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# Multifunctional Structures for Advanced Spacecraft

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**Next-generation spacecraft will require an order-of-magnitude reduction in flight mass compared to current spacecraft designs. These microspacecraft will need innovative design approaches integrating different subsystem functions and new technologies. Multifunctional structure designs offer enabling technology for the microspacecraft by incorporating electronics and thermal control functions into the spacecraft structural elements. In the multifunctional structure design, bulky black boxes, cable harnesses, and connectors are eliminated, and the electrical connections are based on flexible circuit patches and jumpers. The system is ideally suited for high-density electronics such as multichip modules, chip-on-board, and highly miniaturized electromechanical systems devices. Novel thermal management devices are also incorporated into the structure to control localized high-heat loads. A brief overview of the multifunctional structures concept is presented, and the gradual transition of the technology into flight experiments and spacecraft is described. A multifunctional structure experiment was successfully integrated into the New Millennium Program Deep Space 1 spacecraft bus. Data collected from this mission experiment indicated that the electrical connection system was fully functional with no degradation, and the thermal performance measurements were consistent with the preflight analyses. Building on this successful flight experiment, multifunctional structures designs have been transitioned into a few spacecraft subsystems.**

## Introduction

IN the 21st century, the U.S. Department of Defense (DoD) and NASA envision launching and operating large numbers of low-mass, low-cost, miniature spacecraft for various communications, surveillance, and scientific missions. To realize the cost benefits of this vision, an order-of-magnitude reduction in flight mass compared to current spacecraft designs is desired. Revolutionary changes in current spacecraft architectural design, coupled with the development of new enabling technologies, will be required to produce cost-effective multiple microspacecraft (spacecraft mass between 20 and 200 kg). Typical microspacecraft will also have stringent requirements for packaging volume, assembly clearances, rework and test access, and thermal management. To build these microspacecraft, a truly concurrent engineering approach is needed that utilizes recent advances in electronics, materials and structures, and heat transfer design concepts and that integrates electronic, structural, and thermal control functions of spacecraft hardware components.

In the conventional spacecraft, the structural, thermal, and electronic functions are generally designed and fabricated as separate elements. These single-functional elements (usually in the form of load-bearing plates, frames, and shells for the structures; radiators and cold plates for thermal management; and black boxes for the electronics) are then bolted together during the final assembly of the spacecraft. Power distribution and signal transmission between the elements are accomplished by the use of connectors and cable bundles. These cables and connectors are composed mostly of large, bulky casings that do not serve a direct electrical function for the spacecraft, but are required to provide structural support and allow handling during integration and test. Current methods of fabricating spacecraft also have limitations in incorporating advanced miniaturized electronics and sensors due to fundamental requirements for assembly and tooling volumes. For example, electronics assemblies are highly miniaturized, but the need for cabling and test access frequently forces these assemblies back into a full-size chassis with traditional cabling and connectors, thus minimizing any gains.

Recognizing the technology needs of future microspacecraft, Lockheed Martin Space Systems Company—Astronautics Operations (LMAO) has developed an innovative multifunctional structures (MFS) design approach integrating spacecraft electronic, structural, and thermal control functions. This MFS technology development effort was performed in a program sponsored jointly by U.S. Air Force Research Laboratory/Phillips Research Site (AFRL/PRS), Ballistic Missile Defense Office and Defense Advanced Research Project Agency. MFS technology eliminates conventional bulky components (chassis, cables, and connectors) and enables the integration of electronic subsystems such as the data transmission and power distribution networks, command and data handling (C&DH) subsystem, thermal management, and load handling. In particular, the MFS concept involves 1) embedding passive electronic components within the actual volume of composite materials, 2) new approaches for attaching active electronic components to mechanical surfaces, and 3) using surface areas for mounting sensors and transducers.[1–4] Several MFS approaches have been developed for spacecraft.[1] For example, a few of the MFS approaches include integration of sensors and electronics onto a load-bearing panel[5] and embedding sensors, actuators, and power signal conductors into load-bearing composite structures,[6] primarily for spacecraft diagnostics. In contrast, the conventional smartskin approach is primarily focused on placing networks of sensors throughout a vehicle. The smartskin approach relies on centralized electronics in traditional packaging. Flexible circuitry has been used on a very limited basis for elimination of some cable, but there have not been any other significant attempts at the spacecraft subsystem levels, in a manner similar to the MFS design approach.

