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**INTEGRATED UTILITY MODULE FOR  
FUTURE NASA MINIATURE SPACECRAFT**

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### Abstract

To prepare for more affordable missions in the 21st century, the National Aeronautical and Space Administration (NASA) has recently initiated the New Millennium Program for space-validation of selected technologies that will enable miniature spacecraft and microinstruments. One of the candidate New Millennium technologies is related to the development of the Integrated Utility Module (IUM) that integrate structural integrity, thermal management, power distribution, data and signal transmission, radiation and meteoroid protection, and other electromechanical functions into a lightweight, compact, and cableless package.

This paper addresses the proposed development of IUM technology. A fundamental understanding of the role to be played by the IUMs in the development of future NASA miniature spacecraft will be presented. The current state of the supporting technologies will be assessed. Major technology challenges will be identified and discussed. A preliminary set of design requirements, together with an example design concept, will be described and examined.

### Introduction

Future NASA space programs will consist of small spacecraft. To align with the increasingly

more stringent space budget environment, these 21st century miniature spacecraft must have increased capabilities, higher launch rate, and order-of-magnitude reduction of mission life-cycle cost. This can only be achieved by revolutionary changes to current spacecraft architecture design and mission development approach which, in turn, are enabled by intensive infusion of breakthrough, high pay-off technologies.

The process of identifying and assessing the enabling technologies for future NASA missions envisions a versatile and cost-efficient microspacecraft of a modular architecture, i.e., consisting of a number of functional building blocks. The functionality of a building block may be on-board computation, data handling and storage, power switching and distribution, avionics, telecommunication, or any combination of these functions. Such a building block can also be an antenna, solar array, or microinstrument. Some of the functional building blocks may be mission-specific and developed to meet unique objectives, but others may also be common to many missions for handling similar spacecraft house-keeping functions. The multi-mission building blocks can be designed and fabricated in quantity to achieve significant reductions in recurring costs for the missions. With very few exceptions, such as the antennareflectors, propulsion tanks, and solar arrays, almost every functional building block is basically a hardware assembly that comprises a finite number of mechanical, electrical, and electronic components. Typical mechanical hardware includes support, containment, and protection structures, thermal control components,

cables, harnesses, and connectors. The electrical/electronic components to be used in the 21st-century microspacecraft and microinstruments will most likely be discrete high-density electronics. These high-density electronics are generally in the forms of two-dimensional multichip modules (MCMs) and three-dimensional, stacked MCM packages (i.e., MCM stacks).

There are significant parallels in the technology development for future microspacecraft and that for electronics packaging and interconnection, both are striving to put more functionality into smaller and less expensive modules. Designers, using MCMs

module, called the Integrated Utility Module (IUM).

Utility is redefined to include structural support and containment, load carrying capability, geometry control, thermal management, power distribution, data and signal transmission, radiation and meteoroid protection, and other electromechanical functions that are essential to the proper functioning of any spacecraft subsystem. An IUM may carry a single functional MCM stack or several MCM stacks as illustrated in Figure 1. The development of IUMs will take full advantage of recent advances in many technologies, including lightweight advanced materials, multi-functional structures, autonomous and miniature thermal management, cableless

