On-board Data Handling for Ambitious Nanosatellite Missions using Automotive-grade Lockstep Microcontrollers

Hannu Leppinen
Huld

Antti Kestilä
Finnish Meteorological Institute

ON-BOARD DATA HANDLING FOR AMBITIOUS NANOSATELLITE MISSIONS USING AUTOMOTIVE-GRADE LOCKSTEP MICROCONTROLLERS

Hannu Leppinen[(1)], Antti Kestilä[(1)], Pauli Pihajoki[(2)], Jukka Jokelainen[(1)], Touko Haunia[(3)]

[(1)]*Aalto University, Department of Radio Science and Engineering, Otakaari 5A, 02150 Espoo, Finland, +358 50 420 5840, hannu.leppinen@aalto.fi*
[(2)]*University of Turku, Department of Physics and Astronomy, Tuorla Observatory, FI-20500, Piikkiö, Finland*
[(3)]*Finnish Meteorological Institute, Erik Palménin aukio 1, 00560 Helsinki, Finland*

ABSTRACT

After a decade of experimental nanosatellite projects, the past few years have seen a growing trend of utilizing nanosatellites in more complex scientific and commercial missions. More complex nanosatellite missions typically involve longer target lifetimes, sophisticated instruments and complex ground operations. These missions can achieve lower costs than traditional satellites by using commercial off-the-shelf (COTS) components where possible.

However, COTS components may not function reliably in space for extended periods of time, and more ambitious missions with longer lifetimes require more reliability than experimental nanosatellites. Components developed by the traditional space industry are known to be reliable and robust, but they are usually too expensive and bulky compared to the requirements of nanosatellites. Using components designed for terrestrial safety-critical applications, such as automotive use, could provide cost savings while maintaining reliability compared to space-grade components.

This paper considers the Texas Instruments Hercules TMS570 microcontroller family for the on-board data handling (OBDH) system of a nanosatellite mission in development at Aalto University. Several parties, including NASA, already plan to use Hercules in space applications. The proposed on-board computer (OBC) design is based on a Texas Instruments TMS570LS3137 Hercules Safety Microcontroller with built-in fault tolerance, including two processors running in lockstep and error correction codes (ECC) implemented in internal memories. Other components in the OBC are selected from automotive and other high-grade catalogs. The proposed OBC design is compared to LEON-based traditional OBCs and some CubeSat designs, and the built-in fault-tolerant lockstep architecture is compared to some previous fault-tolerant methods used in nanosatellites. Using microcontrollers with built-in fault tolerance for nanosatellite OBDH provides more reliability while speeding up mission development.

1 INTRODUCTION

The CubeSat platform, earlier used exclusively for one-off technology demonstrations and education, has started to gain commercial applications. Several companies are planning to offer commercial Earth observation services using CubeSats, and the first satellites are already in orbit [1]. Commercial CubeSat utilization underlines the commercial potential of nano- and microsatellites in general.

Commercial endeavours require more reliability than one-off technology demonstrations. The traditional space industry produces reliable components, but systems designed for large satellites with potentially decades of lifetime are not suitable for nanosatellites with restricted size and shorter lifetimes. On the other hand, commercially utilized nanosatellites would benefit from reliable operation during their lifetime to maximize their duty cycles. Ambitious nanosatellite missions therefore demand more reliability at a smaller size and a lower cost.

The challenges for space electronics come from the pre-launch, launch and operational phases. During design, assembly, storage and transportation in the pre-launch phase, the selected and procured components may age several years and possibly are not at the leading edge of technology at the time of launch. However, if the components have been procured before they become obsolete, this rarely causes problems since the mission and system designs are based on existing components. During the launch phase, the electronics are subjected to shocks, vibrations and noise. This is mostly an issue for mechanical structures and should not be a problem unless the electronics have weak solder joints.

