Design of a Modular Avionics System for a Two-Stage Sounding Rocket

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Georgia Tech Experimental Rocketry (GTXR), a project team of the Ramblin' Rocket Club (RRC) aims to send a two-stage rocket past the Karman line. To accomplish this, the avionics system consists of a primary flight computer and auxiliary systems. The primary flight computer is responsible for state estimation, initiation of stage separation and parachute deployment, and providing second-stage telemetry. The auxiliary systems provide redundancy and first-stage telemetry, ground communications, and video of the flight. This paper will describe the hardware architecture for the primary flight computer. Modeled after CubeSat avionics stacks, the flight computer is a custom modular system comprised of four PC104 boards, providing power storage, power distribution, state estimation, and telemetry and communication, respectively. Boards are connected via a PC104 stack header and communicate with each other via a controller area network (CAN) bus. The power board provides regulated power to the entire system. The state estimation board collects data from a suite of primary and backup sensors including inertial measuring units (IMU), magnetometers, barometers, a high-G accelerometer, and a global navigation satellite system (GNSS) receiver. The control/radio board is the central decision-making board. It uses information from the state estimation board to ignite the second stage and activate recovery systems. It is also responsible for streaming telemetry to the ground station during and after flight. The flight computer will be tested during Summer 2024 on a single-stage rocket called Strange Magic in preparation for future high-altitude two-stage flights.

I. Nomenclature

ASK	=	Amplitude Shift Keying
$CoCom$	=	Coordinating Committee for Multilateral Export Controls
$COTS$	=	Commercial-off-the-shelf
CAN	=	Controller Area Network
DC	=	Direct Current
FSK	=	Frequency Shift Keying
$GTXR$	=	Georgia Tech eXperimental Rocketry
$GNSS$	=	Global Navigation Satellite System
IMU	=	Inertial Measurement Unit
MCU	=	Microcontroller Unit
RRC	=	Ramblin' Rocket Club
$UART$	=	Universal Asynchronous Receiver
PCB	=	Printed Circuit Board

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II. Introduction

Georgia Tech eXperimental Rocketry (GTXR) aims to be the first student project to design, manufacture, and fly a two-stage sounding rocket past the Karman line [1], the arbitrary altitude separating the upper atmosphere from space. Founded in 2018, GTXR has launched four two-stage sounding rockets, which have allowed the team to develop the expertise and operational capability to build complex vehicles with higher and higher altitude goals. These launches have provided the team with experience in the operation of avionics systems for launch vehicles under real launch and flight conditions. The avionics system is responsible for multiple critical functions during flight including second-stage motor ignition, parachute deployment, positioning and attitude estimation, and telemetry.

In the past, GTXR has used COTS flight computers, produced by other amateur rocketry organizations and companies to meet the avionics requirements for our vehicles [2] [3] [4]. However, these systems present challenges when scaling up to large rockets. COTS avionics systems are typically single-board computers that prioritize small footprints and tight volume budgets to fit inside small-diameter vehicles. This leads to a lack of redundancy in power and sensor systems, which generate single points of failure and increase the safety requirements during launch operations. Additionally, these systems implement state machines for flight event programming that assume flight in single-stage vehicles or are too simple to program the complex event logic needed to deal with all possible states of a two-stage vehicle. Finally, as their use tends to be stand-alone with no other supporting avionics systems, these systems lack the low-level interfaces our team needs to effectively integrate them with the rest of the avionics systems present in the vehicle.

Failures in COTS avionics systems have caused the failure of the last two sounding rockets GTXR has produced. In 2023, the COTS avionics system triggered recovery charges at launch, causing parachutes to be ejected as the rocket began to leave the launch rail [5]. At 4,000 ft and at only 4 seconds into the 8-second first-stage burn, the avionics system ignited the second-stage motor. This resulted in a hot staging and both the first-stage and second-stage motors flew next to each other until first-stage burnout. It was later determined that a software bug in the firmware caused a timer to begin on the boot of the flight computer instead of on launch. This bug was undetectable because of the simplistic interface that the COTS avionics system provided. Although we typically assume that commercial products have been thoroughly tested, in the case of COTS avionics systems new products are not always thoroughly exposed to flight conditions and rarely have been tested against the complex launch operations that are required with our two-stage design.

