two decades, between a one- to two-order-of-magnitude reduction in weight and power has been obtained by switching from discrete electronics to ring laser gyros and interferometric fiber optic gyros. Figure 3-3 shows the overall trend in gyroscope development by the key industry partners.

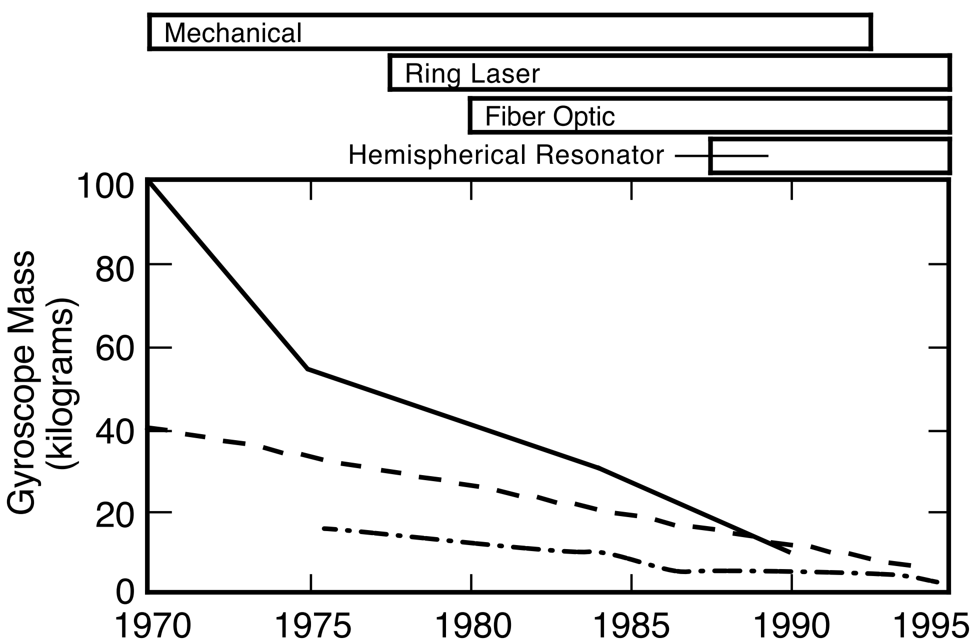

Figure 3-3. Evolution of gyroscope mass from three manufacturers

Once a satellite's attitude has been determined, and the desired corrections to this attitude have been calculated by onboard processors, it is necessary to change the orientation of the satellite in space by using some type of actuator. Reaction wheels, control moment gyros, momentum wheels, torque rods, and jets are normally used for such a purpose. Most spacecraft use one or more of these devices to control spacecraft motion.

3.4.2 Technologies for Evolutionary Change in Attitude Control Systems

The Air Force should fund promising developments in several aspects of ACS systems. The weight and power of stellar reference systems can be reduced further over the next ten years by using a wide-field-of-view stellar compass with charged coupled devices and an integrated computer system with a large star catalog. Similarly, the weight and power of inertial reference systems (gyroscopes) can be reduced; the most recent gyros use application-specific integrated circuits. Another factor-of-ten reduction in weight and power can be expected over the next ten years by continued development of interferometric fiber optic gyro using integrated optoelectronics. MEMS-based gyros with a drift rate less than one degree per hour are now being developed. A parallel technology development is Global Positioning System (GPS) subsystems, now coming into use for on-board trajectory state determination. Using multiple antennas (interferometry), GPS can also be used for attitude determination. Technology development leading to autonomous state and attitude determination with potential elimination of star sensors, gyros, and ground tracking should continue.

On-board high-speed computation and massive data storage have enabled the use of more sophisticated algorithms to perform required mathematical computations and data manipulation for the ACS. Continued development and test of new algorithms will be required to reduce cost (reusable software) and implement modern algorithms (such as neural nets and fuzzy logic) for improved performance, increased autonomy, and fault detection and recovery. In some cases, computational power could replace sensors.

The control moment gyros are where the biggest improvement in ACS systems can be made over the next ten years, by developing control moment gyros on the order of a few pounds able to achieve a pointing accuracy on the order of a few arc seconds. Electric propulsion, a revolutionary technology that will be discussed later in this chapter, will introduce new requirements on ACS components.

3.5 Command and Data Handling Systems

Spacecraft command and data handling systems typically have three elements:

- Processing systems
- Data transfer systems
- Data storage systems

Although one could conceive of a satellite that does not store data (communications satellites essentially perform this function), most satellites have the capacity to store data onboard for transmission to the ground at a later time.