In the operational phase, both operational and environmental demands are placed on equipment in space. The main environmental hazards are vacuum, thermal variations and radiation. The main problem caused by vacuum are tin whiskers forming in lead-free tin solders over several years, but even commercial nanosatellite programs rarely aim for over a few years of operation. With a reasonable passive thermal design, thermal variations should not cause problems for electronics inside the satellite. The most important environmental long-term concern for electronics is the radiation environment: both single-event effects (SEE) and total ionizing dose (TID) effects need to be taken into account. Single-event effects can be divided to two main categories: single-event upsets (bit flips) and single-event latchups (short circuits). Bit flips can occur everywhere where electric charge is used to store bits, such as registers and volatile and non-volatile memories. Effects can vary from relatively benign noise in data to serious errors in software execution, possibly leading to loss of mission. Short circuits can cause permanent damage to devices unless current is limited and the device power cycled when problems are detected. So-called micro-latchups may cause only minor increases in current, but cause devices to stop working. Most single-event effects can be mitigated by error correction, current limiting, and power cycling unresponsive devices.

Total ionizing dose effects cause cumulative degradation of devices due to accumulated ionizing dose over time. Effects are usually first noticeable as changes in the electrical parameters of the device, such as increase in power consumption. This degradation eventually leads to device failure. Most COTS components survive at least 5 krad(Si) of total dose, and even the moderate shielding provided by CubeSat frames in LEO mean that it often takes years to accumulate this dose. [2]

Operational demands include fault-tolerant operation in conditions where diagnostics and fixes are extremely difficult. The spacecraft may enter an unsafe configuration due to a radiation-caused error or a ground control error. This must be mitigated by a mechanism that allows the spacecraft to return to a safe configuration, from which normal operations can eventually be resumed. Single points of failure should be avoided in system design; workarounds need to exist for every single broken component that would jeopardize continued operations. This is usually achieved using redundancy.

According to Eickhoff [3], on-board computers should provide failure robustness using internal redundancy, electromagnetic compatibility with the space environment including the radiation environment, and a variety of bus interfaces to interface between other spacecraft subsystems. On-board software should be a real-time control software that allows remote and automated control of the spacecraft. The largest issues for on-board computers in space are radiation hazards and operational fault tolerance. Like the space industry, automotive and aviation industries place emphasis on reliable operation of equipment. Fault tolerant electronic systems have become more important in the automotive and aviation industries due to the trend of moving from mechanical systems to electronic x-by-wire systems. [4] Using components and technologies developed for automotive and aviation industries can leverage the huge research and development resources of these industries. For example, Texas Instruments has brought the automotive-grade TMS570 lockstep microcontroller family, with many internal fault tolerant features, to the market. The internal fault-tolerant features in TMS570 allow run-time correction of several error conditions.

1.1 On-board computer requirements

The example case discussed in this paper is an Earth remote sensing nanosatellite project in development at Aalto University, referred to in this paper as the Aalto satellite. The project requires a minimum spacecraft endurance of two years. Since the project concentrates on actual remote sensing and not on technology demonstration, the equipment is preferably overengineered for longer lifetimes. The main purpose of the Aalto satellite OBC is to schedule and distribute commands, collect and produce housekeeping telemetry, and provide a CCSDS-compliant TTC interface. The OBC must be able to command the satellite using CAN bus, since CAN bus is robust and has good COTS component availability. Requirements therefore include:

- CCSDS compliant telemetry and telecommand interface
- storage and distribution of telecommands at specified instants of time
- housekeeping and telemetry
- master of the CAN spacecraft data bus
- reliable mission life of at least 2 years
- CubeSat-compatible form factor

In this case, the on-board computer does not process payload data; it only acts as a high-level controller of the satellite. Using the fault-tolerant Hercules microcontroller in the OBC provides reliability greater than what was achieved with earlier CubeSats, while falling short of the strictness and cost of the traditional space industry. Separate Hercules processors are used in orbit and payload control, and payload data processing is done using FPGAs, leading to reduced RAM and mass storage requirements for the OBC and other controllers.

2 HERCULES TMS570 FAMILY

Texas Instruments Hercules TMS570 is a microcontroller family designed for automotive-grade safety-critical applications, with aerospace and avionics as possible secondary applications. Vaughan [5] states the TMS570 family has been developed in part to simplify the development of fault tolerant systems that meet the strict safety standards in the automotive and aerospace industries. TMS570 has been designed with internal diagnostics, lockstep processors and error correction features that increase fault tolerance. Texas Instruments also provides an integrated development environment with development tools, such as a Misra-C checker, that can be used to aid development of reliable software.

