Streamlining Sounding Rocket Avionics: Preliminary Design for a Scalable and Modular Distributed System for Liquid Bi-Propellant Rockets

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November 6, 2023

Abstract - This research paper presents the development of a scalable and modular distributed avionics system for liquid bi-propellant rockets, utilizing low-cost hardware and commercial off-the-shelf (COTS) components. The primary focus of this study is to address the challenges of conventional systems, including high costs, limited scalability, and inaccessibility of space-grade electronics. Through extensive experimentation and testing, we have successfully validated the performance, functionality, and reliability of our avionics system. By employing a design approach that emphasizes standardization, simplification, integration, and optimization, we have created a cost-effective, reliable, and adaptable avionics solution for amateur and semi-professional rocketry applications. The paper outlines the system design, testing methodologies, and highlights the successful validation of our hypothesis through rigorous testing. We present the results of G-loading tests, CAN BUS communication tests, temperature and humidity validation, and the overall functionality of the system. Through this research, we have made significant progress in advancing the field of modular avionics systems for liquid bi-propellant rockets and have demonstrated the potential for efficient and accessible rocket technologies in various mission scenarios.

I. BACKGROUND

Sounding rockets have long been used for scientific experiments in microgravity, atmospheric research, and other space exploration applications[1]. However, the avionics systems for these rockets can be complex and expensive. Therefore, our challenge was to design an accessible, low-cost, and scalable system that utilizes commercial off-the-shelf (COTS) components for use in amateur and semi-professional rocketry.

The key limitations of conventional systems are the inaccessibility of space-grade electronics, high costs, and limited scalability of these systems.

II. INTRODUCTION

We aim to develop a scalable and modular distributed avionics system for liquid bi-propellant rockets that is built with low-cost hardware and COTS components while maintaining high reliability.

The scalable design for a modular system is built upon both the needs of our mission, and from reviewing past research, It is heavily inspired by Kawase, M. et al. at JAXA[2] who propose that a modular system is beneficial and can be achieved using common control, power, and network elements that allow for scalability and type commonality.

The mission definition and system testing architecture is inspired by the work of the US Air

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[1] Collins, K. N., Burt, A. O., & Moser, M. D. (2010). A Student Approach to Rocket Design. In 46th AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit (pp. 1-10). Nashville, TN.

[2] Kawase, M., Tamura, M., Sunami, K., Izumi, T., & Morita, Y. (2008). The avionics system design concepts for the advanced solid rocket. Acta Astronautica, 63(7-10), 1226-1231. doi:10.1016/j.actaastro.2008.05.002

Force Academy[3], but streamlined for a more specific and tangible system design approach.

The specific choices for the common elements are based on the mission requirements of the sounding rocket it is designed in mind, Halya, namely the high-g tolerance, vibration tolerance, temperature tolerance, humidity, and the ability to complete the mission profile.

III. HYPOTHESIS

Our hypothesis is that it is possible to design and build a modular avionics system for a liquid bipropellant rocket using low-cost hardware and Commercial Off-The-Shelf (COTS) components. This system should enable continuous monitoring throughout the rocket's mission trajectory, endure heavy landings, and facilitate location and recovery. We aim to investigate the ways to create an electronics system capable of monitoring a 2000 lbf engine, withstanding 17 Gs, being cost-efficient, vibration-resistant, and maintaining reliable communication with ground stations, while adhering to the principles of modularity and scalability[4].

IV. REQUIREMENTS

The objective of our research was to streamline the avionics of sounding rockets by developing a scalable, modular, and cost-effective distributed system for liquid bi-propellant rockets using COTS components. Our primary focus was on meeting four critical requirements that a rocket must withstand. The first requirement was to endure harsh environments, including extreme temperatures, humidity, vibration, and high-g. The second requirement was to integrate a myriad of sensors and ensure a high sensor read rate, which is necessary for gathering accurate data. The third requirement was to establish reliable communication between the rocket and the ground station using various standard[5] communication protocols, such as CAN, Serial, I2C, SPI, WiFi, and LoRa. Lastly, the fourth requirement was to enable the rocket to transition seamlessly between programmed system states.

