Notre Dame Rocketry Team (NDRT) Payload
360° Rotating Optical Imager (TROI)

Thomas Coverstone, Jacob Elwell, Ian Horvath, Chris Troyer, Mike Troyer

University of Notre Dame

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1 Introduction

Every year, the National Aeronautics and Space Administration (NASA) hosts a student launch competition in Huntsville, Alabama, for high school and college programs across the country. As a part of this competition, there is a payload challenge that varies from year to year. Here at Notre Dame, an interdisciplinary team of students, including but not limited to mechanical, aerospace, and electrical engineers, comes together to produce a payload that fulfills all the mission requirements of the challenge. Within the Notre Dame Rocketry Team (NDRT), the EE Senior Design Team worked as a group of dedicated electrical engineers to provide expertise and complete the electrical component of the design. Generally, this year's payload challenge involved developing a system capable of rotating a camera and performing different image processing operations based on commands sent from NASA's ground station, over radio frequencies. The specific challenge requirements are described further in the following *System Requirements* section.

The payload designed by NDRT this year, referred to as the 360° Rotating Optical Imager (TROI), physically consists of two custom printed circuit boards (PCBs) housed between two bulkhead plates, a 3D-printed camera arm connected to a lead screw and stepper motor that were also housed between the bulkheads, as well as another stepper motor and commercially available camera PCB module both mounted on the end of the camera arm. The rocket's nose cone is designed to separate before landing by the controlled detonation of a black powder charge, creating an opening in the front of the rocket tube. Upon landing, the TROI uses a stepper motor to drive the camera arm forward, outside of the front rocket tube. The secondary stepper motor rotates the camera according to commands received from NASA. Electronically, the TROI consists of three subsystems: the RF subsystem, the ESP32-CAM subsystem, and the

ESP32-Main subsystem. The RF subsystem receives radio transmissions, demodulates them, and relays them to the ESP32-Main subsystem. The ESP32-CAM subsystem rotates, captures images, and processes them according to commands received from the ESP32-Main subsystem. The ESP32-Main subsystem serves as the primary control center for the payload, responsible for interpreting data from sensors, interpreting data received from the RF subsystem, and controlling the ESP32-CAM subsystem accordingly. The structure and subsystems of the TROI are discussed further in Section 3, *Project Description*.

Our design meets expectations. All subsystems reliably perform their respective functions independently, and effectively integrate to function as a coherent overall system. The RF subsystem consistently receives and demodulates radio packets with great accuracy, the ESP32-CAM subsystem effectively rotates and captures and processes images according to commands it receives, the ESP32-Main subsystem effectively communicates with and controls both subsystems. The payload team tested the TROI extensively in the workshop, and in a series of test launches. In the workshop tests and final test launch leading up to NASA's competition, the TROI met expectations and functioned without error. Unfortunately, during the competition launch on April 16th, the rocket's recovery parachute became tangled and did not deploy, causing the rocket to impact terminal velocity. While the TROI electronics survived the impact, the 3D-printed materials shattered and the lead screw bent upon impact. These materials were not designed to withstand such an impact, and their damage rendered the TROI incapable of deploying after the landing (the front of the rocket tube was also plugged with a thick layer of mud due to the impact of the landing). Although the TROI failed to meet expectations on the day of the competition, this was due to an error in the recovery system, outside of the scope and control of the TROI. While this is unfortunate, it is not intended to place blame on the recovery system; recovery is a complicated task and it is difficult to account for unusual circumstances such as a parachute failing to deploy, especially since this had not occurred in previous test launches. Nor is this intended to provide an excuse for the TROI failing to function on the day of the competition. The TROI functioned without error during tests conducted the night of April 15th, giving the payload team full confidence that the TROI would have functioned had the rocket landed softly as expected.

2 System Requirements

The payload challenge of this year's student launch competition was to produce a system that (1) is capable of taking images in a 360º range about the z-axis (normal to the ground plane) after landing, (2) is able to receive radio communication via Automatic Packet Reporting System (APRS), and (3) is able to perform a variety of actions according to commands sent via APRS, including but not limited to mechanical rotation of the imaging system and digital image processing. In addition to these general requirements for mission success, the payload system was required to adhere to certain parameters such as camera FOV and deployment methodology. The entirety of the payload requirements are outlined as described in the NASA Student Launch Handbook:

All payload designs shall be approved by NASA. NASA reserves the authority to require a team to modify or change a payload, as deemed necessary by the Review Panel, even after a proposal has been awarded.

1. College/University Division—Teams shall design a payload capable upon landing of autonomously receiving RF commands and performing a series of tasks with an on-board camera system. The method(s)/design(s) utilized to complete the payload mission shall be at the team's discretion and shall be permitted so long as the designs are deemed safe, obey FAA and legal requirements, and adhere to the intent of the challenge. An additional experiment (limit of 1) is allowed, and may be flown, but will not contribute to scoring. If the team chooses to fly an additional experiment, they will provide the appropriate documentation in all design reports so the experiment may be reviewed for flight safety.
2. Radio Frequency Command (RAFCO) Mission Requirements

2.1. The launch vehicle shall contain an automated camera system capable of swiveling 360º to take images of the entire surrounding area of the launch vehicle.

2.1.1. The camera shall have the capability of rotating about the z axis. The z axis is perpendicular to the ground plane with the sky oriented up and the planetary surface oriented down.

2.1.2. The camera shall have a FOV of at least 100º and a maximum FOV of 180º.

2.1.3. The camera shall time stamp each photo taken. The time stamp shall be visible on all photos submitted to NASA in the PLAR.

2.1.4. The camera system shall execute the string of transmitted commands quickly, with a maximum of 30 seconds between photos taken.

2.2. NASA Student Launch Management Team shall transmit an RF sequence that shall contain a radio call sign followed by a sequence of tasks to be completed. The list of potential commands to be given on launch day along with their radio transcriptions which shall be sent in an RF message using APRS transmission in no particular order are:

A1—Turn camera 60º to the right

B2—Turn camera 60º to the left

C3—Take picture

D4—Change camera mode from color to grayscale

E5—Change camera mode back from grayscale to color

F6—Rotate image 180º (upside down).

G7—Special effects filter (Apply any filter or image distortion you want and state what filter or distortion was used).

H8—Remove all filters.

2.2.1. An example transmission sequence could look something like, “XX4XXX C3 A1 D4 C3 F6 C3 F6 B2 B2 C3.” Note the call sign that NASA will use shall be distributed to teams at a later time.

2.3. The NASA Student Launch Management Panel shall transmit the RAFCO using APRS.

2.3.1. NASA will use dedicated frequencies to transmit the message. NASA will operate on the 2-Meter amateur radio band between the frequencies of 144.90 MHz and 145.10 MHz. No team shall be permitted to transmit on any frequency in this range. The specific frequency used will be shared with teams during Launch Week. NASA reserves the right to modify the transmission frequency as deemed necessary.

