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MA61C-SmallSat

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ABSTRACT

The Multipurpose Adapter Generic Interface Connector SmallSat (MA61C-SmallSat) adapter, developed by Space Products and Innovation (SPiN), supports nine interfaces on 28 ports, configuring 11 sensor and actuator groups. The intelligent MA61C-SmallSat is an intermediate layer between satellite electronic components and the onboard computer, facilitating seamless data routing and communication interface adaptation. It was developed for the modular Attitude Determination and Control System (mADCS) project, funded by the European Space Agency (ESA), which aims to create a versatile 'modular-ADCS' subsystem for small satellites. This system integrates the MA61C-SmallSat hardware board, boasting plug-and-play adaptive software for effortless integration and universal ADCS software. The project, informed by Earth observation, telecommunication, and space tug missions, features a flexible attitude control architecture capable of accommodating various scenarios, including spin-stabilised communication satellites and star mapper-based Earth observation missions. This paper details the development and testing of the MA61C-SmallSat board, highlighting the transition of MA61C from the EGSE unit to the SmallSat version and presenting results from the mADCS project testing phase.

MODULAR ADCS

The Smallsat industry is experiencing rapid expansion, primarily emphasising expediting payload deployment into orbit. Consequently, mission designers are inclined towards acquiring off-the-shelf closed-loop systems, eschewing the time-consuming development of control algorithms. As these technology demonstrators progress towards operational status and constellation deployment, the focus remains on swift payload integration akin to CubeSat developers. Thus, a pressing need arises for a fully modular solution encompassing hardware interfaces, software drivers, and attitude control mechanisms to cater to diverse satellite masses and applications. The Modular Attitude Determination and Control System (ADCS) project aims to fulfil this need by developing a 'modular ADCS' subsystem for small satellites, comprising a versatile hardware board (MA61C by SPiN) equipped with seven communication interfaces, plug-and-play adaptive software facilitating device recognition and driver installation, and universal ADCS software provided by TU Munich (TUM).

Reference Missions

For creating modularity it was required to define different reference mission with different requirements that are in the same domain (LEO, small satellites, low cost) that would be candidates for such system. Three reference mission scenarios were selected for the project with the launch customer to establish the modular ADCS system requirements. The set of sensors and actuators for every mission is selected to fulfil the minimum end user needs while keeping the complete functionalities of each mission. [1]

Earth Observation

In the context of Earth observation, the primary mission objective aligns with that of numerous Low Earth Orbit satellites: to conduct imaging operations within designated regions of the planet and subsequently transmit acquired data to ground stations. Due to the heightened sensitivity associated with imaging tasks compared to communication scenarios, a precise pointing accuracy of 0.05 degrees (in nadir pointing mode) is mandated for this reference scenario. Furthermore, considering the anticipated use of an optical camera as the primary payload for this mission, the orbit selection entails a Sun Synchronous Orbit characterised by a circular trajectory at an altitude of approximately 500 kilometres. [1]

Following are the sensors whose inputs will be used in the attitude determination and control system in this scenario:

- Star Tracker
- Magnetometers
- Sun Sensors
- GPS

The actuators to be used in the attitude determination and control system in this scenario are as follows:

- Reaction Wheels
- Magnetorquers

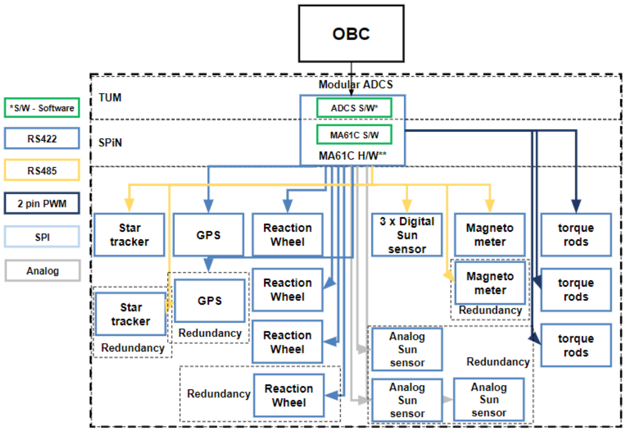


Figure 1: Earth Observation (EO) Reference Mission [1]

Telecommunication

In the communication scenario, the primary aim revolves around positioning the spacecraft, which operates at an altitude higher than that of low Earth orbit (approximately 1200 km), to ensure continuous Earth-facing orientation of the mission payload—in this case, the antenna—resembling typical operations in communication satellites. Various operational modes are envisaged for this scenario, including safe mode, detumble mode, sun pointing mode, deorbit mode, and nadir pointing mode. [1]. Following are the sensors whose inputs will be used in the attitude determination and control system in this scenario:

- Stellar Gyroscope
- Magnetometers
- Sun Sensors

The actuators to be used in the attitude determination and control system in this scenario are as follows:

- Reaction Wheels
- Magnetorquers

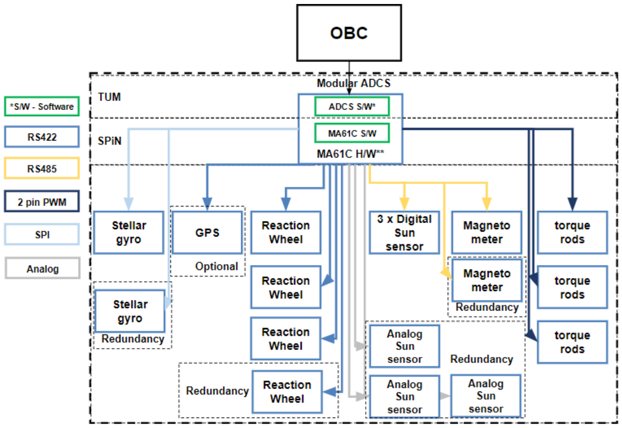


Figure 2:Telecommunication Reference Mission [1]

Space Tug

The Space Tug reference mission aims to transfer the target spacecraft of the tug mission to a specified altitude or orbit. Given that this mission encompasses both in-plane and out-of-plane transfers, a reaction control system equipped with thrusters is imperative. The payload for this mission consists of other spacecraft(s) destined for deployment into their target orbits, necessitating a change in the centre of mass during operation.. [1]

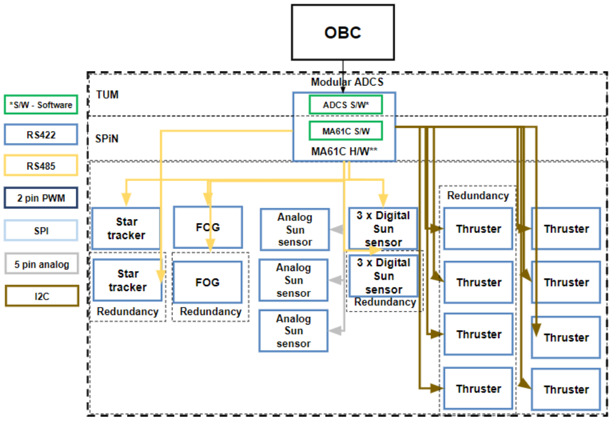


Figure 3: Space Tug Reference Mission [1]

Following are the sensors whose inputs will be used in the attitude determination and control system in this scenario:

- Star Tracker
- Magnetometers
- Sun Sensors
- Fiber-Optic Gyroscope

The actuators to be used in the attitude determination and control system in this scenario are as follows:

- Thrusters (at least four thrusters will be needed for 3axis body control), 8 for redundancy

MA61C-SMALLSAT

The MA61C-SmallSat seamlessly adjusts between communication interface and protocol standards from various suppliers to match the unique standard of the onboard software. This streamlines communication between the SmallSat's onboard software and subsystems, including AOCS sensors and actuators, communication systems, power management, and payload operations. At its core lies the Leon-3FT processor, equipped with SpaceWire, CAN bus, I2C, GPIO, RS4222, RS485, and SPI interfaces, facilitating command and control of subsystems. Except for SPI and I2C, all interfaces serve as inputs and outputs, enhancing flexibility and interoperability. [3]

Gap Analysis

The baseline for the MA61C-SmallSat board shall be MA61C-EGSSE, detailed in [2]. There are some differences in the design of the board. The major hardware differences between the two design versions are explained below.

- The EEE chosen components are not rad-tolerant and shall have rad-tolerant equivalents.
- The PCB board design shall follow IPC3 standards.
- A DC-DC to convert input voltage range to operating voltages (+3.3V DC and +1.8V DC) for memory chips and other peripherals

Changes in Hardware Design and Trade-off

Apart from the updates with rad-components and better design qualification, the interfaces were to be updated according to the requirements of the reference mission. This resulted in the following changes. Justifications of the interfaces on MA61C-SmallSat are mentioned in Table 1. This resulted in the following changes:

- IPC3 standard PCB design, manufacturing, and assembly.
- Dual footprints to have alternative rad-tolerant EEE components.
- Possibility to have the secondary GND of the board connected to the unit structure
- External connection to SpaceWire, CAN, RS422 (full-duplex), RS485 (full-duplex), SPI, I2C, and 11 GPIO
- Two A2D converters interfacing the analogue connections to SPI
- 4 x RS422 (3.3 TTL level) and 1 x RS485 (full-duplex) interface.
- 3 H-bridge ICs to connect to PWM lines
- The connectors for the MA61C are:
    - SpaceWire: MDM9
    - CAN: DSUB9
    - Analog Pins, GPIOs: MDM 37
    - SPI+I2C+PWM: MDM15
    - RS422/RS485: MDM25
    - Power/JTAG: DSUB9

Table 1: MA61C Interface Justification

Interface	Available Ports	Telecommunication	Earth Observation	Space Tugs
RS422	5	5 4 RW, 1GPS	5 4 RW, 1GPS + 1 for Redundancy	0 Not used
RS485	2	2* 1 Magnetometer + 1 for Redundancy, 3 Digital sun sensors + 3 for Redundancy OBC	2* 1 Magnetometer + 1 for Redundancy, 3 Digital sun sensors, 1 Star tracker + 1 for redundancy	2* 3 Digital sun sensors + 3 for Redundancy, 1 Star tracker + 1 for redundancy, 1 FOG + 1 for Redundancy

Interface	Available Ports	Telecommunication	Earth Observation	Space Tugs
		commanding	OBC commanding	OBC commanding
PWM	6	6 3 Torque Rods (2 per Rod)	6 3 Torque Rods (2 per Rod)	0 Not used
SpW	2	2** OBC commanding	2** OBC commanding	2** OBC commanding
Analog	16	15 5 Pins x 3 Analog Sun Sensors	15 5 Pins x 3 Analog Sun Sensors	15 5 Pins x 3 Analog Sun Sensors
CAN	2	2** OBC commanding	2** OBC commanding	2** OBC commanding
SPI Master	1	1 1 Steller Gyro + 1 for redundancy	0 Not used	0 Not used
I2C Master	1	0 Not used	0 Not used	1* 4 Thrusters + 4 for Redundancy

*N&R = Nominal and Redundant

** OBC commanding possible port

PCB and Casing Design

The MA61C-SmllSat assembled PCB is shown in Figure 4 and Figure 5. Table 2 summarises the features of the board.

Table 2: MA61C-SmallSat Features

Parameters	Description
Size	105 mm x 105 mm (without casing) and 110 x 110 mm x 35 mm (with casing)
Weight	150 grams (without casing) and 450 grams (with casing)
Standard	IPC 3
Processor	GR712RC dual-core 32-it fault tolerant LEON3-FT SPARC V8 processor
Clock	50 MHz
Power Supply	+ 3.3 V DC to + 24 V DC input
Interfaces on the board	JTAG, SpaceWire, CAN, RS422, RS85, I2C, SPI Analogue, PWMs, and GPIO
On-board memory	SRAM, FLASH
Port Speed	SpaceWire - Up to 200 Mbit/s, nominal 10Mbit/s MILbus – 1Mbit/s CAN-bus - 1Mbit/s I2C interface - up to 0.4Mbit/s SPI interface - up to 20Mbit/s RS232/RS422/RS485 interfaces - up to 10Mbit/s Debug port - 1 Mbit/s

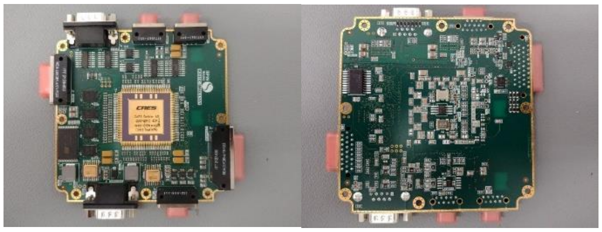


Figure 4: MA61C-SmallSat Top and Bottom Layer

Figure 5: MA61C-SmallSat with Casing

The MA61C-SmallSat casing is shown in Figure 6 and Figure 7. It is made of Aluminium 6061. The railing holes of MA61C-SmallSat are also grounded; therefore, when the hardware is connected to the casing, the structure is automatically connected to the secondary ground of the board. There will be two changes in the upcoming casing design for the QM version:

- Adding an external chassis point to connect the structure to the satellite structure,
- Upgrading the design to add tiny holes around the casing for pressure equalisation.

