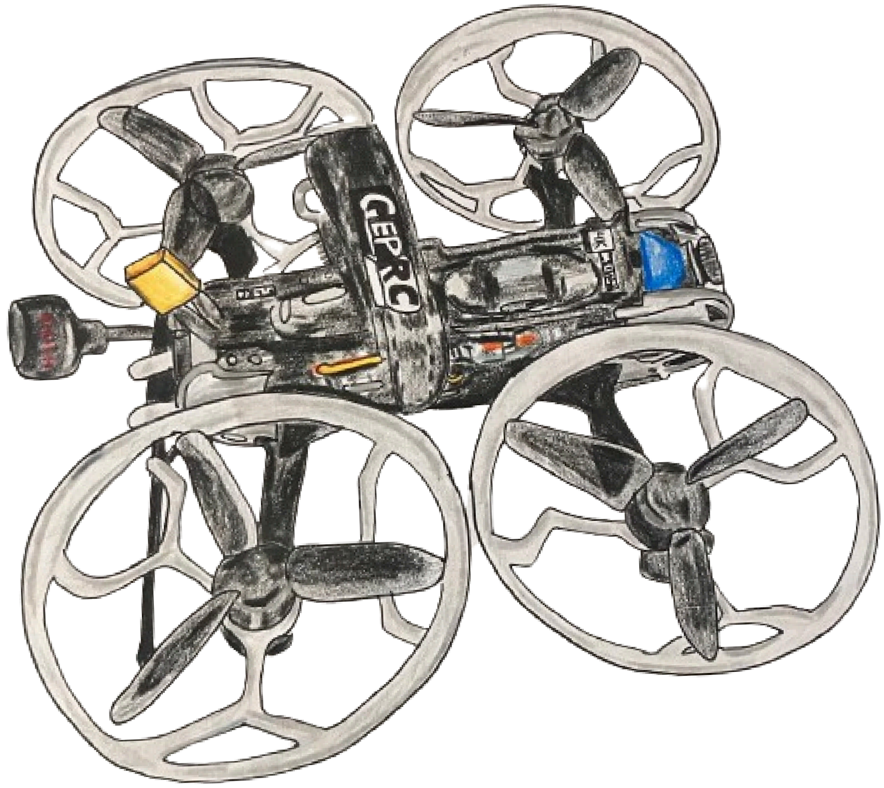
Reverse Engineering Challenge 2024

When Toys Become Weapons



Gael Force Robotics
5327J

Dublin, California

By: Jia, Arjun, Rohith, Priyani, Akshaya, Aarini, Esha, Kavya, Mohit & Klymentii

Word Count: 496/500
Including: Title Page, Findings, Conclusion, Descriptions
Not Including: Table of Contents, Secondary Captions, Media, Links

Table of Contents:

1. Introduction

Hello! We are **5327J**, a VRC team from the Bay Area. One of our most active members, Klym, is a 16-year-old refugee from Ukraine.

Throughout the season, Klym has taught us not only valuable engineering lessons but also educated us on the harsh realities of war. Our concerns grew as the war escalated, particularly regarding the use of technology for destructive purposes. We observed the increasing utilization of FPV commercial drones, the same ones children fly as toys, to drop explosives remotely without directly exposing soldiers. However, such drones have severe security flaws, endangering operators and civilians near conflict zones. Driven by these concerns, we chose to reverse engineer an FPV drone similar to those used in the Russia-Ukraine war, with the objective of dissecting its inner workings and identifying vulnerabilities. We hope to apply our engineering knowledge to the real world while also raising awareness about the dangers of misusing technology.

“*At the start of the Russia-Ukraine War, I witnessed a drone attack. The first thing I remember was a strange noise, as if a giant mosquito was flying outside my block of flats. I went to the window to see if I could find the source of the sound, but it got quiet very quickly. Just as I was about to turn away, I heard an explosion and I saw flames burst out at the Power Station, just a few kilometers away from my flat. The sirens of cars went off at the same time and I could feel the floor beneath me shaking for a moment. Thankfully by the evening, the news reported that nobody was killed in that explosion, yet it has affected the power distribution of the northern district of Kyiv where I used to live. Had the drone landed closer, then my flat would have probably been destroyed and I, as well as my family, could have been severely harmed or even killed…*”

- Klymentti Zhyliaiev

CineQueen 4K 3-Inch Hybrid Quadcopter

ALL diagrams in this entry were created from scratch using google drawings.

2. Preparation

Plan

- **Formulate** a plan and start background **research**

Sketch

- Start **sketching** and creating diagrams of drone

Hypothesize

- Develop **hypothesis**
- Begin **deconstructing** drone

Research

- Start **labeling, color-coding** and **researching** different components of the drone

Documentate

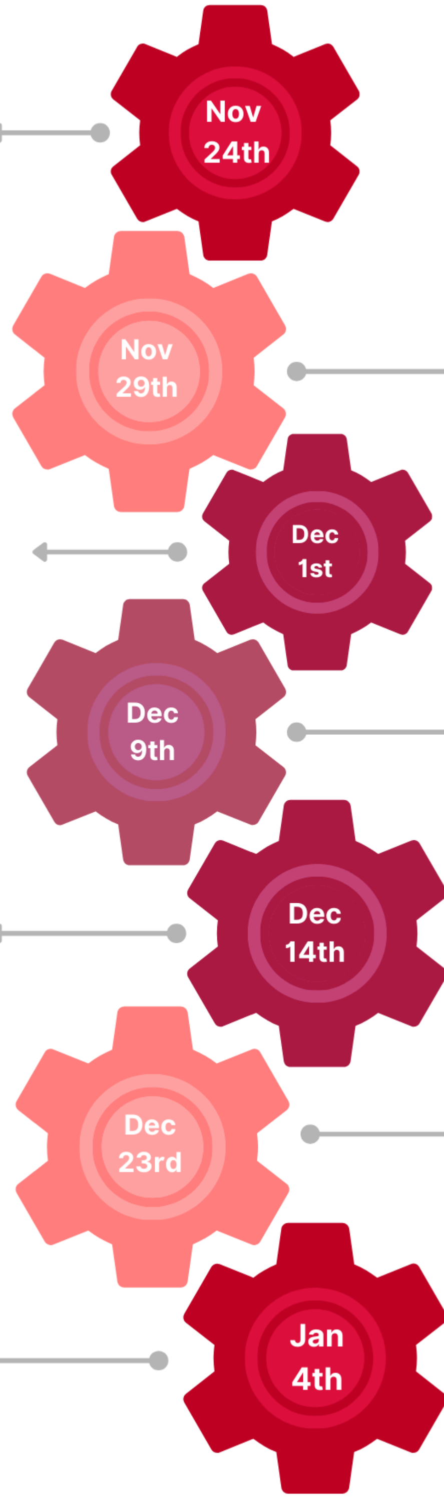
- Create a **rough draft** for our documentation
- Design detailed **diagrams of components**

