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Overview of the Twardowsky Hybrid Sounding Rocket Avionics Design

KOŚCIANEK Bartosz†*, MIKULSKI Maciej**, *WOJCIECHOWSKI Konrad***, BRESLER Karol**

** ISAE-SUPAERO, University of Toulouse,*
10 avenue Édouard-Belin, 31055 Toulouse, France

*** Warsaw University of Technology,*
Plac Politechniki 1, 00-661 Warsaw, Poland

bartosz.koscianek@isae-supaero.fr – maciej.mikulski.stud@pw.edu.pl – konrad.wojciechowski.stud@pw.edu.pl – karol.bresler.stud@pw.edu.pl

† Corresponding Author

Abstract

For the past 10 years, the Students' Space Association (SSA) at Warsaw University of Technology has been developing sounding rockets to study lower levels of atmosphere and perform scientific experiments. Twardowsky is the first rocket propelled by a hybrid rocket engine, being developed as a small scientific payloads launcher.

This paper covers technical design of the Twardowsky avionics systems and the philosophy behind their creation, followed by a description about planned implementation. Conclusions and lessons learned are presented, along with challenges that had to be overcome during the design process, as well as plans for further work.

1. Introduction

Sounding rockets have been used for atmospheric, microgravity and astronomy research since the late 1940s [1]. Numerous programmes were developed, such as the ESA MAXUS, TEXUS and MASER, the NASA Sounding Rocket Program and the Polish Meteor series of rockets developed by the Institute of Aviation for research in meteorology [2]. Such undertakings were almost exclusive to large, often state-funded, research agencies. In recent years, it became apparent that experiments deployed from sounding rockets can be a tremendous opportunity for students to learn about engineering and project management. This led to the emergence of various CanSat competitions, as well as large-scale projects aimed at university students such as REXUS [3]. To facilitate a CanSat competition, a rocket capable of carrying several experiments is needed. The Polish Small Sounding Rocket Program, started in 2011 by the Rocketry Division of the Students' Space Association (SSA) at the Faculty of Power and Aeronautical Engineering, Warsaw University of Technology, aimed to develop such rocket [4][5]. In 2016, the first flight of the TuCAN CanSat launcher rocket, propelled by a solid rocket motor and capable of carrying up to 8 experiments to an altitude of 5000 meters, took place. In order to make the rocket safer for ground crew, more scalable and easier to transport to launch sites abroad, it was decided to develop a hybrid rocket engine as a next step. Thus, the Twardowsky project was started [6]. To ensure crew safety, as well as the successful realization of the mission, a dedicated avionic system had to be developed. This paper focuses on that system, its architecture and how it was influenced by other subsystems and external constraints.

The general overview of the Twardowsky rocket is outlined in Section 2. Requirements for the discussed system and the philosophy behind its design are presented in Section 3. Section 4 describes the system architecture and provides details about individual subsystems. Section 5 provides a brief overview of initial tests that have been performed and their results. The last section offers conclusions and final thoughts on the design.

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2. Twardowsky project overview

Twardowsky is the first rocket utilizing a hybrid propulsion system developed at the Students' Space Association. Its goal is to deliver a payload to an altitude of around 3000 m and then safely land using a parachute. The payload is a dedicated CanSat Deployment System, designed to carry up to 8 CanSats and deploy them at desired altitude. A CanSat is a small experiment contained within a volume of a typical soda can, weighing below 350 grams. Such experiments are usually made for various competitions by high school and university students to learn engineering skills typically needed in the space industry. The deployment system is designed around thermal knives which are used to cut a wire holding two fairings. After the fairings are separated, CanSats are pushed out using rubber bands, similarly to the system used on the TuCAN rocket [5]. After the payload is deployed, the rocket's parachute recovery system is activated, deploying a drogue parachute. Later, at an altitude of four hundred meters above the ground, the main parachute is deployed, slowing the rocket to a velocity of about 8 m/s.

