Executive Summary – Main Tasks

Initial TENG Research	Research on DC TENGs Material Pairs Research
Codebase Testing	Testing CRSF Library Testing HC-12 Library Iterative Testing of Hardware
Transmitter & Receiver Communication	HC-12 Function & Range Tests CRSF Drone Simulations
Receiver Design	Receiver Circuit Concept Receiver PCB Layout Mounting Solution Design

Executive Summary – Task Requirements

Task	Description	High Level System Requirement	Outcome
DC Teng Research	Early research into feasibility of self-power, via means of DC TENG.	The TENGs should completely or partially contribute power to the transmitter circuit.	Fail
Material Pair Research	Research into best combinations of TENG materials for optimal power and sensor outputs.	The TENGs should completely or partially contribute power to the transmitter circuit.	Fail
HC-12 Library Testing	Rendering assistance to team-member writing HC-12 drivers via help testing and debugging.	The transmitter circuit must transmit data reliably (>99% success) within a 100m range.	Success
CRSF Research & Library Testing	Rendering assistance to team-member writing CRSF drivers via help testing, researching and debugging.	The receiver circuit must be able to interface with the RF components and the drone.	Success
Iterative Hardware Tests	Ongoing testing of sub-systems and system via tests of HC-12, CRSF connection, Rx PCB etc..	The receiver circuit must be able to interface with the RF components and the drone.	Success
HC-12 Function & Range Tests	Testing functionality of HC-12 wireless transceiver for range, power draw and reliability.	The transmitter circuit must transmit data reliably (>99% success) within a 100m range.	Success
CRSF Simulations	Simulations of drone on Betaflight, testing reliability and usability of code and hardware.	The receiver circuit must be able to interface with the RF components and the drone.	Success
Receiver Circuit Concepts	Initial research and design of the receiver circuits for communication with the drone.	The drone must be able to communicate and be controlled by a receiving microcontroller.	Success
Receiver PCB Layout	Implementation of receiver circuits in real hardware, designed for flight-use onto a PCB.	The drone must be able to communicate and be controlled by a receiving microcontroller.	Success
Drone Mounting Solution	Design of a bespoke solution to mount Rx PCB to drone whilst protecting sensitive components.	The receiver circuit must be able to be mounted to the drone.	Success

Introduction & Background - Project

- The project's original aim was to develop a smart sleeve for astronauts that enables control of remote vehicles via Triboelectric Nano Generator (TENG) sensors.
- Additionally, the project investigated whether TENGs can facilitate more advanced human-machine interfacing in other areas, such as drones (in this case).

Introduction & Background - Problems

Several questions raised, among which:

- Is TENG-based self-power possible?
- What's the best method for communication between two boards wirelessly for drone use?
- What's the best method for communication with the drone itself?
- Can a board be designed to fulfill communication with drone, but still be mounted to it?
- And how reliable is everything above?...

Introduction & Background - Aims & Objectives

To help answer the questions raised, I was focused on several objectives:

- To investigate potential methods of self-power for TENG circuits.
- To investigate, test and implement wireless communication methods for board-to-board communication.
- To perform research into drone communication protocols and implement whichever seems appropriate.
- To design a board, and mounting solution, for the drone; implementing results from research done.

Each of these objectives had to satisfactorily work and meet the high-level system requirements previously set out…

Q: Is TENG-based Self-Power Possible?
AC vs DC TENGs

During early planning, the need for self-power in the transmitter smart glove was highlighted. AC TENGs, while capable of power and sensing, require additional circuitry for rectification to power DC devices like the MCU and RF components. This led to considering DC TENGs as an alternative. DC TENGs simplify the circuitry by eliminating rectification, reducing component count and associated losses. Additionally, they produce less noise, minimizing crosstalk and ensuring precise sensor readings. Investigation into DC TENGs revealed the TPU-PTFE combination as optimal, with a charge density, in theory, of 8.80 $mC\ m^{-2}$.

My primary role was investigating the feasibility of DC TENGs, however this role lost focus in place of Ion Injection TENGs, and later deprioritized once self-power was abandoned as an idea.

Q: Is TENG-based Self-Power Possible?

Ion Injection in TENGs

As the project progressed, the team decided to experiment with ion injection instead of the proposed DC-TENG solution. Ion injection, based on another research paper, offers higher charge and voltage levels, making it a potentially superior solution. Further research on combining DC-TENGs with ion injection was planned, but ultimately results for Ion Injection was disappointing and plans for self-power were abandoned.

Q: What’s the best method for communication between two boards wirelessly for drone use?

Selection of HC-12 (Competition)