Analyze

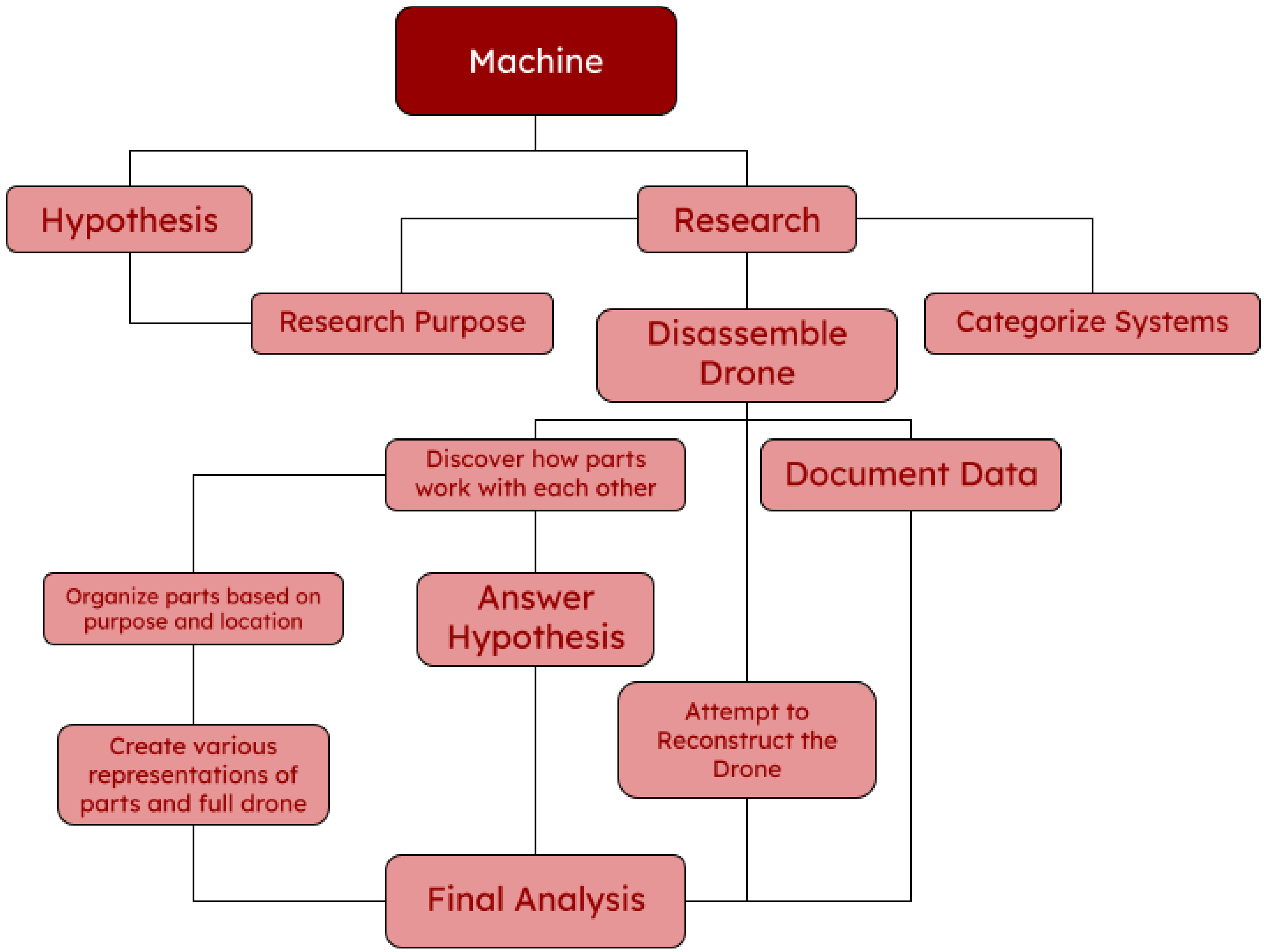
- **Analyze** inner workings of the drone
- **Plan out field trip,** contact drone companies

Reconstruct

- **Reconstruct** drone and **answer hypothesis**
- **Finalize** draft for **documentation**



2.1 Plan



Before starting, we outlined a rough breakdown and order of tasks.

2.2 Field Trip

5 of 21

Request by Local Students for Informational Field Trip Inbox

Kavya Srivastava
to info, me

Hello, hope you are doing well! I am a student from Dublin High School speaking on behalf of our school robotics team, 5327J. We are currently working on a project where we deconstruct drones and conduct research on each of the components for a reverse engineering challenge. Our team was hoping to schedule an hour long visitation somewhere between January 3rd to January 5th. We are aiming to have mini field trip with around 5 team members where we could visit the facility, receive feedback on our project, and gain further knowledge about drones in general.

Thank you,
Kavya Srivastava

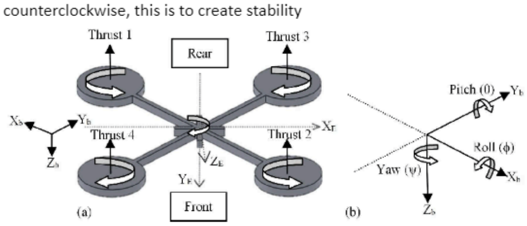
Reply | Reply all | Forward

With no response from drone companies, we conducted our own background research.

2.3 Background Research

Background Research: Our team conducted background research to better understand quadcopter drones and their electrical systems.

→ Frame
- Frame Model:GEP-CQ3(Improved version,Including Guards)
- Quadcopter → two motors move clockwise while the other two move counterclockwise, this is to create stability



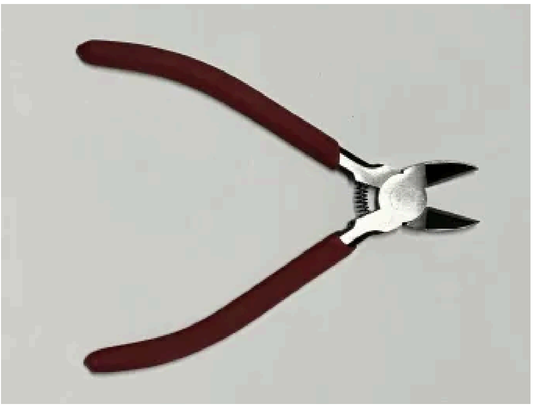
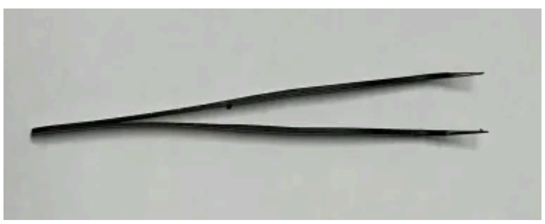
- Material: 3K carbon fiber
  - Properties: light and stiff, high specific strength, corrosion resistant

→ Battery
- “Intelligent”: ver-charge protection, temperature data, charge cycle history, and communicate power output to the drone
  - Purpose: ensure battery safety during flight