Twardowsky is also the first rocket developed by the SSA to participate in the Spaceport America Cup, an annual competition for student rocket teams taking place in New Mexico, USA. The goal of the competition is to reach an apogee as close as possible to the one set by the category rules. Set apogee can either be 10,000 ft or 30,000 ft above ground level, while carrying no less than 8.8 lb of payload. One of the reasons for using a hybrid propulsion system in the design was the ability to transport the rocket abroad, as solid propellants cannot be transported by air and require special permits and care. The Twardowsky propulsion system uses nitrous oxide as the oxidizer and hydroxyl-terminated polybutadiene as fuel. The fuel can be transported abroad without any special provisions, and the oxidizer is easily available for purchase on site. Moreover, hybrid propulsion systems offer more safety for the ground crew, as the two agents are physically separated and often require external energy or a catalyst to start combustion. This reduces the risk of accidental ignition during preparations. Such a system also offers the ability to tune its performance to the atmospheric conditions at the launch site by changing the amount of oxidizer injected into the chamber. This means that the team can more accurately tune the combustion system to reach targeted apogee.

Such a mission profile demands a robust avionic system, capable of not only gathering and transmitting basic information about the flight, like position and acceleration, but also monitoring the state of the oxidizer prior to and during launch, as well as supporting payload and recovery system deployment.

3. Design philosophy

To improve reliability and robustness of the design, exceptional care has been taken to develop a requirement tracking system. The system requires all on-board devices to be described in terms of their needed capabilities and design considerations. The tool used for this purpose is a multi-parameter registry that is constantly being updated throughout the design process to ensure that requirements are reasonable for a student project but also strict enough for all systems to meet all mission objectives. There are requirements that are imposed by the Intercollegiate Rocket Engineering Competition (IREC) [7], as the rocket is being designed to compete in Spaceport America Cup competition, and requirements that are not mentioned by IREC but concern environmental conditions at the planned launch site.

All work concerning system engineering was conducted according to tailored ECSS standards and handbooks. Most notably, ECSS-M-ST-10C, ECSS-E-ST-10C, and ECSS-E-ST-10-06C. Such standards are commonly used in the aerospace sector, and as such, a student project had to selectively implement parts of those documents for them to be viable.

There are several requirements that concern all systems. These include thermal endurance, which was one of the biggest concerns when designing the system. As temperatures at the planned launch site in New Mexico state can exceed 37°C, the avionics system must have been designed with even higher temperatures in mind, as there is no planned cooling system inside the rocket.

Space constraints were another key factor to consider. Some of the rocket's modules limit the design of the avionics system by imposing required dimensions of avionics subsystems. While the nosecone provides plenty of space for most electronics, the recovery module, for example, is limited in the space it can provide to pyrotechnical electronics. The same restriction applies to the payload module as well. These avionics subsystems cannot be placed inside the nosecone because of the functionalities they provide or the interfaces they have with other components, such as cameras.

The main communications bus chosen for the Twardowsky rocket and the avionics system is the CAN bus. Its robustness was a crucial factor in the decision process. Furthermore, some information about the rocket's state is required to always be shared between avionics subsystems via the CAN bus. This includes the flight stage and flight

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parameters critical for decision making. This requirement provides higher reliability and confidence that no subsystem would malfunction should a wrong request be sent mistakenly or after the main flight computer's malfunction.

Another compatibility requirement focuses on interfaces between all avionics subsystems in the nosecone. Due to several avionics boards being present there, it was decided that those subsystems would be required to have the same size and stack connectors to be able to implement a classical stack architecture. Those requirements enable subsystems to be stacked on one another and mounted using spacers and bolts to have a reliable connection.

Although the first power supply concept required a single power supply to be used for power delivery to all subsystems, such idea was deemed unviable after the initial tests. The current requirement states that several boards must have their own lithium-polymer batteries. This requirement simplifies the design in terms of power buses present throughout the rocket and increases confidence in the power supply.

4. System architecture

4.1. Preliminary design

Because the designed system has to perform several different and complicated tasks, it was decided that the only viable approach is to split the system into modules. The system been divided into three main parts:

- primary avionic system
- secondary avionic system
- payload modules

The primary and secondary avionic systems contain safety and mission-critical hardware – telemetry systems and parachute recovery system electronics. To further increase reliability, both systems have been designed to contain different hardware. As per requirements, systems are powered from separate sources, and use separate wiring where possible. The payload modules provide additional functionality, such as video recording and payload deployment.