These issues have led the team to begin the development of a custom flight computer that can overcome the challenges that high-power two-stage sounding rockets present. Although developing custom avionics is a time-consuming, complex, and costly endeavor, the team's need for high-redundancy, safe avionics systems demands a custom solution.

III. Design and Requirements

The flight computer is the central piece of a larger avionics system. The flight computer is responsible for executing all critical events such as second-stage ignition and parachute deployment and for gathering all data required to make decisions related to those critical events. The avionics system also includes auxiliary systems. Auxiliary systems are isolated devices that are completely passive and have no control authority. These devices include cameras to film the flight and small COTS avionics systems to provide additional telemetry.

A. Technical Requirements

1. Power

The flight computer must have the ability to provide regulated voltage to all subsystems, monitor voltage rails, and control the battery management subsystem. To support different power requirements, the flight computer must have four voltage rails: 12V, 5V, 3.3V and an Always-On 3.3V rail. The voltage rails must supply at least 1.5 A, 8 A, 4 A, and 1.5 A, respectively. The Always-On voltage rail must provide power to the Microcontroller Unit (MCU) and other critical peripherals on the power system. This is required for reboot resilience and control over the other voltage rails. The flight computer must be able to be powered from three different sources: a lithium-ion battery pack, an umbilical connection, and a Direct Current (DC) power supply. The battery pack must be the source of power for the flight computer during flight. The umbilical must be used to charge the battery pack, provide power to all subsystems when the rocket is on the launchpad, and provide reliable communications between the flight computer and the ground station. The DC power supply input must be used as a power supply for the flight computer on a benchtop for testing and evaluation. Switchover from different power sources must be managed by a seamless switchover power mux. The flight computer must monitor and control the charging of a 4S1P lithium-ion battery pack, which acts as the main power supply. To achieve this, the flight computer must use a battery manager IC on the battery board whose capabilities include overcurrent, undervoltage, overvoltage, and reverse polarity protection. Due to operational safety requirements stemming from launch operations, two pull switches are required for launch operations. The first will connect the battery pack to the power board but not the inputs of the voltage regulators that provide power for non-always-on rails. The second pull switch will provide power to the voltage regulators and it must be up to the power board MCU to control the operation of the regulators to provide power to the rest of the flight computer. This start-up sequence will allow the team to perform validation checks of the power system before connecting sensitive systems.

2. State Estimation

The state estimation system must support a suite of primary and backup sensors used for state estimation. These include inertial measurement units (IMU), global navigation satellite systems (GNSS), barometers, and magnetometers. The system should have high-speed memory access, have the capability of storing data on a micro-SD card, and be reboot tolerant.

3. Control

The control system is responsible for actuating events during flight following a prescribed flight plan. It must also be able to detect deviations from said plan and act to minimize the risk to the vehicle, maximize altitude and recovery likelihood, and above all ensure the safety of the vehicle during launch operations when personnel are actively working or are in the vicinity of the vehicle. As such the primary requirement for the control system is the implementation of a configurable state machine, which can be modified to follow any prescribed flight plan and can recover from failures. The control system is also responsible for orchestrating communications between the flight computer and the umbilical system, which is connected before launch and provides the team with direct low-level access to the flight computer as a whole. It is also responsible for storing and retrieving flight data into non-volatile memory for later recovery or transmission. Finally, as the control system is responsible for commanding the firing of pyrotechnic devices, the control systems must implement arming logic to safeguard the vehicle against improper or unexpected deployment of pyrotechnic charges.

4. Communications

The flight computer must be able to provide telemetry regarding the attitude of the rocket and the health of each subsystem. The communications system must be able to use frequency shift keying (FSK) and amplitude shift keying (ASK). The radio board must operate at a carrier frequency between 902 MHz and 928 MHz following the 915 MHz ISM band, supply 1 W of power to the antenna, and operate in half-duplex. The radio board must employ an antenna with a 3 dBi gain resulting in approximately 2 W of radiated power. To implement this, the radio board must contain a transmit and receive module, an RF front-end module, low-noise linear regulators, and a low-power MCU. The MCU on the radio system must be able to communicate on the main CAN bus and as a backup to the control board MCU via a universal asynchronous receiver (UART) to relay telemetry.