The highest-end Hercules model, TMS570LS3137, operates at clock speeds of up to 180 MHz and has 3MB program memory, 256 kB RAM and 64 kB emulated EEPROM. Relevant safety features include two processors running in lockstep, error correction codes (ECC) in all internal memories and internal voltage and clock monitors. [6] Some of the main parameters of TMS570LS3137 are listed in table 1.

TMS570LS3137 has two Cortex-R4F CPUs running in lockstep. The operation of the primary CPU is checked against a secondary CPU that has a physical separation inside the package and a temporal separation of two clock cycles. Mismatch in the CPU outputs causes an interrupt and an error signal. TMS570 also has ECC in all internal memories. Voltage and clock monitors respond to gross deviations from nominal parameters, but external voltage monitoring is recommended as an additional safeguard. Startup diagnostics are performed at boot, and errors again cause a signal to be output to the error pin. Some errors detected by the diagnostics can be corrected transparently at run-time, and uncorrectable errors cause an error signal to be output. The features of TMS570LS3137 are depicted in figure 1.

Table 1: Main parameters of the TMS570LS3137 microcontroller (QFP package). [6]

Item	Description
Type	TMS570LS3137 microcontroller unit, quad flat package
Manufacturer	Texas Instruments
Part number	TMS5703137CPGEQQ1
Clock speed	160 MHz
Flash memory	3 MB
RAM	256 kB
Emulated EEPROM	64 kB
Main interfaces	3x CAN, 4x SPI, 2x UART, I2C…
Supply voltages	1.2 V, 3.3 V, 5 V
Power consumption	<< 1 W
Temperature range	-40°C to 125°C
Other	2 Cortex-R4 CPUs in lockstep, ECCs in internal memories External Memory Interface for SDRAM/NOR flash

TMS570LS3137 also has three internal CAN bus controllers. CAN bus is a reasonable choice for the data bus of a small satellite because of its robustness, extensive COTS component availability and the ongoing ECSS standardization effort. [7]