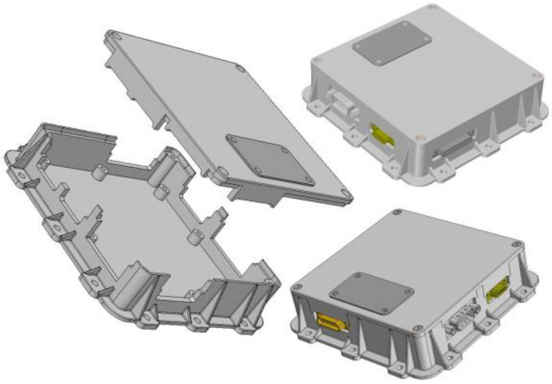


Figure 6: MA61C-SmallSat Casing View (1)

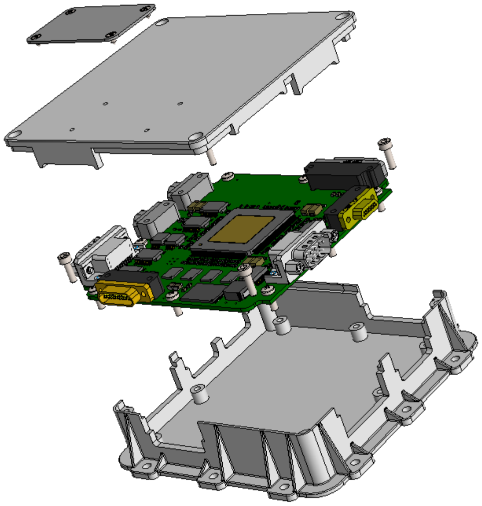


Figure 7: MA61C-SmallSat Casing View (2)

MA61C-Software

On the software side, protocol definitions from subsystem datasheets are analysed and converted into electronic data sheets (EDS), setting up drivers and updating the database. The MA61C firmware acts as an abstraction layer between applications and hardware, supporting multiple parallel applications and containing databases for telecommand, telemetry, configuration settings, packet composition, and ADCS calibration values. EDS are written in JSON, facilitating easy processing by languages like C and Python. The processing software, written in Python, converts EDS into a format compatible with onboard software. Protocol definitions, encapsulated within different embedded protocols, specify interface types, interaction methods, character encoding, and packet structures. The MA61C API aids application software in command, telemetry, and settings management, while a GUI provides a user-friendly interface for commanding and monitoring subsystems, verifying them with the MA61C unit before integration. The functional design includes diagrams illustrating command issuance and telemetry collection within the MA61C SmallSat unit framework. Detailed working and explanation of MA61C-Software can be found in [1], [2], and [5]

TEST AND VERIFICATION

In the Modular ADCS project, three different mission scenarios exist. Independent of the scenario type, the system test setup includes the following components:

Figure 8 shows the device under test. It is the mADCS node, which consists of MA61C-SmallSat hardware + MA61C-SmallSat software, hosting an external ADCS software. .

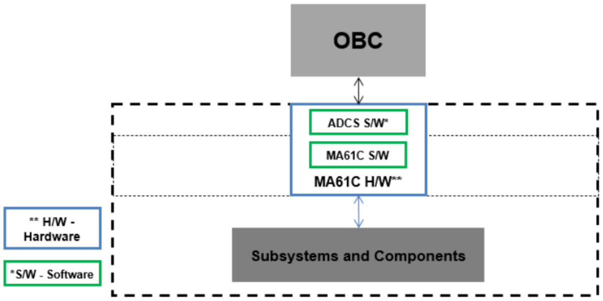


Figure 8: mADCS Node Schematics [4]

- TUM Simulation Desktop: Acts as a simulator for testing, connected remotely to the SPiN Test Desktop.

- SPiN Test Desktop manages test cases and is a hub for the Modular ADCS MA61C Node, MA61C EGSE, and Arduino.

- MA61C EGSE: Functions as an engineering model, connecting equipment via RS485 and RS422 interfaces.

- MA61C Modular ADCS Node: As explained before, it is the primary device under test, with TUM software uploaded for evaluation.

The details of the test setup are provided in [1].

Results

The steps followed during the test and verification are

- Test and verification of MA61C-SmallSat hardware.
- Integration of MA61C-Software to MA61C-SmallSat.
- Functional test to verify the working of MA61C with emulated sensors/actuators.
- Hardware in the Loop (HiL) and Software in the Loop (SiL) tests for earth observation, telecommunication, and space tug reference missions.

The details of emulated sensors/actuators and HiL results are provided in [1] and [4].

MA61C-SmallSat Hardware Test

Before getting into functional tests, a large amount of analyses were performed on the MA61C-SmallSat hardware to make sure that the electrical parameters worked as per design before integrating MA61C-Software into it and performing functional tests. The power consumption, frequency, and basic interface communication tests (for SpaceWire, CAN, I2C, RS422, RS485, SPI, PWMs, and GPIO) are performed in this stage. Figure 9 and Figure 10 showcase the test setups for electrical tests, and Table 3 shows the power consumption for the MA61C-SmallSat device.