MFS is a dynamic design approach, which will continue to include improved concepts by integrating advancements in sensors, electronics, and other subsystem technology. The purpose of this paper is to briefly describe the MFS design approach and to discuss a few spacecraft flight experiments designed to validate the MFS technology. Toward that purpose, key features of the MFS design approach and specifics of a technology demonstration panel are discussed next. Several successful and upcoming flight experiments are also described that illustrate the potential benefits of the MFS technology. Finally, the MFS technology transition effort is described with a discussion of system-level payoffs, and an Advanced Technology Demonstration Spacecraft program, which incorporates MFS technology elements.

## MFS Design Approach

The MFS design approach uniquely combines the advances in the area of electronics [e.g., two-dimensional/three-dimensional multichip modules (MCMs) and flexible circuit connections], high-performance composites (for structures), and thermal management[3,6]

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**Table 1 Conventional spacecraft elements and corresponding MFS elements**

| Current spacecraft element | MFS element |
|---|---|
| Traditional printing wiring board | MCM |
| Motherboard/power and ground planes | Cu/PI flexible circuit patch |
| Cables/harnesses/connectors | Cu/PI flexible jumpers |
| Electromagnetic interference shielded box | Composite cover |
| Thermal–structural panel (with and without radiation hardening) | Composite panel |
| Removal/replacement | MCM socket |

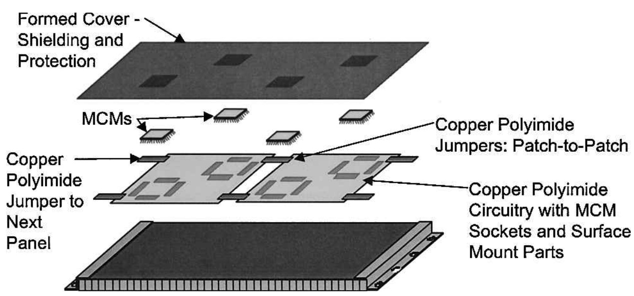


**Fig. 1 Exploded view of MFS panel construction that shows flexible circuitry, jumpers, MCMs, and MCM socket system.**

into an integrated system that eliminates the normal partitions between subsystems. This unique design (Fig. 1) consists of multilayer copper/polyimide (Cu/PI) circuit patches used for local electrical connections and embedded heat-transfer devices that are incorporated within a structural composite panel. The outer, that is, space viewing, surface of the composite panel is designed to act as a radiator. Electrical connections are placed in the Cu/PI layers, circuitry is implemented in the MCMs, and flexible circuit jumpers serve as electrical connections for power distribution and data transmission. Thermal management devices embedded in the panel may include miniature heat pipes and various types of high-conductivity thermal doublers and straps. Flexible circuitry adds very little thickness to the panel ($<0.25$ mm), and the overall thickness is determined by surface-mounted parts such as MCMs. Table 1 lists the MFS elements such as flexible circuit patch, flexible jumpers, MCMs and composite panel, and corresponding elements of conventional spacecraft including printed wiring boards, cables, and connectors.

On the surface of the structural panel, advanced MCMs that perform specific electronic subsystem functions are bonded to the circuit patches that are connected with flexible jumpers. Flexible circuit jumpers are also used to connect patches from one panel to patches on adjacent panels. Each electronic/electronic (i.e., MCM/patch and patch/patch) and electronic/structure (i.e., patch/composite skin) interface is demountable, thus providing a cost-effective, modular, reliable, and repairable architecture for cable-free spacecraft. Also note that the flexible circuit architecture is compatible with heritage connectors and may form the basis for a hybrid system that uses existing hardware.