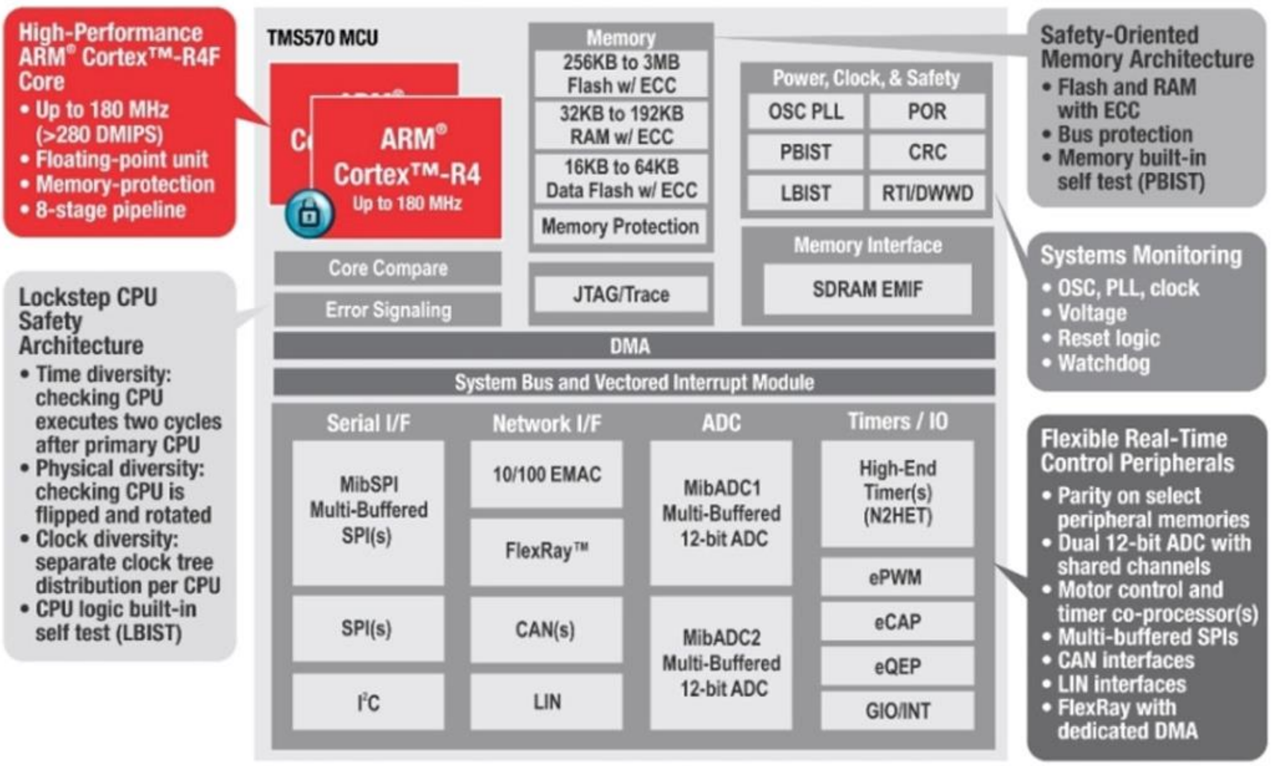

Figure 1: Internal structure of the TMS570 microcontroller unit. Source: Texas Instruments.

2.1 Suitability for space applications

The primary environmental concern with microcontrollers is the radiation tolerance. Texas Instruments provides radiation test data only under a non-disclosure agreement. However, TMS570 already has limited flight heritage aboard two successful CubeSats, CubeBug-1 and -2 [8], and both Surrey Space Centre and NASA plan to use it in upcoming missions. This constitutes an experimental demonstration of the basic viability of TMS570 for space applications.

Taylor et al. found in [9] that the high performance and internal fault tolerant features of the TMS570 allow it to carry out many tasks performed earlier by other devices in the space industry. The TMS570 will be used in the TechDemoSat-1 mission as an intelligent supervisor in the Micro Radiation Environment Monitor (MuREM) experiment.

NASA selected TMS570 for the motor driver electronics of the Robonaut 2 Climbing Legs. TMS570 was selected to achieve acceptable performance for the system in the EVA radiation environment. NASA has performed radiation testing on all Climbing Leg electrical components, including TMS570, and found that all radiation-induced events are detectable, non-hazardous and non-permanent. Additionally, NASA has used thermal vacuum testing on the Climbing Leg actuators and motor driver electronics, including TMS570, to verify that all materials in the Climbing Legs are EVA compatible. [10]

3 ON-BOARD COMPUTER CONCEPT

The designed Aalto satellite on-board computer uses the Hercules TMS570LS3137 microcontroller, as this highest-end model has internal 3 MB Flash memory and 256 kB RAM. Chips with quad flat packages (QFP) have been selected to facilitate reliable manual soldering. No external RAM is needed since the most intensive operations performed by the OBC are telemetry and telecommand processing. Telemetry and telecommands are formatted according to CCSDS protocols for compatibility with commercial ground station providers. The external memory interface of the TMS570 could be used to include additional RAM, if such a need should arise. In that case, error correction would need to be separately implemented for the external RAM. Payload data processing is intensive, but performed by stand-alone FPGAs in the reference mission. The OBC operates the payload, but as the payload data is processed and downlinked by a separate system, no extra RAM is needed in the OBC. Instead, the external memory interface is used to interface with a redundant mass memory system to store command schedules, telemetry and configuration information. Texas Instruments provides drivers for NOR flash and SDRAM support. At the time of writing NAND flash was not directly supported and required custom drivers. This could be a limitation if fast, high-density memory is required. SPI can be used to interface with SD cards, providing large capacity with limited speed. SD cards are used for prototyping, but because of radiation reliability issues with SD cards, the flight model instead uses redundant NOR or NAND flash memories for the mass storage system.