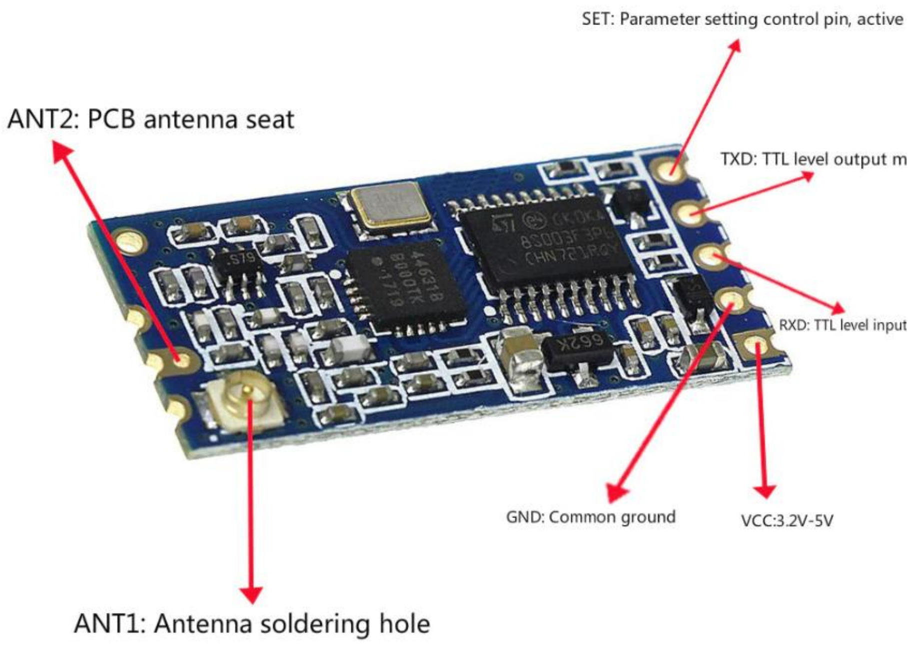


Diagram of HC-12

Device	HC-12	NRF24L01
Frequency Range	433.4 MHz to 473.0 MHz	2.4 GHz ISM band
Communication Range	Up to 1,000 meters	Up to 100 meters
Power Supply	3.2V to 5.5V	1.9V to 3.6V
Data Rate/Baud Rate	1,200 to 115,200 bps	250 kbps, 1 Mbps, 2 Mbps
Interface	UART	SPI
Modes	Multiple modes for speed/range	Enhanced ShockBurst™, low power
Best For	Long-range communication	Short-range communication

The original choice for wireless comms was the Nordic Semiconductor NRF24L01, however this proved unsatisfactory for several reasons during testing:

It was dropping packets - even at very low distances, it used more power than desired, and the use of SPI for the interface required writing complex driver code in C which wasn’t feasible in a short time frame.

Q: What's the best method for communication between two boards wirelessly for drone use? Selection of HC-12 (Specifications)

Overview:

- **Frequency Range:** 433.4 MHz to 473.0 MHz
- **Communication Range:** Up to 1,000 meters in open space with an appropriate antenna
- **Power Supply:** 3.2V to 5.5V
- **Baud Rates:** Supports from 1,200 to 115,200 bps
- **Interface:** UART (Universal Asynchronous Receiver/Transmitter)

Key Features:

- **Long Range Communication:** Ideal for applications requiring long-distance wireless communication
- **Versatile Modes:** Multiple modes (FU1, FU2, FU3, FU4) for different speed, range and power requirements
- **Easy Integration:** Simple UART interface for easy connection with microcontrollers like Arduino and Raspberry Pi
- **Configurable Parameters:** Customizable frequency, baud rate, and power settings via AT commands

From the specifications presented, it is easy to see why the HC-12 was selected for this project use;

It theoretically meets, and exceeds, the range requirement whilst providing a very tolerant voltage input and power usage. It is also very configurable, with plenty of choice for baud rate and frequency depending on range, power and legalities. In this case, 2400 Baud and 459.4 MHz were selected to keep with legal and power requirements.

Q: What's the best method for communication between two boards wirelessly for drone use? Implementing the HC-12

In this project, my responsibilities included assisting in the development of the driver code for the HC-12, performing debugging tasks, and conducting comprehensive full-stack testing. The implementation of the HC-12 was relatively straightforward due to its use of UART, necessitating minimal code. The primary functions developed were:

- **configure_AT_first_time_setup():** This function is used for both initial programming and subsequent reprogramming of the HC-12 module.
- **configure_pins():** Sets up the GPIO pins on the Raspberry Pi Pico to enable UART communication.
- **tx_mode():** Allows the Raspberry Pi Pico to operate in transmission mode, awaiting input from the TENGs to compute CRSF values and transmit them.
- **rx_mode():** Enables the Raspberry Pi Pico to function in reception mode, ready to receive packets from the HC-12 module.
- **send_receiver_command():** Converts CRSF commands into a packet format suitable for wireless transmission.

Q: What's the best method for communication with the drone itself?

Selection of CRSF (Crossfire) over SBUS

SBUS implementation challenges:

- Proprietary system
- Lacks documentation or information on implementing it

CRSF technical advantages:

- Higher baud rates (420kbps vs 100kbps)
- 8-bit cyclical redundancy check (CRC) vs. simple parity check

Additional CRSF benefits:

- Supports telemetry feedback from drone's flight controller to transmitter
- CRSF is open-source and online documentation available for aid in implementation

Q: What’s the best method for communication with the drone itself?
Protocol Structure of CRSF (Crossfire)

[sync] [len] [type] [payload] [crc8]

Singular byte 0xC8

Payload length +2 (type and crc8)

Type of packet you are sending. In our case mostly motor commands (0x16)

16x 11-bit channels spread over multiple bytes.

8-bit cyclical redundancy check on type and payload. Modulo-2 division using poly 0xD5

Q: What's the best method for communication with the drone itself?
Implementation of CRSF (Crossfire)