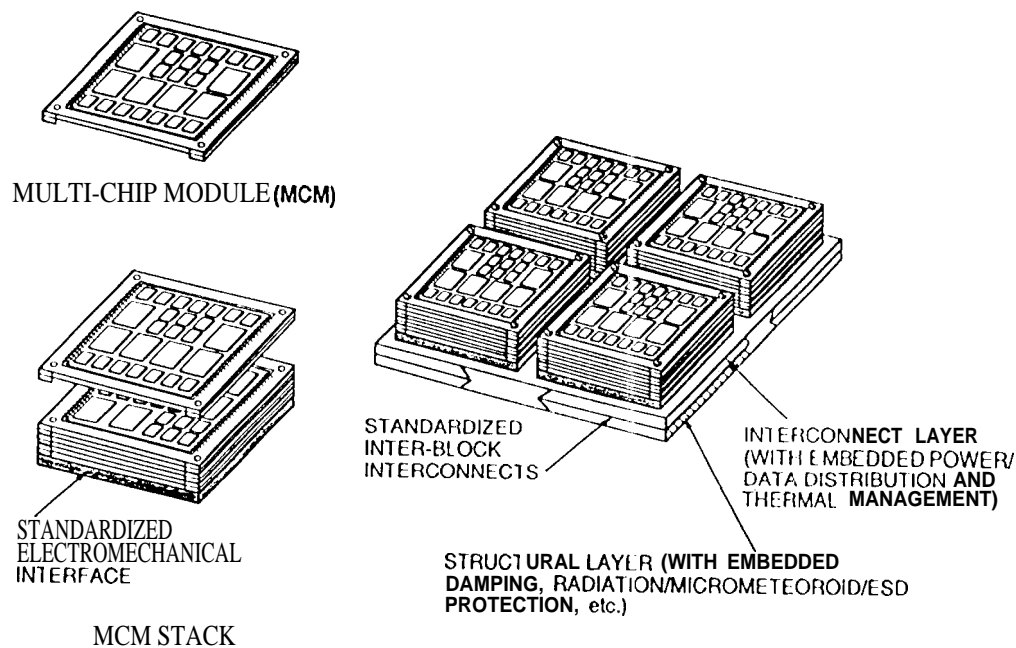


Figure 1. An Example Integrated Utility Module

and MCM stacks, can now shrink whole electronics boards down to the size of individual parts. To achieve full advantage of MCM-based electronics in meeting the goals of future NASA missions, mechanical packaging of spacecraft and instruments must be revolutionized. The electrical/electronics and mechanical systems, which are traditionally developed separately prior to system-level integration, must now be designed, analyzed, and developed in a completely integrated manner. This need has led to the vision that all electromechanical utility functions for the MCM-based electronics are packaged in a lightweight, compact, and cableless

interconnects, high-density multi-chip-module electronics, and integrated design analysis and simulation. It is believed that the IUMs will enable innovative spacecraft and instrument systems architecture and help achieve order-of-magnitude reductions of spacecraft mass, size, workmanship anomalies, and mission life-cycle cost for future NASA science missions. It is also believed that the IUM development should be coupled with the development of a design environment, in which the three major tools of computational intelligence; fuzzy logic, neural network, and genetic algorithm, are implemented.

One of the major challenges in developing the IUM technology relates to the electrical interconnectivity. There are two levels of interconnects for the IUM building blocks. The first level concerns the interconnects for power distribution and data Transmission between the MCM stacks on the same IUM building block, as well as between the MCM stack and mechanical hardware. The second level is the electrical interconnect between different IUM building blocks. Today, wires, harnesses, and connectors provide the interconnectivity between electronic parts, printed wiring assemblies (PWAs), and electrical/electronic subsystems. This interconnectivity is accomplished through discrete wires bundled together to form harnesses. These harnesses are strewn throughout the spacecraft or instrument and attached to the host

mounted on the top and sometimes, bottom plane of the PWA. Interconnection between the parts and the PWA is generally accomplished through solder attachment of the electronic part's peripheral leads to the PWA land patterns (solder pads). While this fashion of interconnection is fairly robust and reliable for past and current mission applications, its application to future microspacecraft and microinstruments is not feasible due to: (1) limitations on wiring density; (2) large mass, power and volume requirements; (3) electromagnetic interference (EMI); and (4) high touch labor requirements

Data from past NASA missions has shown that the cabling mass (i.e., the total mass of cables, harnesses, and connectors) for a typical spacecraft

