Implementation of a Dependable Multiprocessor CubeSat

John R. Samson, Jr.
Honeywell Aerospace., Defense & Space Systems
13350 U.S. Highway 19 North
Clearwater, FL
john.r.samson@honeywell.com

Abstract—Space applications have been, and will continue to be, subject to severe size, weight, and power constraints. The need for and the use of high performance embedded computing in space exacerbates the size, weight, and power problems. Flying high performance embedded computing in CubeSat applications presents particularly unique problems which require unique solutions. Fortunately, there are three technologies that make flying high performance embedded computing on CubeSats feasible: 1) the availability of high power CubeSats, 2) the availability of small, light-weight, low-power, Commercial-Off-The-Shelf (COTS) Computer-on-Module (COM), e.g., Gumstix™, technologies which are potential solutions to the size, weight, and power problems, and 3) platform-, technology-, and application-independent Dependable Multiprocessor Middleware (DMM), which allows COTS COM technologies to be used in space applications. The paper provides a brief overview of these three technologies and presents the results of investigations of DM CubeSat implementations to date. [1, 2, 3]

TABLE OF CONTENTS

1. INTRODUCTION

Flying high performance Commercial-Off-The-Shelf (COTS) technology in space to take advantage of the higher performance and lower cost of COTS-based onboard processing solutions is a long-held desire of NASA and the DoD. Currently, there is increased interest in high performance COTS computing for a wide variety of small space and airborne platforms. This includes CubeSats, High Altitude Airships (HAAs), Unattended Airborne Systems (UASs), and micro Unattended Airborne Vehicles (UAVs). Funded by the NASA New Millennium Program (NMP) Space Technology 8 (ST8) project since 2004, the development of Dependable Multiprocessor (DM) technology is a major step toward flying high performance COTS processing in space. The objective of the ST8 DM technology advance was to demonstrate that a high-performance, COTS-based processing cluster can operate in a natural space environment providing high-throughput, scalable, and fully programmable processing achieving high throughout density, high system availability (> 0.995), and high system computational correctness (> 0.995) in terms of the probability of delivering undetected erroneous or untimely data to the user, with platform-, technology-, and application-independent system software that manages the cluster of COTS processing elements, and platform-, technology-, and application-independent system software that enhances radiation upset tolerance.

In 2007, NASA eliminated the TRL7 technology validation flight experiments, including Dependable Multiprocessor, from the ST8 project. Since that time, the DM project has been trying to find an alternative ride to space to achieve that, all important, TRL7 validation for DM technology. There are a number of options for flying (DM) technology in space. These options include, but are not limited to: 1) flying the original ST8 DM flight unit design, a hybrid cPCI 6U/3U size system implementation, 2) flying a smaller, all cPCI 3U-size, system implementation, 3) inserting DM hardware and software into a user's existing cPCI 6U or 3U size chassis, or 4) porting the DM software to other hardware platforms. The original ST8 DM flight system and two reduced-size DM implementations are illustrated in Figure 1.

An overview of the original DM ST8 flight experiment payload is shown on the left side of Figure 1. The ST8 flight system consists of a Radiation-Hardened Single Board Computer (SBC) which serves as the DM System Controller, four (4) Extreme Solutions 6031 single board computers which serve as the high-performance COTS cluster, a Radiation Tolerant Mass Memory Module, a power supply module, and a Master Interconnect Board (MIB). All of the cards plug into a cPCI backplane primarily for mechanical purposes. The cCPI backplane is only used electrically for power, discrete signals, and reset signals. The COTS cluster is connected with high-speed Ethernet. All boards communicate using TCP/IP. The COTS single board computers are PPC 7447a with

[2] IEEEAC paper #1452, Version 6, Updated January 31, 2011.
[3] The project formerly was known as the Environmentally-Adaptive Fault-Tolerant Computing (EAFTC) project.

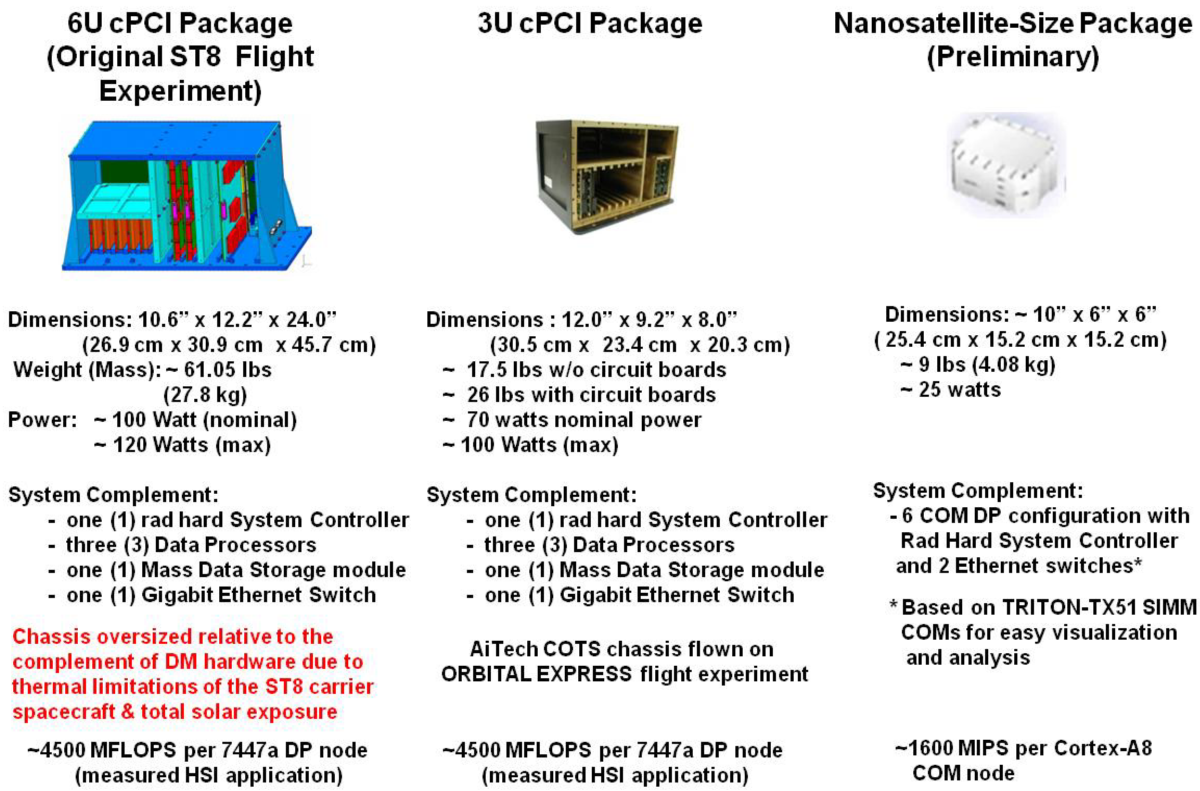


Figure 1 - ST8 and Initial Reduced-Size Dependable Multiprocessor Implementations