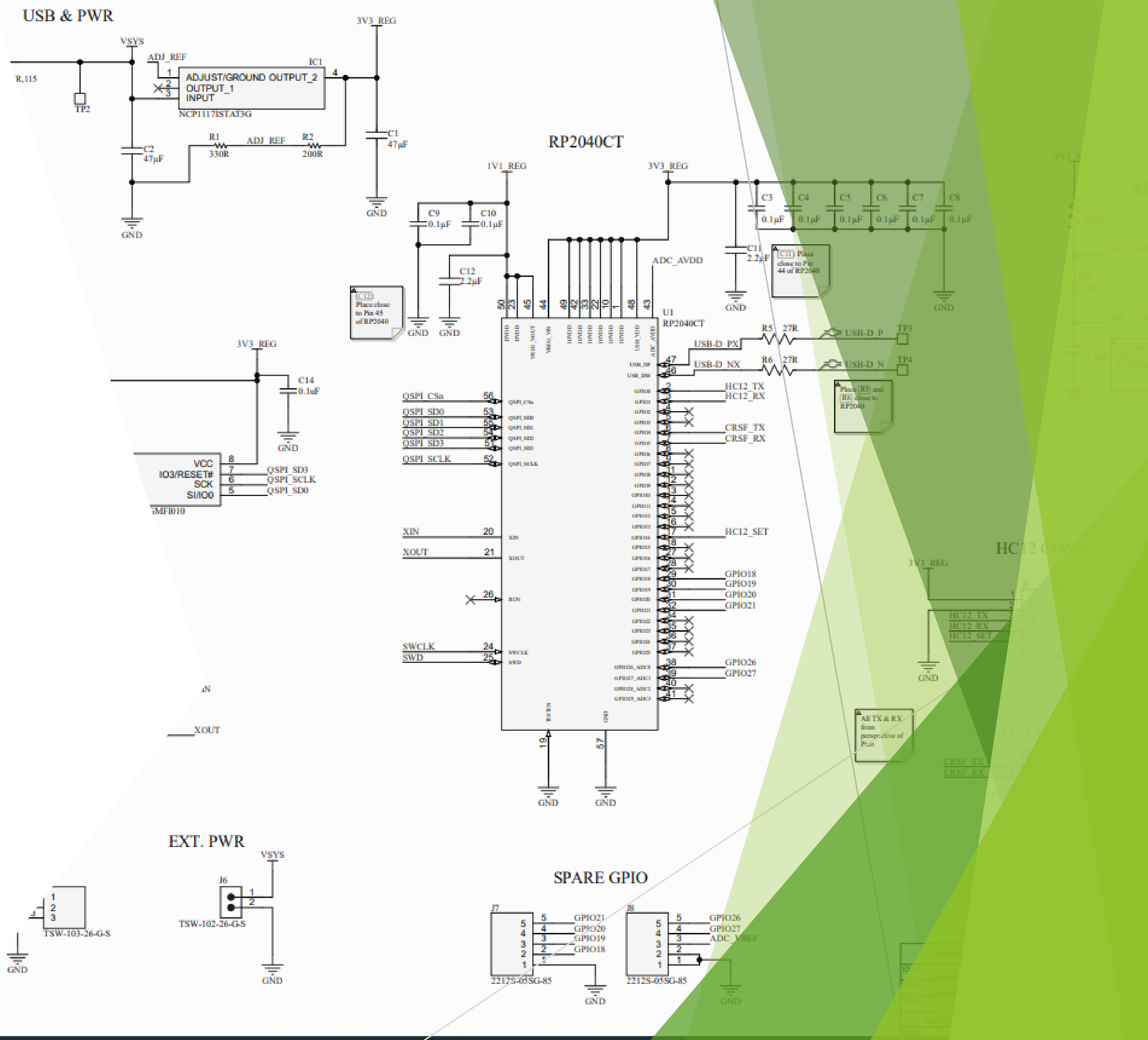
Implementing CRSF took the most time to program and test, being a significantly complex system. It required attempting to override 26 safety systems of the drone and inject our own data, which proved too involved in the time frame we had. My role was to help debug & test the code written, and to provide the hardware/PCB and hardware support, as well as any test equipment needed during testing (such as oscilloscope/bench power supply etc.)

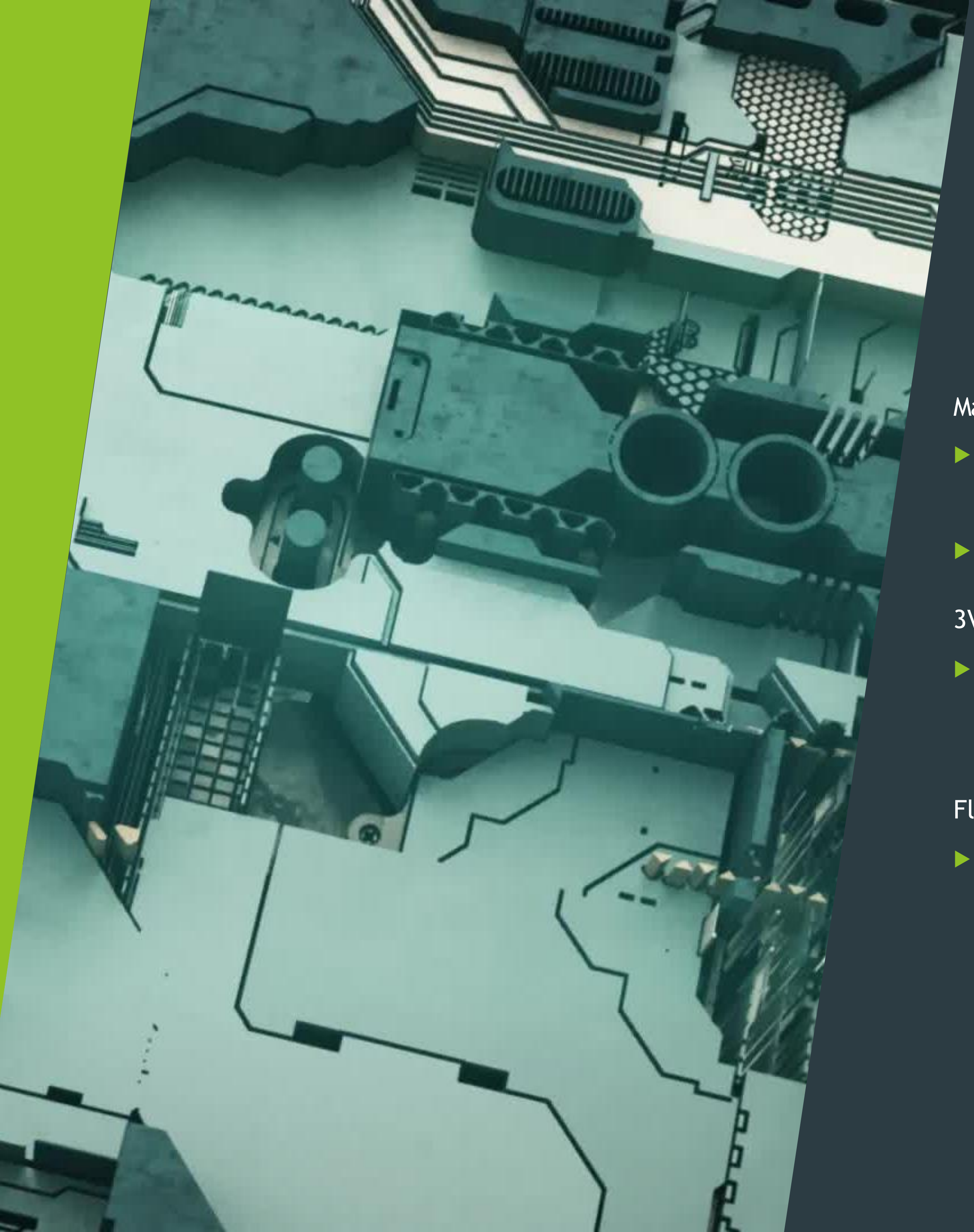
- make_crsf_packet()
  - Wraps payload into CRSF packet structure
- write_crsf_packet()
  - Writes packet over UART to flight controller
- calc_cr8()
  - Calculates cyclical redundancy check (CRC)
- make_crsf_rc_channel_payload()
  - Formats 12-bit channel data into 8-bit bytes
- crsf_data_validate()
  - Validates CRSF values from ADC
- handle_crsf_data()
  - Handles CRSF data from ADC
- Convert_adc_voltage_to_CRSF()
  - Converts ADC voltage to CRSF value based on drone axis