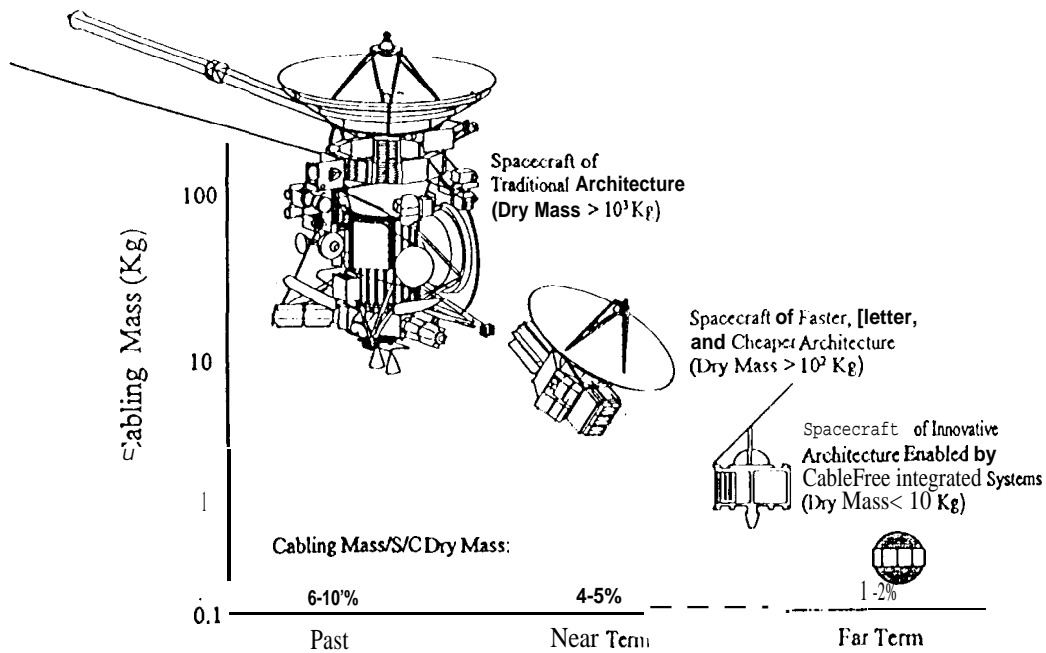


Figure 2 A Benefit Chart for Cableless Microspacecraft

and server systems via bulky NASA flight approved connectors. These connectors provide the interface between electrical/electronics subsystems and the harnessing. Once inside (IIC subsystem, interconnection is accomplished by several means, including PWAs, solder joints, wire bonding and more discrete wiring. Traditional PWA technology is almost exclusively used. PWAs use a rigid dielectric with copper foil traces to provide the signal and power interconnect to electronic parts

represents 6-10% of the total spacecraft dry mass, see Figure 2. Of this mass, 30% is for interconnects (e.g., solder joints and connectors). It should be pointed out that the electronics and other systems aboard a microspacecraft are reduced in size, the ratio of spacecraft mass taken up by cabling of the traditional designs would be significantly higher. This is clearly unacceptable. As to touch labor requirements, although exact data related to cabling Fabrication and assembly is not available; it is

known to be a substantial portion of the touch labor required for spacecraft and instrument production and assembly. High touch labor also adversely impacts the development schedule and will not be acceptable to future NASA missions that demand rapid build and aggressive launch frequency. Reducing touch labor lowers the potential for workmanship anomalies and further reduces the development cost and shortens the development schedule by avoiding rework and repair.

The electrical, as well as the mechanical, interfaces for the MCM stacks will be standardized such that a spacecraft functional IUM building block can easily be reconfigured and reworked without incurring significant cost and time. However, to account for the potential need of MCM stacks that have unique structural, thermal, or electrical requirements, flexibility for ready tailoring and modifications will be considered in designing the standardized MCM stack inlet-faces. This consideration will also be extended to the design of the inter-IUM interfaces.

Future microspacecraft and microinstruments require cableless interconnects technology that is both innovative and cost-efficient to replace the traditional cabling design. Without leap-frog advancements in this area, it will be impossible to meet the mass, size, power, cost, and capability requirements of New Millennium spacecraft and future microspacecraft and microinstruments. Integration of electrical interconnects with thermal management, into the support/protection structures is being addressed at the MCM and the MCM stack levels. Such an integration must be extended to the interfaces between the MCM stacks and the IUM building blocks, as well as the inter-IUM building block interfaces, to reach the goal of building cableless flight systems.

### State of The Technology

#### Multi-functional (Integrated) Structures

The function of spacecraft structures has traditionally been to provide support and protection for other components and subsystems and to keep the spacecraft as a coherent, functional system under external loads and pressure. Structural mass can be up to 25% of the dry mass of a spacecraft

depending upon its design and other factors, including how the term "structures" is defined. In addition to making rigorous efforts to reduce the mass of structures, spacecraft developers have also been interested in using the structures to do more than only the traditional function. Spacecraft designs that use the outer bus walls as substrates for solar arrays or as radiators for thermal management, and that use propellant tanks as part of the core structures (this can be thought of using part of the core structures to contain fuel) are some examples. Or the primitive "multi-functional" structures.

