InnoCube - Technology Demonstration of a Wireless Satellite Bus and An Experimental Solid-State Battery

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Abstract

The Innovative CubeSat for Education (InnoCube) is a joint project of the chair of Information Technology for Aerospace at the University of Würzburg and the Chair of Space Technology of the Technische Universität Berlin. A 3U CubeSat is developed in a four-year project, planned as technology demonstration of two innovative technologies: SKITH (SKIpTheHarness), a wireless satellite bus technology and Wall#E, a carbon fiber-reinforced plastic solid-state battery. Additionally, an Experiment for Precise Orbit Determination (EPISODE) is included. To demonstrate the SKITH concept a wireless data exchange between all satellite modules, i.e., the onboard computer (OBC), ADCS, power distribution and conditioning unit (PCDU), up-/downlink transceiver and the payloads is realized within the InnoCube satellite. Several experimental Wall#E structural batteries are placed on the satellite's outer wall, simulating the projected use as satellite structure. For reference, layers are placed on the inside as well. The development is needed to raise the TRL of Wall#E and prepare steps for a further experimental satellite application, WallE2Space. As a structural battery, Wall#E does not match the mechanical and electrical properties of a conventional polymer composite or Li-polymer battery. A separate conventional power system is needed for satellite operations and experimental payload operations, in which a representative operational scenario is simulated. The secondary payload EPISODE is part of the educational strategy of the university and primarily developed within student's projects and theses. The experiment consists of two main components, a custom Global Navigation Satellite System (GNSS) receiver and a Laser Ranging Experiment (CubeLRR). The highly flexible GNSS experiment can support multiple GNSS signals, such as the Global Positioning System (GPS), Galileo and other systems on the L1 frequency. It consists of an antenna, a custom GNSS frontend, and a multiprocessor system which runs the navigation solution and position determination. CubeLRR is a four-prism pyramid shaped Laser Retro Reflector miniaturized to meet the size constraints of a CubeSat. Its purpose is to verify the GNSS measurements.

This paper introduces the current status of the InnoCube development and includes the system details along the technical aspects of the mission design. The main focus is laid on the conception of Wall#E-2-Space and EPISODE as well as their development state.

Keywords: CubeSat; wireless bus; harness free satellite; satellite technology; CubeSat GNSS; laser ranging; structural battery;

1 INTRODUCTION

InnoCube is an ambitious project which carries multiple technologies to shape the design of future small satellites. In a modular 3U CubeSat, two main innovations are placed. The first major deviation to a classical satellite is the bus. Opposed to conventional harnesses, with multiple cables from each subsystem to another, InnoCube tackles the obstacle of power and data distribution with a modular design and an innovative bus network called Skith [2]. The data between each subsystem is exchanged with radio communications located in the ISM band of 2.4 GHz. Each subsystem of the satellite houses two radio chips featuring a micro-controller with an integrated radio transceiver with a transmission power of 9 mW. The second innovation is a CFRP structure, which is able to store electrical energy and can be used as supporting structure of the satellite, called Wall#E. This type of battery allows significant mass and volume reduction of a satellite while maintaining the same performance. Different versions of the structural battery are integrated in the system to characterize their performance in space operations. As an additional payload, a software-defined GNSS receiver based on a FPGA is included in the satellite. More precise determinations of the satellite shall be enabled by a system which is mostly developed by students.