2.3.2. The NASA Management Team shall transmit the RAFCO every 2 minutes.

2.3.3. The payload system shall not initiate and begin accepting RAFCO until AFTER the launch vehicle has landed on the planetary surface.

2.4. The payload shall not be jettisoned.

2.5. The sequence of time-stamped photos taken need not be transmitted back to ground station and shall be presented in the correct order in your PLAR.

3. General Payload Requirements

3.1. Black Powder and/or similar energetics are only permitted for deployment of in-flight recovery systems. Energetics shall not be permitted for any surface operations.

3.2. Teams shall abide by all FAA and NAR rules and regulations.

3.3. Any secondary payload experiment element that is jettisoned during the recovery phase will receive real-time RSO permission prior to initiating the jettison event, unless exempted from the requirement of the CDR milestone by NASA.

3.4. Unmanned aircraft system (UAS) payloads, if designed to be deployed during descent, will be tethered to the vehicle with a remotely controlled release mechanism until the RSO has given permission to release the UAS.

3.5. Teams flying UASs will abide by all applicable FAA regulations, including the FAA's Special Rule for Model Aircraft (Public Law 112–95 Section 336; see https://www.faa.gov/uas/faqs).

3.6. Any UAS weighing more than .55 lbs. shall be registered with the FAA and the registration number marked on the vehicle.

3 Project Description

3.1 System Theory of Operation

The 360° Rotating Optical Imager (TROI) is the engineering solution developed by the NDRT payload design team to complete the payload design challenge. In overview, the TROI consists of a camera, mechanical motors for deployment and camera rotation, and electronics to control these components. The initial concept of the TROI can be seen in Figure 1.

Figure 1. Concept rendering of TROI

During deployment, a main stepper motor that runs along the axis of the rocket's body tube extrudes the camera along a set of guide rails. At full deployment length, once the camera module decouples from the guide rails, there is a counterweight-bearing system that orients the camera module along the z-axis. At this point, deployment is complete. The TROI then passively detects RF transmissions sent via APRS and executes the commands received by electronic-controlled mechanical actuation and digital command processing. Images captured are stored locally with a microSD card on the TROI. The EE Senior Design team's contribution to the completion of the TROI included (1) a general advising of electronic component selection, (2) the production of two custom printed circuit boards (PCBs) to condense and improve the payload design, and (3) contributions to the software design of the payload.

3.2 System Block Diagram

The TROI's overall control flow can be seen below in Figure 2. In summary, the TROI is in initialization standby as the rocket awaits launch and landing. Once a landing has been detected based on data from the two onboard IMUs and a timer set from the initial launch (also signaled by IMU data), then the payload deploys. The first action is a longitudinal extrusion of the camera sensor, followed by the initialization of the RF receiver. At this point, the TROI is "waiting and listening" for commands to be sent from the NASA ground station. The command handling is split between the two ESP32 microcontroller subsystems in the TROI. All mechanical actuation commands are handled by the ESP32 Main subsystem, whereas the software-controlled commands (such as taking and saving images, and applying filters) are handled by the ESP32-CAM subsystem. Once a string of commands has been successfully interpreted and executed, both subsystems return to their standby state.

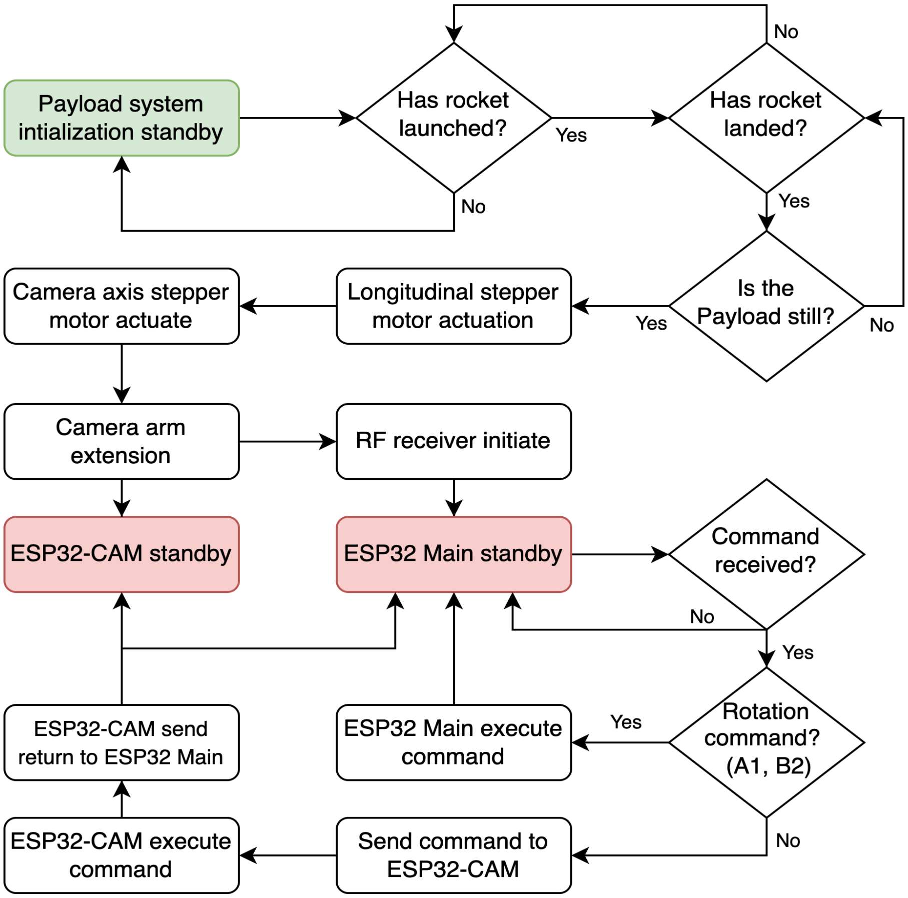


Figure 2. Overall TROI command flow

Figure 3 on the following page shows a block diagram for the TROI, including power distribution and data connections.