3. Disassembly

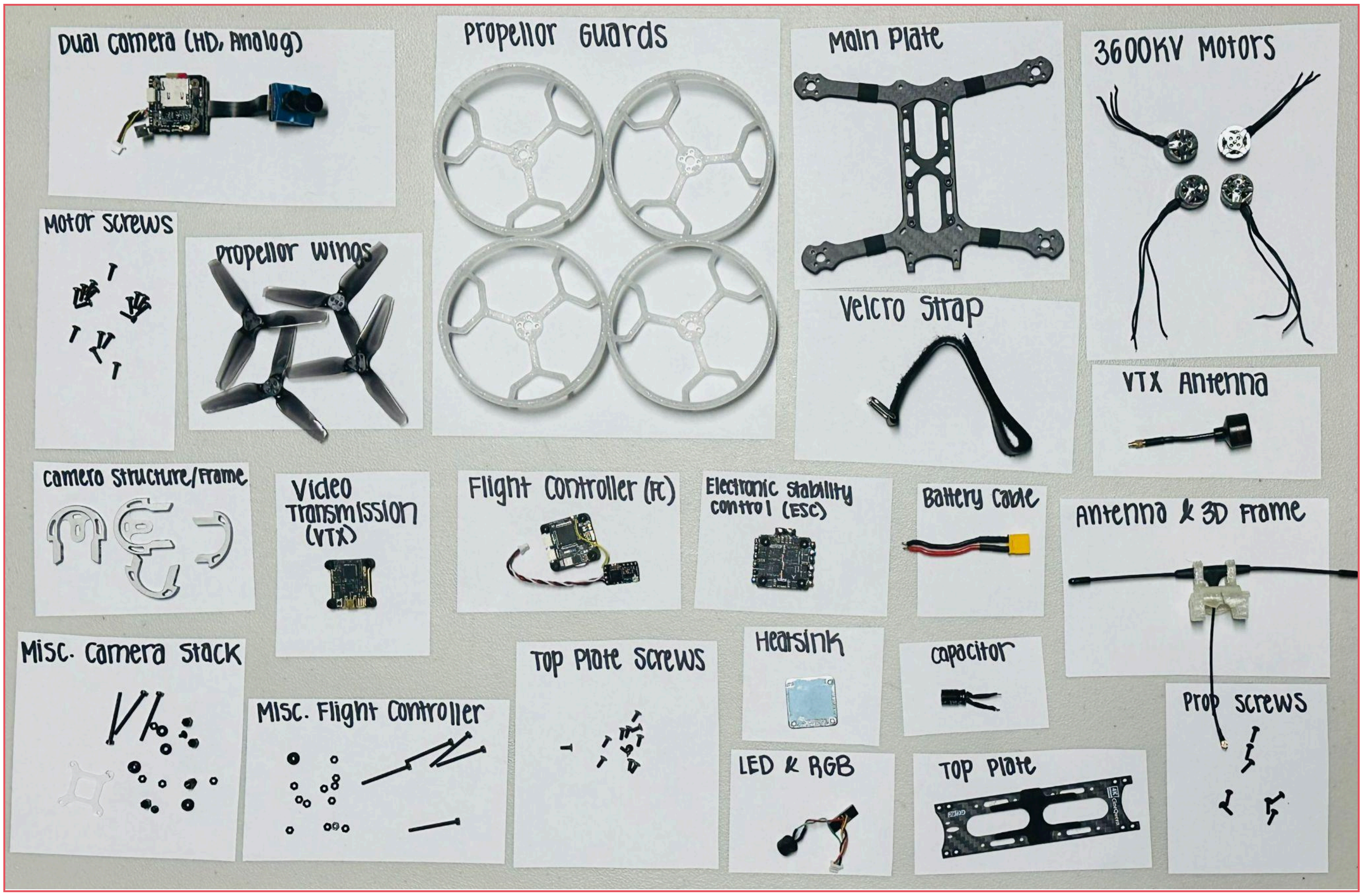
3.1 Instruments

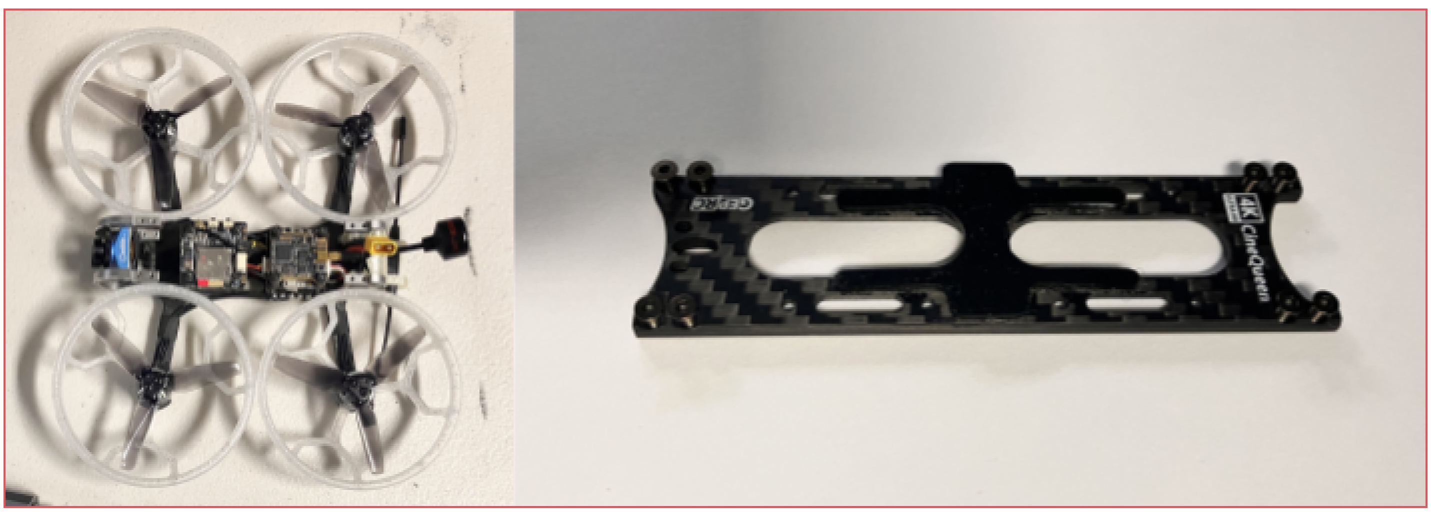
	Electrical Tape **Secures** connections and protects wiring.
	Scissors **Cuts** non-metallic parts.
	Tin Lead **Creates mounting points** when melted.

	Wire Cutters Efficiently **trims electrical wires**.
	Wire Strippers **Removes insulation** from wires.
	Tweezers **Holds** small components in place.
	Electric Screwdriver **Automatic screwdriver** with **replaceable bits**.
	Micro Shears **Precise cutting**.

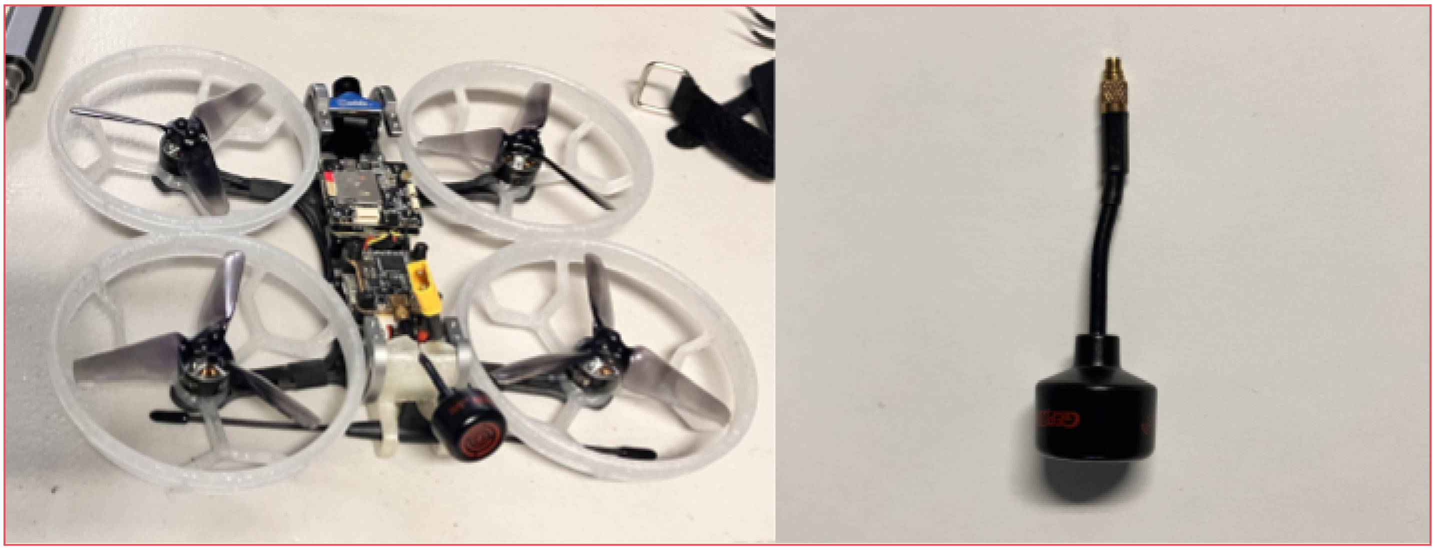
	Desoldering Vacuum **Removes molten solder**.
	Soldering Iron **Melts solder** to create electrical connections.