## MFS Demonstration Panel

Figure 2 shows a prototype MFS system that embodies the successful design, fabrication, and verification of the electronic functionality of C&DH MCMs. The MFS panel was assembled from three pieces of high thermal conductivity composite panels. Flexible jumpers were used to route signals across the mechanical joints between the flexible circuit patches. The signal conditioning patches produced a voltage divider for generating 32 distinct dc voltage levels for use with the analog/digital converter. Dual inline package switches were used for the discrete input control. Light-emitting display indicators were used extensively for digital output and status indication. Two style D-subminiature connectors were mounted on the two side panels to provide external interfaces such as power, commands, and the serial data output.

A thermal doubler plate made of carbon–carbon (C–C) material was used between the MCM and composite panel to dissipate the high thermal loads of the MCMs. This C–C thermal doubler with low elastic modulus (21 GPa) and nearly isotropic thermal conductivity (180 W/m·K) provides a compliant interface between the MCM and composite panel. A space-qualified silicone adhesive was used to bond the C–C thermal doubler to the MCM and composite substrate. A unique mechanical fastening clamp and socketing design was used to hold the leads in the MCM socket strips. This mechanical design ensured that the electrical continuity of the entire MCM-flexible circuit patch and jumpers successfully withstood the typical launch vibration environment.

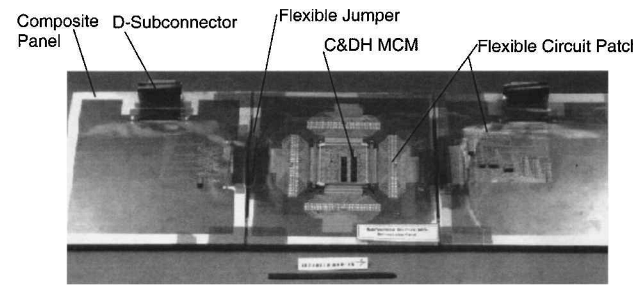


**Fig. 2 Multifunctional structure demonstration panel set that embodies all elements of MCM usage, that is, flexible circuit connections, structure, and thermal control.**

Originally, the MFS system was created to support the efficient integration of MCMs. From early on, rework and repair issues were emphasized, and the system design approach has always included methods for removal and reuse of MCMs, which are usually the most expensive electrical component in the panel. Although this system offers great advantages for designs using MCMs, a decision to globally convert existing printed wiring board electronics to MCMs involves a high nonrecurring cost and has limited benefits for one-of-a-kind spacecraft. Given that all facets of design are highly linked in this approach, a concurrent engineering team must be formed in the early phase of a program to ensure compatibility between the primary subsystems. If the MFS design methodology is followed, program and technical risks are no greater than standard designs and will yield significant mass and volume savings. For example, an independent team performed a study on the global positioning system (GPS) IIR spacecraft to determine the savings resulting from a conservative application of MFS in a new design. More specifically, the acceptable MFS design approach included a few MCMs (currently available) with conventional printed wiring boards, small composite enclosure, flexible harness, and jumpers integrated on a structural composite. The study team found that using the MFS design and new technology, such as lithium-ion battery, high-efficiency solar arrays, and dual-mode biprop propulsion, the volume and mass could be reduced by at least 50% and would enable two spacecraft to be flown on a launch vehicle that currently carries one existing GPS IIR spacecraft.