The primary avionic system is based on the in-house developed on-board computer called Ganymede. The Ganymede has been developed as a universal computer for all SSA's rockets. In its basic form it is a single-board computer with an integrated power supply, memory, radio transceiver and sensor suite. It has been, however, designed as an expandable design. Additional modules extend its capabilities to pyrotechnic actuation and oxidizer state measurement, as well as providing an interface for payload control. They can be either separate modules connected by cable or mounted directly to the PCB using a mezzanine connector.

The secondary avionic system is based on a COTS on-board computer, an Altus Metrum TeleMega. It is a single-board computer capable of both providing telemetry downlink and actuating the recovery system pyrotechnics. The choice of the computer was made based on experience with it on past projects, as well as its compliance with Spaceport America Cup rules.

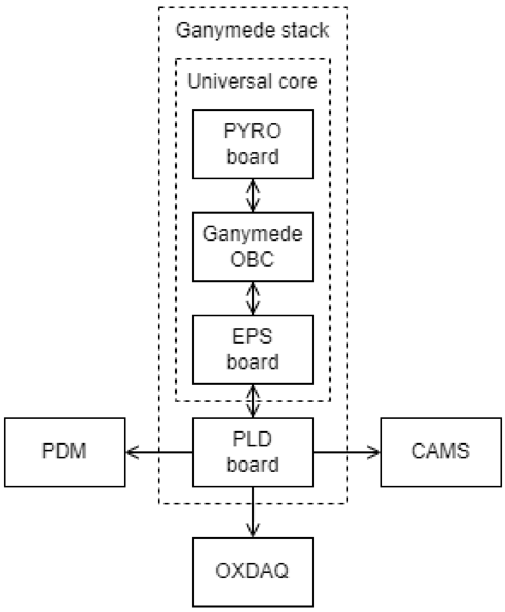

Figure 1 Twardowsky avionics system stack and peripherals

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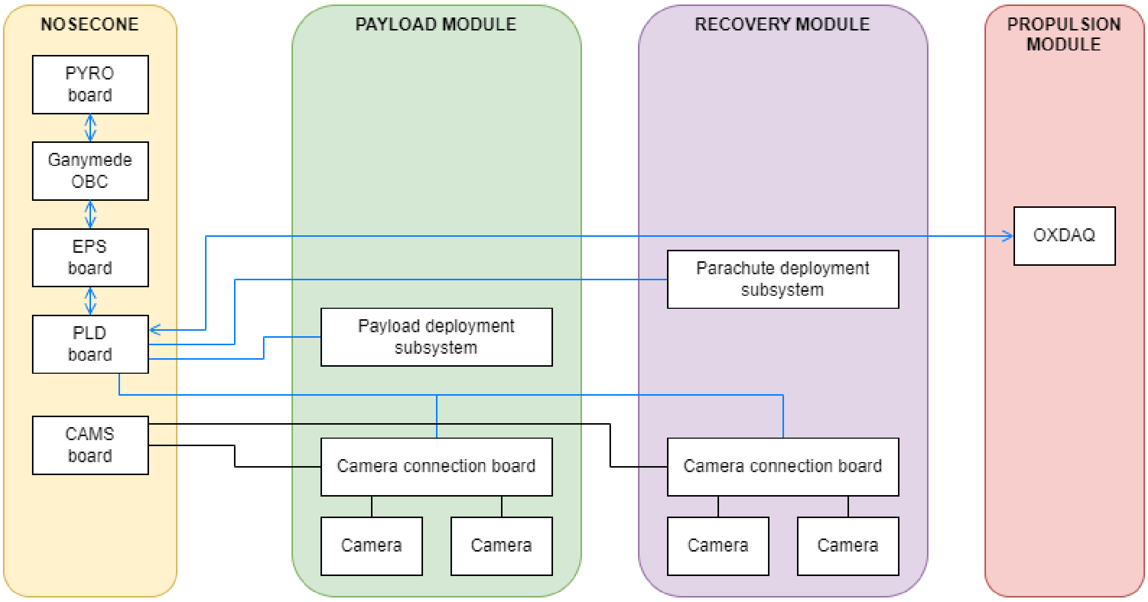

Figure 2 Twardowsky avionics - general overview

Choice of stack-based architecture disqualified using a single power supply module to supply all required power rails. Thus, a decision was made, that the EPS module will only power the primary rail on the OBC stack, while other circuits will be powered from their own batteries locally. PDM and PYRO boards draw considerable amounts of current during actuation of thermal knives and pyro charges respectively, so supplying them with smaller, locally placed batteries prevents considerable power losses in wires. Dedicated power supply for each of these systems also ensures that no excessive loading or transients are present on the lines supplying main digital electronics. Each Raspberry Pi Zero computer on the CAMS board also has its own power converter which is supplied from a separate power source. This allows to choose the batteries for the video capture system to suit power needed for operation during the mission.

