ESR Executive Summary Report

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1. Project Core Data

1.1. Project

Assessments to Prepare and De-Risk Technology Developments -
Compute Module Maturation Campaign

1.2. ESA Contract No

4000131865/20/NL/BJ/ig

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CONTRACT REPORT

The work described in this report was done under ESA contract. Responsibility for the contents resides in the author or organization that prepared it.

Abstract

This document summarizes the findings de-risking activity for the in-house development of an onboard computer (OBC), providing a brief overview of the whole program, major findings, conclusions and next steps.

2. Project Goals Description

Onboard computers (OBCs) are a requirement of every spacecraft, from satellites to rovers. Planetary Transportation Systems (PTS) has taken on the task of developing their own OBC unit in-house, tailored to the companies' needs: the creation of avionics technology in cooperative projects and the in-house development of CubeSats are the current development focus.

The development goals included a durable design and a lightweight, low-power and compact form factor of less than 100x100 mm, without compromising on redundancy and reliability, build with ITAR-free COTS components. Other major points were its robustness against radiation and general configurations to make it well-suited to support other deep space exploration missions. It was planned to raise the TRL from 3 to 4, a prototype integrated in a laboratory environment, withing the frame of the de-risking phase. TRL 5 would be reached in the follow-on phase, with a focus on the testing of the hot redundant OBC.

The further in-house development by PTS shall make the OBC go through full qualification and acceptance testing, and eventually fly on a space mission, reaching TRL 9. It is planned to have the technology flight-tested in own applications before it is sold to customers.

The OBC design was planned to consist of 2 Compute Modules (CM) that interface with the actors/sensors/ communication devices in such a way that both Compute Modules can see and communicate with the hardware. This allows a hot-redundant configuration with full protection for both Compute Modules. On the software side, the CMs run RTEMS with NASA's cFS, making it easy to create highly reliable and testable applications. The addition of Ethernet allows for easy integration into test environments and reliable high-speed connections.

Targeted market opportunities were seen in its high reliability due to its design for redundancy, while maintaining a lower price. Possible customers were seen in companies aiming for miniaturization of satellite platforms, such as LEO and MEO, like Methera, Project Kuiper (Amazon Inc.), Samsung and other new entrants in the market, owing to the low- price high-quality build of the product. Similar use cases were estimated in dedicated 'IoT from high altitude' service providers such as Fleet Space, or agencies and institutional markets such as NASA, European Space Agency, Canadian Space Agency etc.

The board design and prototyping goals have been achieved in the de-risking phase.

2.1. Technical Task Descriptions

The CM is the computing element of the OBC, where the OBC is made up of two CMs (one nominal and one redundant) and a connection board to interface the two. This re-design was built on the TRL-3 level proof of concept design of the CM. The design was updated to improve the thermal/mechanical design of the board, as well as the electronic design, accommodating the requirements that stem from new intended use-cases. The requirements of the OBC and Cm concerning hardware, software, functionality, redundancy and other topics have been discussed in great detail within the technical team. An emphasis was put on understanding the power demands, storage possibilities and security of data to ensure a smooth running of the finalized product. This task was be performed in part as workshops including electronic, mechanical, thermal and systems engineers.

The latest designs fulfill all requirements set internally for this de-risking phase.