B. Operational Requirements

The flight computer must be designed to be smoothly integrated with the rest of the rocket. The structures team will provide guidelines limiting the height and footprint. All connectors must be accessible in an assembled stack and follow a common system.

During launch operations and setup, continuity checks with motor igniters, recovery charges, and staging charges must be able to be performed while shunts are in place and power is inhibited from those charges. Additionally, the flight computer should be able to detect the launch through a physical disconnect such as with the umbilical.

Additionally, it is important to consider that the flight computer must be manufactured by a team of students with limited PCB manufacturing experience and access to equipment. This drives the requirement for test points to be included on all digital buses present on the flight computer. Furthermore, the flight computer must include debug headers, debugging power supply connections, and debug data lines on all microcontrollers implementing the functions previously described.

IV. Implementation

The functionality of the flight computer is split into four boards: power storage, power distribution, state estimation, and control. Separating these systems allowed for parallel development and led members of the team to take ownership of sections of the flight computer. Modeled after CubeSat avionics stacks, the PC104 standard [6] was adopted to follow a standardized approach to communication and power distribution between the boards. In addition to the four main boards, the radio board manages all telemetry and communications with the ground. The radio board is a castellated pad board and is attached to the back of the control board. Data is transferred between boards through a control area network (CAN) bus. The implementation of a shared bus also provides easy distribution of power and communication capabilities to all boards under a common interface, limiting the coordination needed between systems and allowing team members to work independently.

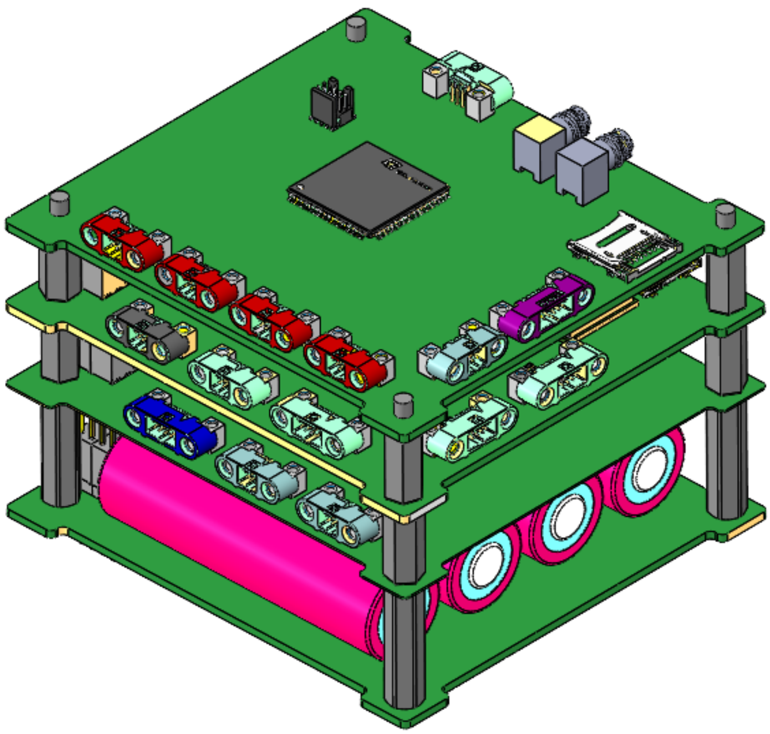

Fig. 1 Render of the PC104 compliant board stack that forms the flight computer.

