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The Impact of Microtechnology on Space System Development*

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Microtechnology has the potential for a great beneficial impact on both the launch and operation of space systems. The reasons for this include savings in the mass, power consumption, volume, and cost of manufacture and testing of space systems. Less apparent, but equally valuable, are the advantages in reliability to be gained by increased redundancy and the reduction of complexity that are inherent in the fabrication processes. Despite the leveraged gains to be had by "microengineering" space systems, the conservatism of the aerospace community will retard the rapid incorporation of this technology into both new and existing systems. This is more true of government space programs where success is measured by lack of launch failures and less true of commercial ventures where success may be measured by other criteria. A successful program for the development and insertion of microtechnology into government systems will need to consider these factors. U. S. Air Force launches have the highest success rate in the world. One can hardly expect an organization to abandon a successful strategy, especially when the risks of failure include increased costs and a loss of capability that is vital to national security. However, there is a strategy for evolving microtechnology in space systems that fits both the risk avoidance culture and parallels the expected development of microtechnology. It starts with the development of autonomous, unobtrusive systems for launch environment measurements and for the determination of health and welfare of both the launch vehicle and payload. As microtechnology progresses and experience is gained, drop-in subsystems can be employed to initially increase redundancy and eventually replace current subsystems. These flightworthy systems can be combined to produce parasitic spacecraft hosted on larger satellites for specialized missions such as the Untethered Flying Observer that is the subject to be considered by one of the Conference Workshops. Finally, truly autonomous microsatellites can be developed as the systems mature and advantageous missions are defined.

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Microtechnology has the potential for a great beneficial impact on both the launch and operation of space systems. The reasons for this are mostly apparent. They include savings (due to miniaturization of components and subsystems) in the mass, power consumption, volume and cost of manufacture and testing of satellites. Less apparent but equally valuable are the advantages in reliability to be gained by increased redundancy and the reduction of complexity that are inherent in the fabrication processes used to produce micro-electromechanical systems. Despite the inherent, leveraged gains to be had by "microengineering" space systems the conservatism of the aerospace community will retard the rapid incorporation of this technology into both new and existing systems. This is more true of government space programs where success is measured by lack of launch failures and less true of commercial ventures where success may be measured by other criteria. A successful program for the development and insertion of microtechnology into government systems will need to consider these factors. This paper suggests a strategy for evolving microtechnology in space systems that fits both the risk avoidance culture and parallels the expected development of microtechnology. Reduced launch costs alone offer substantial initiative for the replacement of traditional space systems with their microengineered equivalents. A Titan IV (SRMU) can launch a payload of 40,000 pounds to low earth orbit at a cost of $200 million.[1] Without including the costs of payload development, manufacture, testing and integration, this cost is roughly $5,000 per pound. Further savings can be achieved with microtechnology by reducing on-orbit power consumption. The marginal cost of adding power to a satellite solar array is approximately $4 million per square meter[2] or about $20,000 per watt. In addition to these demonstrable savings, there are tangible but less quantifiable savings to be had from the increased reliability of microsystems. This reliability results directly from the increased redundancy, built-in test capability and simplified fabrication technology that is microtechnology's legacy from solid state electronics. Finally there are additional savings to be had from the smaller test facilities that will be used to qualify these microsystems.

In addition to savings resulting from modification to existing spacecraft and missions, microtechnology can and will be an enabling technology for whole new ways of doing things. These include both new ways of doing old missions and completely new missions. For example, Janson has outlined a proposal for launching a complete earth observing constellation of nanosatellites with a single Pegasus.[3] Other examples include seeding the moon or mars with seismic microsensors and utility meter reading from space. See the paper by D. Lorenzini and D. Tubis in these Proceedings.