Another important requirement for the power supply system is the ability to charge batteries that provide power to mission-critical systems. This is due to the requirement that those systems shall work throughout the mission and the time the rocket stays at the launchpad before it is cleared for launch can vary.

EPS and CAMS boards also feature charging subsystems. COTS charger module for the TeleMega flight computer was also used. All those chargers are powered from a 12V rail supplied by in-house designed TADEX Electrical Ground Support Equipment (EGSE).

OXDAQ and stack power supply is made of two independent batteries. In case of malfunction of one of the batteries such as loose connector or a damaged wire, power will be continuously supplied to those systems, ensuring reliable and continuous operation.

Due to limited space and ease of maintenance, it was decided that OXDAQ batteries and ORing circuits will be placed in the nose cone. The system itself will be powered through the cable carrying CAN bus lines. To ensure that high enough voltage will be present at input of OXDAQ power supply, 11.1V batteries were used.

4.2. Interconnection system considerations

It can be seen in Figure 2 that within the nosecone itself, there are multiple on-board computers and peripherals. Two approaches were considered: motherboard and stack based one. Motherboard approach had several drawbacks, which among others are:

- large distances between modules required wide PCB traces to reduce power losses,
- improper grounding scheme might introduce ground loops which could be hard to resolve,
- high speed signal PCB traces would be prone to crosstalk and EMI.

Most of these problems are solved when a stack-based approach is used. Smaller distances and more compact design reduce most of the problems present in the motherboard approach. Therefore, a stack-based solution was chosen as a

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main structure inside the nose cone. The Oxidizer Tank Data Acquisition System (OXDAQ) subsystem is the only one that would need to exchange data with the stack, but its position could not be changed.

The stack is located in the nosecone of the rocket and requires wiring system connecting it to other electronic subsystems located throughout the rocket. Modular construction of the rocket body required adding connectors on all harnesses at the boundaries of the rocket modules to allow for disassembly. Decision was made to use readily available signal connectors to decrease cost of the system and remove the need of using specialised tools used in the assembly process.

During the manufacturing, assembly and testing of the wiring system, it became apparent that common signal connectors cannot satisfy mission requirements. Ethernet and DE-15 connectors used for CAN and pyrotechnical channels respectively were too large and barely fit into the space between rocket modules. Cables used for the Ethernet connectors proved to be too stiff and were difficult to fit into tight spaces. The design of the Twardowsky rocket modules means that the access to their interior is possible only through their opposite ends. This caused problems during assembly, as it was often difficult to perform some of the wiring system mating.

Despite all of the mentioned problems, the wiring system was integrated and is functional. Future iterations of the project shall draw from the experience gained during its manufacturing process. Thorough examination of available connector solutions shall be performed in order to reduce size of the system and improve its ease of assembly. Moreover, the addition of removable covers on the fuselage would provide access to the internals of the rocket modules which would further help in the process of rocket integration.

4.3. Internal communication

The internal communication between most of the modules is performed using a CAN bus. It was chosen due to its fail-safe design and wide availability of hardware, both transceivers and microcontrollers with built in peripherals. The bus can be easily extended if needed without the need for a hardware or software redesign. Each module on the Ganymede stack has to connect to the CAN bus.

4.4. On-board computers

Designed avionics stack consists of:

- Ganymede OBC - in-house designed on-board flight computer overseeing all in-house developed electronics present on the rocket,
- EPS board - main power supply delivering 3.3V power to modules, also capable of charging batteries while rocket is waiting on launchpad,
- PYRO board - a board dedicated to firing pyrotechnical charges required to deploy parachutes,
- PLD board - a system that allows communication with boards functioning outside of the stack and supplies power to systems present downstream in the rocket.