2 INNOCUBE SYSTEM OVERVIEW

The 3U primary structure of InnoCube consists of six main components, a top cover, the antenna as a bottom cover, two side walls, a front wall, and rear wall which feature the rails as the contact area with the P-Pod. The side panels have a slotted structure to clamp the module carriers which hold the avionics hardware. Each carrier board has the same dimensions and uses a uniform connector, plugged into the backplane, which serves as the power distribution from the EPS to the individual modules. The structure uses 17 slots, with each system of the avionics using one or multiple slots. Most modules are duplicated for redundancy, however, some modules, such as the PCDU, are spread over two module boards. All data harness are replaced by robust, high-speed, real-time, very short-range Skith radio communications. The second technology demonstration is the energy-storing satellite structure developed in the Wall#E project [5], which can replace conventional battery technology. As a further payload, the hardware for the concept of a software-based solution for receiving signals from global navigation satellite systems (GNSS) will be developed to enable precise positioning of the CubeSat. Figure 1 shows subsystems and components and their respective position inside the satellite. A total of ten module boards with twelve modules are integrated. The main components will be briefly presented in the order that corresponds to the arrangement in the satellite, starting with the retro reflector and concluding with the payload EPISODE. On the nadir cover of the satellite, the retro reflector holder with four prisms is mounted on a cover plate. A laser beam with an incident angle of up to 17 degree directed at the satellite is reflected

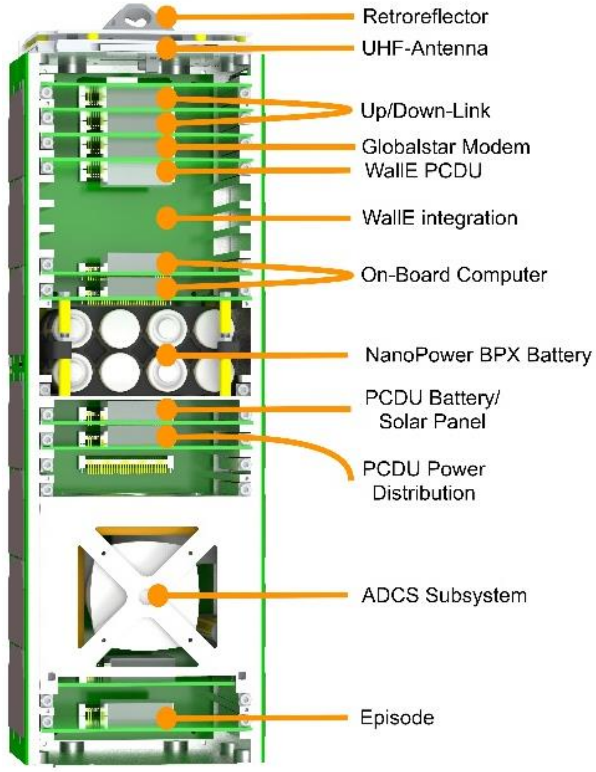

Figure 1: InnoCube system overview [1]

back to its source. This allows a precise position determination that is used as a reference for the on-board position estimation by the GNSS payload episode. The communication system consists of an UHF Antenna III from Endurosat [5] and two module carriers in the satellite, each carrying a MiniSatComm transceiver from RadioBro. The antenna uses four rods and is designed for frequencies in the range 435 to 438 MHz. It features a omnidirectional radiation pattern as well as enables circular polarization of the signals. It is flight-proven and has a redundant deployment mechanism. The transceivers are connected to the antenna via an RF switch, which has an insertion loss of 0.6 dB. It is guaranteed that at any time a transceiver has a connection to the antenna. A concept is developed, which guarantees the receptivity of the satellite at all times and a safe operation, in which no transceiver shall be damaged by a reflecting signal. A Globalstar satellite modem is planned to be implemented for educational and experimental purposes to communicate via the satellite network independent of ground stations.
Wall#E-2-Space is the adaption of Wall#E technology as a payload. It will be discussed in more detail in subsequent section but involves structural elements that can be used simultaneously to store electrical energy. For onboard data handling, one Skith module acts as a master node, which coordinates the data exchange between all modules. All modules are built redundant with two microcontrollers on each carrier card. As the communication and onboard computer subsystems are the most critical, their function is duplicated into two modules. If a module fails in any way, it is shut down, cutting off the power supply. The power subsystem consists of a Nano Power BPX lithium-ion battery [6] in a 2S-4P configuration, with a nominal voltage of 7.4V and 10 Ah capacity from Gomspace. The PCDU system is divided into two module carriers and is developed at DLR-RY in Bremen. The PCDU battery/solar panel module carrier has a maximum power point tracker for each of the 8.4 W EnduroSat solar panels [6] and a charge controller for the battery. The second module distributes the power with a total of three voltage transformers, and 19 switches to supply each module. Each switch has over-current protection, its output current is monitored and is controlled by Skith modules. For attitude determination, a sun sensor is placed on each satellite side. The determined data is transmitted to the ADCS via Skith modules. The attitude control system is mounted in a separate box that can be removed as a whole for test and development purposes. It contains three reaction wheels, three double coiled magnetic torquers and the ADCS module board with two ADCS modules. An advantage of this substructure is the simplified test capability of the correct function of the ADCS. Thus, the box can be operated on an air bearing table to test the interaction of torquers, reaction wheels and position determination. EPISODE is a payload consisting of a software defined radio (SDR) based on an FPGA to determine the position of the satellite from received GNSS data and will be discussed in detail in the following sections.