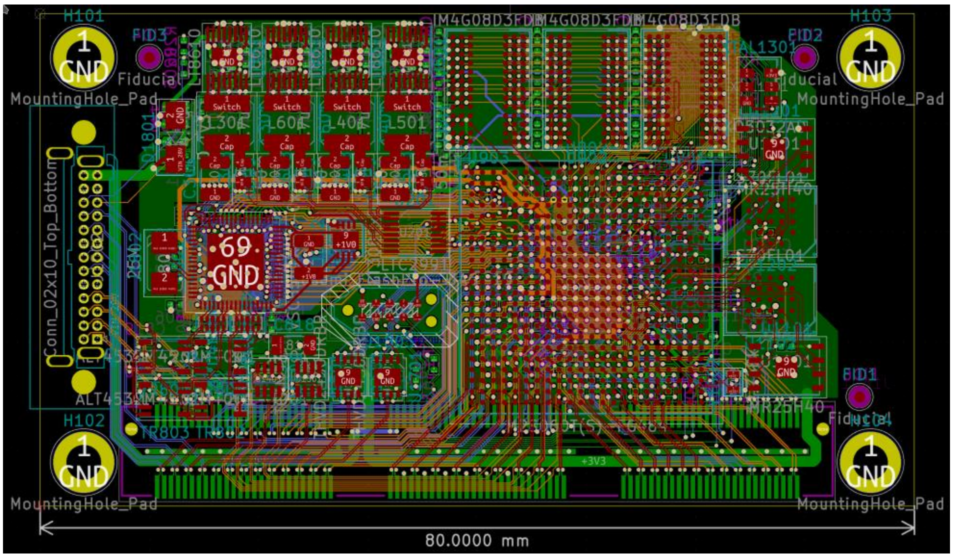

Figure 1: OBC Layout Designs

The design approach for the CM/OBC housing assumes the mounting of the enclosure in an area of the S/C where it can reduce the radiation effects on the electronic and also provide accommodations in order to cover the heat dissipation requirements. It is designed as standard CubeSat sized (100mm x 100mm) enclosure and comprises a high strength aluminum 7075 frame and similar top and bottom covers. The frame provides a stiff support from the CMs as well as the connecting board by mounting on a longitudinal rib feature. It also features the necessary cut outs for the PCB connectors on both sides. Both the M3 and M2.5 threaded connections, for the covers and the boards respectively, will include metal inserts for thread strengthening, to cover repeated assembly and disassembly processes as we all as high load cases (Transportation, Launch, etc.).

Several analysis steps validated the approach:

- A basic thermal analysis has been performed using the Finite Elemente Method Magnetics (FEMM) software. A number of assumptions have been made to simplify the conditions for the simulation but still hold the estimation to be conservative. The conclusion of the analysis is that no additional measures are needed for cooling the PCB.

- A radiation analysis showed that most of the critical parts show very low or well-known failure probability and/or criticality. The analysis of Mission Trajectory, Radiation Environment Models compliant to ECSS-E-ST-10-12C, TID Environment, Fluence Spectra, TID Curves, SEE Environment incl. Proton Flux Energy Spectrum, Galactic Cosmic Ray Flux LET Spectrum and Solar Event Flux LET Spectrum as well as the radiation effects for the CM and its subcomponents identified the sensitive parts in the design, possible component replacement needs and solutions, and their possible failure probability. In the follow-on phase testing for redundancy, several additional examinations are planned

- The mechanical analysis for the CM focuses on quantifying the eigenfrequency values and ensuring that these remain inside the required safe zones in relation to the mission's excitation loads. The assessment was based on "Vibration analysis for electronic equipment" by Dave S. Steinberg and includes the evaluation in terms of bending stiffness of each PCB layer, the technology's ability to to withstand the necessary level of random vibration, and its desired resonant frequency. The results show a comfortable margin of safety compared to the first Eigenfrequency.

- Within the risk anlysis, the possible weaknesses starting from the worst case scenario of total failure or smaller scale scenarios, such as timing issues, are exposed. The corresponding FMECA analysis describes solutions and compensation provisions, such as a redundant CM to avoid the loss of onboard software capability. A special focus is put on the possible effects of radiation and ways to counter them. The OBC requirements and CM requirements are assessed separately.
  The most critical problems involve failures for which no or limited mitigation was found to be possible, with the most severe example being a loss of all power onboard the spacecraft and therefore the loss of power in the OBC. While no mitigation exists for such a problem, it is assumed that the likelihood of this specific problem to occur is reasonably small. Mitigation methods were identified for the other risks
  For the second phase of the project, a more detailed risk analysis of the GSTP OBC with two CMs working in redundancy is planned.