AltiVec on-chip accelerators. The System Controller hosts the Wind River VxWorks OS and DM Middleware (DMM). The COTS data processing boards host the Wind River Carrier Grade Linux OS and DMM (Dependable Multiprocessor Middleware). The DM flight experiment chassis shown is larger than needed to house the complement of flight hardware. The DM ST8 flight payload was designed to operate in full solar exposure. The larger flight experiment chassis was designed with increased surface area to radiate DM system power to complement the limited cooling provided by the ST8 carrier spacecraft.

The DM implementation shown in the middle of Figure 1 replaced the cPCI PPC 6U SBC System Controller with a rad hard cPCI 3U BRE440 SBC System Controller to fit into a smaller, completely cPCI 3U form factor chassis. The DM implementation shown on the right hand side of Figure 1 shows the initial concept for a nano-satellite-size DM design based on the BRE440 System Controller and Triton TX-51 Computer-On-Module (COM) processing nodes.

It became clear that that the quickest path to flight for DM technology is on a Cubesat experiment. This was the initial catalyst for the interest in a DM CubeSat. Flying on a Cubesat means small, light-weight, low power, and low cost. Gumstix™ Overo COM technology plus DM technology offered a potential solution. As a software-based, platform-, technology-, and application-independent technology, DM technology allows space missions to keep pace with terrestrial COTS developments. As a result, the processing technologies used in space applications no longer need to be 2 - 3 generations behind state-of-the-art terrestrial processing technologies. DM technology was developed not to be a point solution, but to be able to incorporate new technologies as they come on-line. Many years of DM design and development were done before the appearance of Computer on Module (COM) technology. Over the years, DM software has been successfully ported to many platforms. Porting to the Gumstix COM technology is just the latest porting target for the DM middleware. This opened up the possibility of a Gumstix-based DM CubeSat.

In addition to DM technology, there are two other technologies that make flying high performance embedded computing on CubeSats feasible: 1) the availability of high power CubeSats, and 2) the availability of small, light-weight, low-power, COTS (Commercial-Off-The-Shelf) Computer-on-Module (COM) technologies which are potential solutions to the size, weight, and power problems. The remainder of this paper discusses these three technologies and the results of the investigation of DM CubeSat implementations to date.

2. HIGH POWER CUBESAT TECHNOLOGY

CubeSat size is specified in terms of the number of "U's" or units, where a 1U CubeSat is, by definition, 10 cm x 10 cm x 10 cm. The earliest CubeSats were 1U, but the 3U

Cubesat has become the most popular form factor today as a compromise between size and capability. 6U and 12U CubeSats are on the drawing boards. One of the reasons for the popularity of the 1U and 3U CubeSat form factor is the availability of convenient launch platforms such as the P-POD (Poly-Picosatellite Orbital Deployer). A P-POD launcher can launch three (3) 1U Cubesats, one (1) 1U CubeSat and one (1) 2U CubeSat, or one (1) 3U CubeSat. The overall size of a 3U CubeSat is 10 cm x 10 cm x 34 cm. The practical weight (or mass) of the CubeSat(s) from a P-POD launcher is ~5 - 6 kg. These challenging form factors provide the outer envelope for the physical implementation of a DM Cubesat.

Power, both generation and dissipation, has been, and will continue to be, a limiting factor for satellite applications. Power is a particularly acute problem for small satellites, such as CubeSats. The power available on the original CubeSats was limited by the surface area covered by the solar cells and the efficiency of the solar cells. The available area for solar cells was reduced by any sensor apertures. In practice, the surface area constraint limited the power available for a 1U CubeSat to 5 Watts (peak) and for a 3U CubeSat to 12 watts (peak). The introduction of thin foldable solar panels significantly increased the power levels available. The addition of four (4) 10 cm x 34 cm hinged solar panels increased the power to 25 Watts (peak). The use of multiple-hinged solar panels plus the 3U CubeSat surface area covered with solar cells increased the peak power to 50-75 Watts. Increased solar cell efficiency and the use of articulated solar panels are pushing the power generation capability upwards to 80-85 Watts (peak). [1]

The power level references in the previous paragraph were relative to peak power capability. On-orbit average power is another important consideration due to spacecraft orientation and eclipse operation when the solar cells are not in view of the sun. The latter requires batteries and battery charging systems for continuous operation during eclipse periods. The on-orbit average power has been limited to 1/4 to 1/2 of the peak power, but the introduction of articulated solar panels that can maintain pointing toward the sun without reorientation of the CubeSat is increasing the percentage of on-orbit average power to peak power to 75%. The increase in available CubeSat power is opening up new opportunities for increased onboard processing. Although CubeSat power generation levels are increasing, thermal dissipation is still an issue.

The new COM technologies are low power, so power generation and dissipation are less of a problem, but the power still needs to be dissipated. Some COMs are built for ruggedized, conductively cooled operation, and some offer operation over extended temperature range from -20^{o}C to +85^{o}C, but many COMs don't have any internal thermal plane. Mechanical analysis showed that, if necessary, COMs can be cooled with standard custom Al (Aluminum) thermal overlay techniques with suitable thermal interface material. [1] The machined aluminum overlays are designed to interface with hot components and also provide structural stiffness. The Aluminum overlays are custom designed for the COM modules and require no modifications to the modules themselves. They are applied only where needed to minimize structural and weight impact on the CubeSat. Structural issues are significantly less with the smaller COM modules due to less inertia and board deflection. For COM-size modules, wedge clamps and extractors are not needed as long as the Aluminum overlay makes good contact with the chassis. The thermal interface material needs to have the usual properties required for space applications: gap-filling, high thermal conductivity, low out-gassing, and compliance (elasticity). Whether or not these cooling techniques are required depend on the COM module and the CubeSat. While power generation capability is increasing, current thermal dissipation capability of CubeSats limits thermal dissipation to ~40 Watts. This provides another physical limitation for onboard processing capability. Fortunately, there are a number of techniques for managing power, e.g., controlling clock speed, controlling utilization duty cycle, etc.

