The AMSAT® Journal

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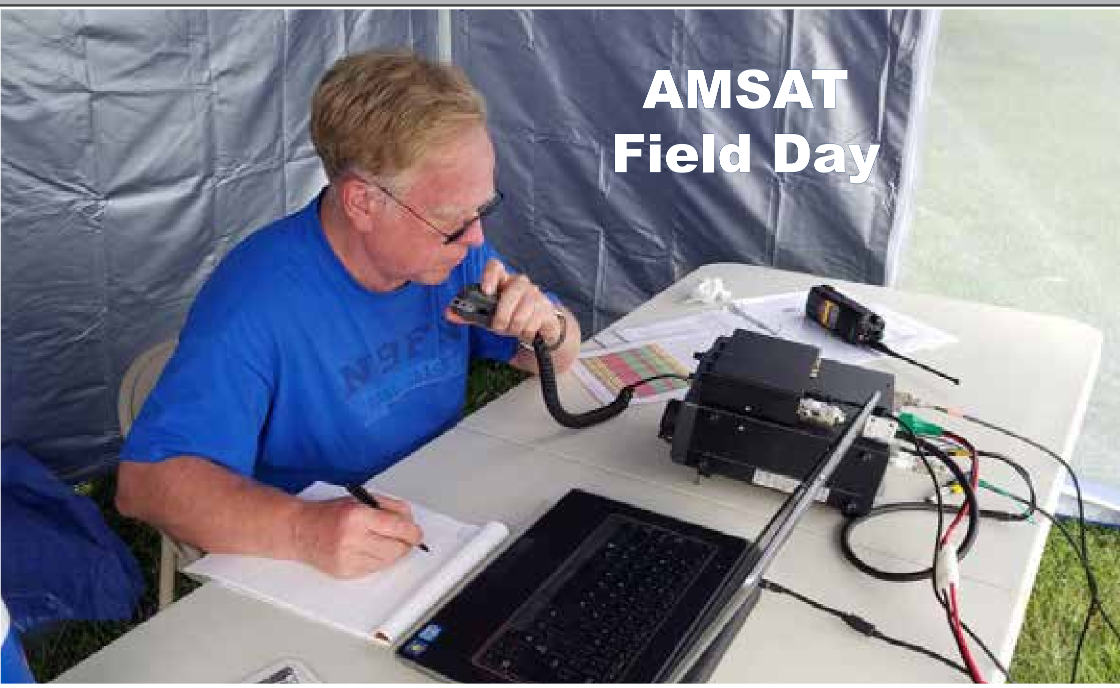
Volume 41, Number 4 **July/August 2018**



in this issue …

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Hence:

$$\left(\frac{2\pi r}{T}\right)^2 = \frac{4\pi^2 r^2}{T^2} = \frac{GM}{r}.$$

Cross multiplying, we get:

$$r^3 = \frac{GM}{4\pi^2}T^2.$$

Since both *G* and *M* are constants, we may rewrite this equation as:

$$r^3 = kT^2$$

where *k* is a constant. Hence we have shown that the cube of the distance *r* is directly proportional to the square of the orbital period *T*, as claimed.

Practical Calculations

For the purposes of our calculations, we shall measure the orbital period T in minutes and the distance r in miles. The radius of the earth is approximately 3960 miles, and so we have:

$$r = 3960 + h$$

where *h* is the altitude (or height) of the satellite above the ground in miles.

Geostationary satellites have an altitude of 22236 miles and an orbital period of exactly one day, which is 24×60=1440 minutes. From this, we can calculate the constant *k* to be:

$$k = \frac{r^3}{T^2} = \frac{(3960+22236)^3}{1440^2} = 8.67\times10^6.$$

Having obtained a value for *k*, we can now calculate the orbital period for a satellite of any given altitude. For example, the International Space Station orbits at an altitude of approximately 250 miles. We may calculate the orbital period as:

$$T = \sqrt{\frac{r^3}{k}} = \sqrt{\frac{(3960+250)^3}{8.67\times10^6}} = 93 \text{ minutes}$$

For a satellite at an altitude of 500 miles, the orbital period is:

$$T = \sqrt{\frac{r^3}{k}} = \sqrt{\frac{(3960+500)^3}{8.67\times10^6}} = 101 \text{ minutes.}$$