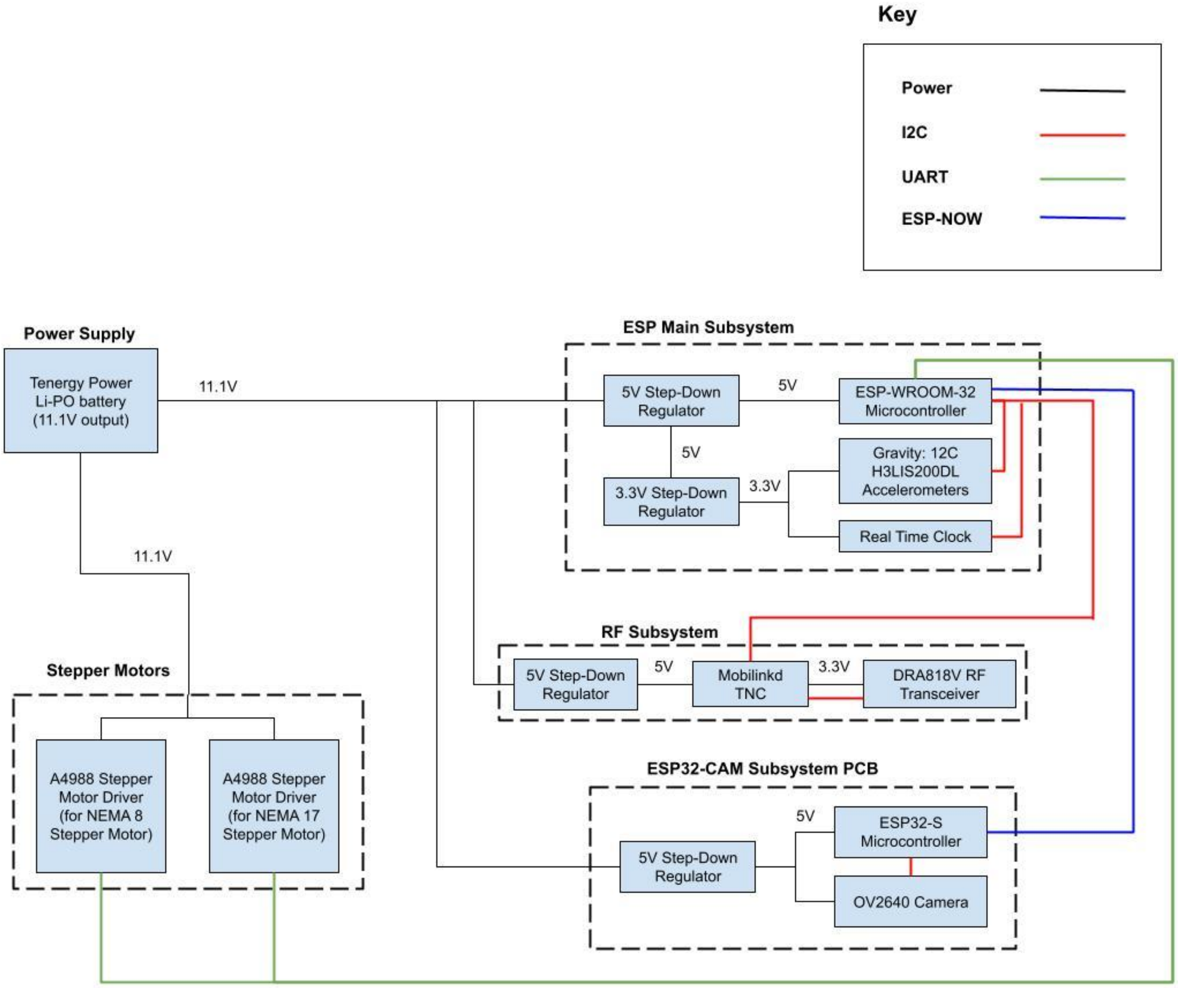


Figure 3. TROI power distribution block diagram

3.3 ESP32-Main Subsystem

The main PCB is used to house the main ESP-WROOM-32D microcontroller, various sensors, and stepper motor drivers, as well as regulate voltage. A custom PCB replaces the need for jumper cables and breadboards, allowing for a cleaner, more reliable design. Each sensor and driver is powered by the regulators and controlled with the microcontroller on this main PCB. The PCB also hosts the pinouts to command and power the freestanding stepper motors and RF devices. The ESP-CAM is powered using cables connected to the PCB and communicates wirelessly with the main microcontroller through the ESP-NOW protocol.

3.4 ESP32-CAM Subsystem

The TROI uses an Arducam OV2640 camera in conjunction with the ESP32-CAM board to take and save images. The OV2640 is a 2MP camera with high image quality and a robust software library for achieving functionalities that the payload challenge stipulated such as image-processing, and the ESP32-CAM board has quality-of-life features such as a built-in microSD card slot. The stock lens that comes with the OV2640 has a field of view of 68°, so a 140° wide-angle replacement lens ended up being used to accommodate a wider field of view. The ESP32-CAM board receives power from the Tenergy Li-Po battery through a 5V voltage regulator. Powering the board with a regulated 5V source allows access to complete camera operation, and having only the power cables connected to the ESP32 module of the rotating arm simplifies the mechanical actuation (specifically the rotation with wires) of the camera.

3.5 RF Receiver Subsystem

The RF system is designed to strictly receive commands from NASA over an RF link during competition with frequencies between 144.90 MHz and 145.10 MHz and convert received radio packets into a form that can be relayed to the microcontroller and camera system. It consists of an antenna, DRA818V transceiver, and a Mobilinkd TNC. The Mobilinkd is a breadboard-based TNC containing a Nucleo-L432KC-All microprocessor and several other electronic components. A breadboard configuration of this system is shown in Figure 4.

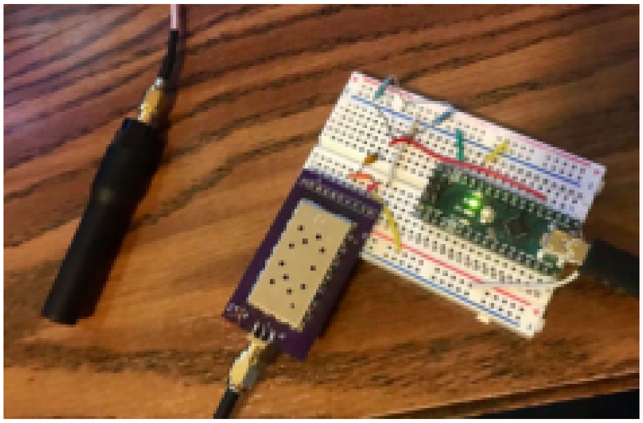


Figure 4. Breadboard configuration of the RF Subsystem, including DR818V and TNC

This breadboard configuration was utilized for development and testing stages. The complete RF system is implemented on a custom-designed printed circuit board (PCB), which houses all electronic components in the RF system and voltage regulators to step-down from 11.1 V at the battery to 5 V required by the Nucleo-L432KC-All as described in Section 6.4.1. A schematic of the RF system is included in Figure 5, and a rendering of the final PCB is included in Figure 6.