The MFS design approach is quite robust because it offers significant gains in reliability by the elimination of the majority of cables and connectors. Currently, it is not uncommon for two circuits to be connected through four hand-terminated mating connector pairs. The MFS approach eliminates the bulk of these connections and, through the heavy reliance on MCMs and other forms of dense electronics, eliminates the majority of printed wiring boards. The ultimate goal of MFS technology is to maximize the ratio of the volume of the fundamental electronic parts to the total packaging volume. Preliminary evaluation of typical spacecraft avionics subsystem-level payoffs indicated that the cable harness, enclosure, and connector mass could be reduced by nearly an order of magnitude by using the MFS design concept. Based on similar studies, it appears that MFS technology has the potential for providing a two–five times reduction in future spacecraft mass and volume, if fully incorporated through the use of MCMs for avionics subsystems, and elimination of the majority of secondary packaging by using flexible interconnect architecture on a lightweight composite structure. MFS is an enabling technology for TechSat21 and future microspacecraft missions envisioned by the DoD and NASA.

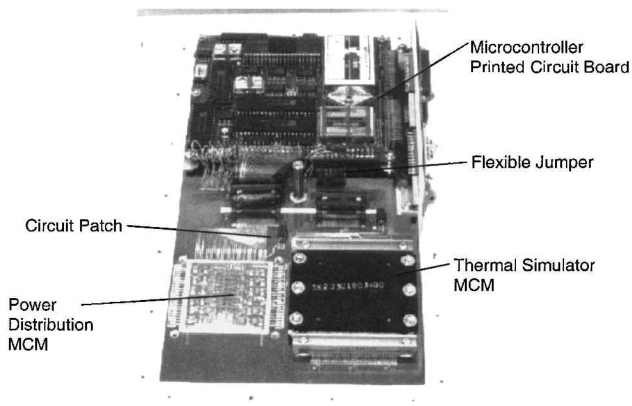


**Fig. 3 NMP DS1 spacecraft multifunctional structures demonstration experiment.**

## MFS Experiments

After the successful development and ground-level demonstration of MFS technology and its elements, LMAO has incorporated the MFS experiments in a few U.S. Air Force and NASA sponsored missions. First, to validate the MFS key technology features, LMAO successfully integrated an MFS experiment on the NASA New Millennium Program (NMP) Deep Space 1 (DS1) spacecraft.[3] Subsequently, flight demonstrations of MFS technology have been included in the NASA NMP Deep Space 2 (DS2) mission, the AFRL/PRS MightySat II Sindri spacecraft, and the Space Test Research Vehicle (STRV-1d) spacecraft. Specific details of the application of MFS technology to these spacecraft are presented hereafter.

### NASA NMP DS1 Spacecraft

The NMP DS1 mission spacecraft (launched on 24 October 1998) has performed an asteroid flyby and will perform a comet flyby in the future. A miniaturized camera and spectrometer, an ion thruster, full onboard autonomy, and new technologies (including MFS) that are included on the spacecraft will enable future space exploration.[7] The MFS experiment panel (Fig. 3) on this spacecraft includes a microcontroller printed circuit board for the spacecraft data collection interface, a power distribution MCM, a thermal simulator MCM, and a radiation-shielding aluminum cover that included a bonded metal-filled composite just above the two integrated circuits of the microcontroller for spot shielding. The MFS demonstration experiment was attached to the exterior of an NMP DS1 structural panel that interfaces with the spacecraft data system using a conventional interface cable. Mass reductions were not a priority due to the nature of the experiment. Hardware installation and rework features of the design were successfully performed on the panel without affecting the panel's integrity. This MFS experiment demonstrates the following key technology elements on a spacecraft structural panel: an embedded electronics connection system that uses flexible circuitry, MCMs and associated socketing, flexible circuit jumpers, anisotropic electrical bonding, temperature sensors, and thermal doublers.

The data provided by the MFS experiment on DS1 included health and status, electrical conductivity measurements, and thermal gradient measurements from the spacecraft panel following a low-level heat input from a multichip module resistor. The as-received data in each data set were verified against the data sets obtained during flight qualification testing of the MFS experiment panel. The in-flight experiment data were consistent with the expected values for the health and status, electrical conductivity, and thermal gradient data. Based on these data, the MFS experiment on DS1 successfully demonstrates full functionality.