As the application of graphite/epoxy composite to spacecraft structures has reached its maturity, more sophisticated and innovative design concepts of multi-functional structures have started to emerge. Many forms of smart (or adaptive) structures, in which sensors and actuators are embedded in the graphite/epoxy composite layers for enhanced responses to external loads, have been developed and their effectiveness proven. Recently, significant development efforts have also been initiated to integrate electronics in layered structures.

#### Lightweight Advanced Materials

Due to launch mass limitations, the search for lighter and better space structural materials has been a continual effort of the aerospace community.

Currently, several structural materials with ultra low density and enhanced electrical and thermal properties are being developed and evaluated. Silica aerogel composites, silicon carbide, and thin film materials for balloon and inflatable structures are some of the examples.

Silicon carbide technology has been developed to the stage that actual applications in spacecraft and instrument are feasible. Specifically, hot-press silicon carbide was selected for the Pluto Integrated Camera Spectrometer (PICS) optical elements and structural components because of its good thermal conductivity, high specific modulus and dimensional stability. A materials characterization effort aimed at establishing mechanical property databases for silicon carbide and the structural joints and attachments used in silicon carbide parts has recently been completed. Processing methods

are also being developed to make layered silicon carbide structures.

Silica acrogel/epoxy composite is another exciting lightweight advanced structural material worthy of further investigation. This material has recently found its application for the Warm Electronics Box (WEB) for Mars Rover. Silica acrogel/epoxy has extremely low density and low thermal conductivity allowing Mars Rover to achieve its thermal, structure and mass objectives

#### Autonomous Thermal Management and Miniature Thermal Control

To reduce flight operations cost, highly autonomous, or "thinking", spacecraft are being planned for future NASA spacecraft. An important element of spacecraft autonomy is autonomous thermal management (ATC), which enables thermal control devices to react, real-time and without being ordered by up-link commands, to the actual flight environments to maintain optimum temperature levels for various operational modes. The main benefit of ATC is to minimize the power required for thermal control, which is traditionally the biggest power users among all spacecraft subsystems. Currently, spacecraft thermal management is set on the ground by design and test. There is very little existing capability to make in-orbit adjustments to temperature levels, heater duty cycle, etc.

The miniaturization of thermal control devices and components is essential for microspacecraft and microinstruments, which allow for much smaller mass and space for all subsystems, including thermal control. Additionally, miniature thermal control devices, such as miniature heat pipes and thermal switches, are needed to efficiently remove heat generated by densely packed chips from MCMs and MCM slacks. Due to the strong demand for consumer electronic products such as note-book computers, significant research and development efforts continuously being undertaken by the universities and industry companies in various thermal control technology areas, including advanced thermal management research for commercial high-density electronics; smart thermal coatings; micro phase change materials; miniature heat pipes; and ultra high thermal conductivity

substrates. The proposed IUM effort will take full advantage of these and other on-going research work, but will focus more on the hardware and software development of compact, efficient autonomous thermal management that employs thermal control devices and components embedded in the multi-functional structures.

#### High-Density Electronics Packaging and Interconnection

Traditional space electronics use nonstandard form factors designed to meet the unique requirements of individual spacecraft. Size and weight requirements for the New Millennium electronics will further restrict use of current standard form factors for electronic packaging and interconnection (e.g., surface-mounted parts on a printed wiring board with traditional back plane). However, the aggressive schedule and cost profile for the New Millennium Project support the use of standardized form factors and interfaces for the electronic packaging and interconnection. This dichotomy between the use of nonstandard electronics and standardized electronic packaging and interconnection will be addressed by the IUM development team. Industrially developed high-density interconnects and packaging techniques must be leveraged to the fullest extent possible. Technologies such as the chip's first approach, fusible substrates, low-temperature cofired ceramic, chemical-vapor-deposited diamond films, flexible interconnects, and photonics should be assessed for incorporation into standard architecture for electronics. Furthermore, the high-volume applications and existing infrastructure of these technologies will help narrow the dichotomy between customized electronics and the industry-established standards.