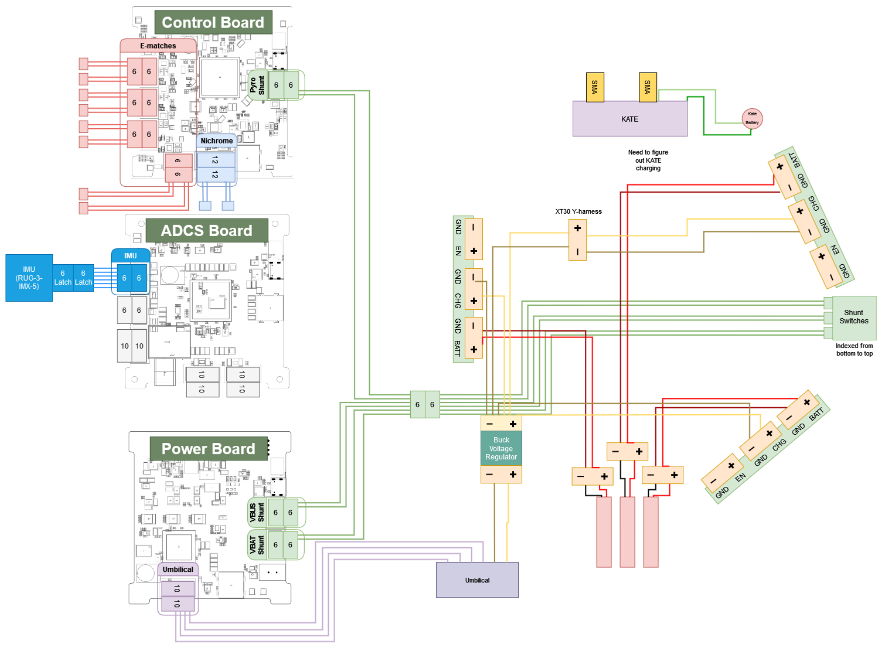

Fig. 2 Diagram of the flight computer board interfaces with the rest of the avionics systems.

A. Power Distribution Board

The main responsibility of the power board is to get power from the provided power sources and return regulated voltages on the main PC104 stack connector which other boards can rely on during operation. The power board schema can be seen in 3, which outlines the flow of power from the possible supply sources to the regulators. The DC power source and umbilical power source are inputs to a power mux, which is connected to the VBUS rail. The output of the battery pack is also connected to the VBUS rail to allow charging when DC or umbilical are present and discharging when they are not. VBUS is then passed to the voltage regulators to provide the required voltage rails to the rest of the subsystems on the flight computer. An important safety feature implemented in this power schema is the ability to only activate the supervisor MCU on this board before the remainder of the stack is powered through the MCU-specific LDO and power mux. This provides the vehicle operators the ability to partially power the power distribution board and perform checkout tests on the regulated power supplies before flight, which ensures that no power-related anomalies endanger the rest of the systems on the vehicle during launch operations.

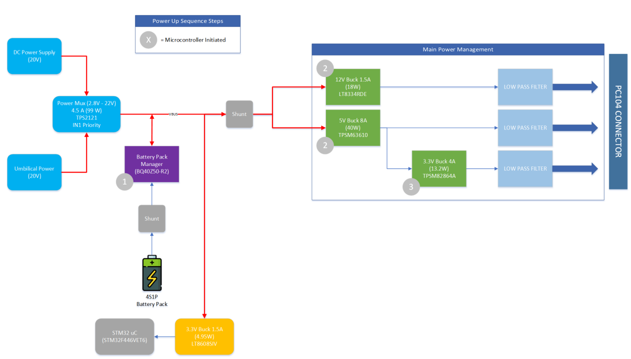

Fig. 3 Power board schema showing the flow of power from the different power sources to the subsystems on the flight computer.