V. METHOD

To achieve these requirements, we set four primary goals for our system. The first goal was to standardize the components across all boards by using common components that have been tried and tested. This approach ensured consistency and compatibility between different boards. The second goal was to simplify the system by minimizing unnecessary redundant components and making upgrades or replacements simple. This step ensured the system's efficiency and maintainability. The third goal was to enable easy integration and verification of hardware to ensure that it works as expected. This approach provided confidence in the system's functionality. The fourth goal was to optimize the system by avoiding over-design, adding redundancy where possible, and mitigating where not feasible. This step ensured the system's reliability and cost-effectiveness.

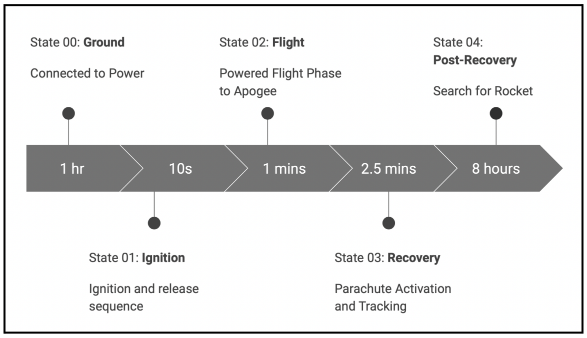

Figure 1: Expected Mission Profile

To validate our hypothesis and assess the performance of our avionics system, we will conduct

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[3] Siegenthaler, K. E., Sellers, J. J., Miller, D. A., Lawrence, T. J., Richie, D. J., et al. (2004). The Undergraduate Satellite and Rocket Design, Fabrication and Launch Program at the US Air Force Academy. In 33rd International Symposium IGIP / IEEE / ASEE 2004 (pp. 1-5). Fribourg, Switzerland: Department of Astronautics, United States Air Force Academy.

[4] Tarrant, C., & Crook, J. (1997). MODULAR ROCKET ENGINE CONTROL SOFTWARE (MRECS). Lockheed Martin Space Mission Systems & Services.

[5] S. Masimore, "A Distributed Avionics Software Platform for a Liquid-Fueled Rocket," Master's thesis, University of Texas at Austin, 2020.

a series of tests addressing the hardware reliability, sensor read rates, communication reliability, and system state transition requirements.

Tests:	Verification:	Location:
Hardware reliability	Environmental Tests (High G, Vibration, Humidity, Temperature)	CMRR
Sensor and System Read Rate (Sensor rate min of 100Hz, ideal 200Hz)	Running all sensors/simulated sensors across all sensor boards and measuring the number of readings obtained within 1000ms, and over 2X of the mission profile (15 minutes)	SEDS Workspace
Comms Reliability	Measure the percentage of communication messages received/sent over 2X of the mission profile (15 minutes), over WiFi and CAN	SEDS Workspace
System State Transition	Verify hardware priority at each system state is adhered to using Hardware-in-the-Loop (HIL) testing	SEDS Workspace

Table 1: Overview of Tests and Validation

These tests will provide valuable insights into the performance, durability, and reliability of the avionics system. By thoroughly analyzing the test results, we can refine the system design and ensure its suitability for the intended application.

VI. SYSTEM DESIGN

Our system design focuses on standardization, simplification, integration, and optimization to create a cost-effective, modular avionics system using low-cost hardware and COTS components. The design choices were made based on the mission requirements and the factors discussed in methods.

Standardization

Based on our requirements, several options for standardizing the common connector system was identified. For our modular avionics system, the connector should be able to carry both power, CAN and other GPIO.