Q: Can a board be designed to fulfill communication with drone, but still be mounted to it?
Initial Requirements

Initial requirements called for:

- RP2040-based Microcontroller Circuit, capable of using C-code drivers written by another team member
- On-board 3V3 power regulator and complementary circuitry, to allow powering from the drone battery with reverse voltage protection
- Mounting hole and profile size compatible with FPV drone (50 mm sqr., with 35 mm sqr. mounting locations)
- GPIO connections for interfacing CRSF and HC-12 (for drone, and wireless communication, respectively)





Q: Can a board be designed to fulfill communication with drone, but still be mounted to it?
Circuit Design Component Selection

Main MCU:

- Needed to be C-compatible, with enough RAM to hold complex driver code in memory. Only RP2040 met this (264kB, much larger than competitors in its class)
- Using the RP2040 also allowed using the Raspberry Pi Pico during prototyping phase

3V3 Regulator:

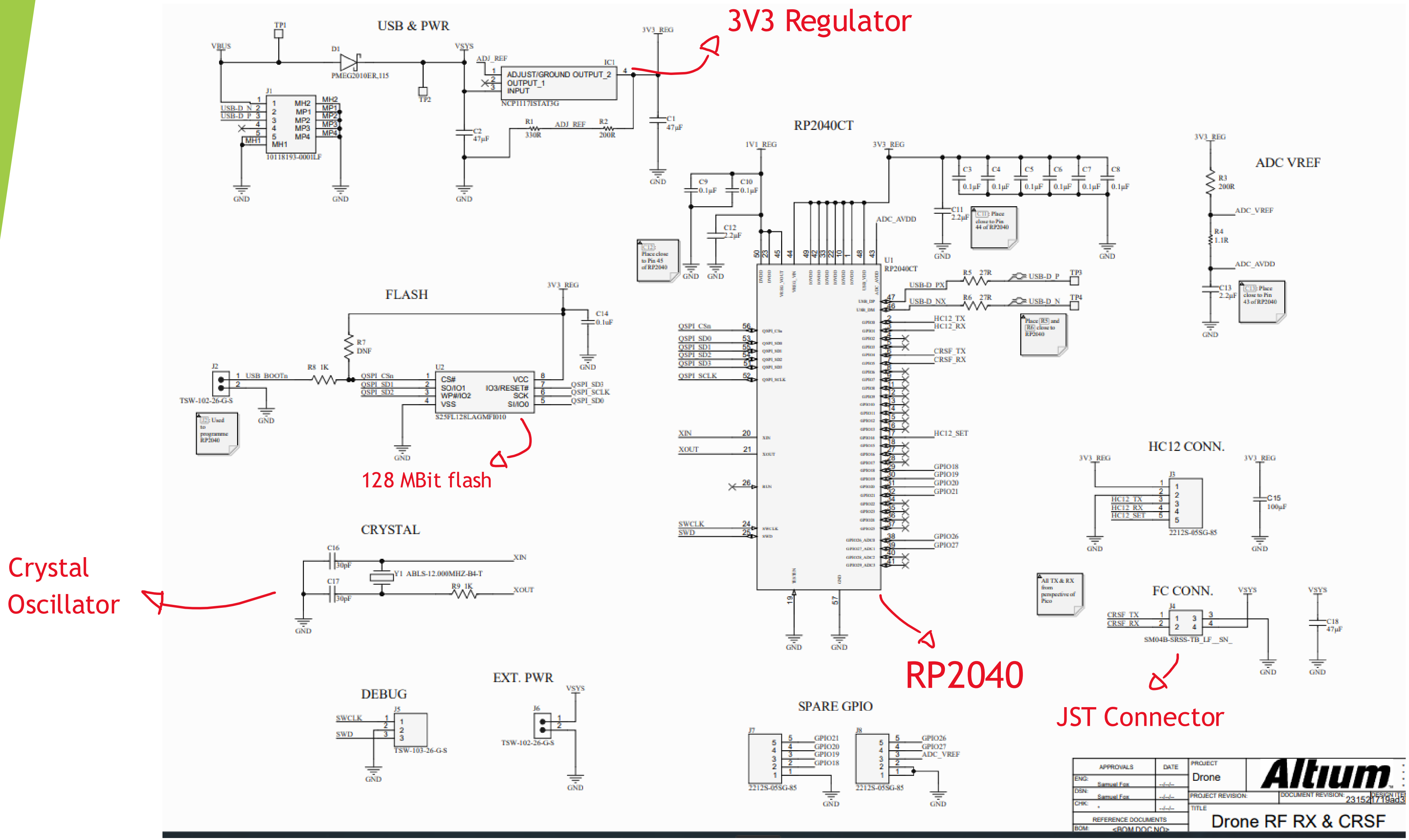
- Needed to have low forward drop-out and be linear to avoid switching noise on such a small board. NCP1117STAT3G met this; a 1A Linear Regulator with a dropout of 1.2 V @ 800 mA (low enough to ensure no issue knocking 5V down to 3V3)