3. COM TECHNOLOGIES

There are many examples of COM technology available today. Gumstix™ Overo technology was the COM technology targeted for the initial DM CubeSat study. Examples of Gumstix technology are depicted in Figure 2 and Figure 3. Figure 2 depicts a Gumstix Overo Fire module. a Tobi-Duo Expansion board, and a Tobi board. The capability of these modules is shown in the figure. The Overo Fire modules have processor, memory, I/O, DSP (Digital Signal Processing), and BlueTooth/WiFi capability. Each Gumstix module weighs 5.6 grams and nominally dissipates ~ 2 Watts. The figure provides a comparison of a Gumstix Overo module with a U.S. quarter. There are other Overo modules: Overo Water modules have processor, memory, I/O, and DSP, but no wireless capability. The Overo Earth modules only have processor, memory, and I/O capability. All offer different onboard processing capability. Figure 3 depicts a Gumstix Stage Coach Expansion board. The Gumstix Stage Coach board contains an Ethernet Switch and can accommodate up to seven (7) Gumstix modules. A fully populated Stage Coach board would consume less than 20 Watts.

4. DM TECHNOLOGY OVERVIEW

DM technology development, the DM TRL6 technology validation effort, and the post-TRL6 DM development effort are documented in References [2] through [9]. Since detailed descriptions of DM technology and DM technology development are available in these references, only a brief overview of DM technology is provided in this paper.

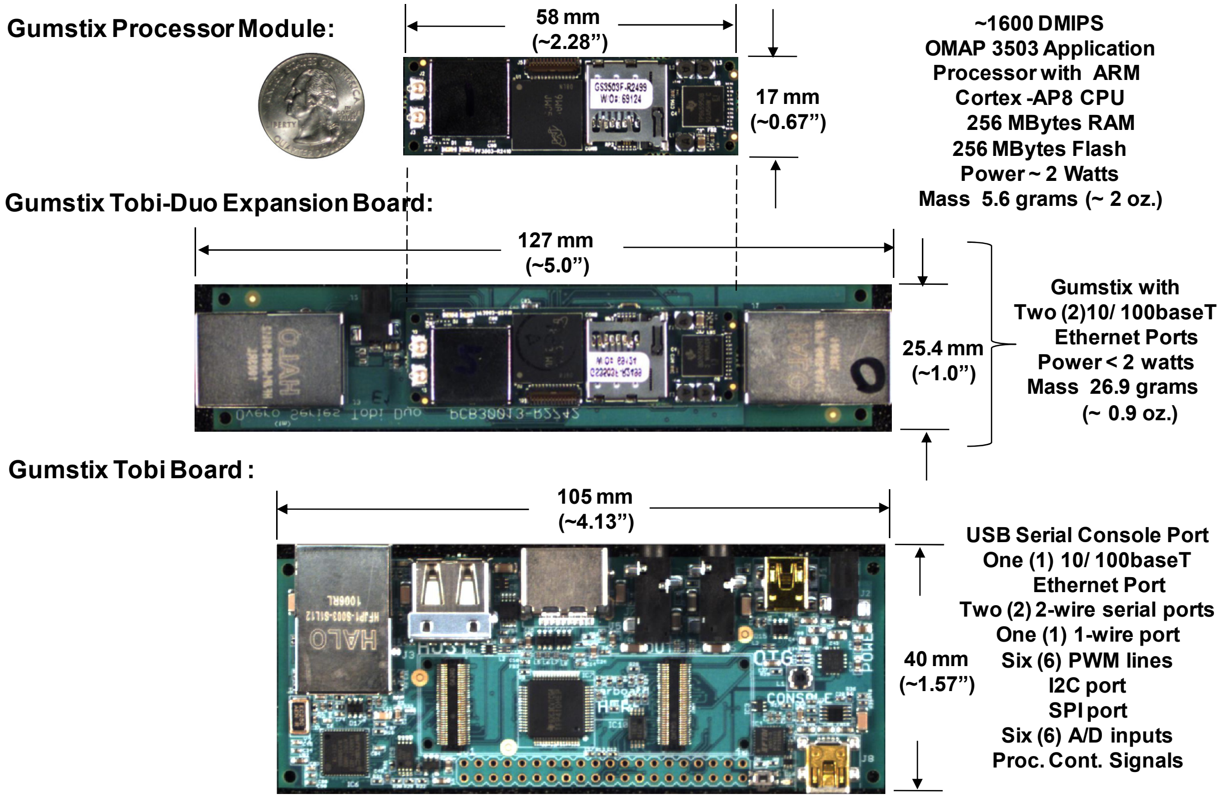


Figure 2 - COM Example: Small, Light-Weight, Low-Power Gumstix Processing

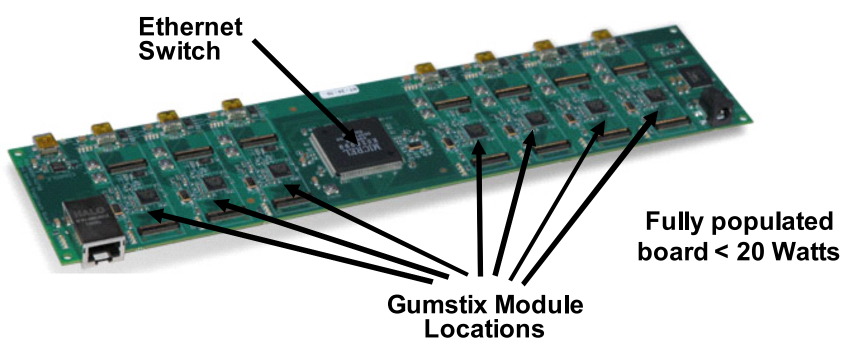


Figure 3- Gumstix Stage Coach Expansion Board: Seven (7) Gumstix Module

The objectives of the DM technology development effort were to:

1. Demonstrate the ability to fly a fault tolerant cluster of high performance COTS processors in a benign natural space environment

2. Implement platform and technology-independent middleware which supports heterogeneous operation and upgrades in hardware and software technology

3. Implement a software development environment that is familiar to application developers and facilitates the porting of parallel Message Passing Interface (MPI) applications from the laboratory to a space platform.