Communication between modules in stack is performed via Mezzanine connectors and CAN bus. This configuration can be seen in Figure 1.

The secondary avionics system, mainly the COTS Altus Metrum Telemega flight computer is also present in the nose cone. It ensures safety and deployment of parachutes at a desired attitude, should the primary system fail. It is also required to carry a COTS flight computer, should the rocket be competing at the IREC-organized competition.

The Ganymede serves as the primary flight computer and is tasked with providing telemetry, radio communications and handling in-flight events. It contains multiple sensors, among which the most important ones are the IMU, which provides information about rocket attitude, and the analog high-g accelerometer, which provides valuable information during the first few seconds of the flight. Secondary sensors include an altimeter and redundancies in the form of a digital accelerometer, a gyroscope, and another altimeter. Information about the current state and information from sensors is periodically saved in computer’s FLASH memory for post-flight analysis. This computer is also able to receive GNSS information for position determination, but this data is not used for staging. All mission-critical data is sent through a RF link to the ground station in case of rocket failure and inability to retrieve the computer after the flight. The Ganymede OBC is presented in Figure 3.

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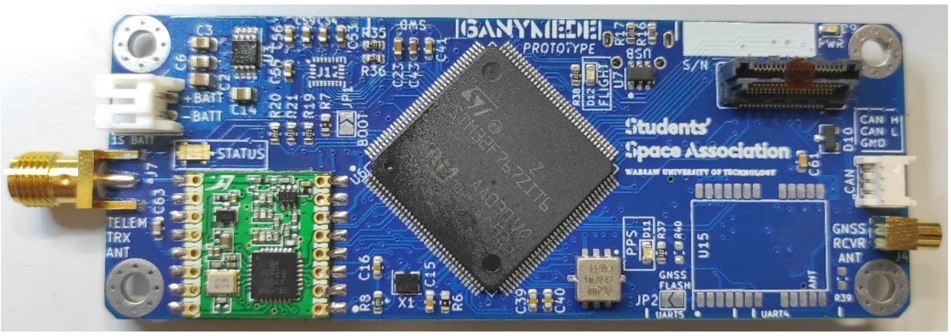

Figure 3 Ganymede OBC

The EPS is tasked with providing power to the stack. It is connected to separate stack batteries inside the nosecone and provides necessary voltages. Its secondary task is to ensure that batteries are charged to last for the duration of the mission, including post-flight search. The power for charging will be provided by connecting the rocket to the ground infrastructure before the flight.

The PYRO board is tasked with handling pyrotechnical charges during the mission. These include the charges for module separation and charges for parachute deployment. The board is able to provide up to 6 separate channels, which is enough not only for the Twardowsky rocket, but also for other projects currently in development.

The PLD board was created due to a need to oversee auxiliary subsystems that cannot be developed as a part of the stack. It is responsible for communication with electronics inside the Cansat Delivery System and commands them in order to deploy the payload. Its secondary task is controlling the OXDAQ state by powering it on or off.

4.5. Deployable payload

The rocket is designed to carry 4 kilograms of payload, contained inside the module between the nosecone and the Recovery System During ascent, the experiments are held inside the module by composite fairings, which are attached using a hold-on and release mechanism based on plastic cords and thermal knives. After reaching the apogee, the thermal knives burn through the cords, which releases the fairings. The CanSats are all then ejected out of the payload module body by tensioned elastic bands. Due to the considerable power required to heat the thermal knives, it was decided that dedicated MOSFET switches will be placed on the PDM board located in the payload module. The knives are powered by separate batteries, so that no excessive load is present on batteries powering other systems. The PDM board is controlled via digital signal lines from the PLD board located in the primary OBC stack. The knives are fully redundant to increase the robustness. Each channel powering thermal knife has to be separately armed and then fired by another command. Initially power switches for thermal knives were located on the PLD board, but a decision was made to move them to a separate PCB, as limited space on the PLD board meant that thermal consideration could not be met, and the system could overheat while being used. Moreover, significant power losses could be present in long wires going from the nose cone to the payload module. The idea of using thermal knives and controlling their behaviour using the PLD board was tested and proved its reliability.