Micro-interconnection technologies will be the primary thrust of this development activity. With the high-performance MCMS on board NASA microspacecraft, propagation delays due to large geometry interconnects will provide a performance barrier. In addition, techniques must be developed which will allow an array of interconnects to be used on a single substrate. Material properties and manufacturing processes will need to support solder attach, adhesive attachment (including elastomeric),

tape automated bonding , "zero" insertion force type connections and fine-pitch wire bonding.

Flexibility of the interconnection selection will be a key factor in creating a standardized electronic packaging and interconnection architecture for the IUM building blocks. The basic technology for high density packaging based upon the MCMS is sufficiently mature and it is the right time to start considering standardization of power and data interconnects for future microspacecraft and microinstruments. The general approach would be to utilize aluminum or copper metallization for power distribution and polymer dielectric for data transmission. The polymer would be selected to optimize operating speed. Stacked MCM modules would employ silicon as the substrate material and direct die attach methods be used - such as bumping directly on the bonding pads. In addition, micro-machining techniques would be applied to incorporate optical waveguides for opto-coupling to enhance speed and lessen susceptibility to EMI. However, state of the art for power and data interconnects will be used to its limits and these limits will need to be advanced. For example, copper metallization has been used in some MCMs for its higher current carrying capacity but higher yield and more reliable processes will be needed. The advantages of thin diamond film will be further developed and its thermal properties more accurately characterized. Designs incorporating direct active cooling of chips either through their immersion in a heat transfer fluid or the flow of such a fluid through passages in the supporting substrate will be considered in cases involving relatively high power dissipation. Fusible substrates afford extensive flexibility in the substrate design, but their effects on many issues, including failure modes, upsets and manufacturability require assessment. In addition, the fine-line, thin-film laminate, and thin-film-deposited substrates need to be studied in achieving the interconnection density required for the interconnection layers of the IUM building blocks,

#### Integrated Design Environment

The state of design technology today is an aggregate of design tools that generate a wealth of disparate data sets that do not fit well into consistent integrated analysis structures. Current

technology does not address the complex questions of capturing design intent and the decisions that lead to a design. An intensive effort is needed to develop the technologies that allow us to capture design intent, provide for easy generation of design alternatives, facilitate systematic search of the design space and virtual design environment tools for IUM building blocks.

Over the past two decades, computer Aided Design (CAD) has matured as a major force in the design of hardware and software. However, much of the cost of the design effort for a large DoD or aerospace project is involved with requirements generation and analysis of design alternatives, manufacturability, documentation etc. Little has been done to make these other tasks less expensive through the use of modern computers.

A single database can be controlled and removes the ambiguity of multiple designs going on at once. The challenge is to maintain and manipulate this database as it evolves over time from project start to project end. Many commercial tools are available to manage specific program database parts, but (here is no available system which integrates them into a seamless environment, and facilitates the analysis within this integrated environment, At the Jet propulsion Laboratory (JPL), the users of the Project Design Center (PDC) and the Multidisciplinary Integrated Design Assistant for Spacecraft (MIDAS) are proposing a collaborative effort that addresses these needs for the IUM designers

The major feature of the PDC at JPL is the information system concept. The system (hardware, software, network, etc.) is used to manage the processes and data involved in the overall project development and industrial manufacturing process. Integration of proven off-the-shelf commercial software tools and modern workstations enables sharing of project data and enhances concurrent engineering capabilities during all phases of a project's development and operation. MIDAS tool was one of the first attempts at JPL to create an integrated design environment. MIDAS allows the construction of a relational database of specifications, previous designs, purchased hardware, and analysis tools to enable development of a new project design based on a set of input

requirements. The proposed PDC/MIDAS effort would result in an integrated design facility which would automate many designs and produce a set of engineering drawings of components which would be highly manufacturable, testable and cost effective. It would deliver test plans, purchasing orders, operational manuals, specification documents and the whole gamut of design deliverables. Successful development of such an integrated design environment will reduce the current life cycle development of spacecraft from six years to six months and at the same time improve the quality of designs.