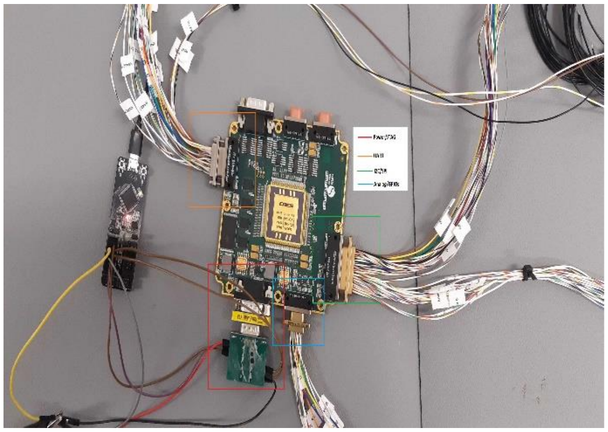


Figure 9: Test Setup with MA61C for Board Level Testing (1)

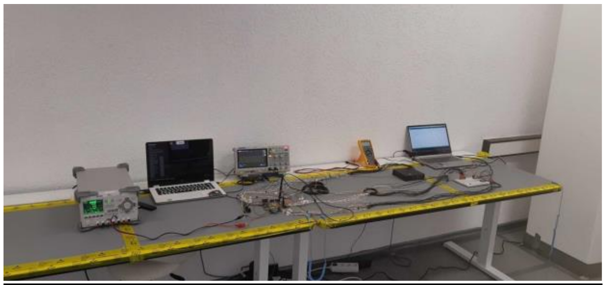


Figure 10: Test Setup with MA61C for Board Level Testing (2)

Table 3: MA61C-SmallSat Power Consumption

Power Consumption of MA61C ADCS Board	Values
Without software	5 V, 190 mA
After the software loaded	5 V, 290 mA

MA61C-Hardware + MA61C-Software integration Test

Three main tests were performed after integration.

- Test to measure the integrated software's frequency run, cycle time, and memory size.
- Test to verify the ability of the MA61C-Software to deliver.
    - Send data to actuator
    - Receiver data from actuator
    - Convert between protocol and format of the sensors and actuators to the type of data by the ADCS software
    - Optional which type of data format (raw or converted)

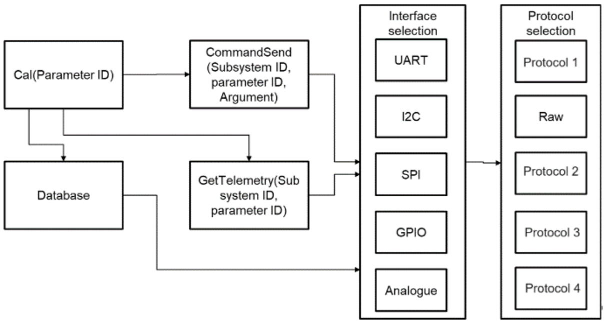


Figure 11: Schematic Showing the Working of MA61C-Software

- Test to measure and record the response time between sending a command and receiving telemetry for each defined sensor and actuator in reference missions. The sensors are disconnected and connected, and the response times after connection and disconnection time are recorded.

mADCS System Test (MA61C-SmallSat Hardware + MA61C-Software + ADCS software)

Figure 12 and Figure 13 show the test setup. It includes the mADCS node, along with MA61C EGSE and Arduino, which hold the simulated equipment models. In this project phase, about 13 separate test cases were created for system tests, and only a part of them will be explained in this paper.

Figure 12: Test Setup with MA61C-SmallSat for Initial Functional Testing (1)

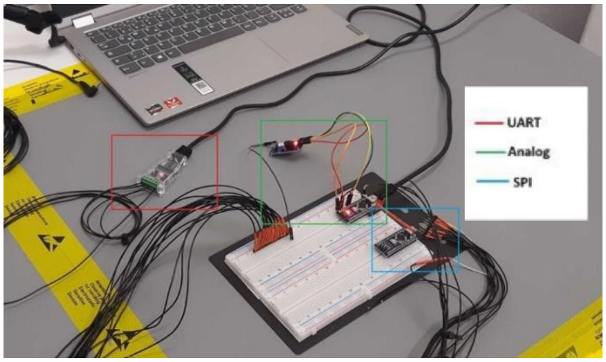


Figure 13: Test Setup with MA61C-SmallSat for Initial Functional Testing (2)

Timing Test and External Commandability

Here, the time required to get the sensor data is measured. The smaller values represent the calibration timing, significantly lower than the acquisition timing. According to the results, average times in microseconds to get the sensor data are:

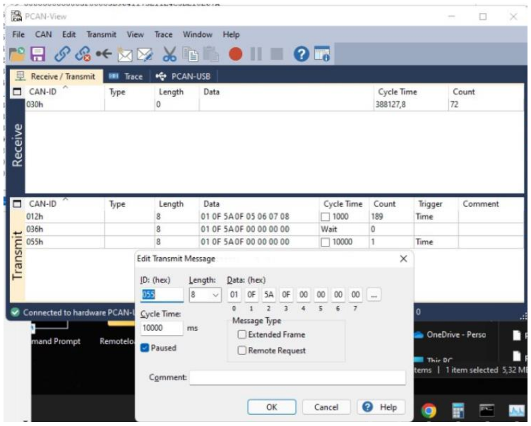
- FSS, MTR and STR: 74.31 ms
- Photodiodes: 41.62 ms
- GPS: 12.17 ms
- FOG: 11.55 ms

The timing to send the actuator TC is

- RW, MTR and Thrusters: 3.50 ms

For the maximum TMTC chain, in which data is taken from either FSS, MTR, or STR and sent to any actuator, the timing is around 77.81 ms, which is lower than the 100 ms specified in the requirement.

The commandability to change modes externally is tested. For this test case, the CAN interface has been used as a commanding interface for external commanding. The PCAN-View software is used with the PEAK CAN to USB converter, connecting the mADCS node to the EGSE remote desktop.



CAN-ID	Type	Length	Data	Cycle Time	Count
030h		0		388127,8	72

CAN-ID	Type	Length	Data	Cycle Time	Count	Trigger	Comment
012h		8	01 0F 5A 0F 05 06 07 08	☐ 1000	189	Time	
036h		8	01 0F 5A 0F 00 00 00 00	Wait	0		
055h		8	01 0F 5A 0F 00 00 00 00	☐ 10000	1	Time	

ID: (hex) 055
Length: 8
Data: (hex) 01 0F 5A 0F 00 00 00 00
Cycle Time: 10000 ms
☑ Paused
Message Type
☐ Extended Frame
☐ Remote Request
Comment:

Connected to hardware PCAN-

Figure 14: External Commandability Test of the System

Figure 14 shows the message that is transmitted. The data representation is as follows:

- Data 0: 01 corresponds to adapter directly, to command equipment directly, 02 can be used (which is shown in another test case)
- Data 1: 0F corresponds to the id of the adapter

- Data 2: 5A is the command id used internally, which is 90 in decimal.

- Data 3: 0F is the desired command which is mode number 15

Another important test was sending commands and retrieving telemetry to/from all simulated models (saved in MA61C-EGSE) to verify the correct response according to the ICD. The schematic of this test is shown in Figure 15. The following few examples will detail the tests performed on all the different ports of the mADCS node.

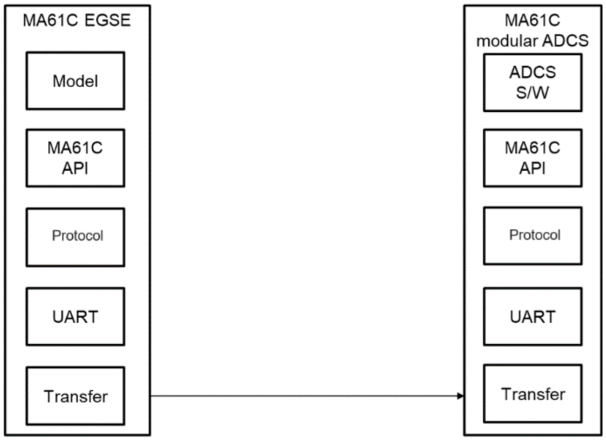
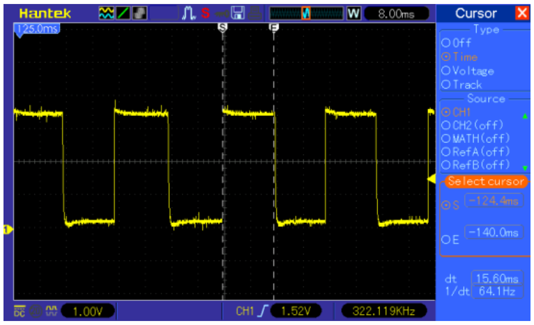


Figure 15: Schematic Showing the Connection Between MA61C-Software and MA61C-EGSE

Magnetorquer (PWM)

Channel 1 (%50 Duty Cycle with 30 ms signal length):

Assessment for PWM Signals: Figure 16 clearly shows that the Modular ADCS Board can adjust the duty cycle for desired applications such as controlling magnetorquers. The rise and fall time of the PWM signals are 5 ms, which is significantly long for high-frequency applications.