3 SKITH

Skith is an acronym for *Skip the Harness.* The idea is to replace conventional wired data connections with a robust low power wireless communication network. It is a development of the Chair of Computer Science VIII of the University of Würzburg[[1]. This concept features many advantages, avoiding issues with cabled connections, reducing the overall mass [1] by up to 10 % and a high flexibility, as each subsystem does not have a physical connection to another. Testability is improved, as no physical access to the integrated satellite is necessary. The Skith interface is implemented using an EFR32FG12 microcontroller by Silicon Labs [6]. It features an ARM Cortex-M4 CPU with a clocking frequency of 40 MHz. The complete board layout for one Skith node is 21 by 31 mm, shown in Figure 2. A front-end with an integrated transceiver and a printed inverted F antenna is used. For safe communications, a transmission power of 9 mW is sufficient in a custom Skith protocol. The parameters of the Skith network are a 2 MHz bandwidth with a maximum datarate of 1 Mbit per second. The microcontrollers are using a dedicated version of the reliable RODOS operating system [7]. To avoid collisions in the network, each module has a timeslot. The synchronisation and handling of the timeslots is coordinated by the master node. The microcontroller is used for communication inside the satellite bus as well as controller for most applications. A redundancy is achieved by implementing two Skith network nodes on each subsystem carrier card in the satellite. Only one node is active at a time, sending keep-off pulses to the other. On the software level, the modular system is continued, with each node using similar software and enhanced functions implemented in apps. As the Skith hardware has never been used in orbit before, it has been tested for its resilience against radiation. A sample of four microcontrollers have been irradiated by a Cobalt-60 source with a mission dose of 0.64 krad/h and a total ionisation dose of 10.8 krad over 20 hours. While testing, the controllers exchanged radio messages and performed memory checks. No memory errors or communication failures were detected. Thus, the Skith hardware shows a suitability for the use in space [8].

Figure 2: Redundant Skith implemenatation on a module board

4 WALL#E-2-SPACE OVERVIEW

Wall#E is a technology which integrates energy storage functions into the supporting structure of spacecraft [9]. For this structural battery, fibre composites will be equipped with solid-state battery materials at nano- and microscale. The aim of research is to investigate appropriate solid-state battery materials and processes for fabricating a structural battery from electrochemically active fibre composite components, as well as to find possible processes to fabricate a functional battery providing storage function and electron transport by partially replacing matrix polymer with active material for anode, cathode, solid electrolyte, and conductivity additive [10]. Within the course of the research, laboratory prototypes were manufactured and the functional principal was demonstrated. For InnoCube, it is necessary to adapt this technology as a payload in a continued project, accordingly named Wall#E-2-Space (W2S). Since Wall#E-2Space is a technology demonstration, it will be integrated as a payload and not as an operational system.

Although W2S is a structural battery it is not used as load bearing structure to comply with CubeSat standard [12], reduce the design complexity, reduce risks, provide shielding for the wireless bus and to lay the focus on the electro chemical and mechanical development of the payload.