### NASA NMP DS2 Spacecraft

The NMP DS2 Mars micropenetrators were designed as probes that would impact on the Martian surface and use the impact energy to sink the forebody while leaving the aftbody (with the rf link) on the surface. The primary mission objective of each probe (two were flown) was to determine the presence of subsurface water. Experience gained in the NMP DS1 design effort was used to support the Jet Propulsion Laboratory in the development of a flexible connection system for the electrical interface tether between the aftbody and forebody. In addition, the MFS flexible circuit connections provided the enabling technology for the local connections between the electronics in the forebody.[8] The miniature, grapefruit-sized micropenetrator precluded the use of hand wiring for the electronics. In Fig. 4, the flexible circuitry for connecting some of the MCMs is shown, along with a sample tether. The tether was used to connect the forebody to the aftbody and deploys in a fan-fold fashion, in contrast to the traditional wire system that is stored on a spool. Numerous pneumatic airgun tests have demonstrated that the tether system is quite robust for this application.

### STRV-1d Spacecraft

The mission of this spacecraft is to test a variety of technologies in a high-radiation environment that occurs in a highly elliptical polar orbit that extends from geosynchronous orbit to low Earth orbit. A top-cover panel (Fig. 5) was designed for the STRV-1d spacecraft to provide the full range of MFS functionality, that is, electrical