Flash Chip:

- Needed to be the largest flash chip compatible with the RP2040 (a 128 Mbit SPI flash chip). Originally selected the S25FL128 from Infinieon, but due to compatibility issues this was changed to a W25Q128 from WinBond (more later)

Q: Can a board be designed to fulfill communication with drone, but still be mounted to it?

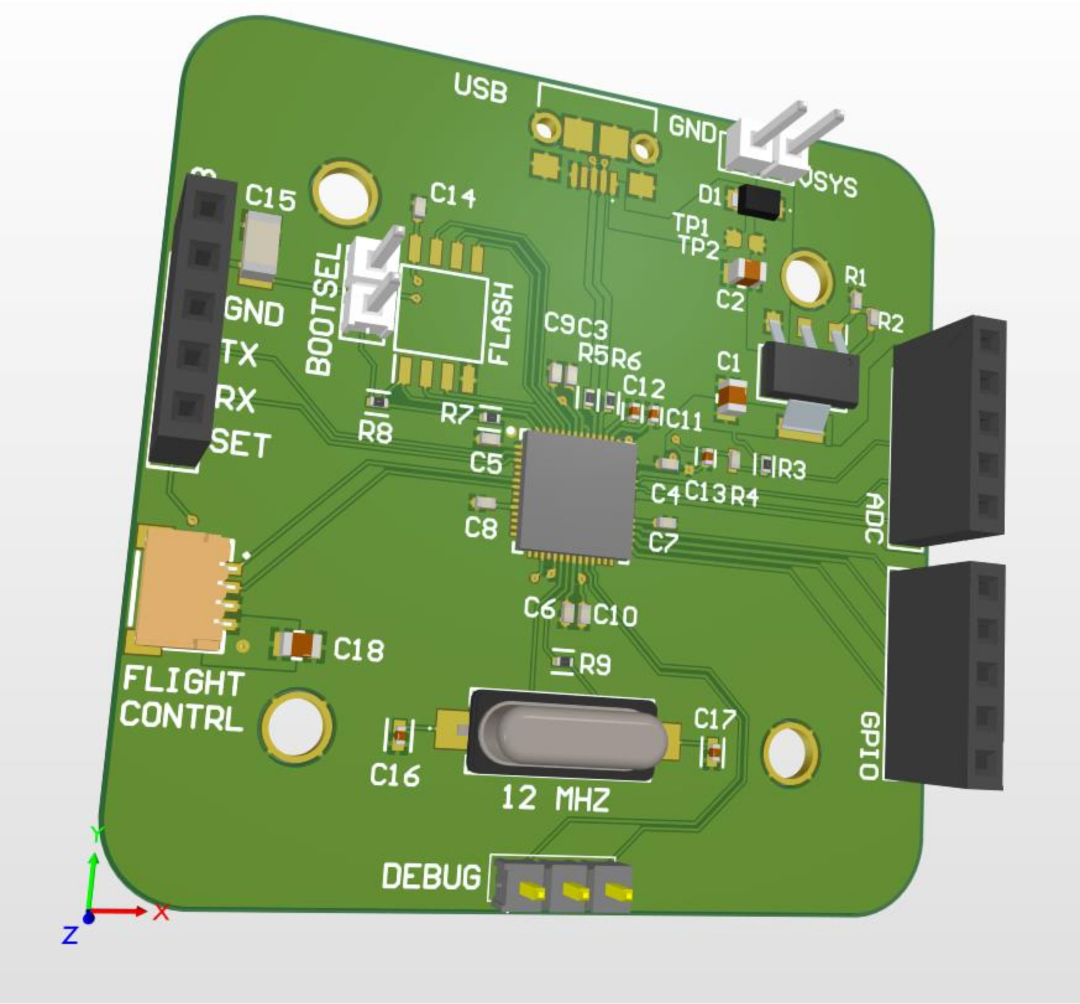
Circuit Design



Q: Can a board be designed to fulfill communication with drone, but still be mounted to it? Board Design Requirements

Board design improved on the stock Raspberry Pi Pico in several ways;

- A more drone-friendly form factor allowing for easy mounting using the pre-determined mounting locations (at 35 mm sqr.)
- Lighter than a stock RP2040 owing to the reduced component count, allowing for a more stable drone in the air
- Secure mounting for CRSF and HC-12 components, including the selection of JST connectors (marked *FLIGHT CONTRL* on board)