For a satellite at an altitude of 750 miles, the orbital period is

$$T = \sqrt{\frac{r^3}{k}} = \sqrt{\frac{(3960+750)^3}{8.67\times10^6}} = 110 \text{ minutes.}$$

Conversely, if we wish to discover the altitude at which the orbital period will be exactly two hours, or 120 minutes, then we may calculate this as:

$$h = r - 3960 = \sqrt[3]{kt^2} - 3960 = \sqrt[3]{8.67\times10^6\times120^2} - 3960$$

$$= 1038 \text{ miles.}$$

If we wish to discover the altitude at which the orbital period will be exactly five hours, or 300 minutes, then we may calculate this as:

$$h = r - 3960 = \sqrt[3]{kt^2} - 3960 = \sqrt[3]{8.67\times10^6\times300^2} - 3960$$

$$= 5246 \text{ miles.}$$

As a final example, the Moon has an orbital period of approximately 27 1/2 days, which is 39600 minutes. From this, we may calculate the Earth-Moon distance as:

$$r = \sqrt[3]{kt^2} = \sqrt[3]{8.67\times10^6\times39600^2} \approx 239000 \text{ miles.}$$

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SpaceVNX: A Path Towards Reliable High-Performance Computing in Small Satellites

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[Note: The work of Jorge Piovesan, Alonzo Vera, and Jeff Love was supported by the United States Air Force under Contract No. FA9453-17-P-0430. Any opinions, findings and conclusions or recommendations expressed here are those of the authors and do not recessarily reflect the views of the United States Air Force.]

Introduction

The small satellite/nanosatellite industry has been successful in using commercial off-the-shelf (COTS) parts to enable low-cost, high-performance space missions. The drawback of this approach is that it sacrifices the reliability of the spacecraft, which limits the applicability of these methods in more critical missions. To address this limitation, this abstract explores an approach to use the VITA 74 standard (VNX) to implement a reliable high-performance computing architecture for small satellites using COTS parts.

The goal of the proposed architecture is to enable more capable, more reliable small spacecraft solutions while giving integrators the flexibility and scalability to implement a wide range of requirements. A backplane architecture like VNX is an optimal approach to achieve this goal because of its modularity, standard interfaces, system management methods, and interconnection topologies.

As a first step towards implementing a reliable high-performance architecture for small spacecraft, this abstract documents an approach to use highly capable COTS parts in conjunction with lower cost Radiation Hardened/Tolerant supervision circuits/ICs to protect the system from Latch-up events and use the VNX architecture to provide redundancy to allow the system to continue operating even after one of these events.

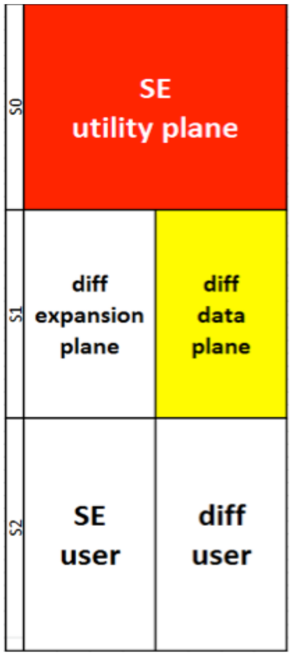

Figure 1 — VNX interconnection planes.