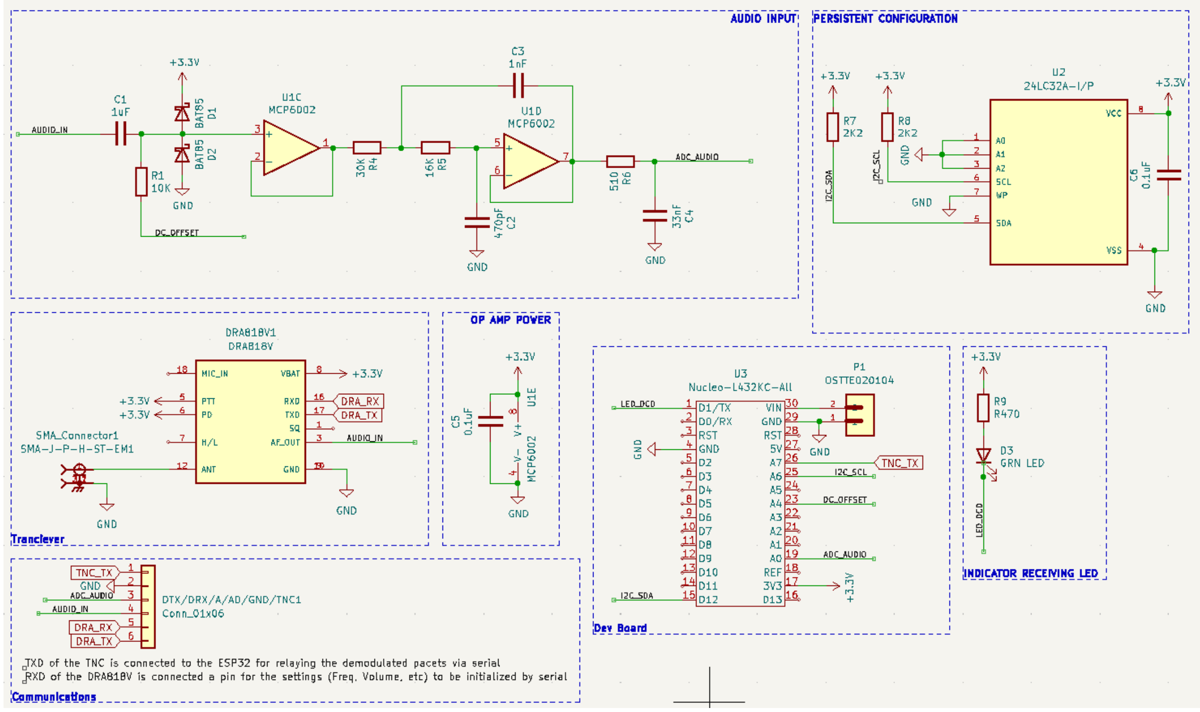


Figure 5. RF Subsystem Schematic including the DRA818V and TNC

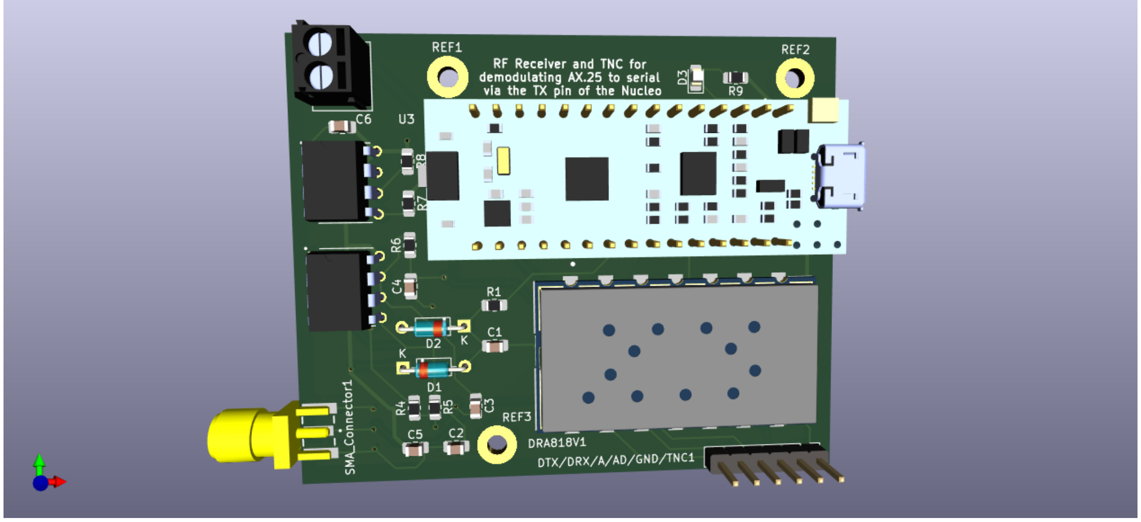


Figure 6. Rendering of the final RF subsystem PCB

To prepare the system for RF reception, the DRA818V transceiver is initialized to the desired frequency ranges via the RXD pin using serial protocol. The DRA818V verified reception capabilities between 144.90 MHz and 145.10 MHz. This initialization method utilizes a modified version of the Arduino-DRA818V library. Radio packets are received via the antenna and transceiver, and then demodulated by the TNC, using APRS AX.25 AFSK 1200 baud packet demodulation. This process converts radio packets into signals that can be sent to the ESP32-WROVER-E via serial for parsing, after which the parsed commands are relayed to the camera system.

A set of initial tests were conducted using the DRA818V with software TNCs such as Direwolf and APRSdroid to verify that the RF system could receive signals with enough resolution to demodulate the AX.25 packets. These tests succeeded, and were followed by another round of tests integrating the Mobilinkd TNC, to verify that the embedded systems TNC could demodulate received radio packets. These tests were also successful. Lastly, a successful test was conducted to send the demodulated packets to the ESP32-WROVER-E via serial connection for interpreting commands.

3.6 Interfaces

The TROI implements a multitude of interfaces. Most of the sensor array is interfaced using the onboard Inter-Integrated Circuit (I2C) bus available on the ESP32. This includes the IMUs and the RTC. Due to the redundancy of the IMUs, both I2C interfaces available in the ESP32 Main subsystem were utilized to avoid having to readdress one of the two IMUs. For both stepper motor drivers, a standard universal asynchronous receiver-transmitter (UART) interface is used.

For communication between the two ESP32 microcontrollers, the TROI implements the ESP-NOW wireless communication protocol. This is a low-power 2.4GHz wireless protocol similar to Bluetooth. ESP-NOW was chosen as opposed to a wired bus communication due to the mechanical requirements of the TROI, especially with the rotation of the camera subsystem. With fewer wires being routed to the camera subsystem, there were fewer complications and critical points of failure with the wiring.

4 System Integration Testing

4.1 Software Testing

The team conducted several software-related tests. The Camera Unit Test verified the camera’s basic ability to take images and apply filters, ensuring that the manufacturer sent a functional product to the team (TROIT.3). This test passed, and integration of the camera subsystem with the TROI was able to continue. The RF Command Processing Test verified the TNC’s ability to demodulate RF commands and send them to the ESP-32 subsystem (TROIT.8). This test passed; the TNC was able to demodulate commands into those capable of being understood by the ESP-32. Successful demodulation verifies the RF system is fully functional and that integration with the camera subsystem may continue. The Camera Stepper Motor Test verifies the camera’s ability to accurately respond to in-house code commands from the ESP-32 by rotating to the correct position (TROIT.9). This test passed. The Camera Baseline Imaging Test (TROIT.12) verifies the camera is able to capture high-quality images within 30 seconds of each other while applying special effects as necessary. The TROI completed commands C3, D4, and F6 for this test. This test passed and allowed the team to continue integrating the camera subsystem. The Camera RF Integration Test verifies the RF subsystem can receive, demodulate, and transmit RAFCO to the camera subsystem, with the camera system accurately capturing images according to RAFCO (TROIT.13). Finally, the Payload State Identification Test verifies that in-house code successfully interfaces with the TROI electronic sensors to identify whether the launch vehicle is in a flying or landed configuration. This test passed; the TROI lead screw actuates only after the sensors have detected landing (TROIT.14). This test demonstrates nominal integration of the TROI mechanical and electrical subsystems.