3.5.1 The State of the Art in Command and Data Handling Systems

During the 1980s, the first 8- and 16-bit microprocessors were used in the spacecraft industry with capabilities of several kilo instructions per second (KIPS). These early processors were fabricated using flat packs on multilayer boards with total of about 4 megabit (Mbit) memory. By early 1990s, more powerful 32-bit processors, built using surface mount techniques on flexible printed circuit boards, were operating at tens of millions of instructions per second (MIPS) with about 16 Mbit memory. One key metric to evaluate the performance of spacecraft processors is the number of MIPS per Watt. Figure 3-4 shows the trend in processor performance. Since the draw-down in the defense budget beginning in 1990, the spacecraft computer market has been increasingly driven by the commercial market. The spacecraft computer industry is very effective in its design choices, separating systems and processors into different levels based on mission criticality. Table 3-1 shows the guidelines being used by industry to select processors for space applications.

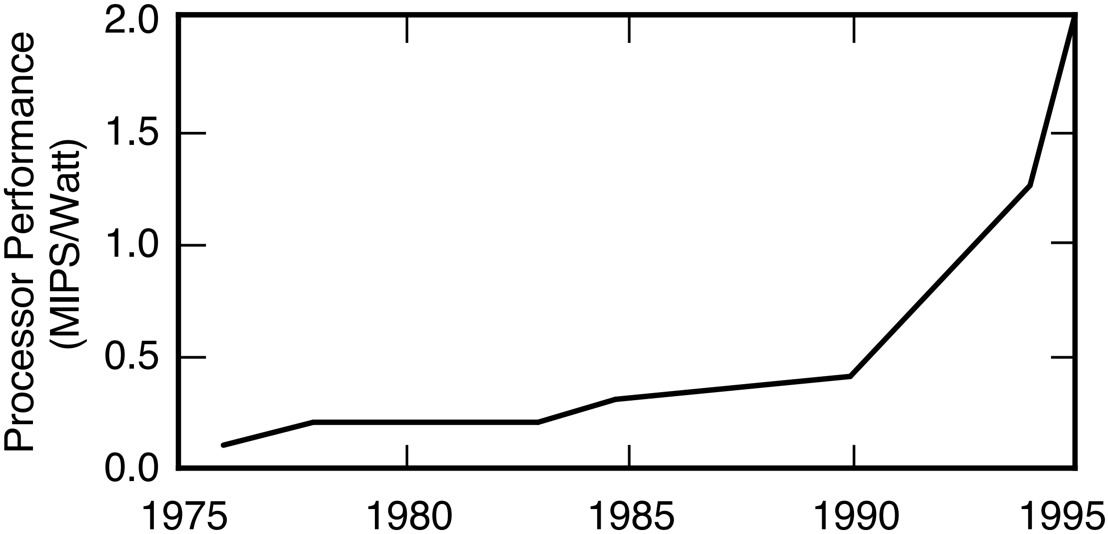

Figure 3-4. Evolution of processor performance

Most modern spacecraft data handling systems operating today use the MIL-STD-1553 interface at 1 megabit per second (Mbps). However, there are two basic limitations in the use of wiring cables for data transfer: weight and speed. Therefore during the last few years a new standard, MIL-STD-1773, has been developed, specifying the use of fiber optics for data transfer at 2 Mbps.

During the last ten years, there has been a tremendous growth in computer solid state memories. Presently, a ten-pound, 256-gigabit-per-second (Gbps), 4-gigaHertz (GHz), solid state memory can be built by using 16 Mbit dynamic random access memory (DRAM) elements. There are other types of memory that are essential for the successful operation of the space systems. Because space systems have to operate in the hostile natural environment of space, static random access memories (SRAMs) are normally used in the processors along with non-volatile memory. In late 1980s 64 kilobit (kbit) radiation-hardened SRAMs became available. 256 kbit SRAMs appeared in the early 1990s, with 1 Mbit SRAMs on the horizon in 1996.