DM technology is a cluster of high performance COTS processors connected with a high speed interconnect and operating under the control of a reliable, possibly radiation-hardened, system controller and platform-, technology-, and applicaton-independent fault tolerant middleware. The system controller provides a highly reliable and SEE-immune host to support recovery from radiation-induced events in the COTS hardware. The DM Middleware (DMM) manages jobs and missions executed on the cluster and, most importantly, enhances the fault tolerance of the system. The DMM controls applications, monitors the health and status of DM hardware and software components, enhances SEU tolerance, and manages the system and application recovery strategies. The features that distinguish DM from other COTS-based solutions are flexibility, scalability, and ease of use which are supported through user-friendly DM mission and job configuration files. Scalability comes in the form of a modular implementation and is limited by the scalability of the high speed interconnect. DM offers user-configurable fault tolerance with options spanning the mission level to the application level. Fault tolerant execution includes replication, i.e., temporal and spatial self-checking (SC) and triple modular redundancy (TMR), combined with more computationally-efficient Algorithm-Based Fault Tolerance (ABFT) [10], [11]. DM can execute multiple missions sequentially or concurrently based on resource availability**.**

DM Hardware Architecture

The DM hardware architecture for a NASA Class C mission is depicted in Figure 4. The basic architecture consists of a system controller that acts as the highly reliable controller for a parallel processing cluster of COTS-based, high-performance, data processing (DP) nodes, a network interconnect, and a spacecraft interface. The system can be augmented with mission-specific elements, including mass storage, custom interfaces, and radiation sensors as required. System Controller, interconnect, and I/O redundancy can be provided, as required, for long-life missions.

DM Software Architecture

The DM software architecture framework is depicted in Figure 5. Figure 5 shows the two types of processing nodes: the first type, the reliable system controller, which can operate through any foreseeable environment without upsetting, for control functions, and the second type, a high performance COTS-based data processor node. A high-level API (Application Interface) and a high-level SAL (System Abstraction Layer) provide both application independence and platform independence, while allowing the particular mission applications and platforms to take advantage of fault tolerance services and reliable messaging offered by the generic fault-tolerant middleware layer. The function of the DM system software is two-fold: 1) to support cluster operation for scalable high-performance systems, and 2) to provide a system environment that enhances SEU tolerance through software SEU-tolerance techniques.

On each data processor resides a job management agent, which executes tasks, relays status to the system controller, detects application hangs and crashes, receives fault detection indications from user-defined detection techniques, e.g., Algorithm Based Fault Tolerance (ABFT), replication comparison and voting results, and captures OS exceptions caused by application exceptions.

To support enhanced SEU-tolerant performance in the DM, the traditional resource management services have been augmented with SEU-tolerant modes of operation including hardware (spatial) and software (temporal) redundancy, rapid detection and recovery from soft errors, rapid detection and recovery from hard faults, and fault/error management services including fault/error logging, fault/error handling diagnostics, management of resource