To mount the OBC to the spacecraft, maintain its structural integrity under the expected mechanical loads, and keep it at an acceptable temperature in the expected thermal environment, an appropriate housing for the PCB has been designed. The design is a result of a trade-off between the optimum thermal, mechanical and electronic design, which in many cases conflict. The housing was designed by a mechanical engineer using CAD software, as seen below:

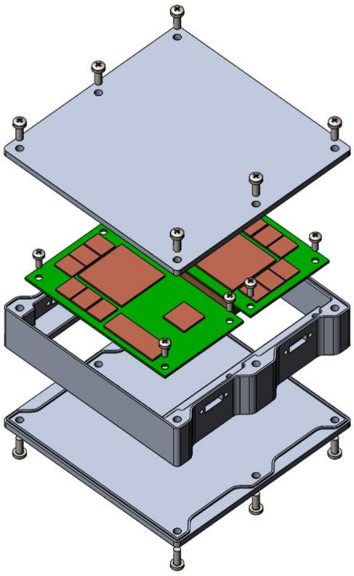

Figure 2: OBC housing – exploded view

The board design and prototyping goals have been achieved with the breadboard shown below.

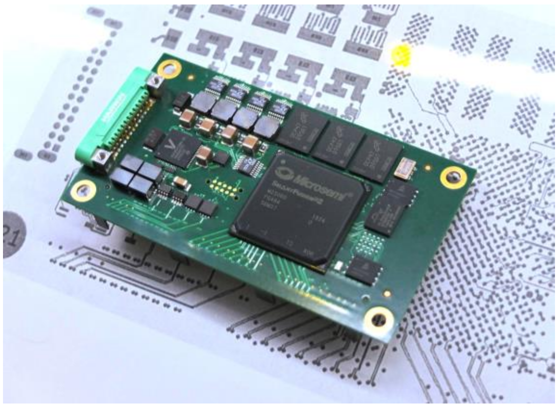

Figure 3: OBC and its design structure

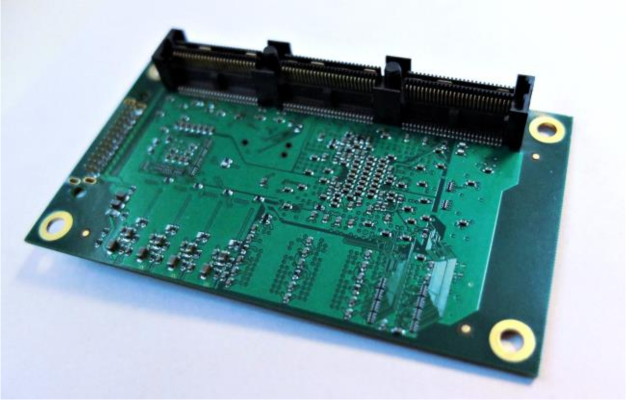

Figure 4: OBC backside

The main design drivers for the PCB design were high density of the components on the board to ensure a small board size factor, better IO bank separation (2 exclusive on the mezzanine connector) and more IOs. Several components were selected specifically based on the availability of the radiation test results. Examples are the power supply and the LT8610. The Bill of Materials (BOM) was consolidated to less than 50 different parts, to reduce complexity and cost in the manufacturing process.

2.2. PCB Development Issues and Lessons Learned

Some components were not available during ordering. Good replacements for some resistors and the DDR3 RAM could be found. In the case of the DDR memory, changing the DDR model has shown that the DDR3 pinouts are standardized, but their case sizes are not. Placing the replaced DDR model on the board has worked with a small 1mm margin, but it would be difficult to place these DDR components on a board with a tighter placement.