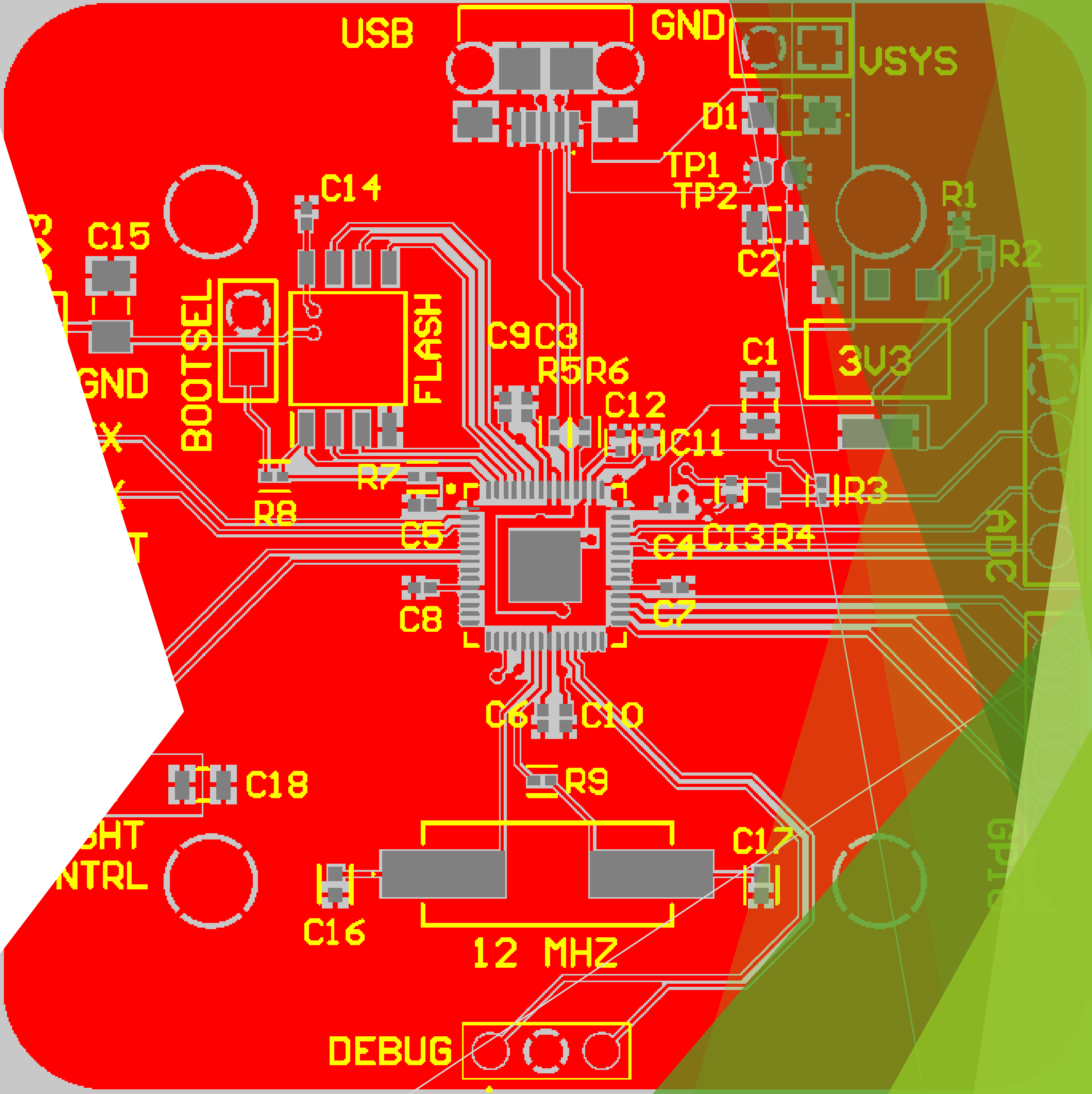


Q: Can a board be designed to fulfill communication with drone, but still be mounted to it?
Board Design

PCB was designed in Altium Designer, a professional software suite used heavily in industry

Several challenges were posed and overcome:

- How to keep USB differential pair at a fixed impendence on such a compact board (90 Ohm)
- How to keep traces short, without crossover and without noise for the flash chip
- Where best to place JST and other connectors for best compatibility