4.1 Objectives

The goal of the Wall#E-2-Space development is to transfer the previous Wall#E research into the technical application for a CubeSat. The focus is on function and operation in a relevant environment. The application as a load bearing structure is intentionally omitted because the second, operationally critical technology test of the Skith satellite bus requires shielding from radiation, which has not been tested for Wall#E. To comply with the CubeSat standard, the basic structure will be made of aluminium. Several experimental structural batteries will be placed on the satellite outer wall with some reference cells on the inside of the satellite. Performance parameters of the structural batteries in particular, various charging parameters such as charge/discharge current as a function of in orbit thermal conditions, the degradation behaviour and long-term influences of space environment will be investigated, which can only be studied to a limited extent in the laboratory. Another aim is to adapt real charge-discharge curves from InnoCube to simulate real operational cycles and monitor the behaviour of the batteries.

To transfer the technology following requirements for the technical applications are formulated:

- W2S payload is seen as a consumer and receives charging current provided by the power management system during experiments.
- W2S has its own PCDU for the experiments and distributes the current received from the EPS.
- There should be at least 1 side wall (1U) of Wall#E structure battery.
- W2S shall record and store charge and discharge currents, temperatures and voltages.
- Payload data shall be stored and recorded.
- Experimental batteries shall be capable of controlled discharge.
- During experimental charging, a current of 1-100 mA (at 3.7V) is required for approximately 100-1 h per cycle. Followed by an identical discharge cycle (data acquisition only).

4.2 **Wall#E-2-Space** ***payload design***

The system consists of three experimental structural batteries on the satellite's outer wall and batteries in three module slots inside the satellite. A module board contains the control and charging electronics and Skith nodes. The general design of the payload system is shown in the block diagram, Figure 3. The electronics board integrates two Skith wireless radio modules and is connected to the backplane to provide power and charging current to the payload. The microcontrollers are used to control and configure the payload. The other main components of the board are the charge controller integrated circuits for each battery cell. The integrated circuits include voltage, temperature and current measurement, which are used for charge control. The batteries can be charged and discharged with configurable currents.