Table 3-1. Processor selection guidelines

Class	Error Tolerance	Function	Processors
Experiment	Loss of subsystems and daily upsets acceptable	Signal processing Data handling and formatting Onboard processing Data reduction	DSP Integer Floating point
Operational	Yearly upsets tolerable/level mitigation	Signal processing Data handling and formatting Data reduction	DSP Integer Floating Point Sequencer
Mission critical	Failure or upset could end mission	Attitude control Ordinance control Command and telemetry	Sequencer Integer

3.5.2 Technologies for Evolutionary Change in Command and Data Handling Systems

There are tremendous technological advantages and cost savings that can be achieved by harnessing the explosion of commercial electronics to the advantage of the space industry. Given the rapid advances of the commercial market, it is logical to expect spacecraft to have 64- or 128-bit processors operating at tens of MIPS per Watt in the next five years. These spacecraft processors will be able to perform 100 to 1000 MIPS with internal memory of 256 megabytes or higher. Although information processing technology is evolving rapidly in the commercial sector, the Air Force has unique needs that the commercial sector is unlikely to address. While the semiconductor industry has mapped out an aggressive plan to increase the performance of silicon integrated circuits, there is little commercial effort in radiation hardening of electronic devices and the commercial sector is unlikely to address these specific needs. Air Force requirements in this area stem primarily from the perspective of spacecraft performance and survivability; the unique timeliness requirements of DoD will require more data processing tasks be performed onboard future spacecraft. The Air Force should invest in innovative techniques for radiation hardening of electronics and should ensure that radiation-hard manufacturing lines for high performance chips are maintained in the US. As commercial space develops, industry will be more likely to support a radiation-hard electronics industry, so investment today by the Air Force is likely to sustain a critical technology that will benefit both national and commercial interests in the next 30 years.

For data transfer applications, optical fibers are an attractive substitute for copper wires, because fibers would have a higher bandwidth and would weigh much less than cables. Entire spacecraft data buses operated exclusively with fiber optic cables should become operational during the next few years. The Air Force should invest to adapt commercial data bus standards to the space environment. Technology efforts should be directed towards developing and space qualifying commercial, non-proprietary standards to future space systems. The Air Force must take the lead in developing a framework for adapting commercial electrical interface standards at the subsystem and system level. Standard interfaces coupled with the adaptation of standard bus protocols of an open architecture will have a profound impact on the design, integration, and checkout of a space system, thereby reducing cost of ownership of the space system.

The basic memory element is likely to be 64 megabytes in 1996 and 1 gigabyte at the end of the century. This new technology development promises an enormous capability to store huge amounts of data in the spacecraft. The Air Force should not just depend on the commercial computer market to develop this technology and attempt to use it in the spacecraft. There are serious concerns about the radiation susceptibility of DRAM memory. As the memory elements become more compact, they are expected to be more radiation sensitive. Therefore, the Air Force should develop a careful program to continue to test the latest DRAM technology and invest in innovative radiation hardening technologies to ensure proper operation during future spacecraft operations.

Low-power, higher-density memories are essential to sustain the performance of future high performance processors. The Air Force should invest in technologies that will dramatically increase the memory densities for future space systems. Technologies such as fully depleted silicon on insulator (SOI) technologies offer the possibility of low power devices and the potential to adapt commercial capabilities to meet the unique Air Force requirements.

As the operation of space systems become more autonomous, non-volatile memory becomes more essential. Currently 64 kbit magneto-resistive RAMs (MRAMs) are becoming available with 1 Mbit MRAMs in the near future. The Air Force should invest in the development of higher-density non-volatile memories. Dramatic advances in higher density memories are essential and some of the technologies that offer great promise are ferroelectric RAMs, vertical Bloch memories, and memories based on calcoginates.

3.6 Thermal Control

Thermal control is critical to the survival of a spacecraft. A spacecraft is subject to thermal loading from solar radiation and from waste heat production by its onboard systems.

3.6.1 The State of the Art in Thermal Control

The combined evolution of high power payloads and light weight structures has made spacecraft thermal control an increasingly difficult problem. The state of the practice is to use a conductive metallic structure to act as a thermal capacitor and then to dissipate heat through radiators. More recently, heat pipes (both fixed and variable conductance) have come into common use to conduct the heat to the appropriate radiators. Carbon-carbon structures are in development to serve as structural elements and take advantage of the high conductivity of carbon fibers, however, the limits of passive thermal control are rapidly being reached. Current technology in passive heat dissipation is 50 Watts per square centimeter; active heat removal can achieve an order of magnitude higher heat flux. Currently there is no ability to interface directly with the multi-chip module (MCM) technology being used for high density electronics packaging.

3.6.2 Technologies for Evolutionary Change in Thermal Control

The Air Force needs to continue investments to develop active thermal control systems for high specific power applications. One major technical challenge is to achieve heat exchanger efficiency within a very small structure and to achieve high conductivity between this structure and an integrated electronics package. With the increased density of electronics components and the possibility of integrating the communications systems along with the RF communications systems in the MCM technologies, it is necessary to invest in innovative active and passive thermal control system. The Air Force should invest in MEMS-based coolers for high power chips, modules, and electronics packages. The Air Force should also invest in highly reliable no-moving-parts coolers and vibration suppression systems.