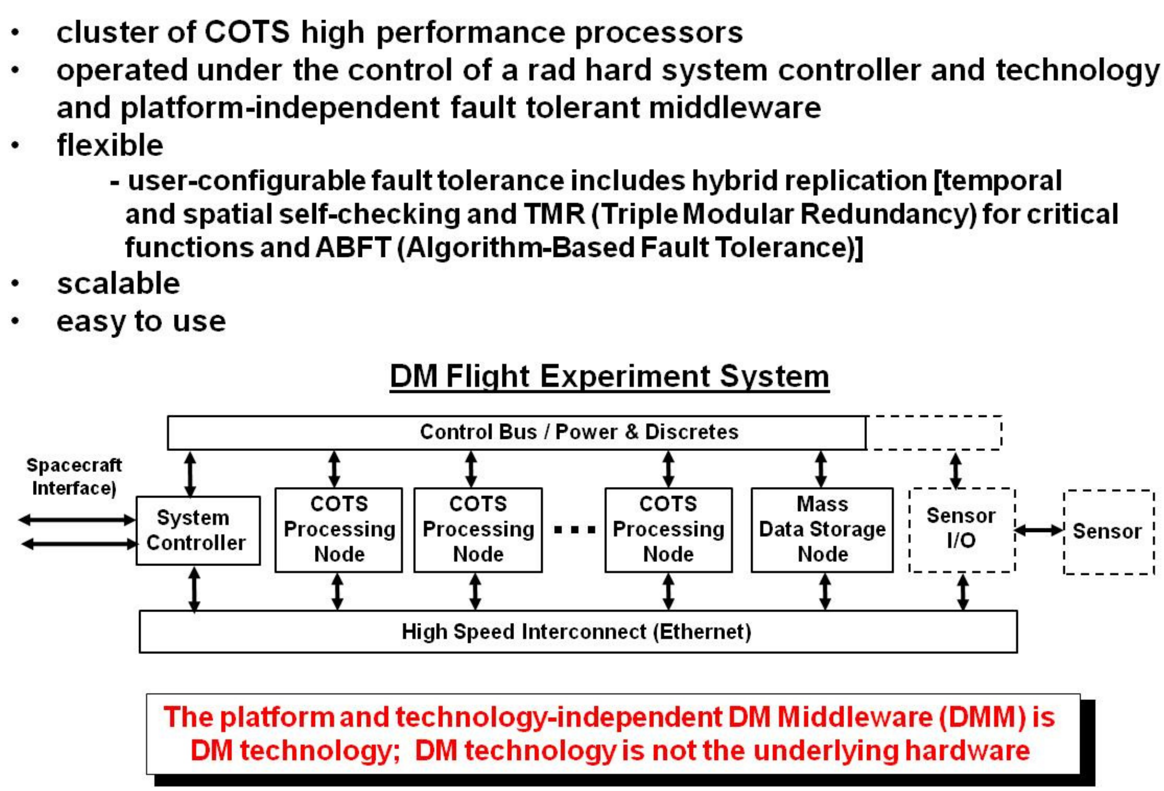


Figure 4 - Dependable Multiprocessor Hardware Architecture

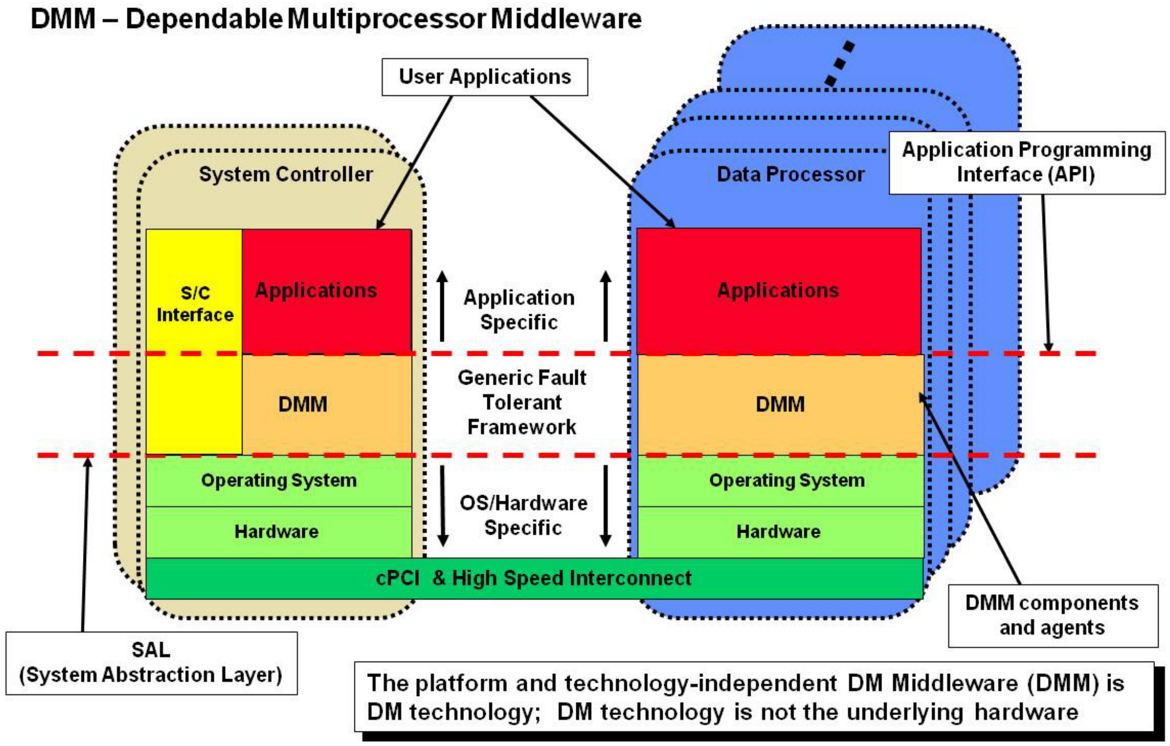


Figure 5 – Dependable Multiprocessor Software Architecture Framework

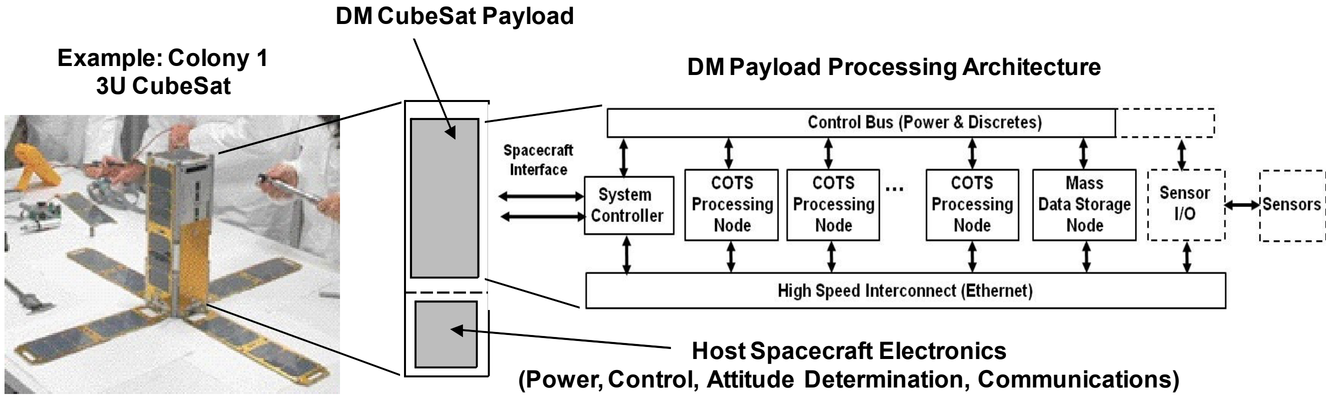
health status, management of application/process status, and management of redundancy and spare elements. The flexible, efficient, and cost-effective integration of user-selectable cluster management and SEU tolerance enhancement software to achieve high reliability and high availability in a wide variety of missions and environments is one of the key benefits of DM technology.

The DM project did its TRL6 technology validation in 2008 and 2009. The DM TRL6 technology validation demonstration included system-level radiation beam testing in which one (1) COTS DP board was exposed to a proton beam while executing the TRL6 application suite and operating in the context of a DM flight system including all DMM, experiment interface, and experiment data collection software. The system-level radiation testing validated DM design and operation in a radiation environment. DM met the objectives and the intent of the NMP TRL6 development effort and brought the goal of flying COTS in space closer to reality. Perhaps, most importantly, DM effort refined and demonstrated the process for flying COTS in space.

5. DM CUBESAT FLIGHT EXPERIMENT CONFIGURATION

A possible DM CubeSat flight experiment configuration is illustrated Figure 6. As indicated in the figure, the basic CubeSat bus components, a power system module, an attitude determination and control module, a host bus control module, and a communication module, are assumed to fit within 1U of a 3U DM CubeSat. These are standard off-the-shelf CubeSat modules available from a number of vendors. The remaining 2U segments of the DM CubeSat are available for the DM CubeSat payload which consists of DM cluster and any sensors and sensor interfaces that can fit within the volume and power constraints of the CubeSat. The nominal 3U DM CubeSat illustrated was assumed to have a mass of ~6 kg, a peak power of ~56 Watts, and a nominal on-orbit average power of ~20 Watts.

The original implementation of the DM CubeSat payload processing cluster is shown in Figure 7. This implementation is based on the use of Gumstix processor modules, a reduced-size Gumstix Stage Coach board, and the existing cPCI-size 3U BRE440 DM System Controller, as shown. The figure illustrates the side view and axial view of the DM CubeSat. Staying with the philosophy of flying COTS, the only way to put the existing 10 cm x 16 cm cPCI-size 3U BRE440 processor into a DM CubeSat form factor is to mount it on an angle as shown. Mechanical analysis indicated the angular mounting presented no structural problems for the DM CubeSat flight configuration. This was viewed as a clever solution, deemed to be feasible low risk, and minimal cost, but not really practical for a real application because it wastes too much space. Alternative solutions for the DM System Controller are being explored. The options range from a COTS controller whose reliability and radiation tolerance match the reliability and radiation tolerance of the CubeSat bus



Launch Size: 10 cm x 10 cm x 34 cm

Deployed Size: 78 cm x 78 cm x 34 cm

Mass: < 6 kg

Power: ~ 56 Watts (Peak) ~ 20 Watts (On-Orbit Average)