4.2 Demonstration Flights and Testing

The TROI flew in the vehicle demonstration flight attempt on February 18th. The team tested the retention, launch and landing code, and longitudinal stepper motor deployment subsystem through this launch. The TROI did not fly in its complete configuration nor was running the finalized code; hence, this flight does not qualify as a payload demonstration flight. Images of the TROI after landing are shown in Figure 7.

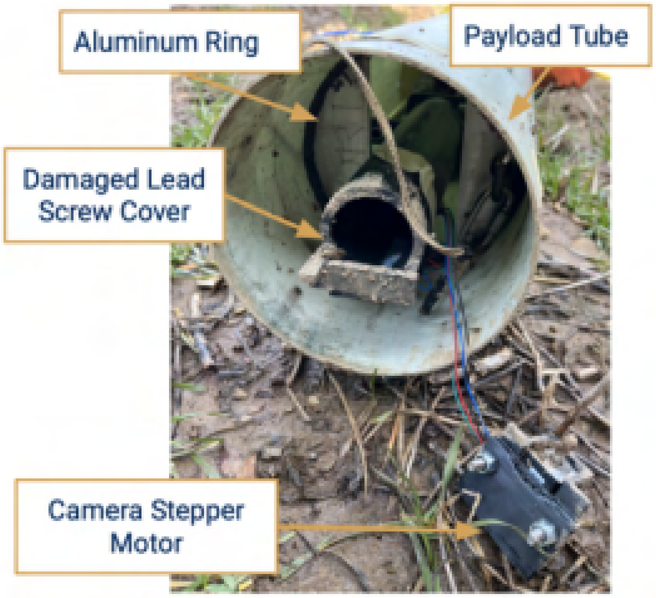


Figure 7. Payload after landing at VDF attempt

As demonstrated in Figure 7, the TROI was successfully retained in the vehicle demonstration flight attempt. There were a combination of successes, failures, and damages to the payload resulting from the flight.

The TROI was successfully retained in the vehicle demonstration flight attempt. All hardware remained intact and functioned as intended, and no electronic connections were disconnected. However, the TROI prematurely deployed about 60 seconds into the flight. This was determined to be due to a coding error in the launch and landing detection code. This error has since been corrected. Additionally, the TROI will wait 90 seconds after launch to start detecting landing as an additional redundancy considering flight length requirements (NASA Req. NASA 3.11.)

The premature longitudinal stepper motor deployment caused the lead screw cover and lead screw to sustain the force of the payload body tube landing. This caused the 3D printed lead screw cover to fail, and the 1/4 in. diameter 303 stainless steel lead screw bent. The damage to the lead screw is shown in Figure 8.

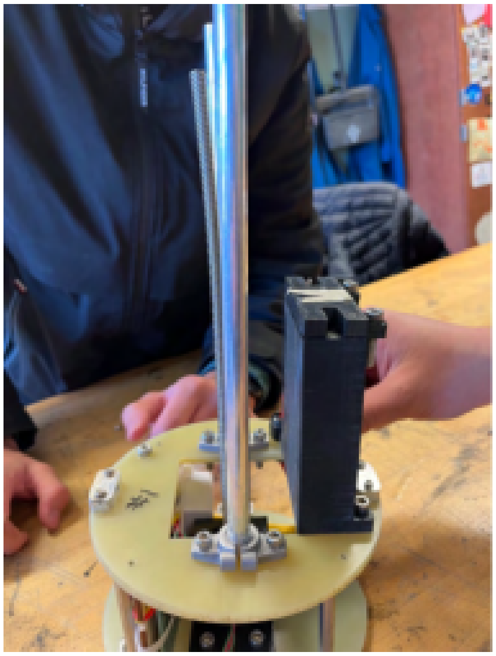


Figure 8. 75: Lead Screw Damage after VDF Attempt

Figure 8 demonstrates the noticeable deformation in the lead screw. This damage required the replacement of the lead screw. Four options were considered: reorder the original part, replace the lead screw in the existing stepper motor, use a coupling nut to attach a new lead screw to the existing lead screw, or replace the total lead screw and stepper motor assembly. All four options were explored in parallel, causing the team to try to machine a custom coupling nut as described in Section 6.3.1.2. This effort failed, and the team decided not to disassemble the stepper motor. A replacement of the original part would not arrive in time for the FRR milestone, so that option was not considered. The team acquired a replacement lead screw and stepper motor assembly and chose this option to remediate the damage due to launch as the only available option. The team reconfigured the necessary parts of the payload to work with the new lead screw size. The available lead screw has a diameter of 8mm (0.315 in.).

The TROI successfully completed a payload demonstration flight on February 26th. The TROI was successfully retained throughout the entire duration of the flight in its final configuration. The TROI successfully detected launch and landing. The payload started deployment upon landing, however, the payload jammed against the recovery aluminum bulkhead, causing the TROI to fail to reach its maximum linear deployment. The upper lead screw cover also failed to exit the guide rails. The TROI received APRS commands and demodulated most packets successfully. The APRS packet commands ("C3 A1 D4 C3 F6 C3 F6 B2 B2 C3") were successfully parsed to the
camera and the correct order of pictures were taken.

Radio frequency testing was conducted with a ground station at the launch site using a transmitting eight watt Baofeng UV-5R Pro, with a ten inch dipole antenna, horizontal polarized. The receiving end in the payload consists of a 2.5 inch dipole receiving antenna. APRS packets with the following commands were outputted every thirty seconds to simulate launch-day conditions: "C3 A1 D4 C3 F6 C3 F6 B2 B2 C3". An after system prognosis dictated that the system did receive and demodulate APRS packets that were transmitted. However the rate of demodulation was significantly lower than testing before the launch. Looking at system error as a whole, the team realized that since the antenna was aft a few inches of the aluminum bulkhead, it is likely that packet receiving on the antenna was impacted substantially. This resulted in the decision to upgrade the RF system. Changes were made to add additional filtering and gain control as well as a higher baud rate microcontoller. Additionally, the test ground station setup was not as powerful as NASA's ground station. NASA's ground station at Huntsville proved to be powerful enough to allow the new RF system to receive at a long range even without the aid of an antenna.

5 Installation Manual

5.1 Installation

Find the TROI installation and setup instructions documented within the “NDRT 2022-2023 Launch Procedures - Huntsville Edition” document, included in Appendix A. This contains the installation instructions for preparing the payload for launch as well as instructions for installing the system into the rocket.