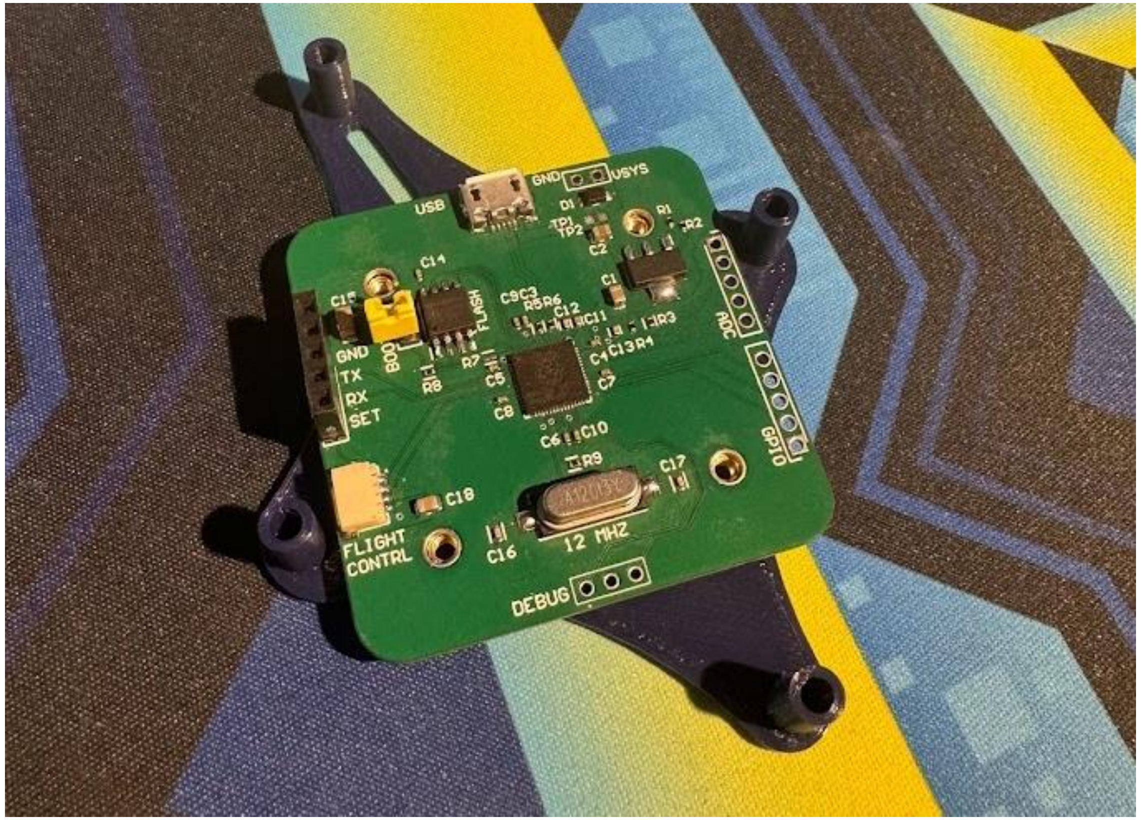
Q: Can a board be designed to fulfill communication with drone, but still be mounted to it?
Board Mounting Design

Once the board was designed, a mounting solution was needed:

- Mount on underside of drone
- Centrally mounted as not to disturb Centre of Mass
- Small and light enough to not cause extra unneeded weight on drone, but strong enough to protect the PCB and HC12 as well as wire connections to the drone

To achieve these points, a plate was designed that replaced the existing drone underside ‘skid’ plate, but with spacers and mounting holes placed in such a way that a board could be mounted in the gap between the plate and drone.

Q: Can a board be designed to fulfill communication with drone, but still be mounted to it?
Board to Drone Mounting



From the above design, the plate was printed in PLA filament from a home 3D printer. The resulting plate was sturdy and rigid, providing good protection to the PCB and the related wiring.

The image, left, shows the board mounted to the plate. Longer bolts would then be placed through the tall spacers to mount to the drone from the underside.

Q: And how reliable is everything above?... Testing HC-12

Initial Test:

- **Objective**: Verify basic functionality.
- **Method**: Send 9 ASCII bytes ("Hello Sam\n") over a short distance.
- **Outcome**: Successful; HC-12 received the correct message.

Range Test:

- **Objective**: Evaluate range capabilities.
- **Method**: Configured two HC-12s to send "Hello" while increasing the distance.
- **Results**:
  - **100m (Line of Sight)**: Reliable connection.
  - **Beyond 100m/With Obstructions**:
    - Some packets received successfully.
    - Other packets were missing data or corrupted.

Conclusion:

- **Requirement Achieved**: The transmitter circuit reliably transmitted data (>99% success rate) within a 100m range.

Q: And how reliable is everything above?... Testing CRSF

Control Axis Test:

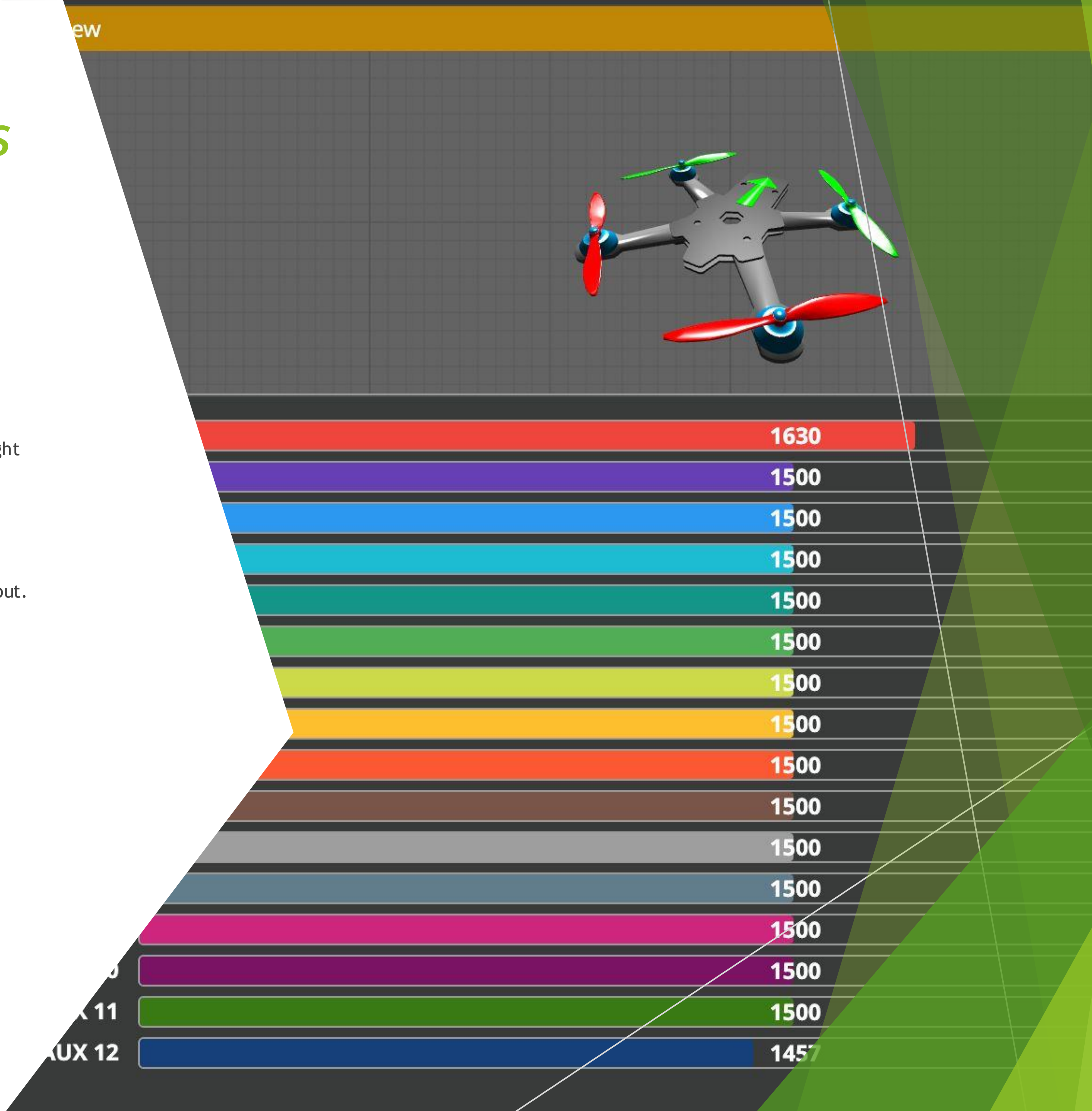
- **Objective**: Verify control over roll, pitch, and yaw.
- **Method**: Commands issued via the receiver to the drone's flight controller; compared CRSF values with Betaflight simulation.
- **Outcome**:
  - All three axes performed perfectly.
  - Motion and CRSF values matched the programmed input.