3.1 Fault-tolerant architecture

Failures can be divided into two main categories: systematic failures and random failures. Systematic failures, such as programming errors, result from failure in design, manufacturing or from failing to follow best practices. Random failures are random defects that result from the working environment of the device, such as radiation-induced bit flips and short circuits. As random failures cannot be completely prevented, focus must be on mitigating and handling them. Fault tolerance is always based on redundancy which can be spatial, temporal or informational. The chosen fault-tolerant approach is based on the shared-memory dual-lockstep architecture concept described by Baleani et al. [4]. A similar architecture is also described by Vaughan [5]. The fault tolerant architecture of the Aalto satellite OBC aims to be tolerant of failure of any single component. Two cold redundant Hercules microcontrollers with their own clock systems and power supplies are used. The circuit allows only one Hercules to be powered at the same time. MSP430, a CubeSat-proven 16-bit microcontroller, is used as an arbiter to switch between the Hercules systems. The circuit is designed in a way that one of the redundant TMS570 microcontrollers is enabled by default by a pull-up resistor in case the MSP430 arbiter fails. A common mass storage system is available for both Hercules microcontrollers through the Hercules External Memory Interface pins. The mass storage system consists of physically redundant memory circuits that store identical data. Both power systems can be used to power the mass storage system. A bus switch is used to select which Hercules system is connected to the spacecraft data bus and to the mass storage system. The fault tolerant architecture is depicted in figure 2.

The error signals and heartbeats provided by the TMS570 MCUs are used as inputs for the MSP430. Certain errors, such as compare errors between the two processors inside the TMS570 and uncorrectable memory errors, cause an error signal to be output from the error signaling module pin of the Hercules. This signal can be used to reset the system or perform other actions to respond to the error. In the Aalto satellite OBC implementation, any error severe enough to cause an error signal to be output causes a system reset. The design provides fail-silent operation: if a Hercules determines it cannot function, it goes silent, and tries to reboot; if this doesn't help, the MSP430 arbiter switches to the other Hercules based on the lack of a heartbeat. The internal fault protection mechanisms in the TMS570--lockstep CPUs, ECC and voltage and clock monitoring--allow correction of some error conditions, such as bit flips, at run-time; if the corrections fail, the error signal from the error signaling module (ESM) can be used to reboot the system or give control to the backup Hercules. Single-bit errors in a single RAM block are corrected transparently in run-time; two-bit errors in a single memory block cause an error signal to be triggered.

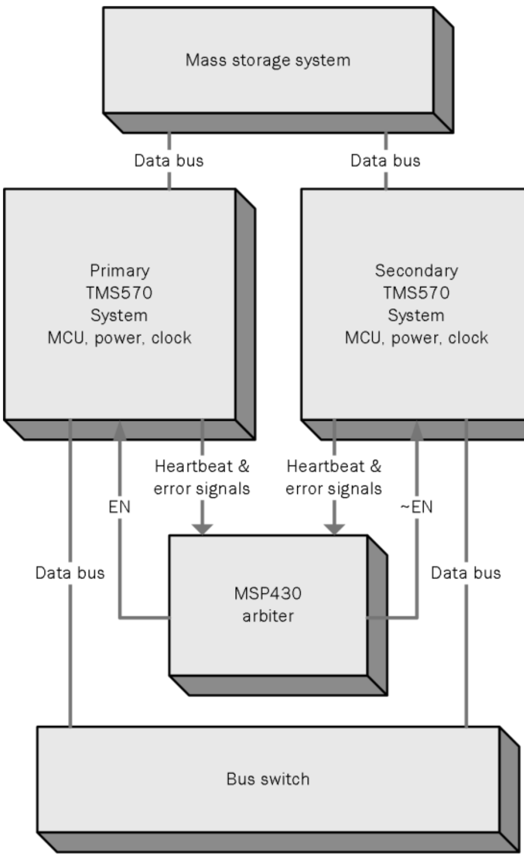

Figure 2: The TMS570-based fault-tolerant architecture. A low-power MSP430 is used as an arbiter. A pull-up resistor enables the main TMS570 in case the arbiter fails.

In addition to this cold-redundant architecture, a hot-redundant architecture could also be used in hard real-time systems. Instead of a conventional two out of three-voting, two Hercules processors could be run in parallel, performing the same operations with same inputs but with only the primary one being allowed to control the system. If the primary Hercules detects a serious fault, it can use its error pin to signal a secondary Hercules to take control while it restarts. Control can be returned to the primary controller when it signals “ready” to the secondary Hercules. [5] However, this hot-redundant, fail-operational architecture is not considered necessary for the on-board computer of the Aalto satellite.