The produced six-layer board with 90µm structures and 150 µm vias is cheaper and easier to work with compared to a board that would have more layers and larger structures (8- or 10-layer boards). The six-layer board allows the DDR memories to be connected very close and tight to each other. For a board with more than 6 layers, the board thickness increases and that requires more expensive via connections, e.g., blind and micro vias.

In case of connectors, it is good to check the cost of a crimping tool before placing the connector on the PCB during the design phase. Otherwise, the production costs might increase due to the expensive tool parts.

2.3. Software

The GSTP OBC software demonstration development was based on available in-house software. This previously developed software included the basic driver layer with functional subsystems tests (DDR, MRAM, Flash) and RTEMS 5 operating system running on the previous generation of the SmartFusion2-based Compute Module.

The delta-development for the GSTP OBC project included setting up the NASA cFS to run on top of RTEMS on the CM and setting up the NASA cFS Ground System for basic TM/TC capabilities on a developer laptop.

The major work items include:

1. Connecting NASA cFS' TM/TC applications to the CM's Ethernet using RTEMS network stack.
2. Mounting the cFS configuration files into RTEMS RAM file system that makes them available for reading by the cFS at runtime.
3. Creating a "GSTP OBC" cFS application for basic TM/TC commanding. This cFS application responds to "Ping" and "HK" (housekeeping) commands from the developer laptop and responds with basic TM packets recognized and displayed by the cFS Ground System.

All embedded software and development tools are collected in a single Git repository. The flight software is harnessed with a CMake build system. The development tools for flashing, debugging, and other tasks are implemented using Python Invoke library.

A single repository for the GSTP OBC demonstration with a proper modularization of the components helps to understand and maintain the software and allows to extend it easily in the future. A special care has been taken of separating the unmodified parts of the Microsemi firmware from the parts customized for the needs of the demonstration. All customization points are either extracted as separate CMake targets, e.g., startup-files CMake target, or the custom additions to the C files are explained with extensive comments, e.g., RTEMS linker script details.

2.3.1. Minimal examples

A set of 3 additional basic examples of running software on the Compute Module have been included to the GSTP OBC demonstration. These examples include: minimal possible C binary without any standard library that only steps over a breakpoint continuously, a classical blinking LED example and an example of writing to UART. These examples were instrumental in troubleshooting several issues during the finalization of the development bootloader and setup of NASA cFS. When a more complex software didn't work, it was very practical to go back to the level of basic working examples and continue building up from their level.

2.3.2. NASA cFS momentum

The GSTP OBC software demonstration uses NASA core Flight System software from the GitHub repositories taken and frozen from their development state as of April 2020. Since the end of 2019, the development state of the NASA cFS has been a very actively moving target with a number of changes introduced to the project and application tree which caused breaking issues for the cFS users in the NASA flight software community. One particular source of changes is the evolution of the cFS build system, which is now based on CMake by default and is being iterated on for better modularity and cross-platform usage by the cFS development team.

The GSTP OBC software demonstration is also based on CMake. A separate integration layer for interfacing with NASA cFS had to be created to integrate with the changing specifics of the cFS' build system details. In future developments, it should be possible to reduce the integration effort by upgrading the CMake layer to the latest and improved state of the cFS build system.

2.3.3. NASA cFS Ground System

The NASA cFS Ground System has proven itself to be very basic and not so easy-to-use software. During the GSTP OBC project phase, a number of issues were clarified with the NASA cFS developers on the NASA cFS Community Forum. The discussion in the forum thread "cFS Ground System: The right way to define commands" (September 2020) has produced the following results: NASA cFS Ground System is open source and is supported by NASA, but it is not in the active maintenance phase by NASA and the use of the Ground System is discouraged by some core cFS developers. The Ground System scripts for the generation of TM/TC information are known to contain a number of bugs which have been reported by PTS. As of March 2021, they remain only partially fixed by NASA. The most stable signals about the alternatives to the Ground System received on this thread and other threads: using COSMOS or OpenSatKit instead of the NASA cFS Ground System.

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