CAN Connector	Pros	Cons
D-Sub Mini	Low Cost, Metal Case, Screw-on, High pin current capacity[6]	Bulkier
Registered Jack	Low Cost, Clip-on for easy connect or disconnect	Plastic Case, Low current per pin capacity
Molex Latched Connectors	Clip-on for easy connect or disconnect	Medium Cost compared to above
TE Connectivity Satellite Mil-spec cables[7]	Metal Case, Screw-on, High Pin current capacity	Much Higher Cost compared to other options

Table 2: CAN Connector Evaluation

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[6] "DB25-PD datasheet - Specifications: Connector Type: D Sub; Series: DPD; For Use With," DigChip, 2023. [Online]. Available: https://www.digchip.com/datasheets/parts/datasheet/2136/DB25-PD.php#:~:text=Electrical%3A%20Operating%20voltage%3A%20%2F%20DC,max.%20Current%20rating%3A%205%20Amps%20max.

[7] "List of Microdot Models & Products | TE Connectivity," TE Connectivity, 2023. [Online]. Available: https://www.te.com/usa-en/plp/microdot/ZndK.html.

Each of these options has its own advantages and disadvantages, and the choice of connector will depend on factors such as budget, durability requirements, and ease of use. Considering the low-cost hardware and COTS components approach in our hypothesis, options like D-Sub Mini and Registered Jack could be more suitable. However, the final decision, taking into account the specific requirements of the avionics system and the mission profile, was the D-Sub Mini 25 pin connector..

Simplification

By using a single merged power and CAN bus, we reduce the complexity of connections, leading to fewer potential points of failure. The modular nature of the system allows for effortless integration of components, making it easy to add or remove elements as needed. We may be able to reduce power requirements after testing, as including capacitors for solenoids and e-match relays will reduce stress on the power supply during key points of the mission profile. This streamlined approach ensures scalability, allowing the system to grow and adapt to various mission requirements and rocket sizes.

Integration

Our design aims to integrate all essential components into a single system, enabling seamless communication and functionality. With standardized PCB boards and mounting positions, we can easily incorporate new modules as needed. The flexibility of the CAN protocol promotes scalability by providing a versatile platform that can accommodate various mission objectives and payloads. The user-friendly nature of the design ensures that integrating new components is straightforward, supporting the evolution of the system over time.

Optimization

The system design focuses on identifying ways to reduce costs or redundant parts that do not add safety. By using a robust standardized connector and adhering to internal standards, we can optimize the manufacturing process and streamline the assembly of the avionics system. This approach allows for easier maintenance and upgrades, ensuring a reliable and cost-effective solution for liquid bi-propellant rockets. The adaptability of the system enables rapid response to new requirements, enhancing scalability and ensuring that our avionics solution remains relevant and valuable in a wide range of applications.

VII. EXPERIMENTATION

PCB Fabrication and Assembly

This section provides an overview of the three printed circuit boards (PCBs) that were fabricated as part of our research project. The PCBs were designed with specific objectives in mind and played a crucial role in advancing our design from concept to reality. Each board served a distinct purpose and contributed to the comprehensive evaluation of our design's performance under real-world conditions. The following subsections provide detailed descriptions of each PCB, highlighting their key features and functionalities.

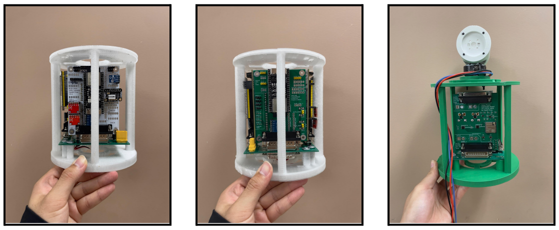
(a) (b) (c)

Figure 2: a) HIL Board in enclosure, b) DAQ Board in enclosure, c) SMD Power Board in enclosure

Board 1 - HIL Validation Board:

The first board, designed for Hardware in the Loop (HIL) validation, featured a 32G accelerometer (LSM6DSO32) for dynamic force measurement, a humidity and temperature sensor (AHT10) for environmental monitoring, and provisions for up to 16 digital-to-analog converters (DACs) with two 8-channel I2C multiplexers. For CAN communication, the board utilized the ESP32S3 microcontroller, which integrated a CAN controller. It employed the SN65HVD230 CAN transceiver to enable seamless data transfer and system integration during the HIL validation process.