3.2 Deconstruction Steps



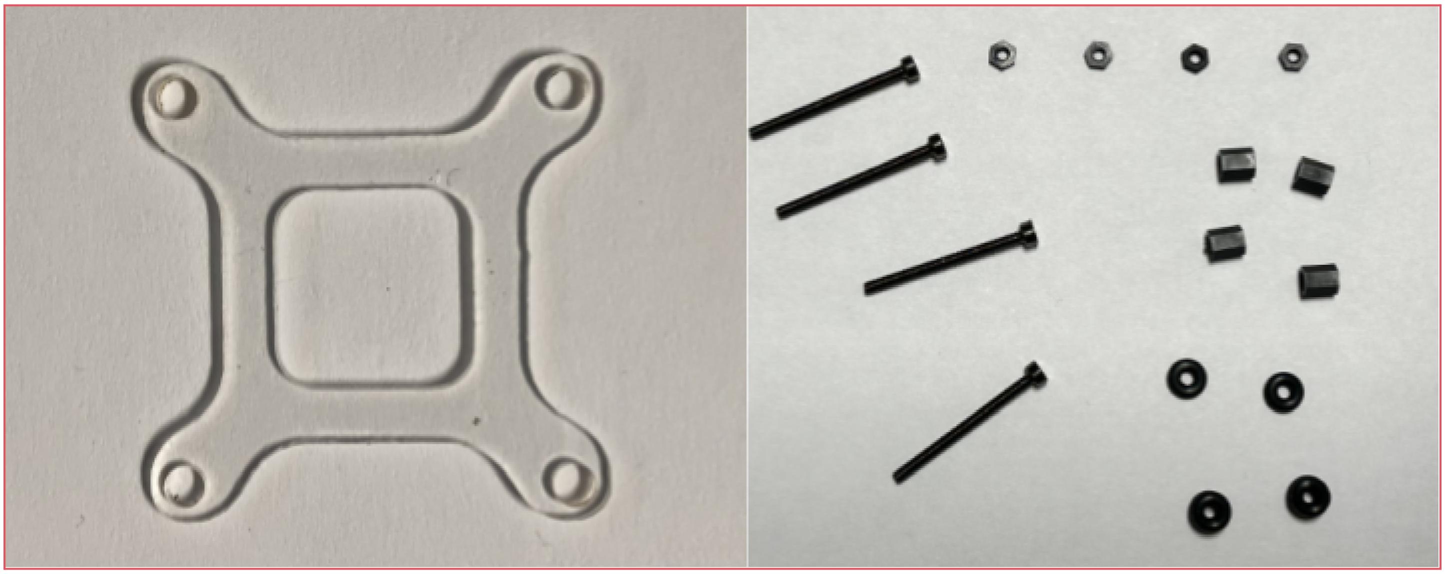


Step 1: Remove Top Plate



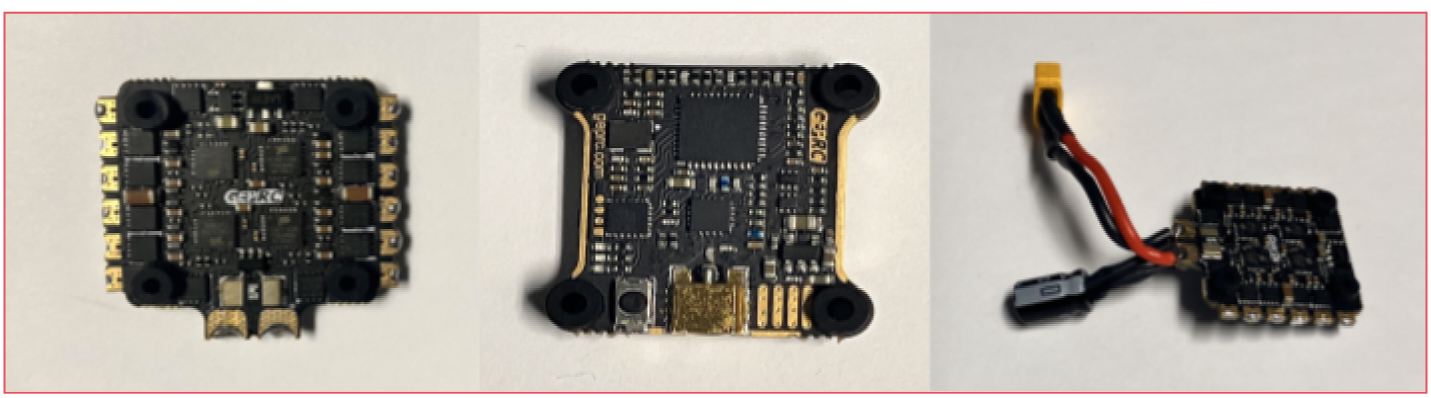
Step 2: Disconnect the antenna from the drone

Step 3: Remove propeller guard and the propellers

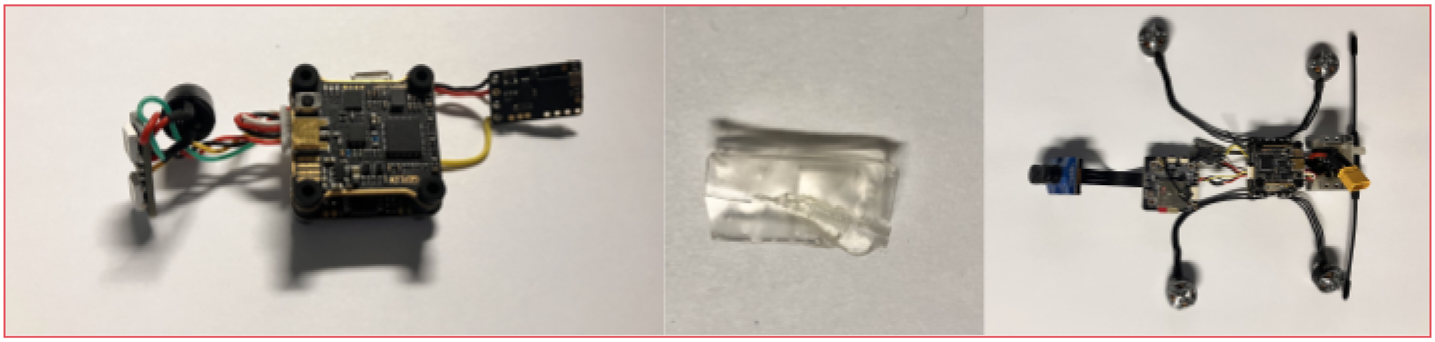


Step 4: Deconstruct camera stack and soft mounting.