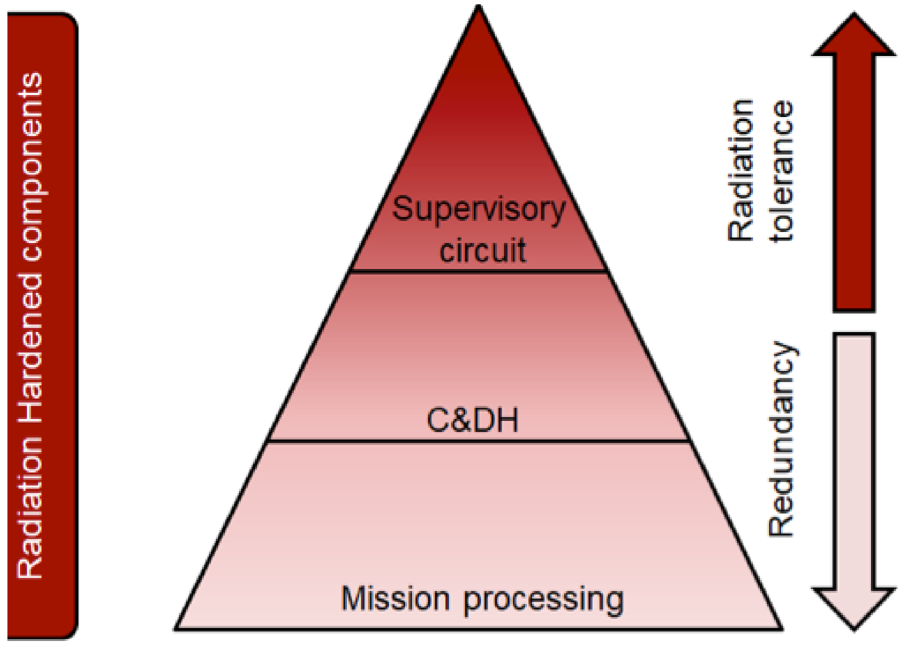

Figure 2 — Approach to improve reliability in nanosatellite missions without substantially increased costs.

Background

VNX is a variation of the VPX standard that reduces the complexity and size of VPX towards applications of limited SWAP. The VNX interconnect backplane consists of five planes (Figure 1): 1) The utility plane, 2) The Differential data plane, 3) the Differential expansion plane, 4) the Differential User defined plane, and the 5) Single-ended user-defined plane. Two types of modules exist. A 19 mm module, and a 12.5 mm module. Each of these modules is connected via an FMC-type connector to the backplane with a different number of pins (400 for the 19 mm and 200 for the 12.5 mm), distributed among this connection planes.

The utility plane is used mostly for power distribution and system supervision. Signals include 4 different power rails, I2C communication, systems reset signals, PCIe clock distribution, and some pins for user-defined signals.

The differential data plane and the differential expansion plane are used for high-speed data transfer between modules. The data plane uses PCIe as interconnection fabric, while the expansion plane can be defined by the user for but can also be used for additional PCIe interconnection.

The differential and the single-ended user defined planes are used for other types of data transfer between modules and are wholly reserved for the user to define the protocols.

Implementation Approach

We propose to address space reliability (especially radiation tolerance) through a combination of radiation hardened (or tolerant) semiconductors, redundancy, and circumvention and recovery approaches. A critical parameter to be considered when designing the proposed architecture is cost-effectiveness. The small satellite and nanosatellite markets require cost-effective solutions; therefore, complex radiation hardened components are not attractive alternatives to implementing this architecture. However, radiation tolerance is important to provide guarantees of mission success. Therefore, we propose to design an architecture that uses radiation hardened/tolerant components in the simpler but more critical subsystems of the spacecraft (e.g., Housekeeping), while implementing redundancy and circumvention and recovery (when desired) in the most complex subsystems of the spacecraft (Mission processing). This is represented in Figure 2. Note that criticality is understood as tolerance to downtime, where more critical systems are allowed minimal downtime (if any), and less critical system can have sporadic periods of downtime.

The preliminary architecture we studied included a System Controller module in charge housekeeping and supervising reliability features, two redundant Computing modules (that include storage), and two redundant I/O modules as shown in Figure 3. The focus of this study is to address possible Latch-up conditions by including overcurrent protection devices where commercial off-the-shelf (COTS) components are used.

The System Controller module (19 mm) includes the radiation tolerant supervisory IC, and COTS PCIe switch and clock references, with overcurrent protection to prevent damage in the PCIe ICs in case of Latch-up. The Computing module (19 mm) consists of a Latch-up overcurrent protection circuit and a single board computer (SBC) as a mezzanine card. Finally, the I/O module (12.5 mm) consists of a latch-up overcurrent protection circuit and the circuitry required to convert PCIe (or any other protocol) to the desired I/O protocol(s).

The approach to interconnect the modules in this preliminary architecture and provide some level of redundancy in the interconnection fabric has the following characteristics:

- The system controller supervises the other modules via I2C, and ON/OFF, and STATUS signals that are routed in the utility plane.
- The modules exchange data via high-speed PCIe lanes. Some of the lanes are connected through the PCIe switch in the system controller module, while other lanes connect a pair of modules without the PCIe switch to provide connectivity redundancy.