5.2 Setup

- Verify that the TROI system battery reads a voltage within the acceptable range of 9.6 to 12.6 V using a digital multimeter. If any battery does not have an acceptable voltage, charge the battery using a portable DC power supply or replace the battery.
- Ensure that the TROI in its entirety is void of scratches, cracks, or any other damage. Repair as necessary. In order to ensure the TROI system is operational, verify that the correct code is loaded onto the microcontroller.
- With the battery status verified, connect the microcontroller to the battery.
- Connect the green wire from the 3.3 V battery to the pin label.
- Connect the blue wire from the radio transmitter to the microcontroller receiver.
- Once the battery connection is made, the microcontroller will be searching for radio signals. Once the circuit is in its "listening" stage, an LED light will light up on the circuit indicating that it is on and functional.
- Note: If this LED light does not flash, obtain the Payload Squad Lead’s laptop to ensure that the correct code is uploaded to the microcontroller. If the LED light still does not flash, turn the system off and restart this procedure.

- Ensure that the indicator light on the RF transceiver module is on. If this light does not flash, resolder or rewire connections as necessary.
- Ensure that the indicator light on the camera is on. If this light does not flash, resolder or rewire connections as necessary.
- Remove the lens cap from the camera.

5.3 Operation Testing

- Ensure calibration before integration is satisfactory. Obtain the laptop with the appropriate code and set up the ground station to send instructions to the TROI.
- Set up the TROI to receive radio frequencies.
- From the ground station at a certain radio frequency, separate from the NASA-defined frequency, send a set of movements to be performed by the TROI.
- Observe the TROI's movement and inspect if the payload moves as expected from the set transmission. If the payload does not move as expected, turn off the system and apply lubricant to allow the motor arms to work properly. Reactivate the electronics and repeat these procedures.
- Note: If reconnecting the accelerometer does not fix the drifting, verify that the transmission has been received and that all subsystems are active.

5.4 Troubleshooting

1. Initialize the ground station and prepare for transmission.
2. Initialize the payload radio and prepare for transmission.
3. Transmit a series of commands from the ground station to the payload radio.

4. Assess whether any commands were received and if they were comprehended correctly by the payload radio.
5. If the payload does not properly receive the ground station commands, ensure the radio frequency is correct and that there is no static on that frequency. Following these checks, repeat procedures one through four.

6 To-Market Design Changes

Although the TROI was developed for a NASA competition, without a commercial context in mind, there are several areas that could be improved upon were this a product being brought to market. The first would be to increase battery capacity. Size and budget limitations determined the batteries used for the functional prototype of the TROI. With a larger budget, the opportunity to obtain higher quality batteries that offer more capacity than the Tenergy Li-Po batteries, while still remaining within size constraints for the TROI. In a real-world situation, a rocket might remain on the launchpad for an extended period of time, potentially much longer than the duration (based on rules of NASA's competition) that the payload team had to account for in the design of the functional prototype. A larger battery capacity would ensure that the TROI functions properly even after an extended waiting period on the launch pad.

Another significant design change would be including a secondary, telescoping camera arm at the end of the camera arm in the current TROI design. In the current TROI design, the camera can rotate 360^{o} about the z-axis, but since the camera remains level with the rocket tube, about 180^{o} of this field of view will be looking into the rocket, making it useless. This secondary camera arm would elevate the camera above the rocket tube, allowing for a full 360^{o} field of view of the area outside of the rocket. This idea was originally proposed for the TROI, but was not pursued due to its complexity and the time constraints presented by the NASA competition.

A third significant change would be the use of stronger materials for the 3D-printed sections of the TROI, guide rails, and the lead screw, since these were the sections that failed during the crash landing at the launch in Huntsville. Stronger materials would lead to a more resilient TROI. However, the parachute failure at the Huntsville launch was highly unusual, and it is not clear if stronger materials would allow the TROI to remain functional after such a forceful impact. It may be more worthwhile to invest time and resources in ensuring that the recovery parachute always deploys properly.

Other minor design changes include adding a speaker to the TROI and tapering the guide rails near the decoupling point. The speaker would be used to provide an audible signal that the TROI is ready to deploy and begin taking pictures. The current TROI operates silently, meaning that users must wait until after a launch to check the microSD card and ensure that the system functioned properly. An audible signal would provide live confirmation that the TROI is working as expected. This idea was also considered in the development of the functional prototype, but was not pursued due to time constraints. Additionally, on the current version of the TROI, the flat, untapered ends of the guide rails make it difficult to reset the 3D-printed camera arm after deployment, since the holes in the camera arm must be exactly aligned with the guide rails in order to place the arm back on the rails. This is a minor problem, but can be frustrating when one has to reset the camera arm often, such as on Demo Day. Tapering the guide rails would make resetting the TROI's primary camera arm easier.

7 Conclusion

The TROI is an imaging system capable of responding to commands sent over a radio frequency link. It is divided into 3 subsystems, the ESP32-Main, ESP32-CAM, and RF subsystems. Each of these is responsible for a different set of tasks related to the project requirements. The RF subsystem receives and demodulates radio signals. The ESP32-Main subsystem takes data from the RF subsystem and other sensors, relays commands to the ESP32-CAM subsystem, and controls the TROI stepper motors. Finally, the ESP32-CAM subsystem rotates its camera, and records, edits, and timestamps images according to directions received from the ESP32-Main subsystem.

While there are areas for improvement, as discussed in the previous section, the system functions as expected, reliably and accurately meeting the project requirements established by NASA for its annual rocketry competition, described in Section 2 - *System Requirements*. Rigorous testing has been conducted using the fully integrated TROI system, according to the procedures described in Section 4 - *System Integration Testing*. These tests demonstrated that the TROI successfully deploys the camera when landing is detected; accurately receives, demodulates, and responds to commands sent over a radio link; and successfully records and edits images according to received instructions. In addition to building this functional prototype, the Payload and senior design team have also together produced documentation on installation, setup, testing, and troubleshooting for the TROI.

It is unfortunate that the TROI did not have the opportunity to perform to its potential during the competition launch at Huntsville. However, this was due to circumstances outside of the TROI's control and scope. Additionally, this final outcome does not take away from the larger development process that has taken place over the past two semesters. The NDRT Payload and senior design team learned about radio communications, PCB design, and image processing, as well as general project development experience that is valuable in an engineering context. For these reasons, the members of the NDRT Payload team and the senior design team feel that this project has been a success and a worthwhile experience.