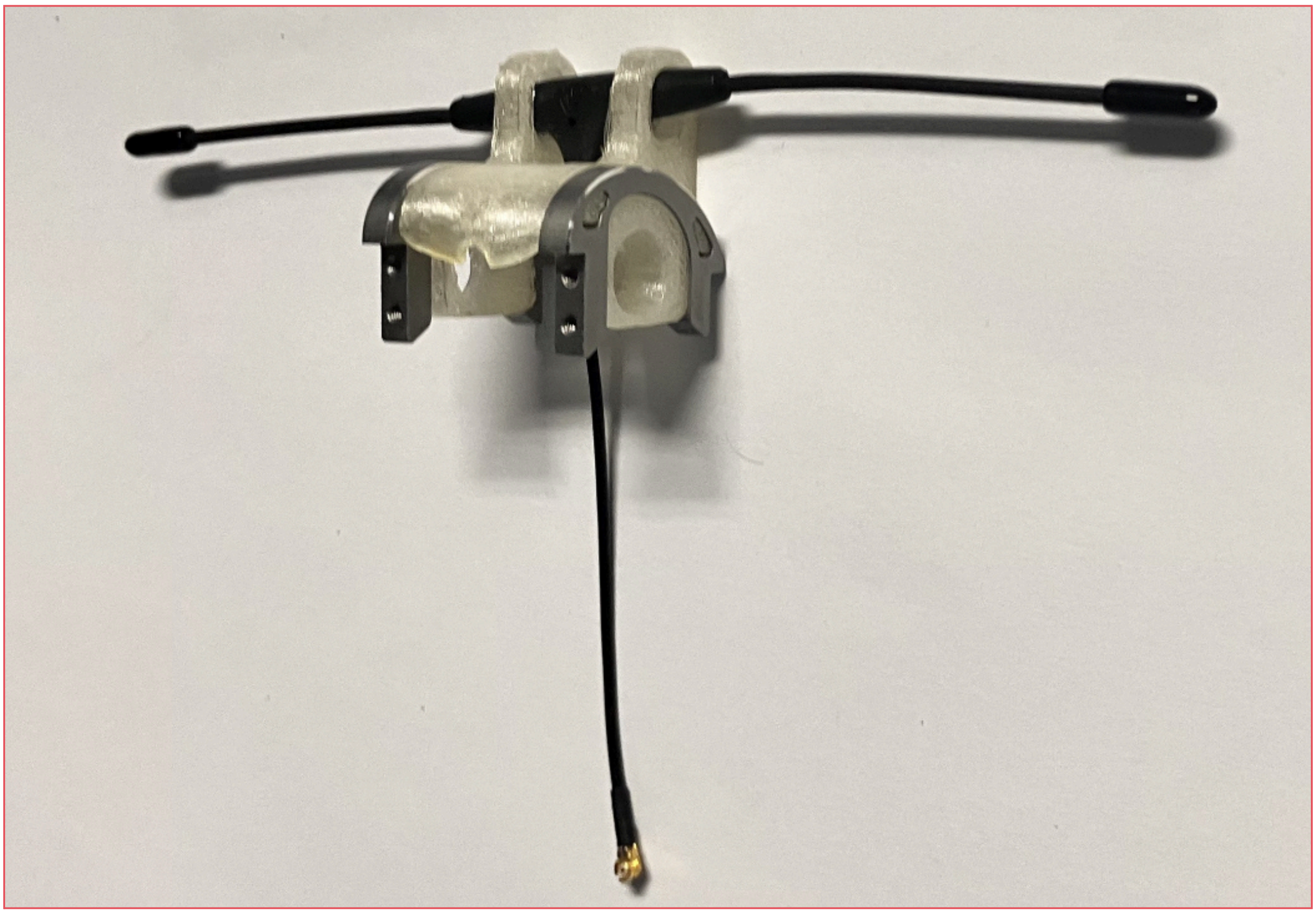
Step 5: Deconstruct camera structure/frame and dual camera



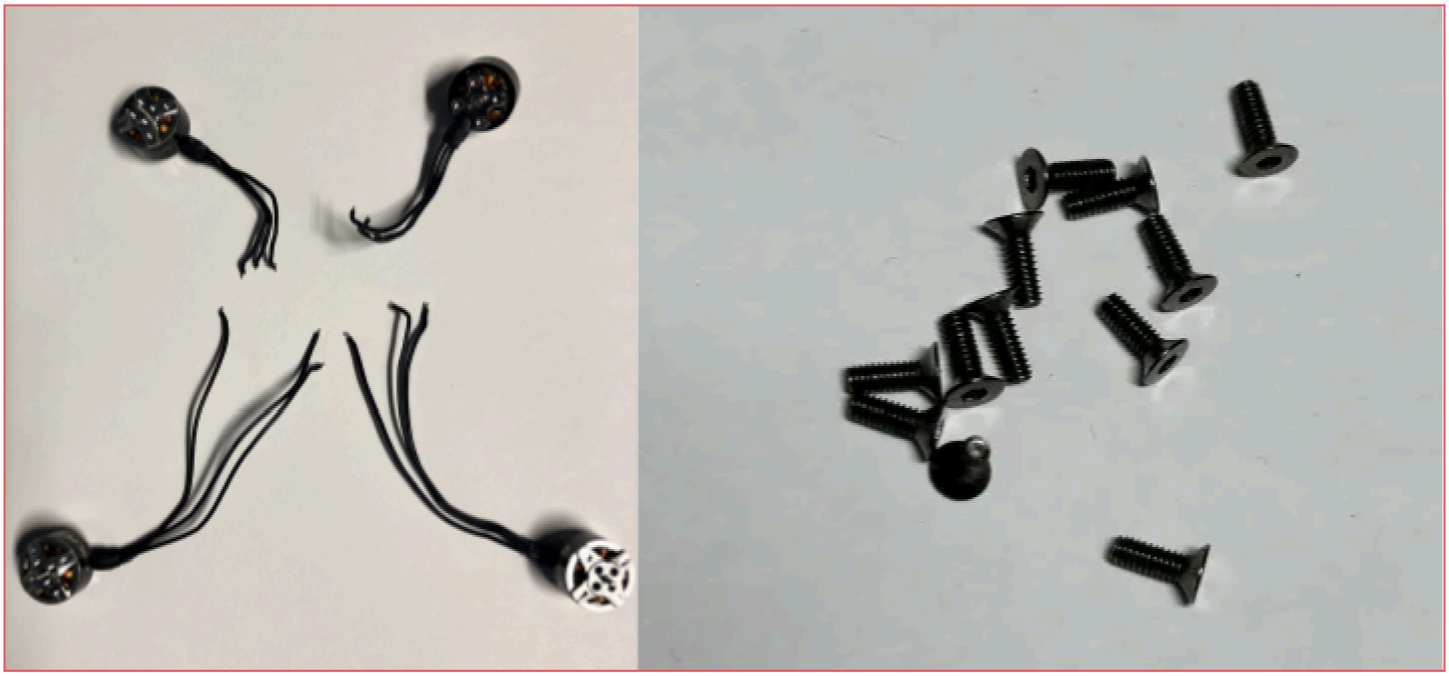
Step 6: Remove: VTX, ESC, battery cable & capacitor



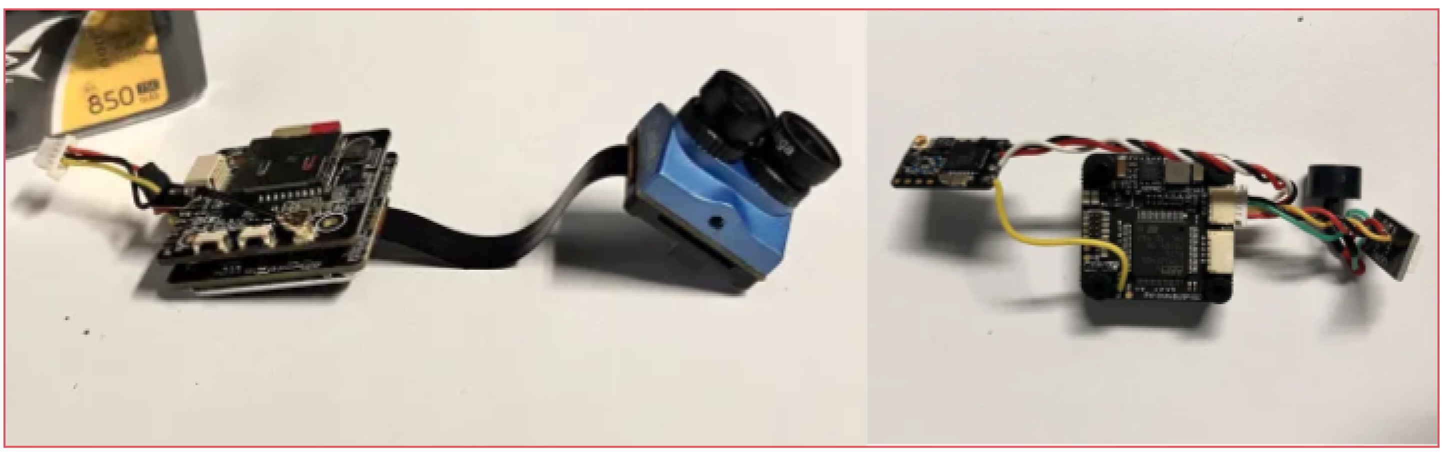
Step 7: Carefully cut gaffing tape and remove FC and LED/RGB.