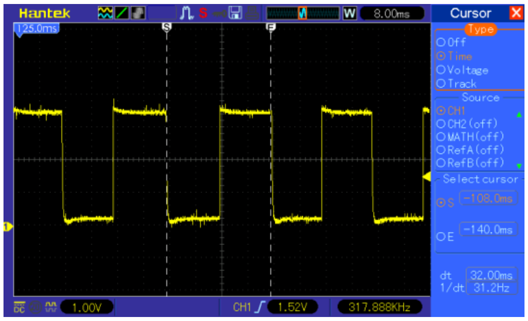


Figure 16: 50% Duty Cycle Oscilloscope Measurement

Coarse Sun Sensor (Analog input to the mADCS board)

For an input voltage of 0. 1.968 V, the measured output is given below in Figure 17.

```
Which Channel?
C:4
V:1.96459
V:1.95238
V:1.95482
V:1.95299
V:1.95177
Which Channel?
```

Figure 17: Analog Input Measurements

For analogue input channels, received voltage values from the Modular ADCS board differ from the actual amounts by around 1% on average, which is an acceptable amount of error that the ADCS software can compensate for.

Star Tracker (STR) and Thrusters (I2C)

Star Tracker sends the data as quaternions in decimal and hexadecimal using the I2C protocol connected to Arduino (data is encapsulated according to one of the subsystem protocols). The MA61C-SmallSat board, integrated with the software, calculates the quaternion values (raw data) produced by the star tracker equipment model and processed in Arduino.

Thrusters are actuators that only receive data. The thrusters with I2C in the reference mission only have on/off commands without any protocols. This verification is also applicable to the thrusters to demonstrate communication on I2C.

Fine Sun Sensor (FSS), Magnetometer (MTM), and Fiber Optic Gyro (FOG) (RS485)

The FSS and MTM parameters are sent from MA61C EGSE, that holds FSS and MTM equipment models to the Modular ADCS board. When related subsystem is selected, the data sent from the sensor equipment model changes accordingly. First, FSS subsystem is selected, and raw data comes directly from RS-485 is read by the Modular ADCS board. Then, the raw data is calibrated into the location of the sun in the sun vectors. On the second part, magnetometer is selected as the subsystem and similar to FSS, raw data that is created by MTM equipment model and flown through the RS-485 interface is read by the board. Again, raw data is calibrated into magnetic field values of Earth in nT. The same process is followed for Fiber-optic gyro, which uses the same interface (RS-485) and outputs the angular rate of the satellite.

GPS Receiver and Reaction Wheels (RS422)

The Modular ADCS board requests the GPS Receiver's data by sending it to the appropriate TC specified in the GPS Receiver. Since the reaction wheels use exactly the same data interface and formatting to receive TC's, it is seen sufficient only to test the GPS receiver in this test case because reaction wheels do not send a specific type of TM, unlike GPS Receivers. The hexadecimal data taken from the equipment model is being processed in the Modular ADCS board and converted into meaningful parameters for ADCS software, which is position and velocity vectors. Like I2C, hexadecimal data is being sent to Arduino from MA61C EGSE. It is being sent from port 4 of EGSE to Arduino.

HiL and SiL Tests

The mADCS project results were divided into simulative validation of the ADCS software and HiL tests with MA61C hardware (Figure 18 and Figure 19). The SiL test, performed at an external lab, provided inputs for the HiL tests.

Comparison showed that the error norm between true and estimated attitude stayed below 0.3°, indicating successful attitude estimation. The error between desired and estimated attitude was high but showed a converging trend (Figure 20). Reaction wheel torque comparisons revealed slight deviations due to hardware-induced delays and single-precision telemetry. The details of these results, limitations in the output, and lessons learnt are explained in [1].

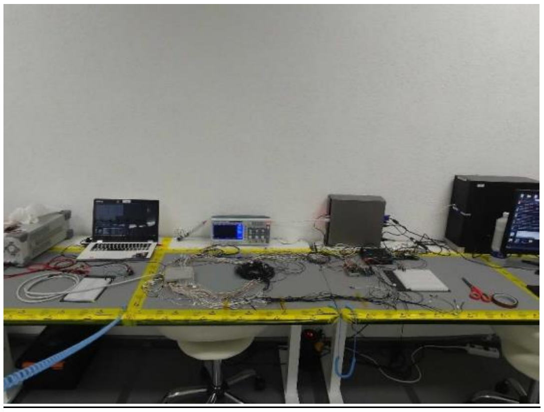


Figure 18: Test Setup for Earth Observation Simulation [1]