4.6. Camera system

Twardowsky rocket will carry 4 cameras, each connected to a dedicated Raspberry Pi Zero computer. All computer modules are connected to CAMS board which provides them with 5V power rail and means of connection to the primary OBC stack. CAMS power supply system consists of four identical circuits, one for each computer, which are themselves composed of a step-down converter, battery charger and a power switch. PLD board is an intermediary in communication between main OBC and Raspberry Pi computers. It can communicate with them via UART interface and has one dedicated GPIO pin for each computer. This single GPIO acts as a trigger to start recording of in-flight video. Additionally, it controls the power switches in order to turn computers off during times when video recordings are not performed. Recorded videos are saved on Raspberry Pi Zero’s SD cards for post-flight analysis.

It was concluded that flexible flat cables normally used to connect cameras to Raspberry Pi Zero computers are not durable enough to be used in the design, due to their susceptibility to mechanical damage during handling and integration of the rocket. Ribbon cables were used in previous projects, such as the TuCAN rocket, where they proved

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to be robust means of connecting cameras to Raspberry Pi computers. Flexible flat cables are only used to connect cameras to adapter boards and to connect Raspberry Pi Zero computers to CAMS board as shown in Figure 4.

Recent developments at SSA have shown the new Raspberry Pi CM4 board as a promising alternative to the now used Raspberry Pi Zeros. It offers much higher processing power in a similar form factor as Zero, while at the same time it allows for replacing SD Cards with onboard data storage. It is critical, as vibration during the launch, ascent and descent can be significant and can damage or temporarily disconnect SD cards. One CM4 could also handle more than one camera, allowing to decrease the number of computers present in the nose cone, thus simplifying the design. The only downside to this approach would be the need to design a carrier board for CM4, which could prove to be more complicated than the design of the CAMS board.

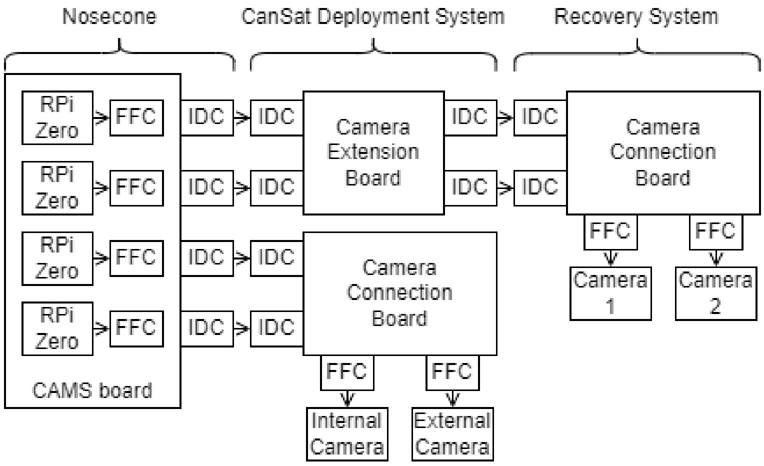

Figure 4 Twardowsky camera distribution initial plan

4.7. Recovery system

The most important aspect of the recovery system present onboard is the PYRO board. It consists of an independent microcontroller communicating with Ganymede OBC and dedicated pyrotechnical ignition channels. As previously mentioned, PYRO board communicates with other modules via CAN interface. After receiving a dedicated command, the corresponding pyro ignition channel is fired. The board additionally provides capability to selectively test circuit continuity and ensure that a pyrotechnical charge is properly connected and ready to be used.

All channels are galvanically separated from each other, thus requiring a dedicated battery. Galvanic separation provides increased safety and eliminates additional stress on main batteries when a pyrotechnical channel is activated. Besides galvanic separation, all channels feature full redundancy of components, allowing for increased reliability.

In case the PYRO board fails to activate any pyrotechnical channel, the COTS computer (Telemega) is configured to activate necessary pyrotechnical charges. This is due to safety concerns and Telemega's proven reliability.

