5.0 Crosscutting Technologies

5.1 Introduction

The government has made significant investments in space systems and technologies that have enhanced communications, weather prediction, navigation, and remote sensing. Much of today's commercial space industry is based on these past government investments. Commercial industry will invest in those technologies and systems for which there is an acceptable risk and return on investment. Industry is not likely to make large, high-risk investments of the type the government has made in establishing the viability of various fundamentally new space applications.

Today's commercial use of space is market driven. Services are provided by space systems that are either unique, more cost-effective, and/or better than what can be provided by other means. Industry is taking advantage of rapid advances in electronics, communications, and information technologies to increase the aperture of space activities that are commercially viable and this trend will continue. Reductions in costs associated with launch, satellite and payload design and production, and space systems operations will also continue to expand the horizons of what is commercially viable in future space systems.

The Air Force of the future must control the high ground of space with systems that are affordable. Affordability will require investments to adapt rapidly advancing technologies and processes from commercial efforts to the needs of the Air Force. This is especially the case in spacecraft manufacturing and operations, where technical advances and commercial practices are substantially reducing manufacturing cycle times, development costs, and operations manpower and costs.

Affordability of function will require a radical shift in the way the Air Force does business in space. Part of this shift will be cheaper, lighter spacecraft launched on cheaper boosters. Another important aspect will be the advent of distributed satellite systems.

In an era of a maturing commercial space industry, the Air Force's hierarchy of preference in acquiring space capabilities should be to buy commercial services where possible and where no compelling military advantage is available at reasonable expense from military augmentation or dedicated systems. Where commercial services are not adequate or appropriate, the Air Force should seek opportunities to augment commercial systems. Where augmentation is not appropriate, the Air Force should, where possible, purchase derivatives of commercial systems using commercial-like procurement practices. Where derivative systems are inappropriate, the Air Force should employ, where possible, commercial commodity bus and payload subsystems and components in military systems. Only as the last resort should the Air Force have to procure specialized satellites, subsystems, and components.

5.2 Commercially Led Technologies for Spacecraft Manufacturing

Spacecraft manufacturing has traditionally been a low-volume, high-cost, high-technology, craft production enterprise. Today's competitive communication satellite marketplace is forcing a paradigm shift leading to substantial reductions in manufacturing cycle time and cost. Standard manufacturing process improvements are being introduced, including statistical process control, lean and agile manufacturing techniques, and use of multi-skilled teams.

Several relevant technologies are emerging that can be adapted to Air Force spacecraft program needs. These include:

- Built-in self test (BIST)
- Multifunctional structures (MFS)
- Accessible stored knowledge (ASK)

A great deal of the manufacturing cycle time and cost are taken with testing because process control alone is insufficient to ensure quality. The BIST concept is to embed hardware and software into electronics to detect, isolate, and either report or correct faults. Use of self-testing electronic systems for fault-tolerant satellites will enable higher quality testing at lower cost for manufacturing and integration of spacecraft. This test hardware and software can be used for health monitoring during the operations phase. Hence, BIST will result in reduced design cycle time, improved system quality, and enhanced system operation.

The rapid advances in large-scale integrated electronics packaging, lightweight composite structures, and high-conductivity materials are enabling the development of an important new manufacturing and integration technology called multifunctional structures. The overall MFS concept is to embed electronics assemblies (e.g., multi-chip modules or MCMs), miniature sensors, and actuators into load carrying structures along with associated embedded cabling for power and data transmission. This level of integration effectively eliminates traditional boards, boxes, large connectors, bulky cables, thermal baseplates, etc., thereby yielding major weight, volume, and cost savings. Studies show that elimination of cables and electronic enclosures, along with full utilization of lightweight composite structures, could yield up to a 70% weight saving and 50% increase in available volume over traditional structural and electronics packaging techniques. These integrated modular structures could be designed to be highly reliable, reproducible, and repairable, and amenable to low cost manufacturing processes. Each major improvement in miniaturization of components, sensors, and devices becomes a candidate for integration into MFS. For instance, thin film technology, embedded antennas, structural vibration isolation devices, and other smart materials applications are natural inclusions into this global concept.

The technology enabling digital recording, storage, manipulation, and transmission of images (accessible stored knowledge) is advancing at an astounding rate. For example, design engineers, manufacturing engineers, and management have all been using computers and work stations to simplify their tasks. With advanced ASK technology, the worker on the shop floor can now get help with an ever-increasing complexity of tasks. Traditionally, manufacturing process plans have come to the shop floor in the form of sketches, diagrams, and written work instructions, all drafted by process engineers. Now, the technology is in place to provide the shop floor technician clear, concise instructions for the work to be performed in an easily understood way, i.e., in the form of computer-generated imagery. The time required for understanding a work plan then goes from hours to minutes, and the quality of understanding is substantially better. Potential problem areas can be graphically illustrated for knowledge retention. The use of animation, and eventually virtual reality, will accelerate training and improve quality. Air Force funding should be focused on adapting commercially available technologies to Air Force needs in terms of standards, techniques, and methods such as these.