3.7 Propulsion

The most dramatic possibility for revolutionary change in spacecraft bus technology would be an improvement in the ability of a satellite to maneuver. This will be enabled by a move from chemical thrusters to electric propulsion for spacecraft maneuvering.

3.7.1 The State of the Art in Propulsion

No significant advances have occurred in the development of chemical spacecraft propulsion during the last 20 years. Most spacecraft continued to use hydrazine as a monopropellant and mono-methyl-hydrazine (MMH) and nitrogen tetraoxide (N_2O_4) for bipropellant systems. During this timeframe, small improvements have been obtained in specific impulse in the monopropulsion system by changing the pressure-fed titanium tank with neodymium nozzle to a piston-pumped system. However, over the last twenty years, the specific impulse of propulsion systems have remained between 200-225 seconds for monopropellant and between 300-315 seconds for bipropellant. Since the propulsion system constitutes approximately 35% of the wet weight in today’s spacecraft, it is necessary to look beyond chemical propulsion to electric propulsion to find breakthroughs in propulsion systems.

3.7.2 Technologies for Revolutionary Change in Propulsion

Electric propulsion is a revolutionary technology that can enable moving spacecraft to different orbits, executing orbital plane changes, and performing routine spacecraft attitude changes. Electric propulsion has a tremendous potential for reducing spacecraft weight, and that would allow the use of smaller launch vehicles with dramatic cost savings. There are three types of electric propulsion: electrothermal (e.g., arcjets), electromagnetic (e.g., plasma engines), and electrostatic (e.g., ion engines). A typical specific impulse is 450-1000 seconds for arcjets, 1500-2500 seconds for plasma engines, and 2000-3500 seconds for ion engines. The three categories of thruster technologies are shown in Table 3-2. Thrust levels are currently very low (fractions of a Newton) and need to be improved for many applications. The power required for an electric propulsion system is proportional to the specific impulse and could require tens of kilowatts of power.

Table 3-2. Classes of Electric Propulsion Systems

Thruster	Specific Impulse (seconds)	Thrust (Newtons)	Propellant
Electrothermal			
Resistojet	300-850	0.125-0.5	N_2H_4, H_2
Arcjet			
1-10 kWe	450-850	0.17-0.23	N_2H_4, NH_3, H_2
10-30 kWe	700-1400	1.0-2.2	
Electrostatic			
Ion Thruster			
1-5 kWe	2000-4000	0.04-0.2	Xe, Kr, Ar
5-20 kWe	2500-6000	0.2-0.6	
Stationary Plasma Thruster (SPT)	800-2500	0.02-0.08	Xe, Kr, Ar
Electromagnetic			
Pulsed Plasma Thruster (PPT)	200-1750	0.000017 - 0.00003	Teflon
Magnetoplasma dynamic (MPD) Thruster	2000-6000	20-100	Ar, H_2

Electric propulsion (EP) has nearly 30 years of space flight experience, during which time thruster designs have matured as improvements based on flight tests and on new technology have been incorporated into operational systems. Nevertheless, EP has so far played only a limited role in military space systems. Technical concerns have included thruster performance, power availability, guidance, navigation, and control (GN&C), and spacecraft interactions. Non-technical issues have included development costs, scheduling, mission constraints at block changes, and lack of familiarity with the strengths and limitations of EP. Nevertheless, EP makes increasing sense as the size of satellites decreases and technology continues to advance.

Advances in solar-electric power, autonomous GN&C, and electric thruster technology can support an expanded role for EP that will help meet the challenge of new mission applications, including advanced space control techniques. The ability to reposition or reconstitute satellites (without a significant penalty to operational life) is needed by military commanders during quick-response deployments. Past EP flights have focused on low-power thrusters for small velocity-change maneuvers. Today, high-power thrusters and solar arrays offer the enabling technology for large velocity-change maneuvers and orbit raising without the time delays characteristic of past EP systems.

Some initial applications of the electric propulsion concept have been demonstrated in geostationary orbit, where some spacecraft use kilowatt-class arcjets to perform station keeping. This initial application is likely to be replaced by ion engines in the near future. The next payoff would be obtained by using electric propulsion for low-altitude station keeping and attitude control, then extending the technology for transfers from low earth orbit (LEO) to geostationary orbit (GEO) where order-of-magnitude weight savings can be achieved. Again, these orbit transfers would require engines capable of handling tens of kilowatts. Electric propulsion can be used for stationkeeping in a distributed spacecraft systems or to make small continuous random changes in the spacecraft orbit to make spacecraft more difficult to track. Finally, only a small amount of propellant need be reserved to deorbit spacecraft to avoid debris.