3.2 Mass storage system

SD cards, interfaced through SPI, could be used for mass storage, and they are a popular option in existing CubeSat on-board computers. Industrial-grade SD cards by Delkin Devices have been radiation tested for total ionizing dose, surviving doses up to 24 krad(Si). [11] The cards are offered in industrial temperature ranges and in capacities between 128 MB and 8 GB. Delkin SD cards are unlikely to succumb to total dose even after several years in space, but single-event effects demand more consideration. Single-event upsets can be mitigated by the internal ECC of the SD cards, but latchups or other single-events affecting the SD card controller could cause component failure. Three redundant SD cards could be used on the same SPI bus, and all data could be redundantly maintained on all of them. ECC within the cards can be used for verifying data integrity, and in case of corruption in a single card, the data can be corrected using a backup stored on another card. The system could tolerate the failure of at least one and even two SD cards. The OBC would need to maintain identical file systems on all three cards. SD cards also facilitate easier laboratory prototyping. However, even multiple redundant SD cards may not achieve high enough reliability for several years. The SD card in the RAX-2 CubeSat failed after a few months. [12] Kimura et al. tested various SD cards in [13] and found that while SD cards can survive high total ionizing doses in Co-60 gamma ray testing, relatively small high-energy proton exposure can irrecoverably damage them.

The mass storage system in the Aalto satellite is therefore based on either NOR or NAND flash memories with available radiation data [14] [15], as Hercules has an external memory interface (EMIF) supporting NOR flash, and custom NAND drivers can be developed. With NOR flash, the storage size is more limited than with SD cards, but this does not pose a problem since the on-board computer does not process payload data, but only handles telecommands and collects telemetry. The bus switch is used to select which Hercules has access to the mass storage system. The file system drivers are implemented in a way that transparently maintains an identical file system on all three memories, and the low-level flash operations are masked in the file system software; for the software developer, it does not matter whether the hardware implementation is SD card, NAND flash or NOR flash. In case of a total failure of the mass storage system, the 64 kB internal EEPROM of the Hercules could still be used to store vital configuration settings and command schedules.

3.3 Software layer

The software layers of the Aalto satellite OBC are depicted in figure 3. The application software implements the CCSDS-compliant telemetry and telecommand interface, command scheduling, housekeeping, and other required features. FreeRTOS is used for scheduling and FatFS for file system abstraction. Texas Instruments provides a hardware abstraction layer code generator (HalCoGen) tool for generating drivers for the Hercules. The drivers generated by HalCoGen are evaluated against the Motor Industry Software Reliability Association’s C coding standard (Misra-C). TI also advocates using FreeRTOS as the real-time operating system (RTOS) layer. FreeRTOS is almost completely Misra-C compliant. Using Misra-C increases software reliability in the Texas Instruments driver and FreeRTOS layers by avoiding the pitfalls of C.

Driver and FreeRTOS code can be auto-generated with HalCoGen and only require configuring some interface parameters for the specific application. Software development can then immediately concentrate on the high-level flight software. An open source File Allocation Table (FAT) file system implementation, FatFS, is used to mask the low-level implementation of the mass storage. FatFS only requires a few hardware-specific drivers to be written.