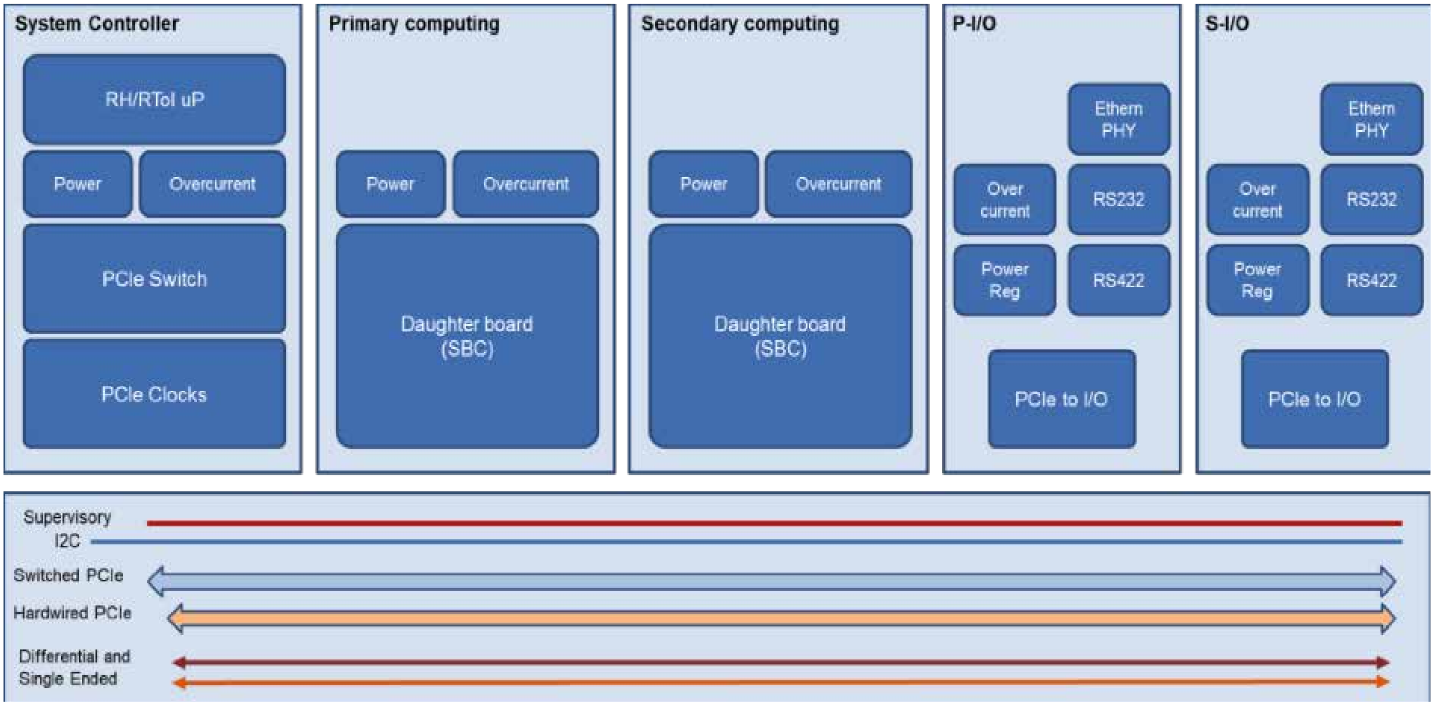

Figure 3 — Preliminary architecture with a System Controller, two Compute modules, and two I/O modules.