Board 2 - Data Acquisition (DAQ) Board:

The second board was dedicated to efficient data acquisition. It incorporated wireless communication capabilities for remote data transmission. Data acquisition was facilitated by an ADC ADS1115 chip. Similar to Board 1, the board employed the ESP32S3 microcontroller with a built-in CAN controller. CAN communication was established using the SN65HVD230 CAN transceiver, ensuring compatibility and smooth integration with other system components.

Board 3 - SMD Power Monitoring Board:

The third board adopted a fully Surface Mount Device (SMD) design and focused on power monitoring and distribution. It featured two INA260 modules for precise power monitoring, enabling accurate measurement and analysis of power consumption. The board included dual XT90s and dual XT60s connectors for efficient input connections. To ensure reliable operation, robust transient voltage suppression measures were implemented. Power usage data was communicated through the ESP32S3 microcontroller, leveraging its built-in CAN controller. The MAX33041E CAN transceiver was used for effective monitoring and control of power-related parameters.

The design and fabrication of these three PCBs played a critical role in evaluating the performance, functionality, and reliability of our design in real-world scenarios. The subsequent sections of this paper provide detailed insights into the design considerations, fabrication processes, and performance evaluations of each board, highlighting their individual contributions to our research objectives.

Sensor, Communication, and HIL Validation:

After the PCBs are assembled, we will validate the functionality of the sensors, communication systems, and conduct Hardware-in-the-Loop (HIL) testing. This process will help us verify that our avionics system can accurately monitor and control the rocket's performance throughout its mission trajectory while withstanding the harsh environmental conditions it will encounter.

Environmental and Additional Testing:

In accordance with the methods outlined earlier, we will perform environmental and other necessary tests to ensure the system's reliability and robustness. These tests will include high G, vibration, humidity, and temperature tests to confirm the avionics system's resilience under extreme conditions. By conducting these tests, we can assess the effectiveness of our design choices and determine if our system meets the requirements set forth in our hypothesis.

Through these future steps, we aim to validate our hypothesis and demonstrate the potential of our cost-effective, modular, and scalable avionics system for liquid bi-propellant rockets.

Software:

The software development for the avionics system involved using the Arduino IDE and writing programs in C++[8]. This allowed for embedded programming on the microcontrollers of the PCBs. The Arduino IDE provided a convenient development environment for compiling and uploading the code to the microcontrollers.

Data recording was implemented using Python along with the Pyserial library. Pyserial was utilized to intercept the serial print output from the microcontrollers and record the data in real-time. This approach facilitated the collection of sensor readings, system status, and other relevant information during testing and operation.

G-loading:

To assess the avionics system's ability to withstand high G-forces, both manual and automated testing methods were employed. For manual testing, a secure attachment point in the form of our DB-25 attachment point was used. Our device was rotated at high velocity to induce centripetal acceleration at a radius of 40cm. The target G-loading was set at 20G, and although the system achieved a continuous reading of 15G, it occasionally peaked above the target threshold.

For automated testing, a balanced arm was utilized, with the PCB attached on one side. The arm was spun using a brushless motor, generating centrifugal

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[8] "Installing ESP32 in Arduino IDE," Espressif Systems, [Online]. Available: https://espressif-docs.readthedocs-hosted.com/projects/arduino-esp32/en/latest/installing.html.

forces. However, the automated testing approach only achieved an effective G-loading of 5G, falling short of the target of 20G. Further improvements may be necessary to achieve the desired G-loading during automated testing.