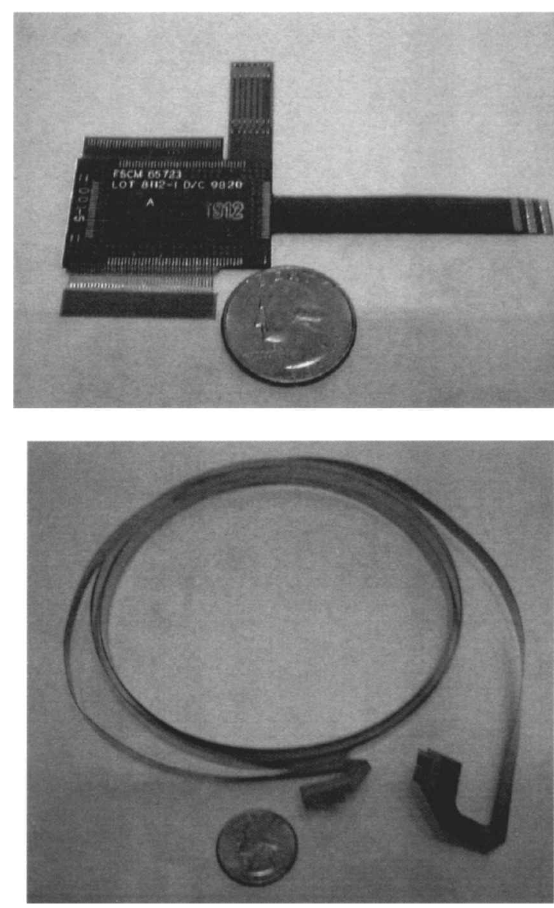

**Fig. 4 NMP DS2 spacecraft flexible circuitry connection and tether system.**

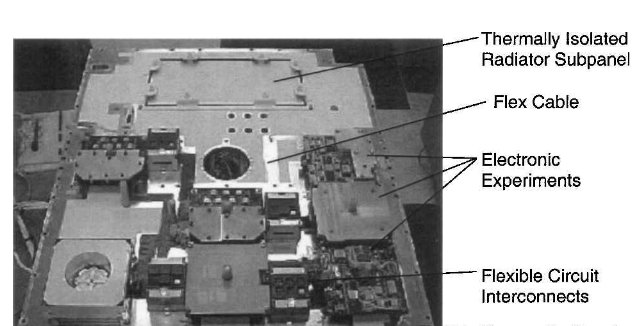


**Fig. 5 STRV-1d spacecraft multifunctional structure cover panel integrated with electronic test bed experiments.**

connections, thermal management,[9] and structural support. The MFS panel satisfies the mission specific requirements of severe thermal and structural environments and provides connections for several electronics experiments. The mass of the flexible circuitry components was 60 g, significantly less than the baseline standard wire approach that would have weighed 516 g (80 m of 26-gauge wire with 15 connectors). In addition, the flexible circuitry eliminated the splices, provided easy-access test points, has lower inductance than wire, and facilitated a simple attachment methodology to the structure. The structural composite panel (replacing a baseline aluminum panel) was designed to satisfy the Ariane-4 launch environment and rigorous thermal requirements associated with a thermally isolated subpanel (of the MFS panel) that supported the cryogenic hardware. The combined MFS panel with the mechanically attached radiator subpanel met the mechanical stiffness requirements and also the thermal resistance requirements. The MFS panel has successfully undergone rigorous integration and test on the STRV-1d spacecraft, and it is planned for launch, as a secondary payload, in October 2000.

#### Sindri Spacecraft

The Sindri spacecraft is an AFRL-sponsored MightySat technology demonstration mission. Power is provided by four solar arrays with different sandwich panel designs, for example, two grid stiffened and two honeycomb core. On one of the solar array panels, the MFS-design-based flexible circuit connections were used to replace all conventional wiring, including turnarounds and connections to the main power bus. This panel configuration provided an opportunity to gain experience in the application of MFS elements to other hardware areas and to identify and resolve potential integration problems associated with soldering and rework of very fine copper traces. Design and fabrication steps were very straightforward and demonstrated savings in mass and manual labor. Use of the flexible circuit elements eliminated the significant effort that is typically required for wire preparation, stripping, forming, and soldering connections for solar arrays.

## MFS Technology Transition

After successfully demonstrating MFS technology on a flight experiment and on the spacecraft bus panels, an AFRL-sponsored effort was directed to initially assess the system level payoffs and subsequently transition the technology to a spacecraft such as TechSat 21.

Therefore, a preliminary study was performed to determine different subsystem level mass and volume savings that could be attained, assuming the MFS technology is mature and ready for transition. Later, a prototype hardware demonstration effort "Advanced Technology Demonstration Spacecraft (ATDS)" (as a pathfinder for TechSat 21) was initiated to develop spacecraft avionics subsystem incorporating the MFS technology elements. A brief discussion of the subsystem-/system-level payoffs and the ongoing ATDS effort is presented hereafter.

#### System-Level Payoffs

Integration of MFS into spacecraft design reflects immediate and significant mass and volume savings over recently launched advanced technology spacecraft like the U.S. Naval Research Office's Space Technology Experiment (STEX) spacecraft. Comparisons of the STEX spacecraft with functionally equivalent MFS hardware elements suggest that significant mass and volume savings can be realized in the electrical power subsystems (EPS), C&DH, and cabling subsystems by implementing MFS technology. For example, the redundantly configured STEX C&DH module weighed 14.2 kg with a volume of approximately 0.02 $m^3$ (1135 $in.^3$). A functionally identical C&DH system (including redundancy) with MFS technologies can reduce that mass and volume to 2.1 kg and 1245 $cm^3$ (76 $in.^3$), respectively. This example represents mass and volume reductions of about 80–90% over advanced C&DH technologies that have been recently flown. This study also reflected similar mass and volume reductions for EPS avionics (88% in mass, 93% in volume) and cabling (85% in mass, 65% in volume).

Results of system-level study conducted by the designers of the GPS IIR spacecraft, as discussed earlier, indicated about 50% mass and volume savings by incorporating MFS and other new technologies. Before to generating a redesign of the GPS IIR satellite, the designers assessed the maturity status of each new technology area in MFS and related technologies. With 50% reduction in mass, volume, and power, a dual launch capability of GRS IIRs on a Delta II launch vehicle could offer significant system-level payoffs.