Figure 6 - DM CubeSat Flight Experiment Configuration

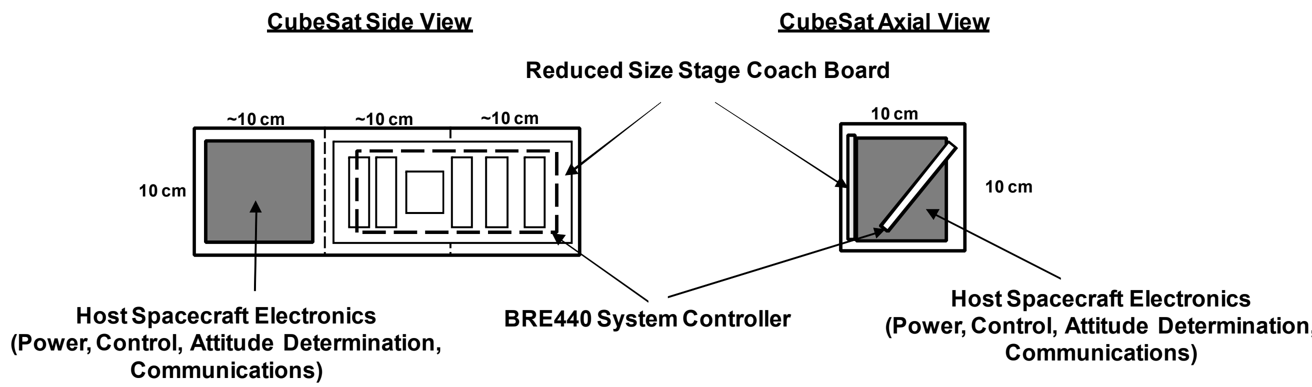
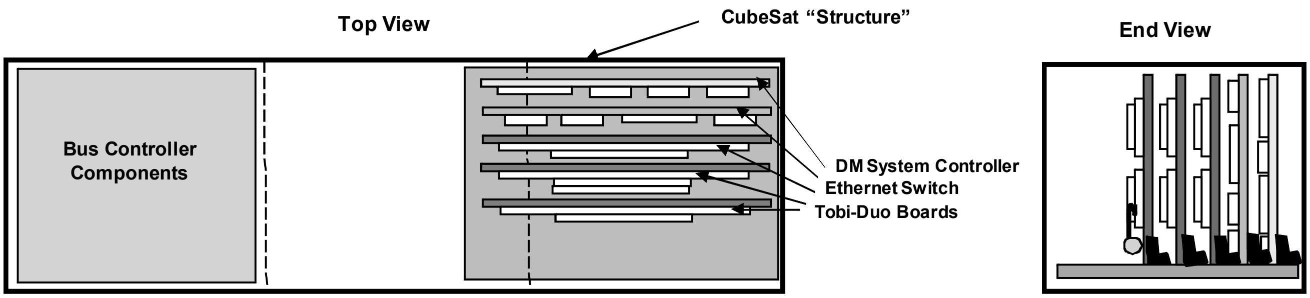


Figure 7 - Original Concept: Gumstix™ and BRE 440 DM CubeSat Flight Configuration

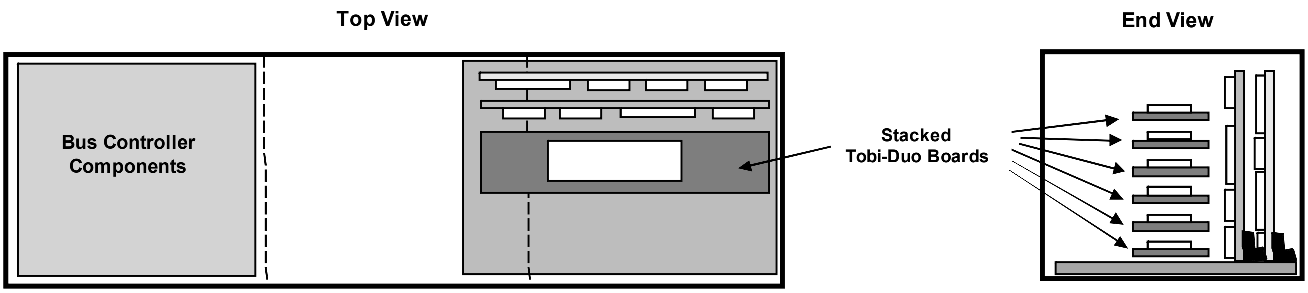
controller to a smaller, custom-designed rad hard controller. DM system error recovery is hierarchical, designed to be able to recover from non-catastrophic radiation induced errors including errors in the System Controller. If a small rad hard DM System Controller is developed, it could also be used as a CubeSat bus controller.

The reason for the reduced-size Stage Coach board is the 29.3 cm x 8 cm x 1.3 cm size of the full-size COTS Stage Coach board. Depending on the size and orientation of the CubeSat bus controller components, it may be possible to fit a full-size Stage Coach board along one side the CubeSat, but a more conservative implementation assumed a reduced-size Stage Coach board which can fit with a 2U segment of the 3U CubeSat. Discussions with the Gumstix vendor indicated that, if needed, a reduced-size Stage Coach board can be obtained. Other System Controller and DM CubeSat mechanical configurations are shown in Figure 8.

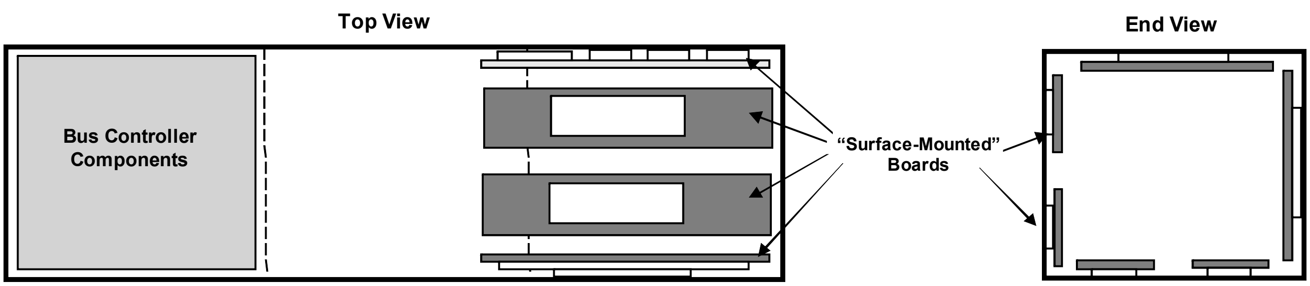
Use of the Stage Coach Board was intriguing because of the integrated Ethernet switch but, while they require a separate Ethernet switch, the Tobi-Duo boards definitely offer much more flexibility in terms of mechanical configuration. Electrically, the Tobi-Duo boards are connected with Ethernet cables. Physically, the Tobi-Duo board can be mounted anywhere they fit in the CubeSat volume to meet spacecraft volume, mechanical, and/or thermal requirements. The Tobi-Duo boards can be stacked vertically (Figure 8a) or horizontally (Figure 8b). They can be mounted around the periphery (Figure 8c), or they can be staggered and mounted in various combinations as shown in Figures 8d and 8e. A DM CubeSat system including 4 – 6 Gumstix Tobi-Duo boards, an Ethernet switch, and a DM System Controller can be packaged in a cluster ~9 cm x ~11 cm x ~6 cm as shown in Figure 8a. The remaining volume in the 2U segment of the 3U CubeSat is available for sensors, sensor I/O, and additional payload processing capability.