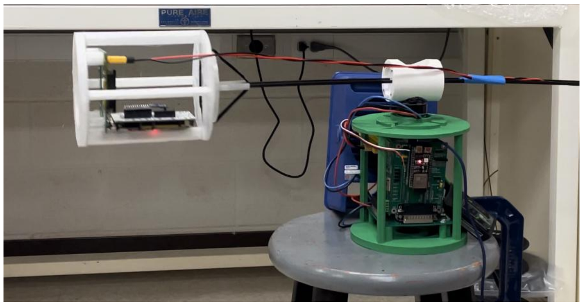


Figure 3: Automatic G-Load Equipment

In both manual and automated G-loading tests, it is important to note that the information collected by the avionics system during these tests was transmitted wirelessly over Wi-Fi to a receiving board. This wireless transmission was implemented due to the logistical challenges associated with testing a spinning object.

CAN BUS:

The avionics system employed the TWAI library, which implements the CAN 2.0 protocol. The CAN messages consisted of a message ID and 8 data packets, each with a length of 32 bytes (256 bits). To ensure efficient data transfer and processing, the data precision was limited to a specific operational range, optimizing the use of resources and maintaining data integrity.

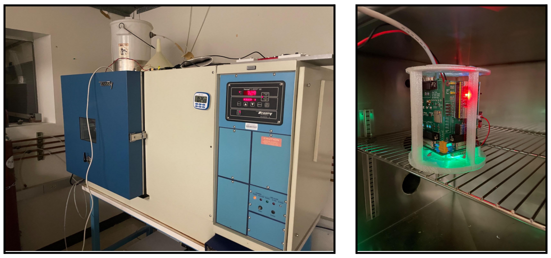
With the current implementation using an open source Real-Time Operating System (RTOS) known as FreeRTOS[9], the avionics system was capable of sending or receiving a CAN message within 1 millisecond (ms), providing a fast and responsive communication interface. In order to simulate Hardware-in-the-Loop (HIL) scenarios, the system was tested with 2, 3, 4, and 5 devices communicating over the CAN bus, evaluating the performance and reliability of the communication protocol.

To ensure reliable data transmission, each CAN message was assigned a counter. By comparing the received message counter with the expected counter value, the system could detect any signal skips or missed messages, allowing for efficient error detection and recovery during data exchange.

Temperature and Humidity:

Temperature testing involved subjecting the avionics system to a maximum temperature of 75 degrees Celsius, which was chosen as it was the highest temperature before the 3D printed structure made from PETG (Polyethylene Terephthalate Glycol) would warp. This temperature was considered to be slightly above the most extreme condition that the avionics system might encounter at a launch site in the Mojave Desert (highest unofficial record[10] of 51 ℃).

To simulate different humidity conditions, a water container with a wick was used as the humidity source. By allowing the wick to saturate, a controlled and stable humidity level was maintained within the testing environment. For long-term testing, a low humidity level was chosen to replicate the arid conditions experienced in locations such as the Mojave Desert.



(a) **(b)**

Figure 4: a) Tenny Environmental Test Chamber b) Hardware inside test Chamber

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[9] "FreeRTOS API Reference," Espressif Systems, [Online]. Available: https://docs.espressif.com/projects/esp-idf/en/latest/esp32/api-reference/system/freertos.html.

[10] "Climate," Fullerton College Science Department, [Online]. Available: https://www.fullerton.edu/dsc/visit/resources/climate.php#:~:text=Summer%20daytime%20temperatures%20in%20most,low%20is%208°F.

To ensure accurate and reliable measurement of temperature and humidity, the avionics system utilized the Tenny Environmental Versa Tenn III test chamber. This chamber provides a controlled testing environment with the capability to simulate a wide range of conditions such as temperature, humidity, and potentially other environmental factors.

VIII. RESULTS

G Loading:

The G-loading tests were conducted using two methods: manual G-loading and the self-developed automated G-load tester.