Step 8: Remove antenna with frame



Step 9: Desolder all four motors

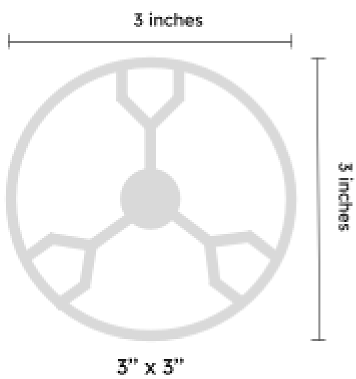
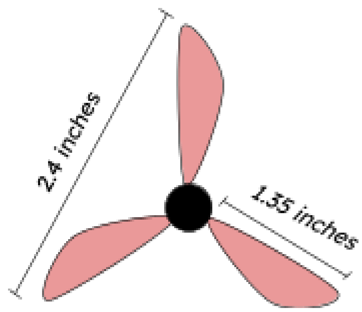
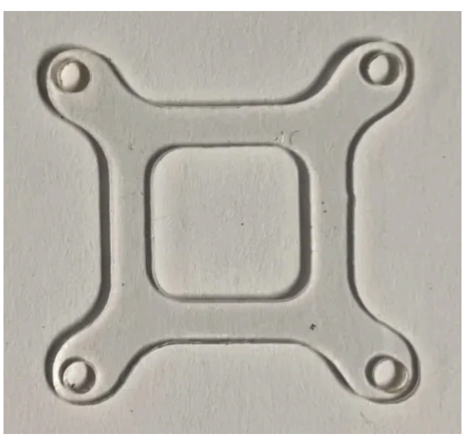
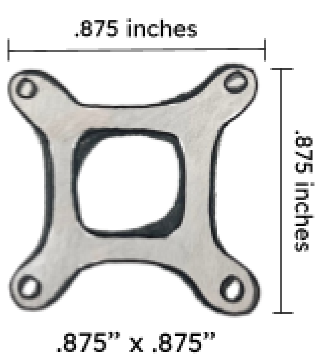


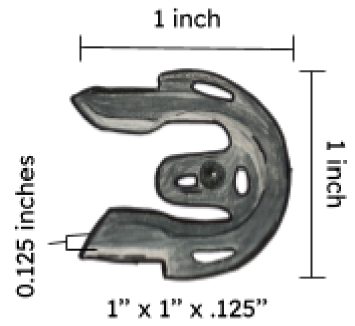
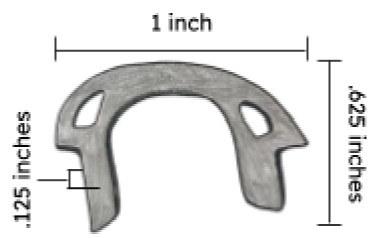
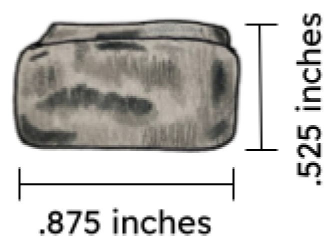
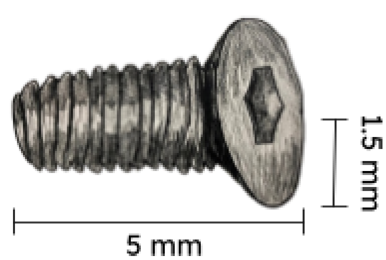
Step 10: Desolder electrical components and PCBs

4. Components

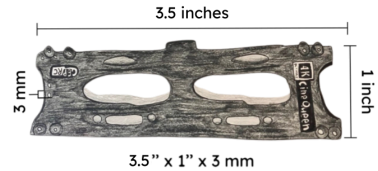
Final Components List

4.1 Non-Electrical

	Propellor Guards:	
		Plastic structures that **protect propellors.** Quantity: 4
	Propellor Wings:	
		Rotates to create linear **thrust**. Quantity: 4
	Camera Stack:	
		**Prevents shorting** of PCBs. Quantity: 1

	Camera Bracing:		Withstands **frontal crashes.** Quantity: 2
	Back Bracing:		**Holds** carbon plates **together.** Quantity: 2
	Receiver Module Insulation:		**Protects** the module. Quantity: 1
	Top Plate Screws:		**Fastens** top plate to body. Quantity: 12

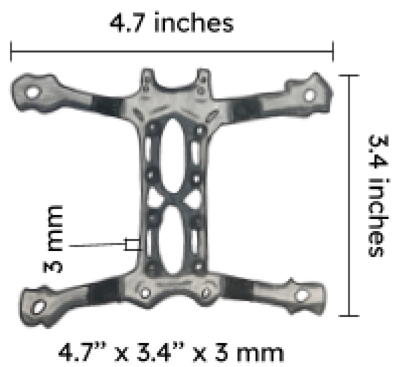
Top Plate:



Protects PCBs and internal components.

Quantity: 1

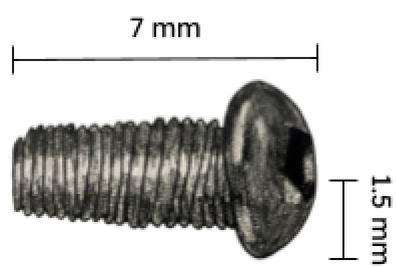
Main Plate:



Holds drone components.

Quantity: 1

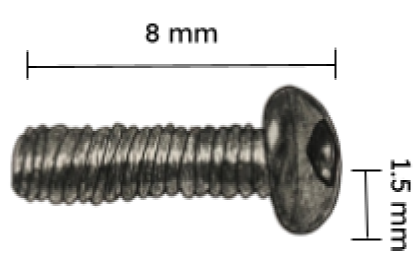
Propellor Screws:



Fastens propeller onto rotor.

Quantity: 8

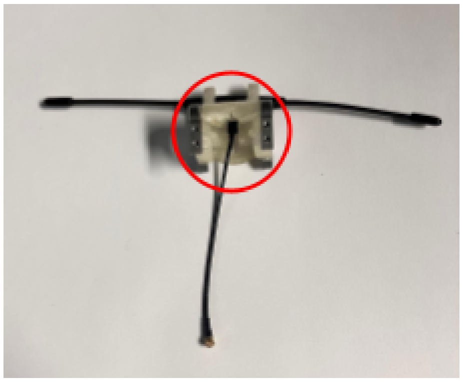
Motor Screws:

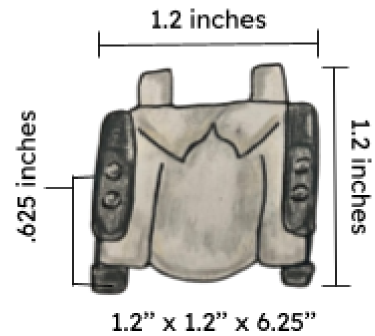


Fastens motor to plate.

Quantity: 16

3D Antenna Frame:

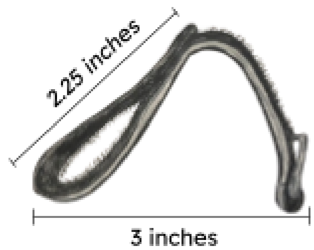




Protects antenna from damage.