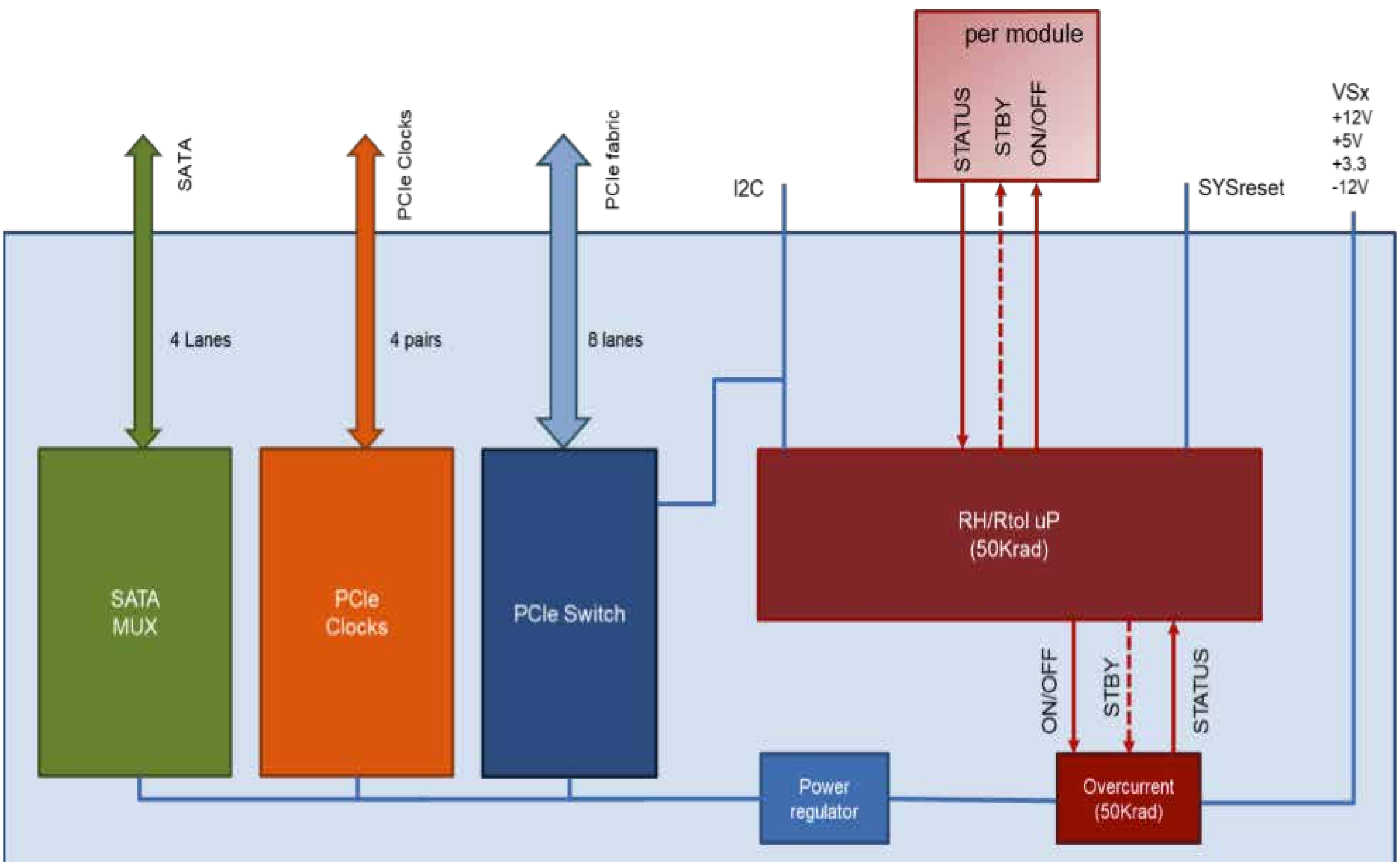

Figure 4 — Block diagram of System Controller Module.