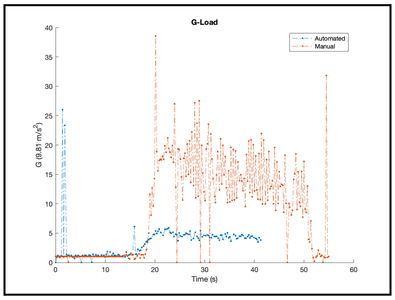

Figure 5: G-Load using manual and automated testing

The graph in figure 5 shows both manual and automated G-loading tests, demonstrating the system's ability to survive and maintain functionality under varying G-force conditions. The manual G-loading test showed continuous readings of 5G, while the automated G-loading test achieved readings peaking at 20G and sustaining around 15G. This indicates that the avionics system performed as intended and that the avionics system was able to withstand the continuous G-forces of 15-20 G that were similar to expected launch loads.

CAN BUS:

A tabletop test was conducted to evaluate the performance of the avionics system's CAN BUS communication with five devices for one hour.

Board ID:	**1 (Power)**	**2 (CAN)**	**4 (CAN)**	**7 (DAQ)**
Receive	705,516	352,760	352,759	570,641
Actual (PPS)	196	98	98	158
Desired (PPS)	200	100	100	200
Missed	0	0	0	0

Table 3: Results of Tabletop CAN Validation

The results were recorded in a table format, indicating the board IDs, received packet counts, packet rates, desired rates, and missed packets. The test results showed a very low miss rate, with no missed packets observed during the test. The received packet counts for each board ID were within the expected range, and the packet rates were close to the desired rates. The avionics system demonstrated efficient and reliable CAN BUS communication, even with the presence of multiple devices and different send frequencies.

Temperature and Humidity Validation:

The temperature and humidity validation tests aimed to assess the avionics system's performance under different environmental conditions.

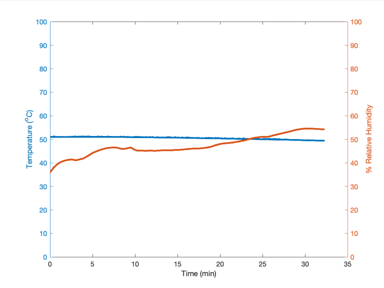

Figure 5: Temperature at 50 ℃ and 50% Relative Humidity

In the initial test, conducted at 50% humidity and 50 degrees Celsius, the system was validated to ensure its functionality and response within the specified environmental parameters.

Mission-like Simulation:

For the mission-like simulation, the system was exposed to a temperature of 75 degrees Celsius and low humidity conditions. During the first 100% of the expected on-ground mission duration, the temperature was elevated from room temperature to 75 degrees Celsius and maintained at that level. The humidity was decreased and maintained below 10%.

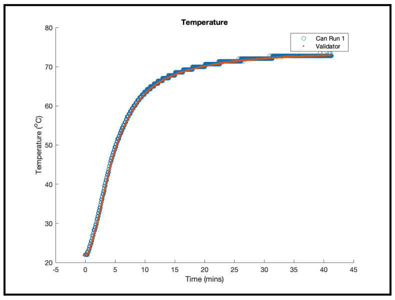

Figure 6: Temperature from both CAN bus and Wifi transmission from Board 7 (DAQ board) during the initial 1 hour

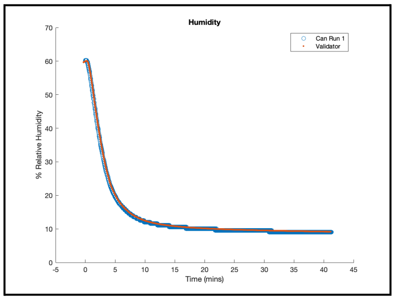

Figure 7: Humidity from both CAN bus and Wifi transmission from Board 7 (DAQ board) during the initial 1 hour

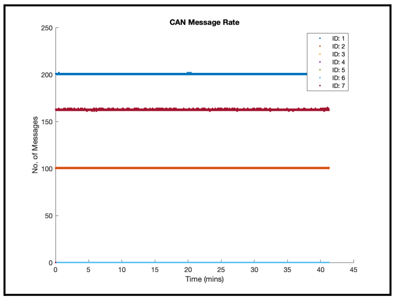

Figure 8: Can BUS transmission from the 3 boards (ID 1: Power, ID2: HIL, ID7: DAQ) during the initial 1 hour