Quantity: 1

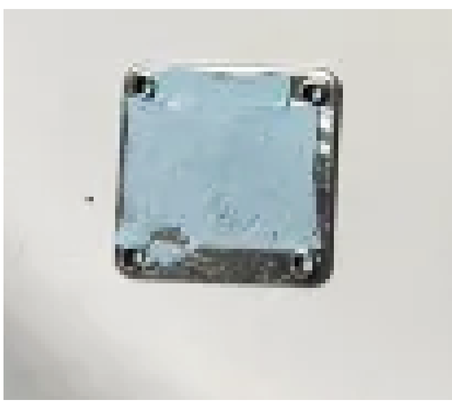
Velcro Strap:

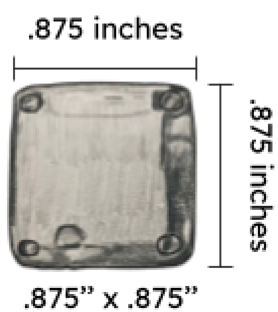


Holds battery on drone.

Quantity: 1

Heatsink:

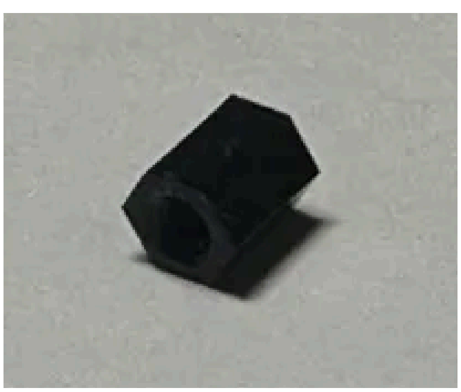


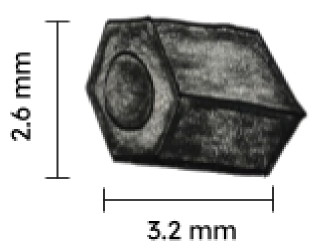


Regulates VTX temperature.

Quantity: 1

Standoff:





Spaces out components.

Quantity: 4

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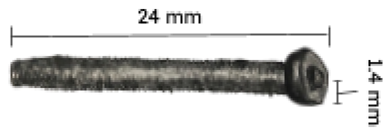
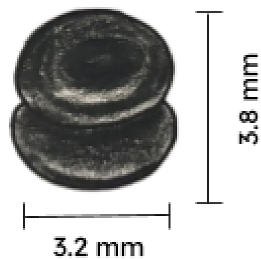
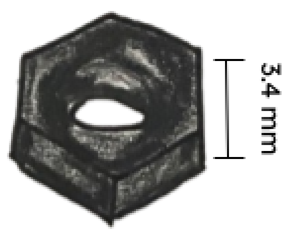
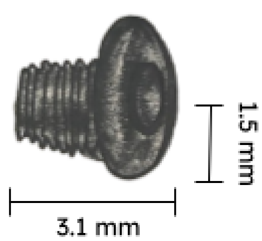
<tr><td>
</td><td>Maintains PCB stacks.

Quantity: 8</td></tr>
<tr><td rowspan="2"></td><td colspan="2">Shock Absorber:</td></tr>
<tr><td>
</td><td>Dampens forces on PCBs.

Quantity: 8</td></tr>
<tr><td rowspan="2"></td><td colspan="2">Nylock Nut:</td></tr>
<tr><td>
</td><td>Secures screws.

Quantity: 16</td></tr>
<tr><td rowspan="2"></td><td colspan="2">Bottom Plate Screw:</td></tr>
<tr><td>
</td><td>Fastens camera to plate.

Quantity: 2</td></tr>
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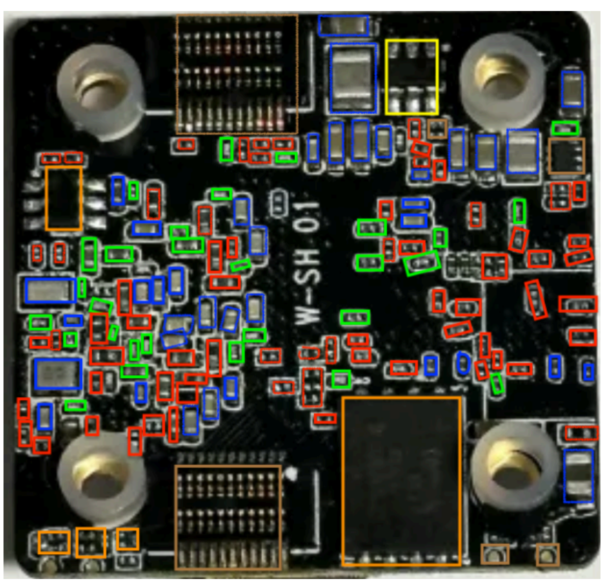
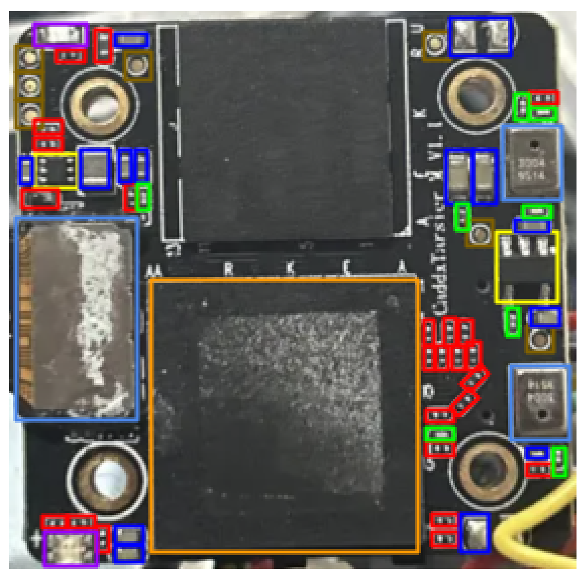
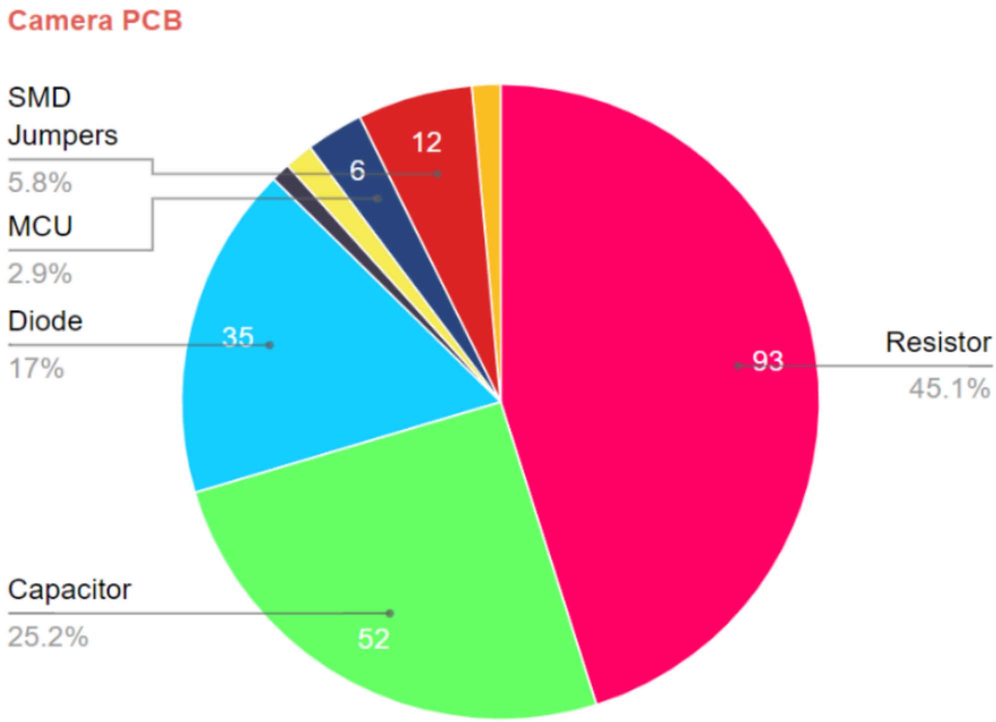
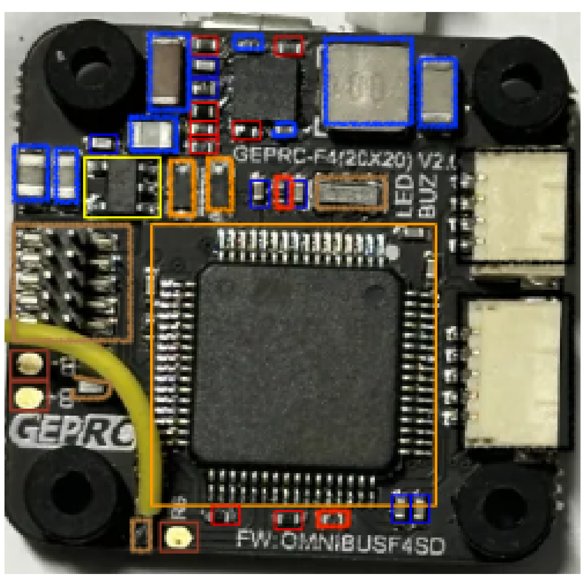
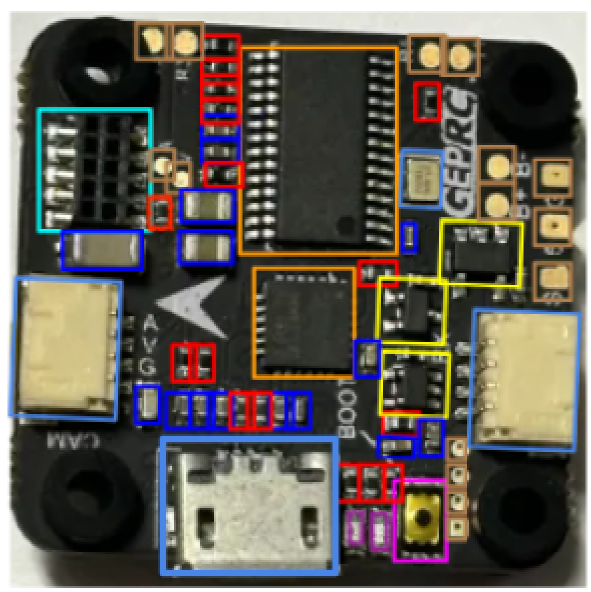
4.2 Electrical