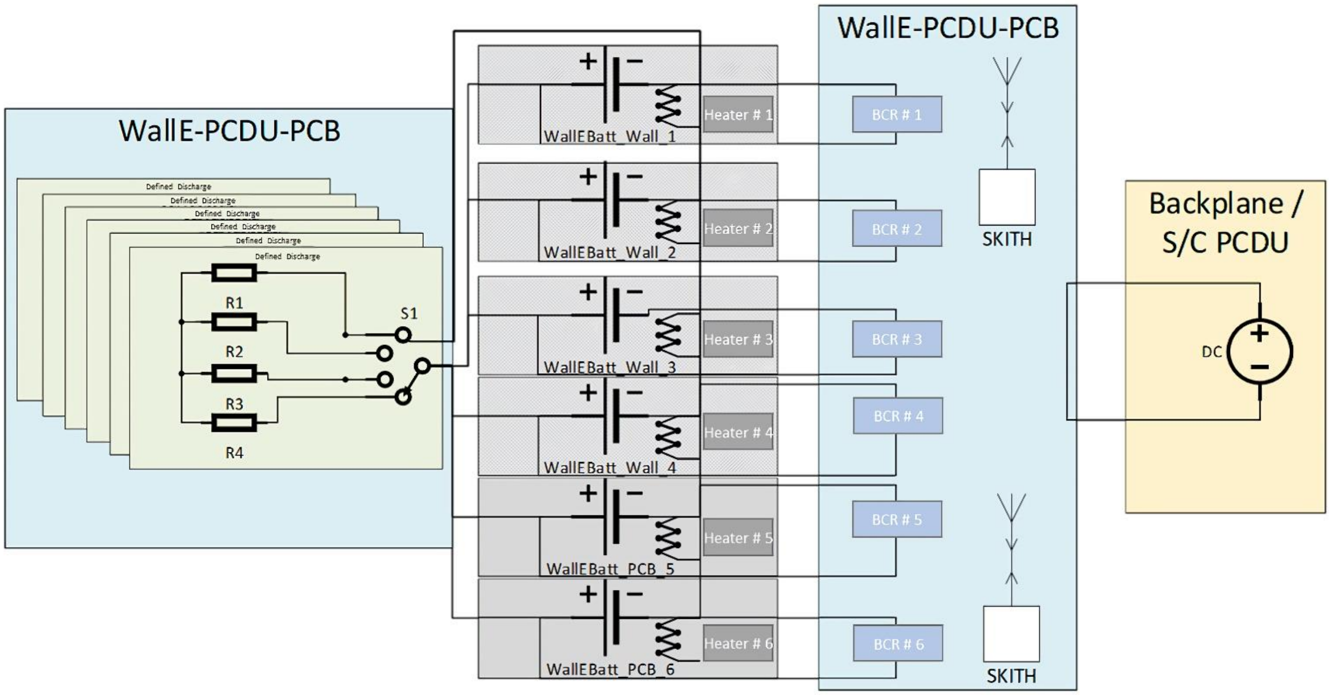

Figure 3: Wall#E-2-Space system diagram.

4.2.1 Experimental battery

The Wall#E-2-Space structural batteries work with functional layers (Figure 4) of a carbon fibre-based cathode with LFP (lithium iron phosphate) as active material, carbon black as conductivity additive and a PEO, lithium metal anode and a separator made of glass fibre coated with PEO and LiTFSi. The functional layers are embedded in a glass fibre layer, the outer layers consist of a layer of GFRP or CFRP. As with standard pouch cells, the cell is contacted via a metal braid that is led to the outside.

Figure 4: schematic structure of Wall#E battery

The dimensions of one battery are approximately 65 mm by 65 mm by 3 mm and can store about 80 mAh. With a density of ~ 2 g/cm³, the weight of the battery is about 30 g. Additionally a 2W heating foil is attached on top of the structural battery to operate at different temperature points. The heater will add another five grams.

On the outer wall, the W2S experimental batteries are attached with four screws and four slots are available for the integration of the electronic board and batteries within the satellite with an installation space of 11.4 mm in a slot.

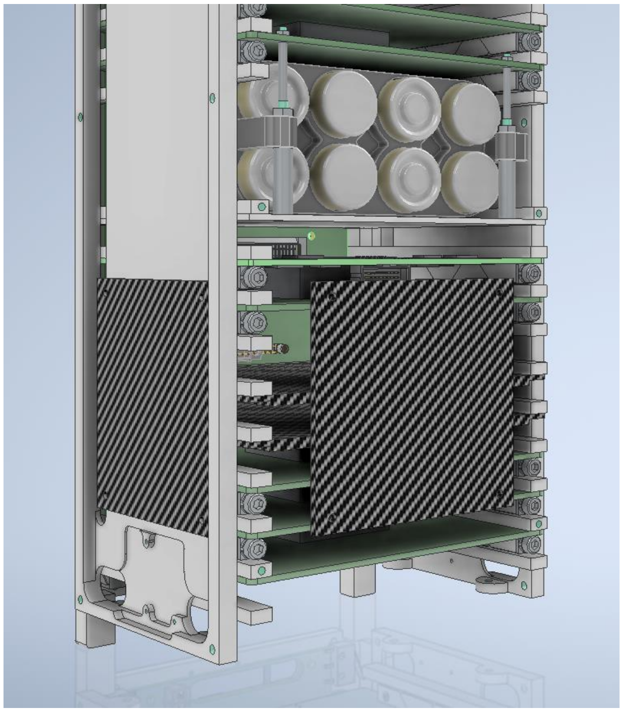

Figure 5: Integration of W2S

4.2.2 Wall#E-2-Space module board

As shown in the simplified system block diagram (Figure 3), the board contains the Skith modules with the antennas in the front board area, charge controllers for the respective structural battery, a temperature control for the heating elements and variable constant current sinks for the controlled discharge of the batteries.