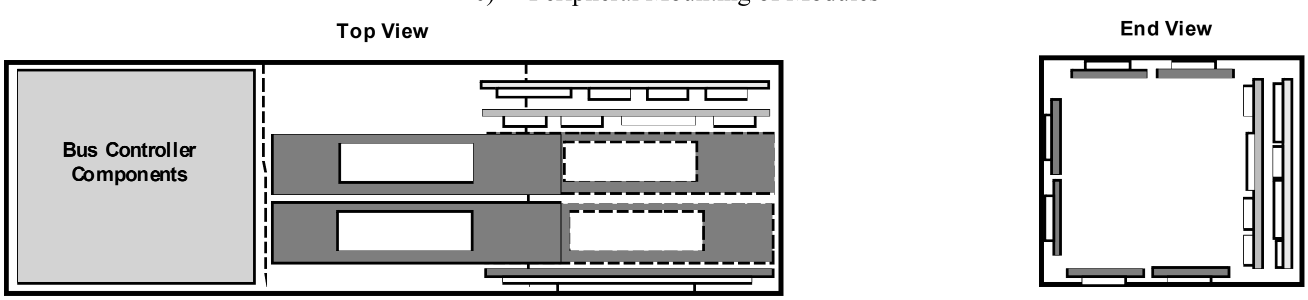
a) Vertical Stacking of Modules



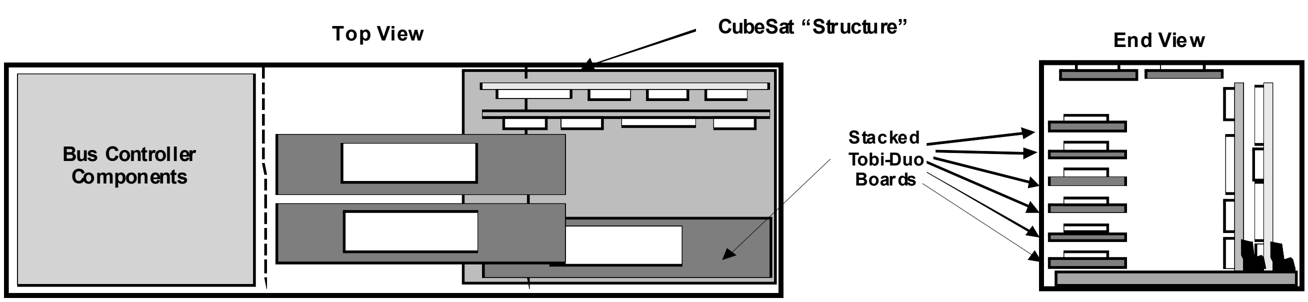
b) Horizontal Stacking of Modules



c) Peripheral Mounting of Modules



d) Staggered, Peripheral Mounting of Modules



e) Staggered, Horizontal, and Peripheral Mounting of Modules

Figure 9 – Multiple Options for DM CubeSat Configuration Using Gumstix Tobi-Duo Boards

6. SUMMARY OF DM CUBESAT EFFORT TO DATE

The DM CubeSat effort to date focused getting DM CubeSat technology closer to flight and reducing the risk of flying a DM CubeSat flight experiment. The DM CubeSat effort comprised a feasibility study which addressed size, weight, power, mechanical (structural & thermal), and radiation considerations of a Gumstix-based DM CubeSat implementation, the successful porting of the DMM to a Gumstix module, and the development of a DM CubeSat testbed. The results of the feasibility study were positive; a Gumstix-based DM Cubesat can be flown in space. Preliminary analysis showed it can survive the launch environment, it can operate in the space thermal environment, and it can operate in the radiation environment of a LEO orbit.

A key part of the process of flying COTS in space is the radiation testing of the parts to understand how they respond to the effects of space radiation. For space applications, the usual sources for radiation testing are protons and heavy ions. However, there was an opportunity to piggy-back on some beam time at the atmospheric neutron test facility at LANL (Los Alamos National Laboratory). A Gumstix Overo Fire module and two (2) Ethernet switches were tested. In five days of testing, no catastrophic latch-ups were observed and the SEE (Single Event Effect) rates including non-catastrophic SELs (Single Event Latch-ups), SEFIs (Single Event Functional Interrupts), SEUs (Single Event Upsets), and SETs (Single Event Transients) were low allowing DM software-enhanced SEE tolerance techniques to be effective. The results of these tests are directly applicable to HAAs (High Altitude Airships) and micro UAVs, which are other potential application areas for Gumstix-based DM processing systems but, with radiation effects modeling tools, the results were extrapolated to several space environments of interest.

The DMM (Dependable Multiprocessor Middleware) was successfully ported to a Gumstix module. The biggest issue to address for the Gumstix port was the Big Endian/Little Endian conversion for the Gumstix ARM processor. With the Big Endian/Little Endian conversion, DM TRL6 applications ran on a Gumstix module under DMM control.

Two Gumstix-based DM clusters were built for use in a DM CubeSat testbed, one cluster consisting of seven (7) Gumstix modules on a Stage Coach board, and the second consisting of a cluster of Tobi-Duo boards. A 3U CubeSat skeleton, a CubeSat bus controller module, a CubeSat communication module, and the complementary ground system emulation hardware were procured for use with the DM CubeSat testbeds. The CubeSat communication module and the ground system hardware enable the demonstration of a complete space-ground RF command and telemetry link.