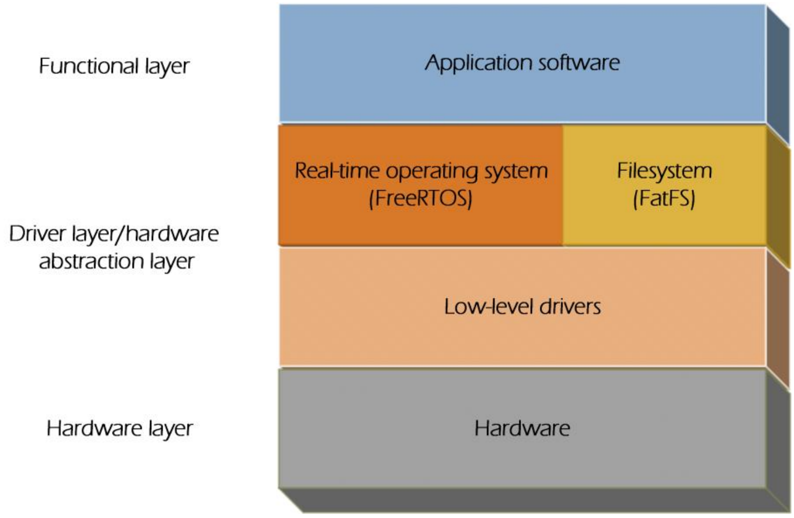

Figure 3: Software layers when using FreeRTOS for scheduling and FatFS for mass storage.

3.4 Other components

Other hardware components needed for the OBC include voltage regulators, overcurrent protection circuitry, oscillators, real-time clocks, bus switch and connectors. The remaining components were selected from COTS catalogs, and candidates with high temperature ranges and either flight heritage or available radiation data were preferred. Flight heritage or available radiation data reduced the need for in-house radiation testing. All the components in the OBC and manufacturing the PCB cost around 500 euros.

4 COMPARISONS

The Hercules-based solution can be compared to previous CubeSat solutions and solutions based on radiation-hardened space-grade processors, such as LEON3FT. Typically, CubeSat OBCs feature ARM7- or ARM9-based CPUs that are not redundant. Mass storage may often rely on a single SD card. Fault tolerance relies on watchdogs, overcurrent protection and sometimes complex error detection circuitry. [16] [17] [18] These OBCs are small, inexpensive, and have low power consumption and short design lives. As these processors do not have as extensive internal error control capabilities as Hercules, implementing diagnostic functions may require complex circuit design. Even an individual Hercules has a good level of run-time protection against erroneous execution.

The traditional space industry uses space-grade processors; in European space projects, on-board computers are often based on LEON processors. [3] For example, GR712RC [19] is a dual-core LEON3FT processor from Aeroflex Colorado, described as having extremely high tolerance to the space radiation environment. It features total ionizing dose immunity up to 300 krad(Si) and single-event upset, latchup and transient hardening both by hardware design and by using error correction codes. LEON3-based onboard computers are reliable, bulky, expensive, specialized and have long design lives. Hardware and software designed specifically for space limits the usefulness of resources and practices in the much larger industrial, automotive and aviation sectors. Specialized space hardware requires special skills and knowledge, while automotive and COTS components allow benefiting from a much larger developer community.

Hercules-based on-board computers are somewhere in between, as they provide more reliability than other COTS solutions while at the same time maintaining the usefulness of the large development communities, techniques and practices. Based on TID tolerance, Hercules processors probably are not suitable for long-term deep space missions, but shorter LEO missions benefit from the more reliable operation offered by the fault-tolerant features.

5 CONCLUSIONS

The traditional space industry has concentrated on building large satellites with long lifetimes. The small satellite revolution has created a new industry alongside the traditional space industry, and the new industry produces smaller satellites with shorter lifetimes. In this paper, the design for a Hercules TMS570 -based cold-redundant on-board computer was presented to meet the requirements of a nanosatellite mission, Aalto satellite, with 2 years of operational lifetime. The existing CubeSat solutions are designed mainly for one-off technology demonstrations, while the traditional space industry components are designed for nearly decades of lifetime. A Hercules-based on-board computer provides an option somewhere in between, and such an on-board computer should provide the required 2-year mission lifetime with low cost. The versatility and robustness of the Hercules allows it to be used in other tasks as well, such as attitude, propulsion and instrument control. This is also the case in the Aalto satellite mission discussed in this paper. While the fault-tolerant architectures considered in the paper are not novel, the TMS570 provides a new, simpler way of implementing them. For nanosatellite missions, Hercules-based on-board computers provide better reliability to price ratio than other, previously available options.

6 ACKNOWLEDGEMENTS

The authors would like to acknowledge Dr. Shengchang Lan and Mr. Bérenger Villat for their work with the Aalto-2 nanosatellite on-board computer, which in part provided the inspiration for this paper. The authors would also like to thank Prof. Shinichi Kimura and Mr. Ryan Kingsbury for discussions on SD card radiation tolerance.