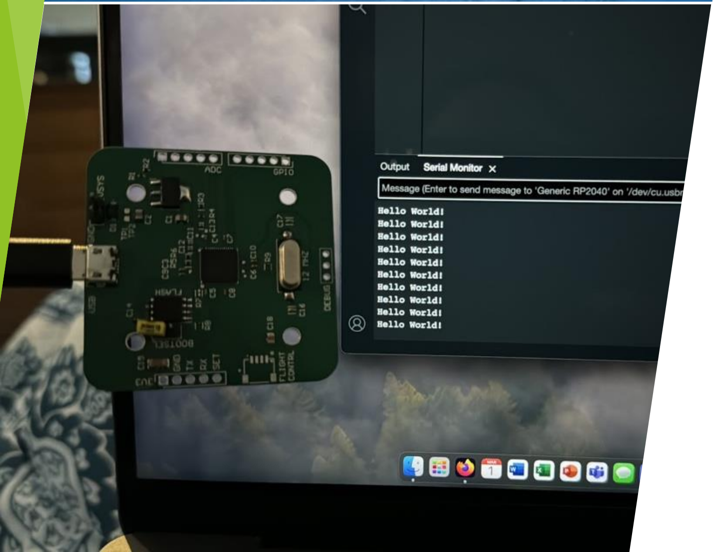
Conclusion:

- **Requirement Met**: "The drone must be able to communicate and be controlled by a receiving microcontroller."

Motor Arming Test:

- **Objective**: Test arming and spinning of motors.
- **Method**: Attempt to meet 26 arm conditions.
- **Outcome**:
  - Successful simulation control.
  - Inconsistent motor arming; frequent failsafe mode activation.





Q: And how reliable is everything above?...
Testing Receiver RP2040 PCB

The final, soldered, receiver PCB worked mostly as expected but testing revealed two minor issues:

- The connection between FLIGHT CONTRL power input and the voltage regulator input had no diode, unlike the USB power input, thereby meaning the board would feed power into the drone when connected to USB debug equipment.
- The original selected flash chip, made by Infinieon, was incompatible with the RP2040 as it used proprietary commands. Swapping this to a WinBond chip with the same package rectified this issue.

Despite these minor problems, testing showed no issues and the communications with the drone via the CRSF wires was fine.

Therefore, the requirement “The drone must be able to communicate and be controlled by a receiving microcontroller.” was met successfully for the hardware, too.

Q: And how reliable is everything above?... Testing System

Video on the right shows the final, complete, TENG to Betaflight testing completed at the end of the project.

This final testing, whilst basic, showed TENG inputs being processed, transmitted, received and decoded by Betaflight (thereby demonstrating the PCB working fine, for example). Unfortunately, due to the 26 motor arming conditions, a final flight test was unable to be performed.

Conclusions

Initial TENG Research

Initial research showed some promise for self-power, especially if using techniques such as DC TENG or Ion Injection. However, likely due to time, technological and skill issues the team could not get this aspect working correctly.

Codebase Testing

The code, as written by another team member, worked almost flawlessly; this of course was a joint effort, and many sleepless nights was spent aiding with debug via assistance with the code writing, debug, hardware support etc.. The only failure in this sense was the failure to overcome the drones 26 safety overrides, and with more time this likely would have passed.

Conclusions

Transmitter and Receiver Communication

Whilst initial selection of the NRF24L01 was unsuccessful, moving on to the HC-12 worked well and everything related to this aspect worked exactly as needed and expected. With more time, I would add an external, drone mounted, antenna to assist in range and reliability.

Receiver Design

The most involved part of the project for me; going forward I would change several things, such as adding the missing diode and reducing the footprint of the board further. However, the board worked as expected even with these issues and therefore can be considered a success.