8 Appendices

Appendix A - Final NDRT launch procedures

Contains information on the installation, setup, testing, and troubleshooting of the TROI and other rocket systems. Information about the TROI specifically can be found in Section 9.3 - TROI Preparation (pp. 15-17), but there is also additional information about the TROI in other sections throughout the document

NDRT 2022-2023 Launch Procedures - Huntsville Edition:
https://drive.google.com/file/d/1g9MqbHooQl0c556XM-AahBIed9ilTK7B/view?usp=sharing

Appendix B - Hardware Schematics

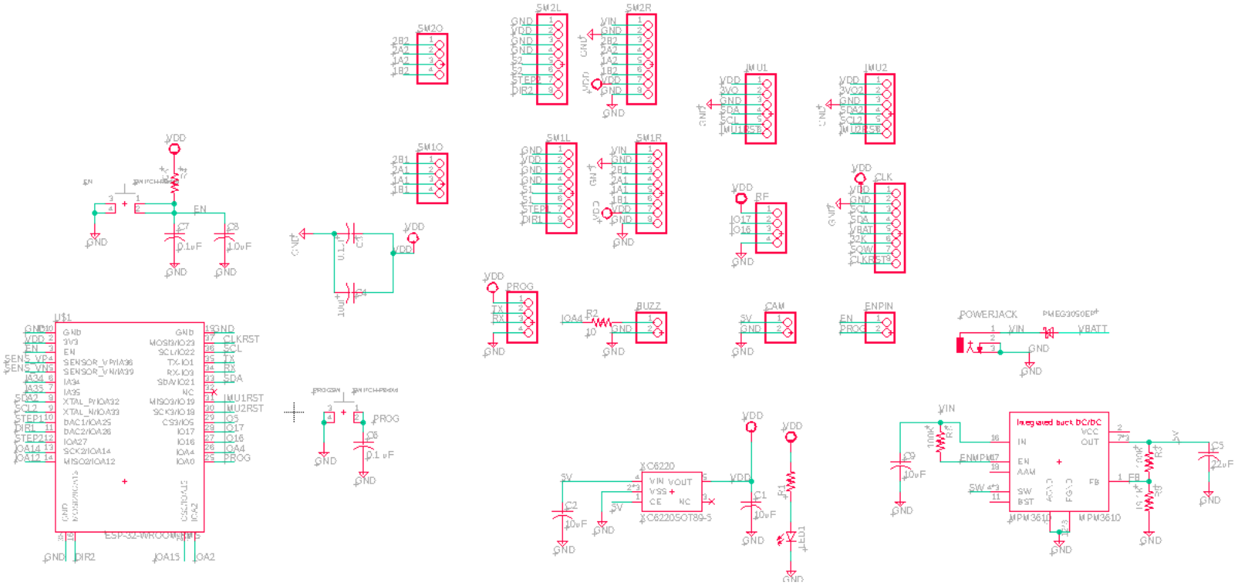


Figure 9. ESP32-Main subsystem schematic

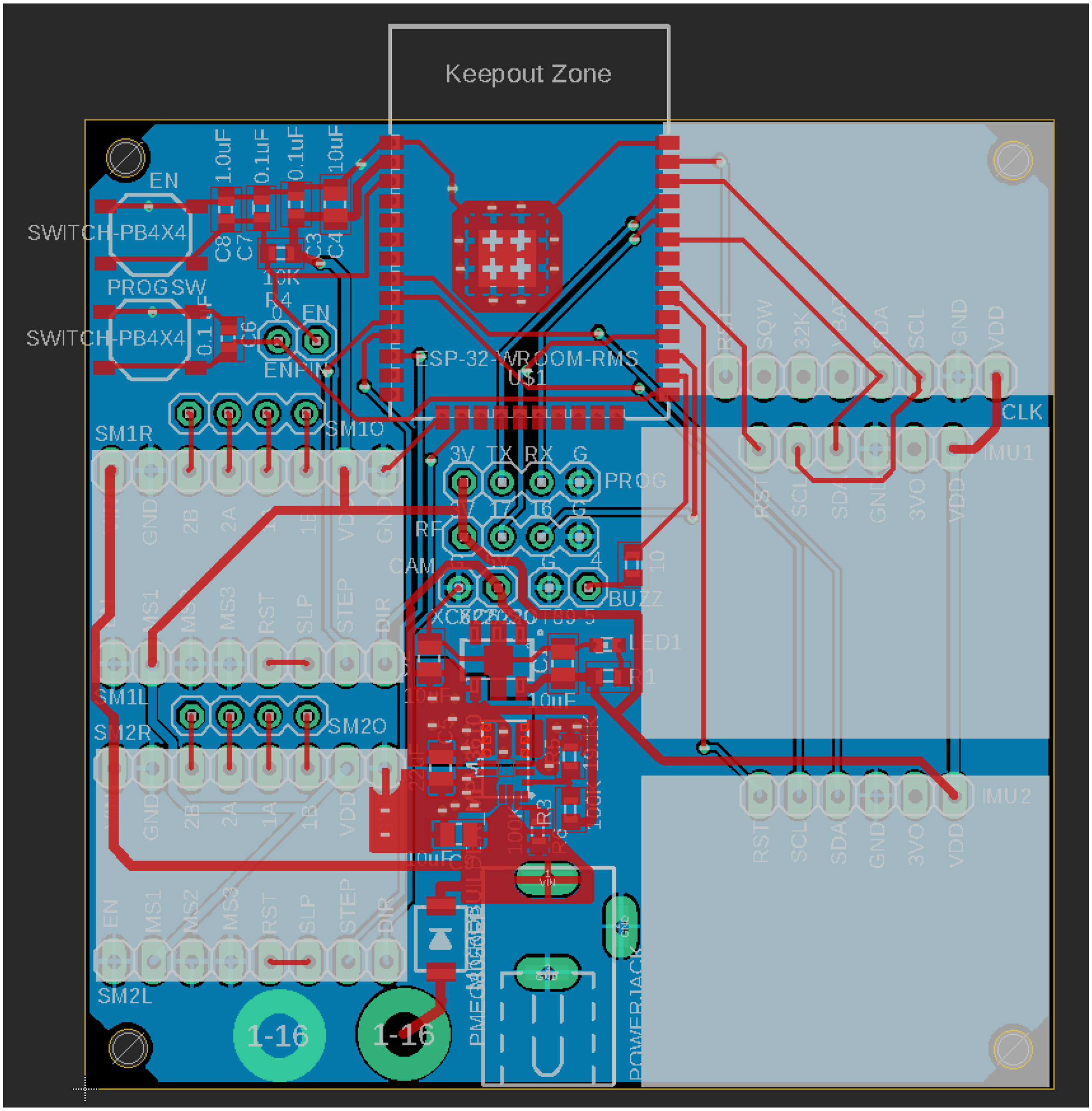
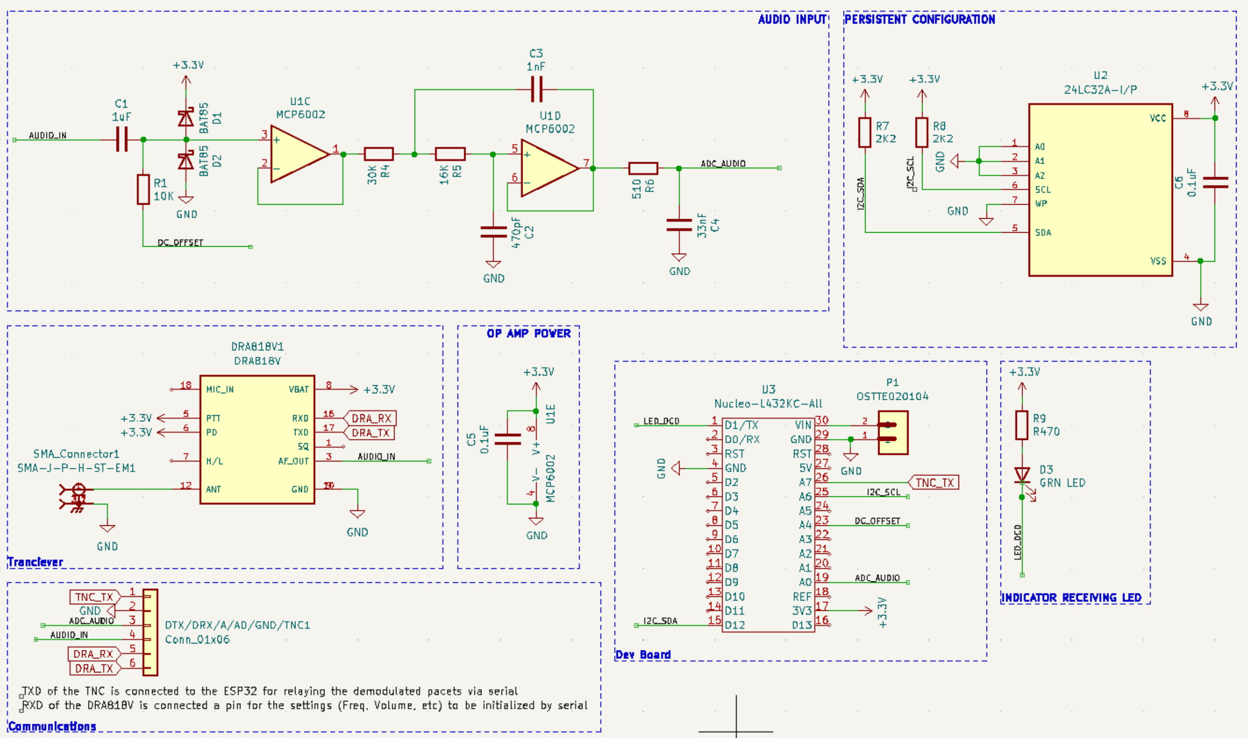