7 REFERENCES

[1] Ball, M., "The Small Satellite Revolution: More Earth Observations at a Lower Cost," 17 Sep 2013. [Online]. Available: http://www.sensorsandsystems.com/article/features/31581-the-small-satellite-revolution-more-earth-observations-at-a-lower-cost.html. [Accessed 21 April 2014].

[2] Fortescue, P. et al., *Spacecraft Systems Engineering - Third Edition*, Wiley, 2003.

[3] Eickhoff, J., *Onboard Computers, Onboard Software and Satellite Operations – An Introduction*, Springer, 2012.

[4] Baleani, M et al., "Fault Tolerant Platforms for Automotive Safety Critical Applications," in *Proceedings of the 2003 International Conference on Compilers, Architecture and Synthesis for Embedded Systems*, San Jose, California, USA, 2003.

[5] Vaughan, A., "Lockstep microcontrollers advance aerospace electronics safety," ECNmag, 22 March 2013. [Online]. Available: http://www.ecnmag.com/articles/2013/03/lockstep-microcontrollers-advance-aerospace-electronics-safety. [Accessed 21 April 2014].

[6] Texas Instruments, *TMS570LS3137 16- and 32-bit RISC Flash Microcontroller Datasheet,* July 2013.

[7] European Cooperation for Space Standardization, *ECSS-E-ST-50-15C DIR1: CANBus extension protocol - Draft in Review,* Noordwijk, The Netherlands: ECSS Secretariat, ESA-ESTEC, Requirements & Standards Division, 2013.

[8] Satellogic, "Canopus: CubeBug CubeSat platform software," 26 September 2013. [Online]. Available: http://1.cubebug.org/post/62309006493/canopus-cubebug-cubesat-platform-software. [Accessed 21 April 2014].

[9] Taylor, B. et al., "The Micro Radiation Environment Monitor (MuREM) and SSTL Radiation Monitor (SSTL RM) On TechDemoSat-1," *IEEE Transactions on Nuclear Science,* vol. 59, no. 4, pp. 1060-1065, August 2012.

[10] Ahlstrom, T. et al., "Robonaut 2 on the International Space Station: Status Update and Preparations for IVA Mobility," in *Proceedings of the AIAA SPACE 2013 Conference and Exposition*, San Diego, California, 2013.

[11] Kingsbury, R. et al., "TID Tolerance of Popular CubeSat Components," in *Proceedings of the 2013 IEEE Radiation Effects Data Workshop (REDW)*, San Francisco, California, 2013.

[12] Springmann, J. et al., "Development and Initial Operations of the RAX-2 CubeSat," in *Proceedings of the Small Satellites Systems Services - The 4S Symposium*, Portoroz, Slovenia, 2012.

[13] Kimura, S. et al., "Breakdown Phenomena in SD Cards Exposed to Proton Irradiation," *Transactions of the Japan Society of Aeronautical and Space Sciences, Aerospace Technology Japan,* vol. 12, pp. 31-35, 2014.

[14] Irom, F. et al., "SEE and TID Response of Spansion 512Mb NOR Flash Memory," in *Proceedings of the 2011 IEEE Radiation Effects Data Workshop (REDW)*, Las Vegas, Nevada, USA, 2011.

[15] Irom, F. et al., "Single Event Effect and Total Ionizing Dose Results of Highly Scaled Flash Memories," in *Proceedings of the 2013 IEEE Radiation Effects Data Workshop (REDW)*, San Francisco, California, USA, 2013.

[16] Electronic Systems Laboratory, University of Stellenbosch, *CubeComputer - General Purpose Onboard Computer Brochure*, Stellenbosch, South Africa, 2013.

[17] GomSpace, *NanoMind A712C Datasheet*, GomSpace, 2013.

[18] ISIS, *ISIS On Board Computer Brochure,* Delft, The Netherlands, 2013.

[19] Sturesson, F. et al., "Radiation Characterization of a Dual Core LEON3-FT Processor," in *Proceedings of the 12th European Conference on Radiation and Its Effects on Components and Systems (RADECS)*, Sevilla, Spain, 2011.