DM Flight Experiment

The DM CubeSat effort was very effective in terms of getting DM CubeSat technology closer to flight and reducing the risk of flying a DM CubeSat. This work helped get DM CubeSat accepted as a 2010 Army SERB (Space Experiments Review Board) flight experiment and a DM cluster accepted as a payload processor for a 2010 DoD SERB flight experiment entitled SMDC Techsat. The SMDC TechSat project currently has a flat-sat demonstration scheduled for June of 2011, a CDR (Critical Design Review) scheduled for January 2012, and a targeted STP (Space Test Program) flight in late 2013 or early 2014. This is a significant development because it puts DM back on track for a TRL7 technology validation flight experiment.

Future Work

In addition to work on the SMDC TechSat project, development will continue on general DM CubeSat technology and on the DM CubeSat testbed. SMDC TechSat work will include finalization of a flyable mechanical configuration. Proton and heavy ion testing of the COTS parts is planned as part of further risk reduction efforts.

7. SUMMARY AND CONCLUSION

DM is an architecture and software framework that enables COTS-based, high performance, scalable, cluster processing systems to operate in space by providing software-based SEE-tolerance enhancement. The platform-, technology-, and application-independent Dependable Multiprocessor Middleware (DMM) is DM technology. DM was developed not to be a point solution, but to be able to incorporate new technologies as they come on-line. DM software has been successfully ported to many platforms. Porting to the Gumstix COM module was just the latest porting target for the DM Middleware. As a result of the DM CubeSat effort, DMM application now includes ARMs.

The results of the DM CubeSat feasibility study were positive; a Gumstix-based DM Cubesat can be flown in space. Preliminary mechanical analysis showed it can survive the launch environment and can operate in the space thermal environment. Preliminary radiation testing and analysis showed that it can operate in the radiation environment of a LEO orbit. Finally, and perhaps most importantly for the DM project, acceptance of DM CubeSat technology as a payload processor on SMDC TechSat puts DM technology back in line for a TRL7 technology validation flight experiment.

ACKNOWLEDGEMENTS

The DM research described in this paper was carried out under the auspices of the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration. The Dependable Multiprocessor effort was funded under NASA NMP ST-8 contract NMO-710209. The DM CubeSat effort to date was funded by Honeywell.

The author would like to thank the following people for their contributions to the Dependable Multiprocessor CubseSat effort: Dr. Matthew Clark, Dr. Eric Grobelny, Dr. David Campagna, Susan Van Portfliet, Matt Smith, John Gourvellec, Lee Hoffmann, Andrew White, Jamal Haque, and Alvin Badillo of Honeywell Aerospace, Defense & Space.

REFERENCES

[1] Samson, John, Jr., "Dependable Multiprocessor (DM) Implementation for Nano-satellite and CubeSat Applications (Challenging Packaging for High Performance Embedded Computing)," 14th High Performance Embedded Computing Workshop, M.I.T. Lincoln Laboratory, September 16, 2010.

[2] Samson, John, Jr., et al., "Post-TRL6 Dependable Multiprocessor Technology Developments," *Proceedings of the 2010 IEEE Aerospace Conference*, Big Sky, MT, March 7-11, 2010.

[3] Samson, John, Jr., et al., "NMP ST8 Dependable Multiprocessor: Technology and Technology Validation Overview," *Proceedings of the 48th AIAA Aerospace Sciences Meeting Conference,* Orlando FL, January 4-8, 2010.

[4] Samson, John, Jr. and Eric Grobelny, "NMP ST8 Dependable Multiprocessor: TRL6 Validation – Preliminary Results," *Proceedings of the 2007 IEEE Aerospace Conference*, Big Sky, MT, March 8-13, 2009.

[5] Samson, John, Jr., et al., "High Performance Dependable Multiprocessor II," *Proceedings of the 2007 IEEE Aerospace Conference*, Big Sky, MT, March 3-10, 2007

[6] Samson, John, Jr., et al., "Technology Validation: NMP ST8 Dependable Multiprocessor Project II," *Proceedings of the 2007 IEEE Aerospace Conference*, Big Sky, MT, March 3-10, 2007.

[7] Samson, John, J. Ramos, M. Patel, A, George, and R. Some, "Technology Validation: NMP ST8 Dependable Multiprocessor Project," *Proceedings of the 2006 IEEE Aerospace Conference*, Big Sky, MT, March 4-11, 2006.

[8] Ramos, Jeremy, J. Samson, M. Patel, A. George, and R. Some, "High Performance, Dependable Multiprocessor," *Proceedings of the 2006 IEEE Aerospace Conference*, Big Sky, MT, March 4-11, 2006.

[9] Ramos, Jeremy, and D. Brenner, "Environmentally-Adaptive Fault Tolerant Computing (EAFTC): An Enabling Technology for COTS based Space Computing," *Proceedings of the 2004 IEEE Aerospace Conference*, Big Sky, MT, March 8-15, 2004.

[10] Jou, Jing-Yang, and Jacob Abraham, "Fault Tolerant Matrix Arithmetic and Signal Processing on Highly Concurrent Computing Structures," *Proceedings of the IEEE*, May 1986, pp. 732-741.

[11] Samson, Jr., John R., L. Dela Torre, J. Ring, and T. Stottlar, "A Comparison of Algorithm-Based Fault Tolerance Traditional Redundant Self-Checking for SEU Mitigation," *Proceedings of the 20th Digital Avionics Systems Conference*, Daytona Beach, Florida, 18 October 2001.

BIOGRAPHY

John R. Samson, Jr. *is a Principal Engineering Fellow with Honeywell Aerospace, Defense and Space in Clearwater, Florida. He received his Bachelor of Science Degree from the Illinois Institute of Technology, his Master of Science degree and the Degree of Electrical Engineer from the Massachusetts Institute of Technology, and his Ph.D. in Engineering Science with Specialization in Computer Science from the University of South Florida. During his 41-year career, John has worked at M.I.T. Lincoln Laboratory, Raytheon Company Equipment Division, and Honeywell Space Systems. His work has encompassed multiple facets of ground, airborne and space-based surveillance system applications. He has spent most of his career developing onboard processors, onboard processing architectures, and onboard processing systems for real-time and mission critical applications. He was Principal Investigator for a pioneering study investigating the feasibility of migrating high-performance COTS processing to space, a predecessor of the work described in this paper. Dr. Samson was the Principal Investigator for the Dependable Multiprocessor project and is currently the Principal Investigator for the DM CubeSat efforts. He is an Associate Fellow of the AIAA and a Senior Member of the IEEE.*