5.3 Commercially Led Technologies for Spacecraft Operations

Spacecraft control and operations have traditionally been unique, highly mission-dependent endeavors tied to a diverse suite of hardware and software developed independently with little or no commonality across platforms. The same competitive forces that are driving changes in satellite manufacturing are also having an impact on how satellites are operated as part of the effort at overall life cycle cost reductions. Increased use of technology and migration to standards and open architectures will serve as catalysts for operational changes.

Driving technologies likely to affect future spacecraft operations will include advances in:

- Digital processing
- Software
- Computing power
- Communications

These technologies will enhance all aspects of the overall spacecraft system, including both space and ground assets, the links between them, and the effectiveness of the people who operate and maintain them. Advances in digital processing being seen today will provide for data compression techniques that improve both bandwidth and data storage capacities, beam shaping algorithms for improved transmission efficiency, and fault-tolerant architectures with self-correcting properties to assure continued operation even under the most adverse of conditions.

The explosion of information systems in recent years has pushed both computing power and software to new levels of speed, complexity, and overall performance. Automated code generation, advanced testing and verification techniques, graphical user interfaces, modular software development, and software reuse are current capabilities that are being applied in commercial software development and will enhance space operations capabilities as they are introduced to that domain. Possibly more significant are the improvements in computing power that provide for increased data storage density and increased processing speed without increased power demands and that serve as the enabling technology for the migration to distributed client/server architectures for nearly any application.

Software represents an increasingly large portion of the development, operations, and maintenance costs associated with space systems. As a crosscutting technology, advances in this domain, which are being driven by the commercial software market, will have significant impacts across the launch vehicle, spacecraft, and ground segments of the system. Object-oriented software development methodologies provide a mechanism for building code that is inherently modular and which fosters reuse. Integration of commercial off-the-shelf (COTS) software further lowers development costs with a penalty, however, of the increased configuration management problems as commercial software is upgraded or discontinued. Advances in open software architectures and standardization such as the common object request broker architecture (CORBA) remove many of the barriers to COTS integration and reuse. Advances in expert systems and improved software algorithms enable more intelligent processes for planning and scheduling and decision aids for anomaly resolution. Graphical user interfaces will migrate to intuitive object and event based interaction that facilitate more robust visualization and higher abstractions for user interaction with the system. Many of these advances, particularly when

coupled with a capability for automated code generation from high level designs and integrated software development environments, allow for rapid functionality enhancement, improved code quality, and the development of the more complex software required to support such tasks as autonomous satellite operations, constellation payload and resource management, and multiple mission management.

Communications technology is another arena where advances are rapid and applicability to the space environment is natural. As bandwidth demands increase, technical solutions include media changes to support the higher frequencies required. Current efforts in fiber networks and laser communications (both in fiber and line-of-sight) are examples of areas where spacecraft and ground operations will benefit from commercial advances. Data compression techniques provide virtual bandwidth expansion and help minimize uplink requirements. Protocol advances such as the development of demand-assigned multiple access (DAMA) further enhance the capability of communications networks supporting the space mission, providing improvements in efficiency and making this resource more ubiquitous and robust. Increases in integration and the improved functionality available in smaller components are trends that provide for increased space-based capability and the move to smaller, autonomous payloads.

The impact of technology on spacecraft operations is potentially dramatic, with a shift from flying spacecraft to autonomous spacecraft operations clearly on the horizon. Today, non-standard telemetry, tracking, and command and control processes lead to costly, complex, and unique requirements for both satellites and the supporting ground infrastructure. Limited onboard data storage and processing capability force mission-dependent architecture differences and require system specific training of operational personnel, as well as unique test equipment and procedures. The movement to almost all digital processing will alleviate this as existing systems are replaced and extended. This technology, which dominates tracking, telemetry, command and communications subsystems, has reduced ground station facility footprints and reduced greatly the need for the tuning and matching of equipment. Both of these factors will allow for the reduction in both facilities costs and maintenance personnel costs. The incorporation of very extensive and responsive built-in test equipment along with the inherent reduction in failure rates for digital circuitry will continue to reduce the life-cycle cost of these systems.

As with digital processing, the emphasis today in exploiting client/server technology is reducing in life-cycle cost and avoiding obsolescence for existing spacecraft systems. There will clearly be few if any new starts sparked by technology for any other reasons. An additional aspect of the distributed computing evolution is its applicability in supporting system consolidations. Consolidation applies to both the direct command and control of space assets and to the decision support systems associated with the utilization of remote sensing system products. Client/server distributed computational systems, communicating over local and wide area networks, will exploit the de facto industry standards and COTS products to maximize future resistance to obsolescence. Improved data base synchronization techniques, operating in near real time while still ensuring total data integrity, are opening up consolidation opportunities for geographically diverse systems and the opportunity to do remote data systems administration from centers of excellence, including contractor facilities. This clearly should reduce the maintenance staffing of those consolidated data systems. The disadvantage in the near term is that the level of expertise required to maintain these systems must rise at the same time, thereby putting pressure on the critical skill pools available.