All organizations conducting business in space stand to benefit from the savings and enhanced capacity to be found in applications of microtechnology. The U. S. Air Force has one of the oldest, largest and most successful operations in space. Its launch vehicles and satellites have the highest success rate in the world as shown in the following tables.[4]

Table 1: USA launch vehicle success/failure record (1984-1994)

Record	DOD Programs	Non-DOD
Success/Failure	101/5	82/8
Success Rate	95.3%	91.1%

Table 2: USA satellite success/failure record (1984-1994)

Record	DOD Programs	Non-DOD
Success/Failure	100/1	69/13
Success Rate	99.0%	84.1%

This record was achieved as the result of a focused program to insure a reliable, uninterrupted, space defense capability and to protect large investments in launch vehicles, payload development and acquisition. If a single launch (booster and payload) costs $1 billion and there are 5-10 launches per year, then the demonstrated >10% advantage in combined launch and satellite reliability over the non-DoD record is worth >$1.0 billion in savings per year. Of course, this is not really savings, but a return on the money and effort invested in building to high standards of reliability, exhaustive testing, and flight qualification of hardware.

The salient point is that one can hardly expect an organization to change a successful strategy, especially when the risks of failure include increased costs and a loss of capability that is vital to national security. Recent experience with small launch vehicle failures gives emphasis to this point.[5]

We can expect that this risk averse strategy will be continued in the future. Several features of this strategy limit development opportunities for new systems, including microsystems. Among them the following:

1) Flight qualification of all new systems

2) Large test and flight costs added on top of any development costs

3) Class 1 changes in vehicle configuration that cost >$1 million

4) Space test opportunities that are limited (See the papers on the STP program and the MEMS Testbed that appear later in these Proceedings)

5) Technology is frozen at beginning of long acquisition cycles

6) Infrequent block changes in existing systems

The Space Test Program has been highly innovative and successful (see the paper by Maj. L. Smith in these Proceedings), but would have to be greatly expanded to provide the increased opportunities for flight qualification necessary to sustain a rapidly evolving program in space applications of microtechnology. Other strategies for initiating new programs either within DoD or with NASA run counter to current downsizing efforts.

There is an alternate strategy for evolving microtechnology in space systems that fits both the risk avoidance culture and parallels the expected development of microtechnology. It starts with the development of autonomous, unobtrusive systems for launch environment measurements and for the determination of health and welfare of both the launch vehicle and payload. Microengineered systems can be used in this way to reduce risk directly and to gather information for design improvements of existing systems. As microtechnology progresses and experience is gained, drop-in subsystems can be employed to initially increase redundancy and eventually replace current subsystems. These flight worthy systems can be combined to produce parasitic spacecraft hosted on larger satellites for specialized missions, such as the Untethered Flying Observer that is the subject of a report by one of the Conference Workshops. Finally, truly autonomous microsatellites can be developed as the platform and its systems mature and advantageous missions are defined.

Let us examine an example suitable for the first leg of this strategy. Titan launch vehicles currently employ the Wideband Instrumentation System (WIS) for inflight monitoring of acoustics and vibration. This system is limited by the availability of telemetry channels to providing data from 23 locations. To move the location of one sensor invokes a class one change with a cost approximating $0.5 million. Checkout and calibration of the WIS are known causes of launch delays and their incumbent costs.

The environments inferred from these limited WIS measurements establish design requirements for avionics modules and other launch vehicle components. The uncertainties that result from limited data require conservative designs with higher costs and higher weights. Despite this conservatism data from nearly every flight prompt redesign and requalification of hardware to meet measured environments that exceed calculated or inferred design environments.

The WIS function can be greatly enhanced with virtually no impact on the vehicle or its operation by inserting autonomous microsensors at critical points where more data are required. The technology exists for making these devices truly self contained with their own power and communications capability.[6] Three dimensional vibration and shock measuring instruments with very high dynamic ranges and self check capability can be assembled in wrist watch sized packages. They can be simply mounted on or next to critical assemblies with virtually no impact on the environment to be measured or the vehicle's power and telemetry systems. An independent monitoring system on the ground would suffice to collect the generated data. Insertion of these devices in parallel with the existing system would be very attractive to those requiring additional data for model development, would result in cost savings by reducing the design margins currently required for instrument packages and would not be subject to the constraints placed on conventional configuration changes. Due to their enhanced measurement capability and flexible deployment features these devices would rapidly prove to be indispensable for launch vehicle design and payload environment definition.