4.8. Oxidizer tank

To safely conduct launch procedure, which includes propellant tank filling and pressurizing, the pressure and temperature inside the tank has to be constantly monitored. To that effect, a specialized system, called Oxidizer Tank Data Acquisition System (OXDAQ), has been developed. The system, comprising of a single PCB, is located on the upper oxidizer tank module bulkhead. It connects to two thermoelectric temperature sensors: one located inside the tank, the other mounted outside of the tank, as well as a single pressure transducer placed on the top end of the tank. Measurement frequency for both temperature channels is 10 Hz, and for the pressure channel it is 1000 Hz. Data is stored in an on-board flash memory and transmitted on-demand to the Ganymede OBC. Due to the system's location, it was decided to power it from a battery located in the rocket's nosecone. This is due to two reasons: the compartment is inaccessible for maintenance after rocket assembly, and placing heavy batteries closer to the tip of the rocket is favourable for rocket stability in flight. The system is connected to the Ganymede using shielded twisted pair cables and 8p8c connectors, typically used for computer networking. Apart from battery power and CAN, the wiring includes an additional power disable signal controlled by the PLD board. This allows for power saving while the system is not in use.

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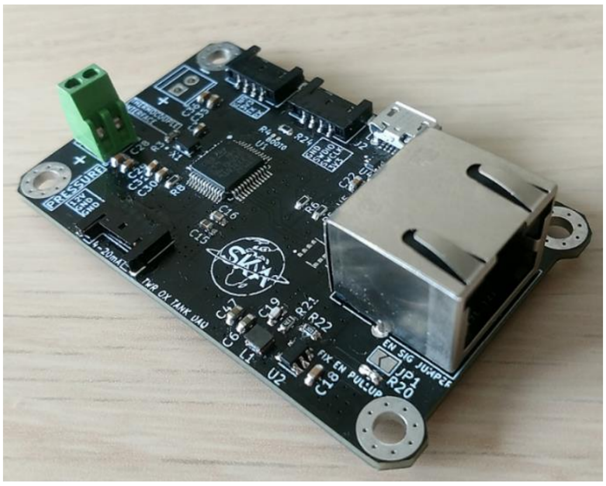

Figure 5 OXDAQ subsystem

5. System tests

The system is yet to be fully tested. Planned general test campaign features separate software tests for all boards featuring a microcontroller, a series of tests using the stack and peripherals, and finally tests featuring a fully assembled rocket with all avionics systems. The test documentation, including detailed test campaign plans and procedures is in preparation. Some of the less complex test campaign plans have already been realized to verify that the hardware was designed and manufactured correctly.

The Ganymede OBC, as the flight computer developed before other subsystems, has already been tested in-flight during FOK rocket's test campaign. The OBC works as intended – it can provide sensor data and handle events during the mission. Its software is constantly being improved and tested at the same time. Latest developments in the area of RF communication are in need of complex tests, introducing communication with the ground station software for command handling.

The camera system has also already been tested on-board the FOK rocket, although with a single Raspberry Pi Zero computer. For the Twardowsky rocket, a fully assembled camera system with four computers and four cameras will need to be checked for performance, but the recording software is flight-proven and reliable.

Initial Ganymede Stack tests are currently in progress, but preliminary results are satisfactory. The EPS board proved that it can reliably provide necessary voltage levels and currents for the stack to work. Battery charging using the designed ground support equipment is yet to be tested, but the charging circuit itself is functional. The PYRO board proved that given a command, it is able to provide current necessary to activate a pyrotechnical charge. The PLD board was able to activate thermal knives in the Payload Module, but its interactions with both the OXDAQ and the CAMS board are still not tested.

Conclusions

The paper presented the general rationale behind the design, assembly and tests of the avionics system for the first hybrid propelled rocket designed by the SSA. General philosophy and requirements behind each part of the system was presented and discussed. The biggest challenges of the design were a tightly constrained space, low budget and a student work environment which can greatly affect any workflow. The rocket itself also required several sophisticated systems, which put even greater pressure on the avionic design. Multiple configurations of the system were proposed, tested and discussed. Architecture that best satisfied the requirements placed upon the design was the stack-based one with a dedicated tank sensor outside of the stack. The stack was designed to be a modular and easily reconfigurable system, allowing for quick prototyping and possible elimination of errors. One of the biggest challenges, not foreseen at the beginning of the project, was the cable handling within the rocket. The selection of connectors, cables and their arrangement within the rocket proved to be a demanding task. Nonetheless, after multiple tests and assemblies the best cable configuration was chosen. Now, after initial assembly and software tests, the avionics systems are waiting for further test campaigns and preparations for the first flight of the Twardowski rocket.

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