Overall mission operations will benefit from technology advances by improvements to mobility, reliability, availability, and security. Lower cost and smaller ground stations provide the potential for increasing the number fielded with the benefit of more timely data dissemination and increased survivability. Vulnerability of the spacecraft segment is reduced by mission profiles relying on autonomous satellite operations with payloads containing integrated C^3I capability. Multi-mission capability and cooperative constellations additionally enhance the flexibility of limited assets.

Spacecraft operations concepts will evolve to adapt to this technology and require a corresponding update to the skills of the personnel operating these systems while facilitating decreases in staffing needs per mission. Intuitive and goal-based interfaces will decrease training requirements and provide for common training across multiple missions; however, the increased operator capability and task complexity imply an increase in the overall system (as opposed to subsystem or task) knowledge required. Use of decision support functionality and built-in test capability will be a key skill.

The fundamental benefit of technology on spacecraft operations is to provide increased functionality and/or lower life-cycle costs. Evolutionary changes to systems, enabled by use of COTS, reuse, and modular designs, not only extend system life time, but lower maintenance costs and shorten cycle times for technology or platform upgrades. Future systems must exploit this by mandating designs that not only provide for incremental changes, but encourage the process as a fundamental way of achieving operational requirements.

5.4 Technology Insertions in Spacecraft Manufacturing and Operations

Specific impacts of technology on each segment will tend to migrate from ground based insertions towards satellite changes eventually providing a degree of autonomy to spacecraft operations that will include resource management, fault detection/correction, and mission planning, scheduling, and execution, all onboard the spacecraft using expert systems and fuzzy logic. Increased processing speed and data storage will enable onboard functionality for even the traditional ground station functions such as command generation, anomaly detection, and data extraction. Open architectures for spacecraft computing and maximization of software reuse will provide for modular designs that lower the cost of upgrades and technology insertions, allowing multiple payload types to fly on a common bus. Communications improvements, coupled with increased on board processing, will meet the telemetry and mission data bandwidth needs of future systems. The establishment of high-bandwidth satellite-to-satellite links using laser or other technology could quickly make cooperative constellations of spacecraft the norm, particularly if coupled with onboard GPS-based positioning and attitude determination. Such constellations would further enhance system reliability, adaptability, and robustness.

Not to be ignored are the near term impacts of technology on the ground station segment. These changes will be introduced more rapidly and in an evolutionary manner due to the better access available. The migration to client/server computing architectures is already having an impact by decreasing the required ground station footprint, enhancing portability, and providing the potential of multi-mission capability. The fault tolerant architectures being developed (along with improved reliability of COTS data processing equipment) will provide for decreasing

maintenance requirements that will help reduce life-cycle costs in addition to their primary goal of improved robustness and survivability. Advances in ground station software have allowed for the introduction of the graphical user interface (GUI) as the primary interaction with the system. Further enhancement to this paradigm will improve the controller's interaction and understanding of the spacecraft and system status with the development of goal-oriented, event-driven commanding and standardized interactive displays. Modular and standards-based designs provide for iterative upgrades to ground station functionality based on advances in technology, functionality, COTS products, or changes in operations concepts. Coupled with automated code generation, new functionality or anomaly resolution will be inserted more rapidly and with greater confidence into operational systems. A key aspect to facilitating continued software technology insertions is that all future software should be designed to be portable to space, independent of its original processing location.

For the ground segment, a possible technology insertion path is as follows:

- Rethink the basic concept of operations for each mission type with the goal of automating routine operations and minimizing routine uplink
- Design any new ground segment software to be portable to space
- Standardize a high-level event definition language to reduce commanding and uplink
- Standardize data and rule representations for rule-based expert systems to allow system reuse

Similarly, for the space segment, a possible approach is:

- As a general approach, utilize the subsumption architecture as a paradigm for developing spacecraft autonomy
- Automate health and status monitoring
- Introduce autonomous spacecraft safing
- Utilize the Global Positioning System (GPS) for autonomous positioning, timing, and attitude determination with automatic reinitialization
- Utilize one-way status monitoring system (vital signs)
- Move command generation on board the satellite to reduce uplink and improve efficiency of spacecraft resource utilization
- Develop open architectures for spacecraft computing and software reuse along with standards for reprogrammable memory, command verification, and telemetry buffering
- Implement onboard anomaly detection and redundant system switch-over
- Design systems to send diagnostic information down as part of vital sign message
- Design systems so that if problem is serious, an emergency signal is sent, using Iridium-type approaches if necessary to page a cognizant operator

5.5 Recommendations for Crosscutting Technology Investments

Essentially all of the technologies that will allow for evolutionary change in Air Force space operations will be driven by the commercial sector. These technologies merit minimal investment by the Air Force, yet the Air Force should do what is necessary to adapt these technologies to its needs. These technologies are:

- Technologies for Spacecraft Manufacturing
  - Built-in self test (BIST)
  - Multifunctional structures (MFS)
  - Accessible stored knowledge (ASK)
- Technologies for spacecraft operations