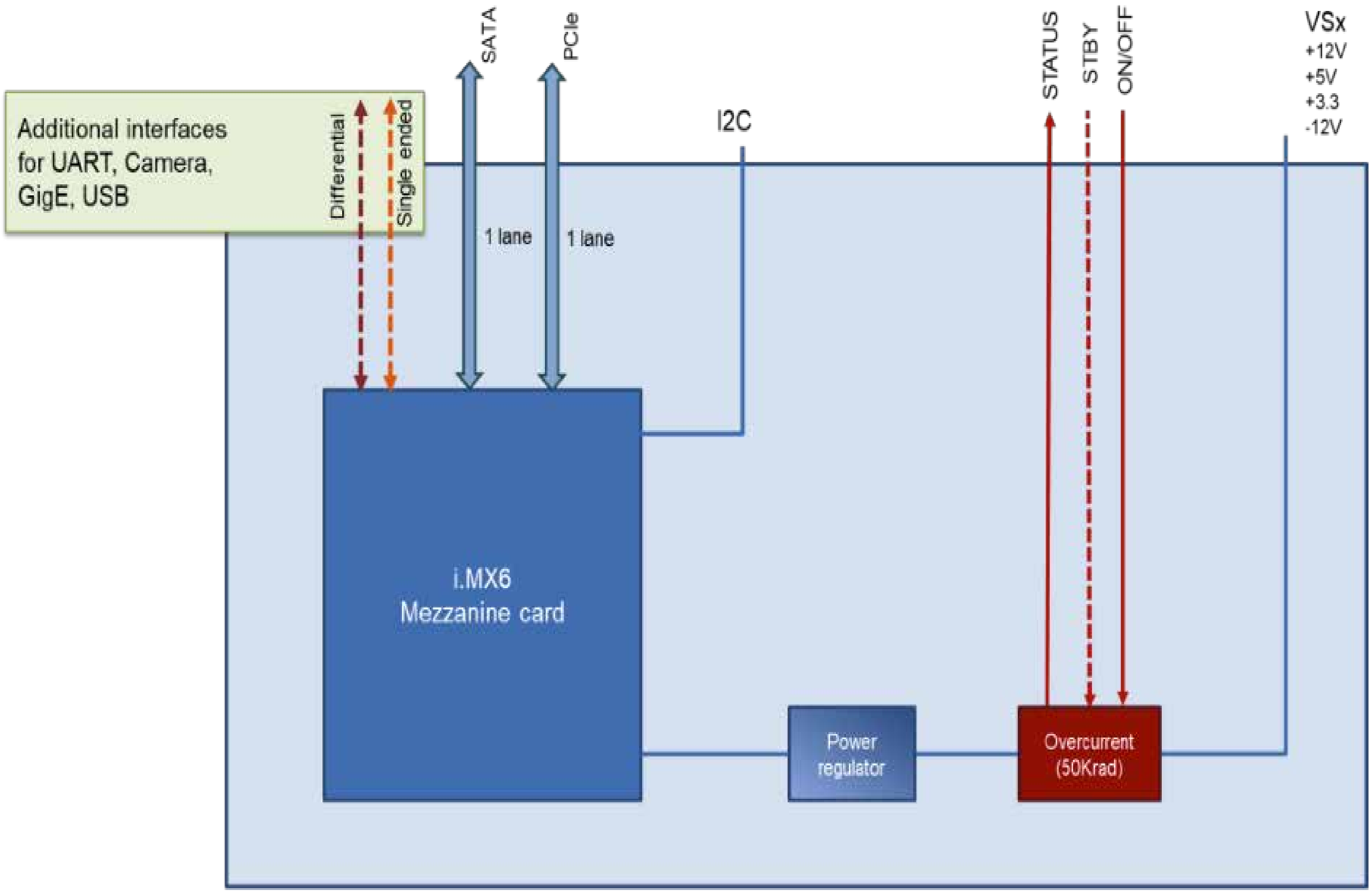

Figure 5 — Example of a compute module based on an i.MX6 SBC mezzanine card.

- Similarly, the differential and single-ended user-defined signals are connected in pairs between all modules to provide different signal paths.

A more detailed view of the system controller module is seen in Figure 4. In this case, the system controller module consists of a Rad-tolerant (e.g., 50KRad) microprocessor, the Rad-tolerant Latch-up Overcurrent Protection IC, a PCIe switch, a PCIe clock source, and a SATA Multiplexer to enable redundant storage modules. The microprocessor has I2C signals and enough GPIO signals to supervise the STATUS and ON/OFF signals of each module in the backplane.

An example of a computing module using an i.MX6 based SBC and a Latch-up overcurrent protection IC that is controlled by the system controller is seen in Figure 5. The SBC mezzanine card uses one PCIe and one SATA connection to interface to an I/O and a Storage module respectively. The interface is done through the PCIe switch and SATA multiplexer in the system controller. Other modules can be implemented using a similar approach.

Conclusions and Future Work

The most essential components of the resulting architecture are:

- A System Controller module capable of supervising all other modules in the system, monitoring for radiation-related failures, and providing high-speed interconnection among modules speed serial fabric (e.g., PCIe).
- Dual redundant Computing, Storage, and I/O modules that implement the mission of the system.
- A backplane interconnect board, where all modules are interconnected.

The main enhancements to the existing VNX architecture are the Radiation Tolerant system controller supervision circuitry, the Latch-Up overcurrent protection methods integrated into the System controller and all other modules, and the inclusion of dual redundancy methods to allow the system to continue operating even after a module suffers a Latch-Up Event.

The next steps towards the implementation of the of a proof-of-concept Radiation Tolerant architecture based on the VNX standard include:

- Implementing and testing the reliability management system using the System Controller module
- Implementing and testing the backplane interconnect fabric that enables the reliability enhancements that were studied during Phase 1.
- Extending the reliability management system to address other radiation-related failure modes (e.g. Single-Event Upsets).
- Involving industry partners such that multiple vendors can demonstrate computing, storage, and I/O capabilities.