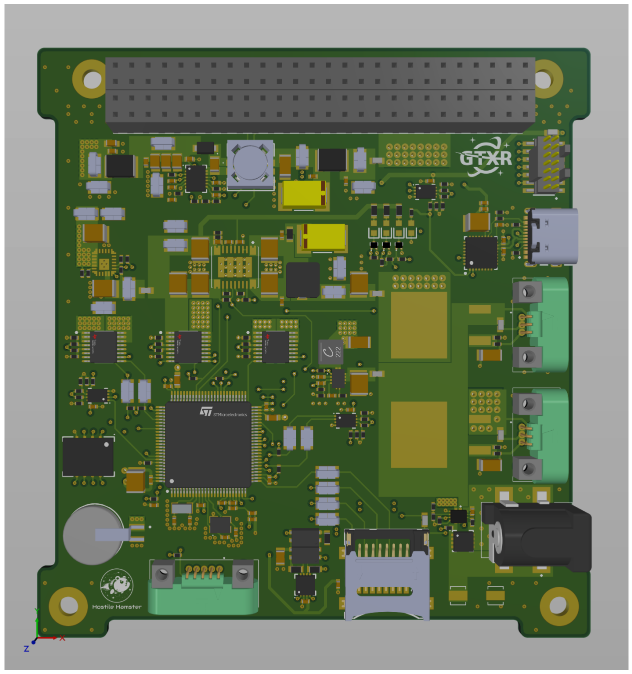

Fig. 4 Top view render of the power distribution board.

B. Power Storage Board

To implement the rest of the requirements on the power system, the battery board takes the role of holding the battery pack and a battery manager IC along with the IC's necessary circuitry. The battery manager IC (BQ40Z50-R2) is capable of cell over-voltage and under-voltage protection, as well as over-current and over-discharge protection. The 4 lithium-ion cells provide power to all the boards of the stack and are constantly recharged during launch operations prior to flight through an umbilical connection to ground equipment.

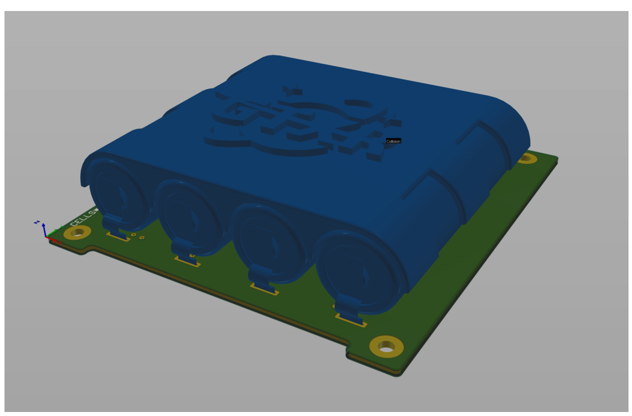

Fig. 5 3D render of the battery distribution board.

C. State Estimation Board

The state estimation board implements the sensors required to estimate the altitude and position of the vehicle during flight. The board implements two dissimilar redundant sensor buses as well as an external chassis-mounted COTS IMU, providing it with three dissimilar information sources to estimate the vehicle's state. This level of redundancy protects the vehicle against single points of failure in its sensor suite and provides the rest of the boards on the PC104 stack with a source of accurate state estimation to base flight event decisions. Furthermore, the board implements a Ublox high-precision GPS module which provides the vehicle with absolute positioning during non-CoCom flight conditions. Finally, the board implements both SD-card-based and non-volatile flash memory for high-quality sensor data storage, which can be retrieved after flight for in-depth analysis of flight conditions.

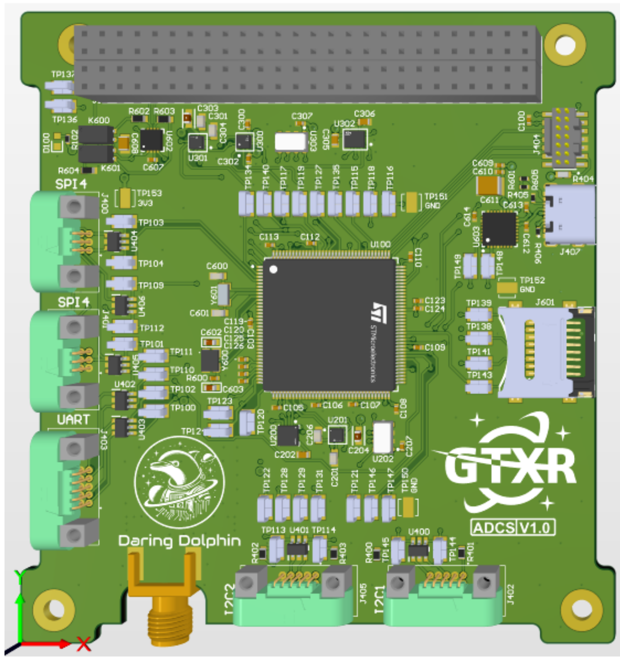

Fig. 6 Top view render of the state estimation board

D. Control Board

The control board is responsible for managing all events during flight and ensuring the safety and success of the launch. It sits at the top of the flight computer stack. This section provides an overview of the functionalities and features of the control board, highlighting its role in controlling the rocket's flight events, making informed flight decisions based on attitude determination results, implementing safety measures, and facilitating communication with other subsystems.