As charge controllers, integrated circuits with programmable battery management and linear charge controllers for single-cell Li-Ion batteries are used. The Skith node running the payload application can change the charging parameters such as battery control voltage and charging current and retrieve detailed information about the device status and errors via the I2C interface. Additionally integrated sensors can measure the charge current, battery thermistor, battery, input, and system voltages. The heater can heat the area of the functional layers and is designed for aerospace applications where low outgassing is required. The supply voltage of 5 V is regulated up to 12 V by using a voltage converter on the board. The maximum power consumption on the satellite power bus is 2.5 W at 5V with the heater switched on.

4.2.3 Payload operations

The concept of the payload operations is in an early state, a broad overview of planned experiments and modes of operation is described. The aim of the experiments is to characterize cell performance, power data, lifetime and cycles under real conditions. Battery data of charge and discharge behaviour is recorded and evaluated at different temperatures and defined load cycles (e.g., 0.1C; 02.C,0.5C, 1C). As an experimental payload, it will be run and used in parallel with the power subsystem. In an initial checkout test a battery is first cycled and electrical parameters are characterized. Subsequently charging and discharging with defined load cases is performed. Finally, the nominal operation should be simulated using the real telemetry of the electrical power system and scale the battery cycle and charge-discharge currents to the W2S capacity.

5 EPISODE

EPISODE is a payload consisting of a GNSS receiver and a miniaturized laser retro-reflector. The goal of the payload is the support in the investigation of space debris. More accurate predictions of the position of the satellite in space shall be enabled, which are a key factor in the reduction of manoeuvring in space. EPISODE addresses this challenge with a navigational experiment consisting of a software-defined GNSS receiver in combination with the highly accurate and independent method of satellite laser ranging. The development of the payload is conducted with the aid of students, using theses and coursework. The corresponding hardware is derived from commercial-off-the-shelf components, which are tested and verified for operating in the space environment. The focus of the payload is adaption and flexibility. The software of the system shall be configurable and updatable in orbit via telecommand. During operations in orbit, different navigational solutions shall be implemented. This way, algorithms can be tested on their performance both in resource utilization and position accuracy. The determined positions will be verified by the simultaneous operation of laser ranging, which is carried out by partnering institutions. The basic operation of the receiver is shown in Figure 6. To determine the position of the satellite, the signal is received by the GNSS front-end, where it is converted into a digital signal and streamed to the multiprocessor-system-on-a-chip (MPSoC). In the programmable logic (PL) block, the signal is matched to the local replica of the unique PRN code of the GPS satellite in view and decoded. The position determination is carried out in the processing system (PS), which sends the determined position to the satellite bus. In operations, the generation of own ephemeris data shall be possible after a couple of weeks. Once a functioning receiver is established, laser ranging experiments will be carried out to characterize of the performance of the payload. The goal is to use different capabilities and evaluate their performance based on precision of determination and power consumption for the use in a future mission of a GNSS laboratory in space, with multiple GNSS sensors, enabling reflectometry.