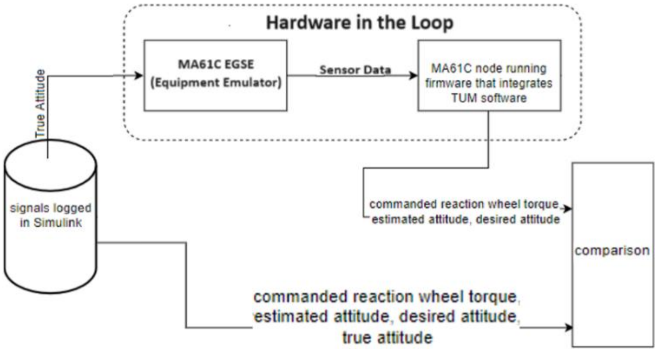


Figure 19: Test Setup in HiL and SiL [1] [4]

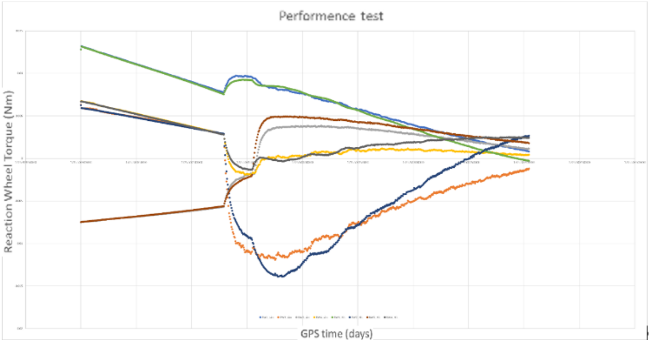


Figure 20: HiL vs SiL Result (Reaction Wheel Torque (Nm) vs GPS Time (days)) [1] [4]

FUTURE WORK

This project resulted in many lessons learned in different aspects of the study. Future work on the ADCS software, HiL, and FDIR is outside the scope of this paper. Below are the four points realised for the MA61C-SmallSat hardware upgrade for the next phase of the mADCS project.

- RS422/RS485 Transceiver: There was an issue with one of the UART ports (UART 6 or RS422/RS485 dual port), which did not work as required. Due to redundancy in the hardware design, the other 5 UART ports were considered. This will be tested and validated in the next upgrade of the design.

- Shielded Cables: During some setups, shielded cables or a ground connection to the structure were required to reduce noise in the JTAG interface. After some analysis, it was understood that additional ground points needed to be added to the Power/JTAG connector. This will be updated in the next version of the MA61C-SmallSat design.

- Multi-Dropping: Because multi-drop in UART (RS422 and RS485) ports is not possible, hot redundancy of components was not checked. For example, when two Star Trackers are connected on the same RS485 line, the redundant one is switched off while talking to the nominal one and vice versa. This will be updated in the future MA61C-SmallSat to have the multi-drop capability with the UART lines.

- Casing Upgrade: In the next phase, the casing design for the QM will be upgraded with a grounding point connecting the structure to the satellite structure and tiny holes for pressure equalisation.

CONCLUSION

The attitude control architecture developed for this project is designed to be both modular and flexible, supporting various mission scenarios, including spin-stabilised, momentum-biased communications satellites and star mapper-based Earth observation missions. Over a six-week test campaign, the MA61C-SmallSat progressed from Technology Readiness Level (TRL) 2 to TRL 5. The system's capability and performance were thoroughly validated through over 30 test cases. These tests included rigorous pointing performance assessments of the ADCS software and evaluations of the Fault Detection, Isolation, and Recovery (FDIR) algorithms, demonstrating the system's ability to detect, isolate, and reboot sensors and actuators. Interface tests involved concurrently using multiple equipment interfaces and data routing between them, and configurable interface tests were conducted for both the On Board Computer (OBC) and equipment. RS422, RS485, I2C, SPI, CAN, and GPIOs from the MA61C-SmallSat board were utilised during verification.

The MA61C software's plug-and-play capability was enhanced to recognise new providers' equipment, simplifying the testing and integration of the complex ADCS subsystem. The ADCS software developed by TUM was incrementally improved to support multi-sensor and actuator configurations, defined by three reference missions covering most current satellite projects.

In the next phase, the system and the MA61C-SmallSat will be developed as a Qualification Model (QM) and tested in an operational environment to reach TRL 7. This stage will include environmental testing for the hardware and simulated environment testing for the sensor inputs. Additionally, adjustments and upgrades will be made to the hardware and software designs to address minor mismatches identified during testing. These improvements will resolve incompatibilities encountered during software integration and issues with one RS422/RS485 transceiver design.

References

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