The Air Force must fund an aggressive program to develop and demonstrate electric propulsion engines with specific impulse between 2000 and 2500 seconds and power handling capability of greater than 10 kilowatts, as well as basic research into the physics of electric propulsion. This class of engine (coupled with an efficient power generation system) could enable the orbit transfer of a several-thousand-pound spacecraft with significant cost reduction. The coupling of high specific impulse and small size makes electric propulsion an ideal technology for small spacecraft.

Two candidate engine types that should be developed are plasma and ion engines. Plasma engines similar to the stationary plasma thrusters (SPT) or the anode layer thrusters (ALT) developed by the Russians could represent the first stage of development. The most important research to develop these engines will be the material selection. Any material must enable lifetimes of 8,000 hours in components such as high-temperature high-energy-density magnets and cathodes carrying over 100 Amperes of current. Development efforts should include ground testing of these engines (to prove lifetimes of up to 8,000 hours) followed by space testing.

Another unique maneuvering technology that the Air Force should investigate is the use of tethers for momentum transfer. Satellite orbits could be raised or lowered by linking satellites temporarily with a nonconducting line. Although conservation of momentum requires that the total momentum of the system be constant, it is possible to transfer momentum from one part of the system to another (i.e., from one satellite to another) during the time they are attached.

3.8 Evolutionary Technologies for Spacecraft Survivability

During the Cold War, space systems and associated ground systems survivability was a key element of the overall strategy in providing highly survivable command, control, communications, and intelligence (C^3I) for the forces. With the inception of the Strategic Defense Initiative Organization (SDIO) and its evolution into the Ballistic Missile Defense Organization (BMDO), emphasis on system survivability had increased. In the current BMDO architectures, however, and with the advent of the Theater Missile Defense (TMD), the development of survivability technology for space systems has taken a dramatic downturn. As DoD increases its reliance on the commercial space assets and as other countries develop a capability to negate US space assets, the potential for a Pearl Harbor in space becomes real. The Air Force has to continue to invest in a range of survivability technologies including defenses against electronic warfare (EW), laser, collateral nuclear, high-power microwave, and miniature kinetic kill vehicle (KKV) threats. The range of technologies for survivability includes hardened materials, radiation-hard electronics, anti-jam (AJ) and LPI technologies, and space debris mitigation and protection technologies. There is significant commercial interest in techniques for debris mitigation, and the Air Force should adapt commercial technologies in this area. The Air Force should invest in the development of a threat reporting system that can unambiguously report threats directed at its space assets and take autonomous actions to minimize the consequences.

3.9 Recommendations for Investments in Spacecraft Bus Technologies

The Air Force should follow a carefully targeted plan of investments in spacecraft bus technologies, investing for evolutionary and revolutionary improvements in all facets of spacecraft buses.

3.9.1 Revolutionary Spacecraft Bus Technologies in Which the Air Force Must Invest

Two spacecraft bus technologies offer the possibility of a substantial increase in the exploitation of space by the Air Force, the potential impact of which is so great that the Air Force must invest now. These technologies are:

- High performance maneuvering technologies such as electric propulsion (with thrusts greater than tens of Newtons, at specific impulses of thousands of seconds at near 100% efficiency, the goal for electric propulsion) and tethers for momentum exchange
- Technologies for high power generation (greater than 100 kiloWatts) such as nuclear power, laser power beaming, and electrodynamic tethers

3.9.2 Evolutionary Spacecraft Bus Technologies in Which the Air Force Should Invest

The Air Force should invest not only for revolutionary change, but for evolutionary improvements in performance or reduced life-cycle costs to its systems. The technologies that offer such benefits in the area of spacecraft buses are:

- Structure technologies (e.g., lightweight structures, active vibration suppression, precision deployable structures, and software-controlled multifunctional surfaces)
- Innovative energy storage technologies (e.g., the electromagnetic flywheel battery)

- Attitude control technologies, including attitude sensors and attitude control system (ACS) algorithms
- Radiation hardening technologies for spacecraft electronics
- Low-observable technologies
- Microelectromechanical systems (MEMS) technologies

3.9.3 Commercially Led Spacecraft Bus Technologies

Another set of technologies that will allow for evolutionary change in spacecraft buses will be driven by the commercial sector. These technologies merit minimal investment by the Air Force, yet the Air Force should invest as necessary to adapt these technologies to its needs. These technologies are:

- High-efficiency energy conversion and storage
- Technologies for debris reduction