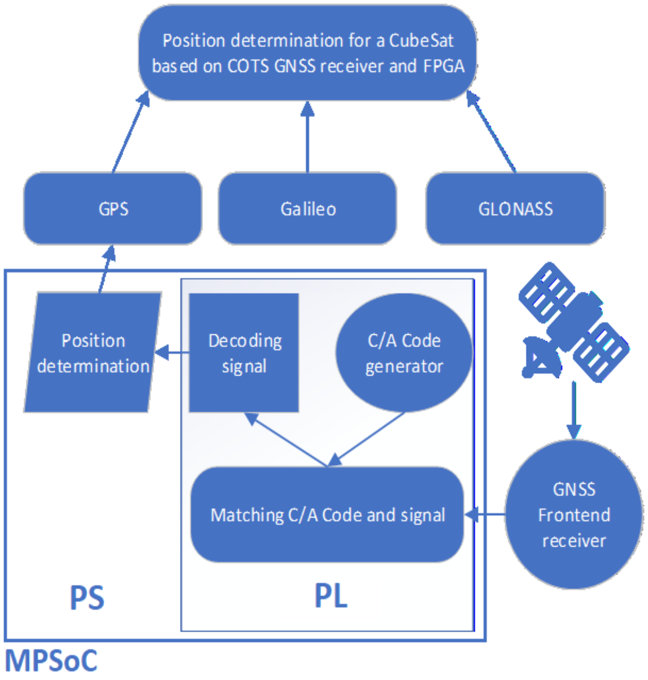

Figure 6: Basic operation and data flow in the processing hardware

5.1 Hardware

The concept of the payload features a commercial front-end high-frequency receiver combined with a heterogenous processing unit containing a FPGA as well as an ARM Cortex processor. With this combination of parallel hardware processing and software flexibility, both strengths of each technology can be exploited. No specialised hardware for the use of space is used to keep the cost of the payload low. For the GNSS receiver, the MAXIM2769 universal front-end receiving chip is used. It has flight experience in some academical missions. The design has been developed in students work based on the open source design of Portland State Aerospace Society [14]. All baseband operations are executed on the chip. Two antennas are paired to the receiver, both operating in the L1 band of around 1.6 GHz. One passive and active antenna is used, with one narrowband antenna capable of GPS and Galileo, the other one being more broad with the additional capacities to receive GLONASS signals. The maxim chip receives the radiowaves and converts them to a lower frequency of 4.092 MHz. As the C/A code modulated onto the GPS signal has a symbol rate of 1.023 Mchips per seconds, this is sufficient for operations. The front-end includes a crystal oscillator with a frequency of 16.368 MHz. The signals are sampled into the in-phase and quadrature components by an analog-digital converter. The raw four-bit datastream is then buffered and passed to the processing unit.

The processing unit, or payload computer, is a commercially available system-on-module heterogenous processing unit, which is the Xilinx Kria K26 SOM. It includes a Zynq Ultrascale+ MPSoC in a low-voltage version with a Vcc of 0.72 V. The processing system of the device consists of a ARM Cortex A53 quad-core with a maximum frequency of 1.3 GHz and a ARM Cortex R5F dual-core with frequency of 533 MHz. The board includes 4 GB, 64 bit-wide DDR4-RAM. The programmable logic of the device consists of 250k logic cells. For interfacing, 127 in-out pins can be used. With a size of the module of 77 by 60 mm, it has a mated height of 15.9 mm. An aluminium heat spreader is mounted on the top of the module. The Zynq processor is prone to cosmic radiation, especially heavy ions [15]. To tackle this, an enclosure of 0.5 mm Wolfram is placed on both sides of the board, covering the Zynq and both connectors and the SD card. This way, the radiation effects are minimized. Additionally, monitoring of all power rails is carried out to quickly detect latch-ups. For system control and interfacing with the satellite bus, EFR32FG12 Flex Gecko wireless controllers are used. A SPI interface is used to transfer the payload data from and to the payload computer, along with GPIOs for enabling different payload operational modes.

5.2 Software

The design of the receiver is software defined. As such, different algorithms shall be implemented during operations, with the possibility to not only change the recording intervals, but also the software operating it. The ARM Cortex A53 is running an embedded operating system. Two options are feasible, with the first one being PetaLinux, which is supported and managed by Xilinx. The second option is to use the RODOS operating system developed by the University of Würzburg. The signal reception is carried out in the front-end, which filters the signal, amplifies it and down converts is to a lower intermediate frequency. The signal is then converted from an analog to a digital and sent as four-bit datastream (I+, I-, Q+, Q-) to the programmable logic block of the processing unit. The programmable logic receives the signals with a voltage of 1.8 V for a logic high. The goal of the hardware processing is to do all baseband processing. A parallel code phase search with a search space for the Doppler shift of 45 kHz shall be implemented in hardware, with the ARM Cortex R5F as a controller. The code generation, matching of the input signal to the generated code and pseudorange calculation can be carried out efficiently using the parallel processing capabilities of an FPGA. The tracking loop shall be able to identify the satellite, determine its shifted frequency, code phase and give a measure of a pseudorange. In the first stages of hardware development, the received data is converted into a serial stream and sent via the Axi Interface to the softcore processor, where an open-source navigational solution, e.g. GNSS-SDR, will be used.