Throughout this test, the system consisting of all three boards, including CAN communication, sensors, and Wi-Fi, operated without issues. The accuracy of the data received over Wi-Fi and CAN was high. However, due to the 256 bit nature of CAN data packets, while we were able to receive a higher frequency of CAN messages, the precision was slightly lower. In the data recorded one hour after the initial run, the temperature was still held at 75 degrees Celsius, and the system continued to function well, with some caveats.

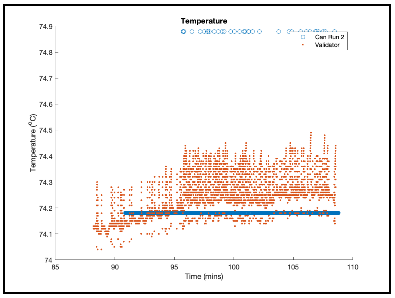

Figure 9: Temperature from both CAN bus and Wifi transmission from Board 7 (DAQ board) starting at the 2 hour mark and ending at the 3rd hour

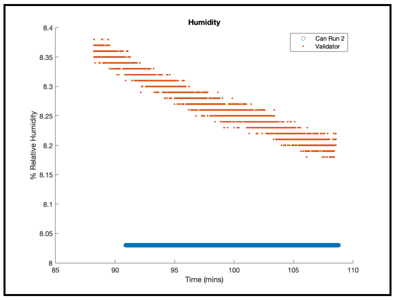

Figure 10: Humidity from both CAN bus and Wifi transmission from Board 7 (DAQ board) starting at the 2 hour mark and ending at the 3rd hour

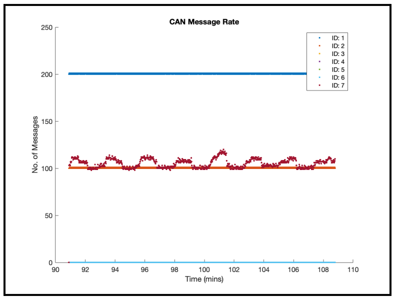

Figure 11: Can BUS transmission from the 3 boards (ID 1: Power, ID2: HIL, ID7: DAQ) starting at the 2 hour mark and ending at the 3rd hour

However, as seen in figure 11, the sensor board's send rate decreased to 100 packets per second instead of the desired 200 packets per second. This discrepancy in send rate could be attributed to factors such as system load or specific conditions encountered during the test and would need to be investigated further. The zoomed in temperature and humidity graphs also better showcase the difference in precision between the Wifi and CAN data, as one is rounded to 0.01, and the other is rounded to the smallest fraction of the operational range. Nonetheless, the information sent from both communication methods remained accurate. It also shows that our hardware is able to survive prolonged exposure to the harsh environments of the launch site.

Overall, the temperature and humidity validation tests demonstrated that the avionics system could effectively operate under mission-like environmental conditions, showcasing its resilience and suitability for liquid bi-propellant rockets.

IX. CONCLUSION

Our research project aimed to develop a scalable, modular, and cost-effective avionics system for liquid bi-propellant rockets using low-cost hardware and Commercial Off-The-Shelf (COTS) components. Through extensive experimentation and testing, we have evaluated the performance, functionality, and reliability of our avionics system.

The avionics system, consisting of three printed circuit boards (PCBs) designed for hardware validation, data acquisition, and power monitoring and distribution, has played a crucial role in advancing our design from concept to reality. Each board served a distinct purpose and contributed to the comprehensive evaluation of our avionics system under real-world conditions.