The control board serves as the central hub for controlling all aspects of the rocket's flight, including staging for sustainer ignition and parachute deployment for recovery. It receives power from the power board through the PC104 connector and input from the ADCS board to accurately make correct decisions during flight.

In addition to receiving input from the ADCS board, the control board is equipped with a sophisticated software-based state machine. This state machine utilizes the data received from the ADCS board to make real-time decisions about the rocket's flight parameters and operational sequences. The state machine is programmed with a series of predefined states and transition conditions that govern the behavior of the rocket throughout its mission profile. By continuously assessing the incoming data from the ADCS board and comparing it against predefined criteria, the state machine ensures that the control board responds appropriately to changing flight conditions, thus optimizing the rocket's performance and ensuring mission success.

To facilitate this seamless communication with other subsystems and components, the control board is equipped with interfaces that support various communication protocols, including CAN bus, UART, SPI, and I2C. These protocols enable the control board to exchange data and commands with other boards on the PC104 bus, such as the telemetry system, payload interface, and avionics subsystems, ensuring coordinated operation and monitoring of the rocket's systems.

The pyro system integrated into the control board is designed to ignite matches using a single MOSFET and incorporates a comprehensive electrical arming system for safety and reliability. The system consists of a pyrotechnic igniter circuit connected to the MOSFET, which serves as the switching element for activating the igniter. Before activation, the pyro system requires an electrical arming sequence to be initiated, ensuring that the igniter cannot be triggered accidentally. This arming sequence typically involves a couple of safety checks and conditions that must be met, such as pulling a series of shunt switches and confirming continuity of the igniter circuit. Once armed, the control board can selectively activate the MOSFET to deliver a controlled electrical current to the igniter, igniting the match and initiating the desired pyrotechnic event. The electrical arming system adds a layer of safety and reliability to the pyro system, ensuring that ignition occurs only under controlled and authorized conditions, thereby minimizing the risk of premature or unintended firing during pre-launch preparations or flight.

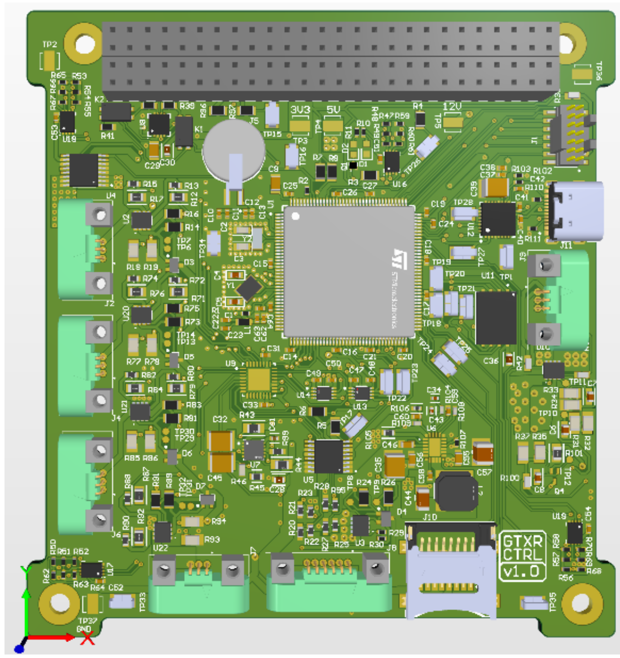

Fig. 7 Top view render of the control board

E. Radio Board

The radio board seeks to satisfy the requirements for communication. Unlike the other boards, the radio board does not follow the PC104 standard. Instead, it is a castellated pad board. Height restrictions of the stack limited it to four boards. The simplest solution was to attach the radio board to the back of the control board, where the control board has direct low-level access to the functionality of the radio board. The radio board uses Texas Instruments CC1101 transceiver IC and the SKY65313-21 RF front end to generate FSK and ASK waveforms and amplify the signal to achieve an output power of 1 W delivered to the antenna and 2 W of radiated power as a result of a 3 dBi gain antenna. This allows the flight computer stack to communicate with ground equipment and provides critical telemetry to the team during flight.