Different open-source algorithms may be used, such as GNSS-SDR, GOOSE or other self-developed algorithms. An application for the system control of the payload computer has been developed in student work as well as a multilateration algorithm, which calculates the position of the satellite based on the pseudorange measurements of at least four satellites.

5.3 CubeLRR


Figure 7: Engineering model of CubeLRR

To ensure a position determination of the GNSS solution and compare the processed data, a laser ranging system is included as a passive secondary payload. The system is a miniaturized laser retro reflector, which is mounted on the nadir pointing cover of the satellite. The ranging experiments will be performed in cooperation with the International Laser Ranging Society as well as different partner universities and institutions. Albeit being constrained to temporal and spatial conditions, a position of an object can be determined with direct terrestrial reference, without ambiguities. The design is based on the successful reflector developed by GFZ Potsdam, called ChampLRR [11]. It has been scaled down to fit the measurements of a 3U+ CubeSat tuna can [11] [13] with an edge length of 34 mm and a height of 15.5 mm, shown in Figure 7. The body is made of Titanium grade 2 to obtain a minimal influence on the thermal conditions on the outside of a satellite in orbit. Four coated 10 mm prisms with flight experience are used.

6 CONCLUSION AND OUTLOOK

The development and transfer of previously investigated innovative new technologies into an application is presented. Using a wireless data bus the satellite system developed demonstrates, verifies and validates the usability and benefits. The use of Skith enables an easily accessible modular structure and the switching of satellite modules within minimum time and effort. To address further research questions for a experimental structural solid state battery a payload for space application is discussed, which should investigate the degradation behaviour and the influence of space conditions on the technology. The challenge is to utilize the small capacity of one cell Wall#E batteries and develop a programmable charging solution capable of a very small charging current. Using a commercial front-end high-frequency receiver combined with a heterogenous processing unit containing a FPGA and an ARM Cortex processor, a SDR GNSS receiver concept gives a high flexibility in the selection of GNSS signals features. An application for the system control of the payload computer has been developed as well as a multilateration algorithm, which calculates the position of the satellite based on the pseudorange measurements of at least four satellites. To verify the GNSS accuracy, a Laser Retro Reflector (LRR) is designed and scaled down to fit to a CubeSat system.

Within the next few months, the hardware will be finalized and tested, undergoing standard procedures required for the verification of a CubeSat. The launch of this project is planned to be in late 2023 or early 2024.

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Acronyms/Abbreviations

BCR – Battery Charge Regulator
CFRP - Carbon fibre reinforced plastics
DLR - German Aerospace Center
DLR-RY – DLR Institute of Space Systems - Avionics Systems
EPISODE - Experiment for Precise Orbit Determination
GNSS - Global Navigation Satellite Systems
GPIO - General Purpose Input/Output
InnoCube - Innovative CubeSat for Education
ISM - Industrial, Scientific and Medical Band
LFP - lithium iron phosphate
LRR - Laser Ranging Reflector (Experiment)
MPPT - maximum power point tracker
MPSoC - multiprocessor-system-on-a-chip
OBC - On Board Computer
OBDH - On Board Data Handling System
PCDU – Power Distribution and conditioning Unit
Skith - SKIpTheHarness
s/c - Spacecraft
UHMW-PE - Ultra-High Molecular Weight Polyethylene

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