Our testing and validation processes have provided valuable insights into the performance of the avionics system. The G-loading tests demonstrated that the system could withstand peak G-forces up to 20G and verified continuous G-forces of up to 15G, validating its resilience under high G-force conditions. The CAN BUS communication system exhibited efficient and reliable data transfer, ensuring seamless integration and communication between multiple devices. Additionally, the temperature and humidity validation tests confirmed the system's capability to operate effectively under mission-like environmental conditions.

The successful design and fabrication of the PCBs, along with the implementation of software for embedded programming and data recording, have contributed to the overall functionality and performance of the avionics system. By adhering to the principles of standardization, simplification, integration, and optimization, we have achieved a cost-effective and modular avionics solution using COTS components.

In conclusion, our research has demonstrated the potential of a scalable, modular avionics system for liquid bi-propellant rockets. The avionics system, with its reliable performance, resilience, and cost-effectiveness, offers a viable solution for amateur and semi-professional rocketry. By continuing to refine and improve the system based on the insights gained from our experiments, we can further enhance its performance and reliability. It is likely that a further developed system will be implemented on the Halya Rocket developed by UC San Diego students at SEDS at UC San Diego for the FAR-MARS competition.

X. FUTURE WORK

In order to further enhance the avionics system and address the findings from the current research, several areas of future work have been identified.

Firstly, it is crucial to develop an improved automatic G-load tester. The current G-loading tester fell short of achieving continuous G-loads above 5G, failing to meet the target of 20G. Therefore, future work should focus on designing and implementing a new system that can generate and sustain higher G-loads effectively. This may involve reevaluating the mechanical components, optimizing the motor system, or exploring alternative testing methodologies to ensure a more reliable test setup.

Another important aspect for future investigation is the performance drop observed two hours after the high-temperature test. To gain a comprehensive understanding of this drop, further analysis is needed. It is essential to identify whether the decline in performance is due to sensor failures or if it is related to the thermal effects on the MCU's CPU. Through diagnostic tests, analysis of sensor data, and monitoring of CPU temperature variations, we will be able to pinpoint the underlying factors contributing to the performance drop. This understanding will inform future system optimization efforts and enhance the overall reliability of the avionics system.

Moreover, future work should involve conducting enhanced environmental testing to evaluate the avionics system's resilience under a wide range of conditions. This includes subjecting the system to extreme temperature ranges, high humidity levels, and other environmental stressors commonly encountered during rocket launches. By replicating mission-like environments more accurately, we will be able to gather comprehensive data on the system's performance, identify vulnerabilities, and implement necessary design improvements. Additionally, exploring the effects of factors such as vibration, electromagnetic interference, and altitude variations will provide a more comprehensive understanding of the system's reliability and robustness.

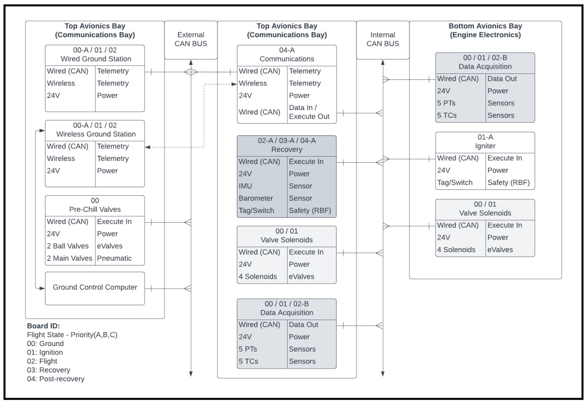

Figure 12: Expected Schematic of Halya Liquid Bi-propellant Rocket

Integration testing with a rocket prototype is another important area of future work. Integrating the avionics system into an actual liquid bi-propellant rocket and conducting tests throughout the rocket's mission trajectory will validate its performance in a real-world scenario. Integration testing will evaluate the system's ability to monitor and control the rocket's performance, withstand the harsh conditions of spaceflight, and ensure safe and reliable operation throughout the mission. This testing phase will provide valuable insights, validating the system's functionality and performance under realistic conditions, and driving further optimization and refinement of the avionics system design.

XI. BIBLIOGRAPHY

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