More recently, NASA is planning to bring computational intelligence into its design and development processes for spacecraft and flight instruments, as well as for aeronautics and high-speed space transports. It is expected that an integrated design environment augmented by computational intelligence tools such as fuzzy logic, artificial neural networks, genetic algorithms, and hybrids tools (e.g., neuro-fuzzy modeling), will have enhanced capabilities related to uncertainties, nonlinearity, and optimization.

#### Development Roadmap

The development of the proposed IUM technology should have direct relevancy to the New Millennium missions. This can be achieved by infusing the IUM technology into the flight hardware development of selected New Millennium electromechanical instruments and subsystems that are MCM-based. An example candidate subsystems is the Three-Dimensional Micro Avionics System currently being developed by the Microelectronics Systems IPDT for the first New Millennium mission. An important consideration for the final selection of target IUM technology applications is the development schedule of the New Millennium missions and associated subsystems. The timing consideration has led to the division of the proposed IUM technology development into three phases, each focused on delivery of flight hardware to a specific New Millennium mission:

- The Phase 1 flight hardware delivery, intended for the first New Millennium mission of a 1998 launch, will be a single IUM building block carrying one or more functional MCM-based

micro-instruments, micro-sensors, and/or other micro-electronic subsystems. Development of this IUM building block will be based on a multi-functional structures design concept that is similar to the one currently being developed by Lockheed Martin under the sponsorship of the Air Force Phillips Laboratory. Depending on the stiffness requirements, the base structure of the IUM building block may not be of a sandwich construction as in the current Lockheed Martin design. If a layered structure is selected for the IUM building block, the material will most likely to be a graphite-epoxy composite. In addition to the multi-functional structures technology, three important IUM technologies will also be incorporated into this Phase 1 building block: (1) cableless interconnects for power distribution and data transmission between the MCM-based subsystems and the multi-functional structure of the building block; (2) miniature thermal control components and devices (e.g., miniature heat pipes, diamond stripes, and phase change thermal storage) embedded in the multi-functional structure; and (3) standardized structural, thermal, and electrical interfaces between the MCM-based components and the multi-functional structure.

- The Phase 2 flight hardware delivery, targeted to support the second New Millennium mission to be launched around 1999, will consist of two or more functionally interconnected IUM building blocks. The IUM technologies to be infused into these spacecraft and/or instrument building blocks will include: (1) multiple functional structures constructed with lightweight advanced materials such as silicon carbide composite; (2) inter-block structural and thermal interconnects; (3) inter-block power distribution and data transmission interconnects that are compact and lightweight, and need a minimum amount of touch labor; (4) autonomous thermal management; (5) improved thermal control components and devices; and (6) programmable chips that serve as patch panels for power distribution, data transmission, and thermal management. Technology infusion of the last item will significantly reduce the number of power and



data wires and thermal control devices required for the building blocks.

- Phase 3, aimed at the 3rd New millennium flight would entail incorporating all aspects of IUM into the spacecraft: (1) fully integrated structure and electronics; (2) advanced materials; (3) IUM block to block interconnect; (4) standardized inter-processor connections with programmable chips; and (5) autonomous thermal management

Similar development approach will be used in each phase to accomplish the technology and flight hardware development goals. Each phased development effort will define the system-level functional and design requirements for the IUM building block or blocks based upon the requirements of the individual mission. The requirements for power distribution and data [transmission are subsystem- or instrument-specific and will drive the wiring design within an individual IUM building block and the design of interconnects between functionally related IUM building blocks. In particular, the data transmission requirements will greatly influence the development of electrical interconnects technology. Additional requirements may also include modularity in design and rework, standardized interfaces with MCMs and MCM stacks, standardized test interfaces, and, most important, well-defined mass and size goals to be used to guide the selection of materials and design configurations of the IUM building blocks.

Once the design requirements for the New Millennium IUM building blocks are defined, the technology needed to meet these requirements will be identified. This will be followed by an in-depth assessment of the availability and readiness of supporting technologies in the required areas. Technology development efforts focused on filling the gaps between what is available and what is needed in each area will be performed. It is anticipated the largest technology gaps may be related to the following: (1) selection and characterization of advanced lightweight materials (that can satisfy multiple and often conflicting requirements related to strength, stiffness, thermal and electrical conductivity and isolation, meteoroid and radiation protections, mass, size, cost, and manufacturability; (2) automation of thermal

management and miniature thermal control devices that can be embedded in thin-walled structures; and (3) cableless power and data interconnects that are compact and reliable and can be fabricated and assembled with a minimum amount of touch labor, and (4) programmable chips for autonomous control of power, data, and heat flows. The technology development efforts will continue throughout the entire performance period of this proposed effort.