Just such an instance illustrating how operations can come to depend on systems meant only to provide awareness exists in the literature. The PAX, 3 axis accelerometer package for vibration measurements, was mounted on-board the Olympus telecommunications spacecraft in order to establish baseline vibration data associated with various functions. The data from this instrument were being gathered primarily for use in the design of a laser communications system.[7] However, PAX was also intended to monitor the evolution of mechanical systems over the life of the spacecraft. It consisted of a 2.3 kilogram package. The sensors were manufactured by the Centre Suisse pour Electronique et Microtechnique in Neuchatel, Switzerland using silicon microfabrication technology.

In 1991 satellite power and attitude control were lost for over two months resulting in on-board temperatures down to -70 °C. Once control was reestablished, comparison of vibration data from the PAX with baseline data accumulated before the failure was used to identify and assess faulty systems.[8] In this manner a scanning infrared earth sensor was found to be the cause of a severe knocking and was turned off before it could cause further damage. Similarly, a reaction wheel bearing was found to be the cause of a recurring "screech." When this noise event was eventually correlated with ambient temperature fluctuations local heaters were used to eliminate it, thereby extending the lifetime of this system. In this manner a monitoring system proved to be essential to the recovery and life extension of an orbiting satellite following a severe anomaly. It is expected that similar events will prove microengineered monitoring systems to be invaluable to launch vehicle and spacecraft operations and will eventually make them required for all spacecraft.

A second example of a current application of microtechnology comes from an entirely different sphere. GaAs used in high speed spacecraft electronics evolve hydrogen gas. When sealed in hermetic packages the gradual build up of gas is sufficient to poison the circuits. It is therefore necessary to test stored units for hydrogen accumulation before they are built into payloads. For this purpose an integral chemical microsensor was constructed that provides accurate, *in situ*, nondestructive monitoring of H_2 in the ambient atmosphere of sealed electronics packages.[9] Packages provided with this self-test capability are inherently more reliable, since faulty units can be eliminated before launch and on-orbit degradation can be diagnosed and isolated.

The second leg of this strategy is based on the experience and capability acquired in developing and employing diagnostics and extends to drop-in subsystems. These systems will be initially employed to increase redundancy, but as experience and confidence grows will eventually replace current subsystems. The incentive to incorporate microsystems in existing spacecraft will be the reduction in weight and power, but the vast enhancement in redundancy and its associated reliability will be an equally valuable gain.

Some of these microengineered subsystems will become available through commercial developments. For example, accelerometers, chemical microsensors, GPS based guidance systems, and microoptics are being rapidly developed for applications in the automobile, chemical, shipping and communications industries. However, those applications that are specific to space will require investment and development sponsored by the end user, if they are to keep pace with the concurrent activity stimulated by the commercial markets. Examples of these later subsystems include propulsion, star and earth sensors and radiation hard microelectronics. For examples of current developments in both commercial and space-specific arenas see the papers in these Proceedings by J. Gilmore, A. Mason, D. Nagel, I. Nakatani, G. Smit, L. Thaller, A. van den Berg, K. Wise and others.

The convergence of the concurrent efforts in the commercial and government spheres will eventually enable microsatellites to be designed as assemblies of subsystems. The first operational microsatellites are likely to be hosted on larger spacecraft and have functions that are limited to diagnostics and local environmental sensing. Small satellites and robots to serve these functions are already under development at Johnson Space Center for shuttle and space station operations[10]. See the paper by C. Price and K. Grimm in these Proceedings. In addition, the Jet propulsion Laboratory, Diamler-Benz Aerospace[11] and Space Industries,[12] have designs for small satellites that fit this category. All of these efforts are fertile ground for microsatellite development.

The first autonomous microsatellites are already being conceptually designed for applications in monitoring terrestrial shipments (see the paper by D. Lorenzini and D. Tubis) and earth observing missions.[13] In order to be effective these satellites will necessarily be deployed in constellations that require cooperative behavior for orbital phasing, drop-out compensation, and potentially phased detection and cellular communications. These capabilities will require advances in communications, navigation, computation and software that will only partially be achieved by commercial enterprises. Government users will need to make focused investments in microtechnology in order to meet their specific missions. However, the payoff in terms of low cost, secure, robust systems that are deployable on demand and can meet old missions in new ways and enable entirely new missions will be sufficient enticement to continue the odyssey.

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