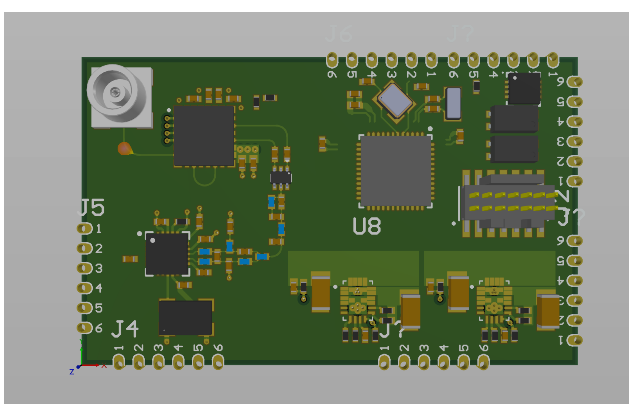

Fig. 8 Top view render of the radio board

V. Assembly and Testing

Once designed, the printed circuit boards (PCB) for each board and their components were purchased. Due to cost limitations and manufacturing concerns, the components were assembled onto the boards manually by the team. Large integrated circuits were soldered to the boards using a reflow oven. All other components were hand-soldered. During assembly, special attention was paid to ensure proper alignment, solder joints, and component orientation to prevent assembly errors. On every board, test points were added to facilitate testing signals through an oscilloscope or multimeter, allowing the operator to monitor and analyze key parameters such as voltage levels, communication signals, and sensor readings.

Currently, the team is working through testing individual boards. The next step will be integration testing. All four boards will be assembled and the systems will be tested together to check compatibility, communications protocols, and coordinated operation. This summer, the flight computer will be installed in a single-stage rocket to test its functionality under flight conditions. The staging hardware will be tested using a test chamber where staging charges will be ignited.

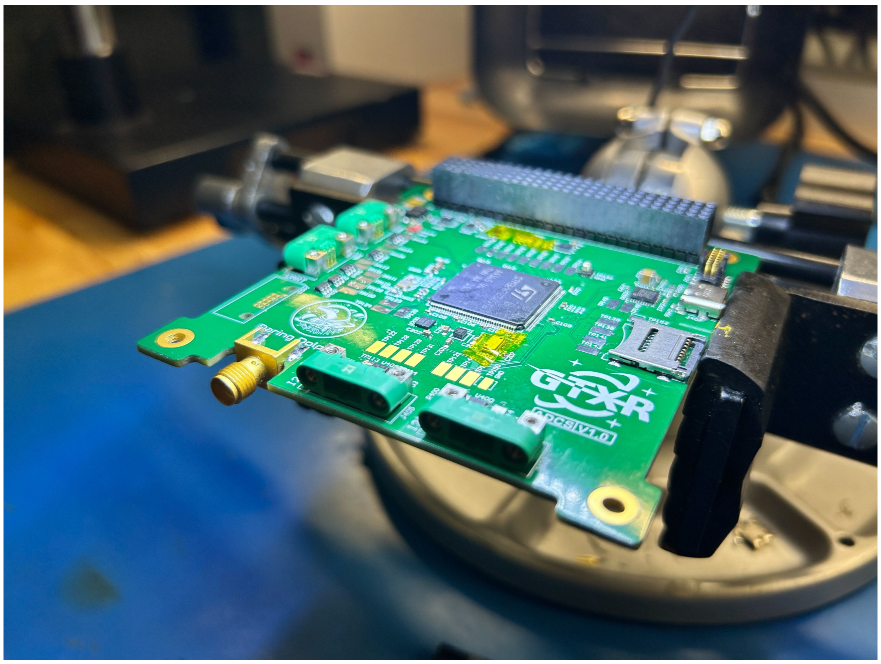

Fig. 9 Assembly of the state estimation board.

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