Simultaneous to the initiation of focused technology development, intensive efforts will be started to develop hardware design concepts for the New Millennium IUM building blocks. Trade studies and optimization of design concepts will be supported by the integrated design environment. While the form of the final configuration of the IUM building block is to be worked out, it is clear that an urgent need exists for a multi-disciplinary tool suitable for analyzing such an integrated system. Fortunately, such a need can be satisfied by enhancing an existing, well-established computer code, MIDAS. With additional software development work, it is possible to use MIDAS to string a sequence of structural, thermal, interconnectivity, micrometeoroid protection, and radiation protection analyses together for system-level trade studies and inter-disciplinary optimization of an integrated product such as a IUM building block. Incorporation of computational intelligence in selected portions of MIDAS will also be a major part of this software development. Additionally, in parallel to the development of integrated design environment, a laboratory test program will be carried out to define modeling parameters, verify modeling assumptions, and validate predicted behavior of the IUM building blocks. In addition to the tests devised to accomplish the system-level analysis/test correlation, this program will also include materials characterizations, measurements of interconnectivity, determination of contact forces, and other tests that are deemed required for the development of a versatile and accurate integrated analysis tool. Once developed and validated, this integrated analysis tool can be used not only to guide the design and design optimization efforts, but also to accomplish rapid-prototyping of the IUM building blocks

After all proposed design concepts are analyzed and optimized to the maximum extent possible, it will be relatively straight forward to downselect the best conceptual design for further development. At this point, a preliminary design review will be held and followed by detailed designs and analyses at the parts level. Engineering drawings that are suitable for fabrication and assembly will be generated. During the detailed design phase, infusion of emerging technologies developed by this and other technology development efforts will continuously influence the designs and bring about design refinements. Toward the end of the detailed design phase, breadboard IUM building blocks will be built for controlled characterization and performance assessment. Qualification-level environmental tests will be performed on the breadboard units to qualify mechanical and electronic designs. The development of a breadboard building blocks will also serve to try out manufacturing, material processing, quality control, assembly, and test procedures. The irregularities and anomalies in these procedures will be identified and corrected prior to the development of the flight IUM building blocks.

The fabrication and assembly of the flight IUM building block or blocks will start after a successful critical design review. The assembled IUM building blocks will be subjected to functional tests and flight acceptance environment tests at the individual block level prior to their delivery to the New Millennium Program for integration onto the spacecraft or instrument. Technical support to spacecraft system-level integration and test activities will be provided and a final report will be prepared to summarize the technical data, results, findings, lessons learned and other development details of the proposed effort.

#### [Conclusion

Microspacecraft carrying powerful miniaturized instruments will enable future NASA science missions that must be more affordable and launched at a high rate and have significantly higher science data return. In order to meet the stringent mass, size, and life-cycle cost objectives, many revolutionary technologies will be infused into the design and development processes of these microspacecraft. The IUM technology is one of

such enabling technologies. This paper has described the IUM concept, its applications to future space flight systems, and a roadmap for its development and space validation.

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The Integrated Utility Module (IUM) concept was first proposed at the Workshop on Future NASA Microspacecraft Technology, held on February 8 - 10, 1995 in Pasadena, California, for the consideration and discussion of the Working Group on Materials, Structure, Packaging, Thermal Control, and interconnection. The many valuable comments and suggestions received from the members of this Working Group are appreciated. The IUM concept was later converted into a formal proposal, entitled "Cableless Architecture and Packaging (CAP) Technology and Computational Intelligence Design (CID) Environment Development," for submittal to the New Millennium Program. Materials of this paper are mainly excerpted from the final write-up of the proposal. The contribution of the JPL CAP/CID proposal preparation team, led by M. Lou and consisting of I. Barla, S. D'Agostino, C. Hsieh, J. Peterson, R. Miyake, and R. Glaser, is acknowledged.

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