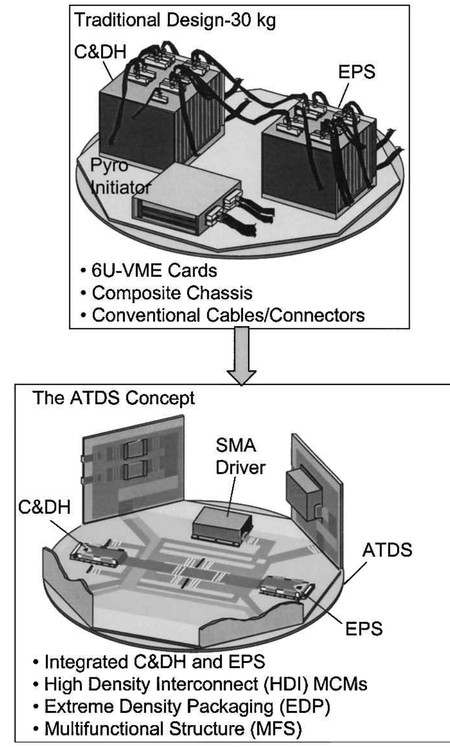


**Fig. 6 Traditional spacecraft avionics subsystem design and the ATDS concept incorporating the MFS design approach.**

#### ATDS

The AFRL-sponsored ATDS program is a step-by-step approach to design, analyze, build, and test a partial protoflight spacecraft bus, before the fabrication of a flight-qualified spacecraft bus structure or parts. The ATDS program significantly benefits from an ongoing internal LMAO effort to design and develop three-dimensional MCMs and extreme density packaging (EDP) for the electronics of C&DH and EPS. Combining the advances in three-dimensional MCMs, EDP, high-density interconnect MCMs, and MFS technology, the integrated avionics architecture will potentially reduce the mass of current C&DH and EPS electronic boxes from 30 kg to less than 3 kg (Fig. 6). Incorporating further advancements in MCM and packaging technologies, the ATDS effort should yield significant mass savings for TechSat 21 microspacecraft over traditional spacecraft design and fabrication.

## Conclusions

Mission and cost requirements have been a driving force to develop miniature spacecraft with significantly reduced mass and volume compared to the conventional spacecraft. Utilizing the recent advances in electronics, materials, structures, and heat transfer design concepts, a multi-function structures design approach has been developed to produce these microspacecraft. Key features of the multifunctional structure design approach that integrates electronic, thermal control, and structural functions on a single spacecraft structural component have been discussed. A demonstration panel was successfully designed, fabricated, and tested to verify electrical functionality of multifunctional structure design architecture, including a notional command and data handling multichip module, circuit patches, and flexible jumpers. The multifunctional structure panel was designed to be robust to withstand the launch vibration environment and to be repairable and reworkable during integration and test phases.

Building on the design and development effort, a multifunctional structure experiment was flown on the NMP DS1 spacecraft. Results of the experiment indicated that the multifunctional structure design maintained electrical continuity and exhibited temperature distribution consistent with the preflight analysis. Later multifunctional structure technology elements were successfully transitioned into NMP DS2 micropenetrator and miniature spacecrafts such as Sindri and STRV-1d.

Multifunctional structure technology provides a new system for packaging spacecraft that permits a two–five times reduction in spacecraft mass and volume, if the technology is fully implemented with the majority of electronics reduced to multichip modules and flexible circuit connections. The results also suggest that recurring costs should be significantly reduced and that the use of automated, mass-production assembly will be achieved in the near future. Multifunctional structure technology elements will also enable a new class of inflatable spacecraft that are based on small, packed volumes and reliable deployment that is free of cabling and entanglements.

At the system level, multifunctional structure design offers several benefits in terms of lower power, reduced launch costs through lower payload mass, enhanced science mass fractions, and novel packaging of spacecraft including large inflatable structures. The multifunctional structure design concept provides a methodology to incorporate new technologies and advances in other subsystem functions such as power, propulsion, and attitude control. Although the primary focus of the paper has been on spacecraft, the multifunctional structure technology could be used to improve the design of automotive, aircraft, and other related systems.

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