Figure 10. ESP32-Main PCB layout



TXD of the TNC is connected to the ESP32 for relaying the demodulated pacets via serial
RXD of the DRA818V is connected a pin for the settings (Freq. Volume, etc) to be initialized by serial

Figure 11. RF subsystem schematic

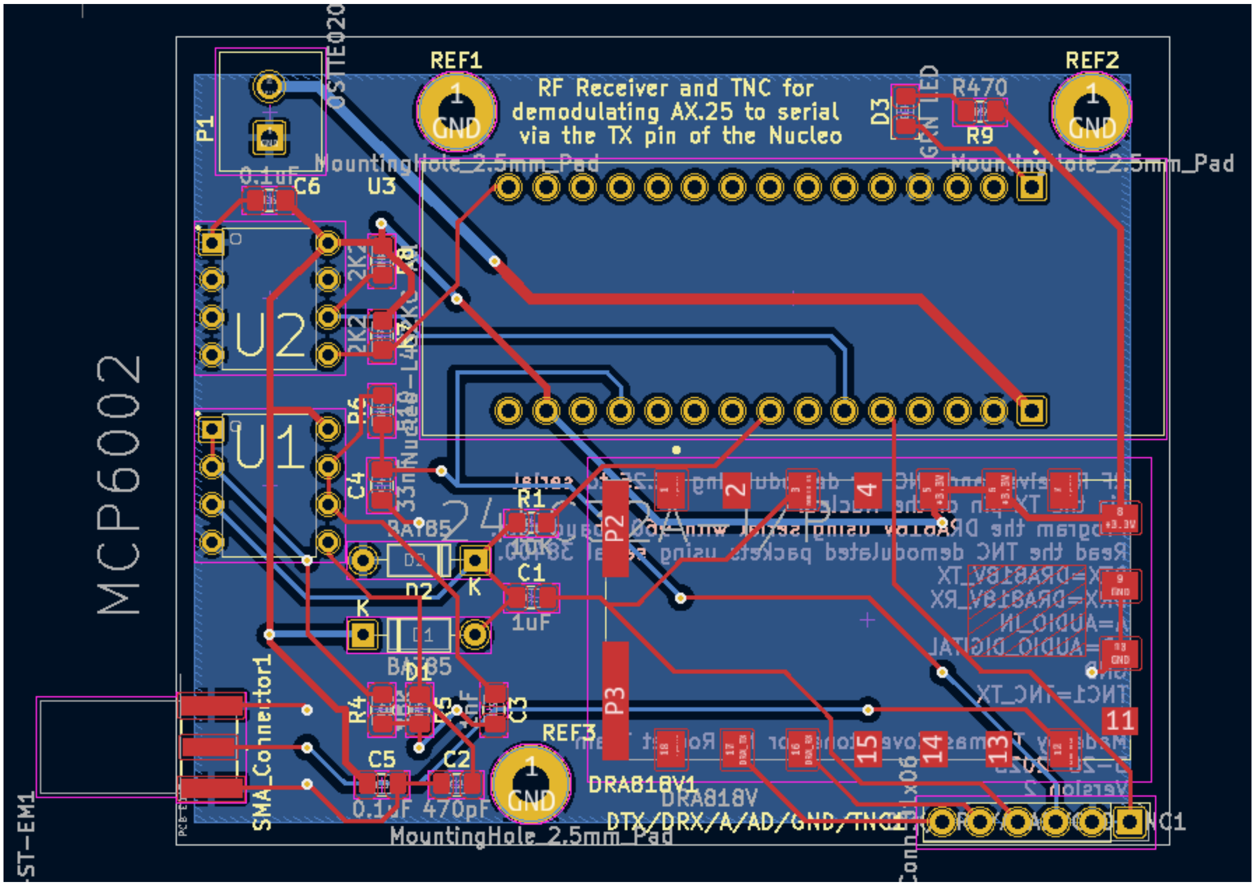


Figure 12. RF subsystem PCB layout

Appendix C - Software listings

1. Audio Signal Experiment Workshop for Generating Test AFSK Recordings: https://signals.nitrocosm.com/go/afsk/
2. APRSDroid for Generating Test APRS Packets: https://aprsdroid.org/download/
3. Document of other helpful software links and guides: https://docs.google.com/document/d/1GAwJKEg9nVzCeIuGVMl8yV36L9iPPD_t/edit?usp=sharing&ouid=109821223716063347823&rtpof=true&sd=true
4. Payload github: https://github.com/SpaceLegosFan/Payload_22_23
5. TNC Example Software: https://github.com/mobilinkd/NucleoTNC

Appendix D - Relevant datasheets

1. A4988 Stepper motor driver
2. BNO005 IMU/Accelerometer
3. DRA818V Transceiver
4. DS3231 Real Time Clock
5. ESP-WROOM-32 datasheet
6. Mobilinkd website
7. MPM3610 Step-down converter
8. XC6220 Voltage regulator