PCB Component Guide

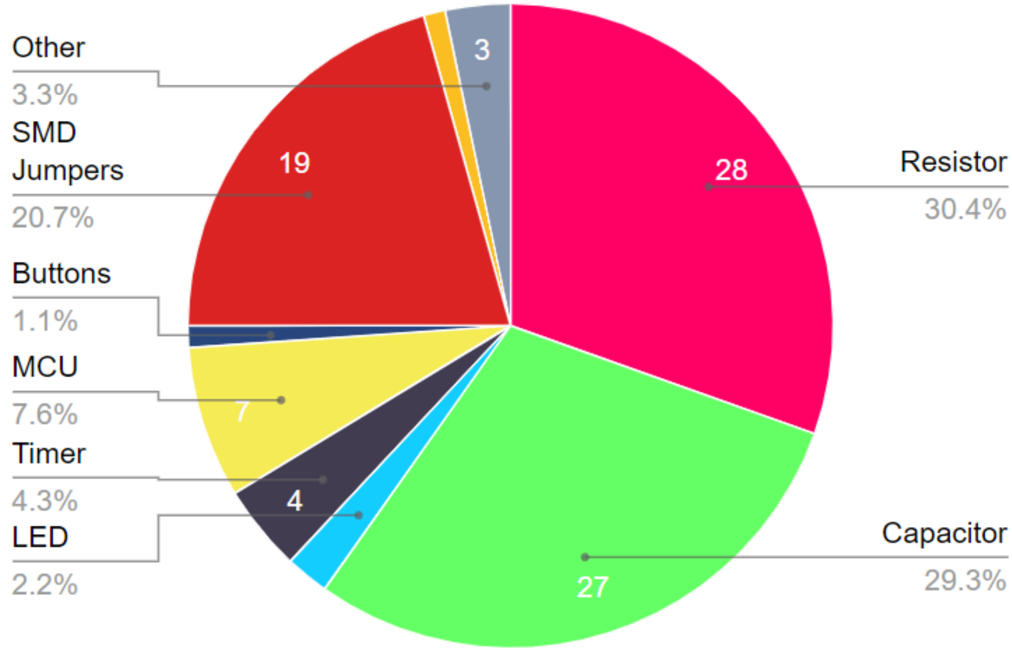
Basic Components Key		
	SMD Jumper	Connection for debugging/toggle
	Resistor	Limits how much voltage can pass
	Capacitor	Builds, stores, and releases electrical charges
	Dupont Connector	Connects parts of the circuit
	Diode	Directs the flow of electricity
	MMCX Transmitter	Send signals over distances
	MCU's	Microcontroller Unit
	Timer	Outputs a signal in a set timel
	LED	Lights up for GUI
	Button	Sends signal when pressed

Camera		

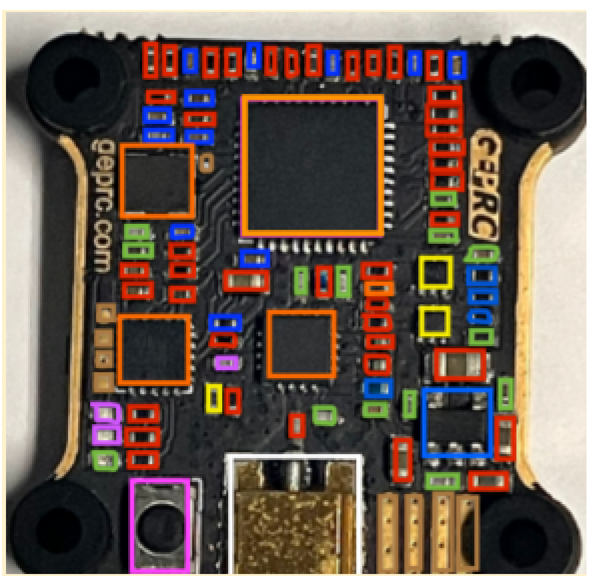


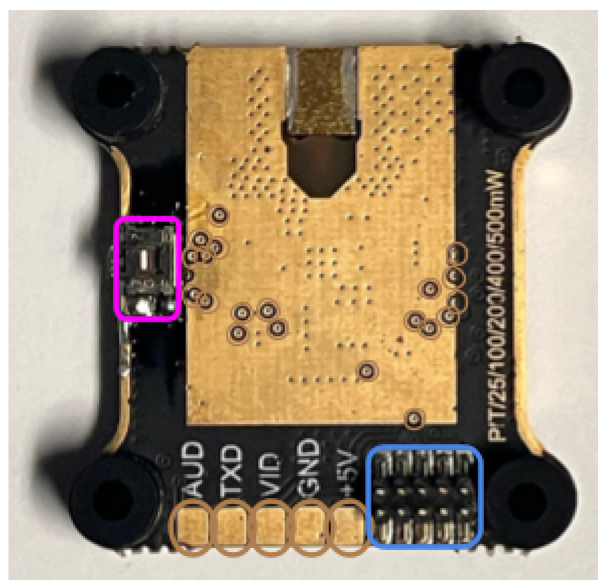
Flight Controller		

FC

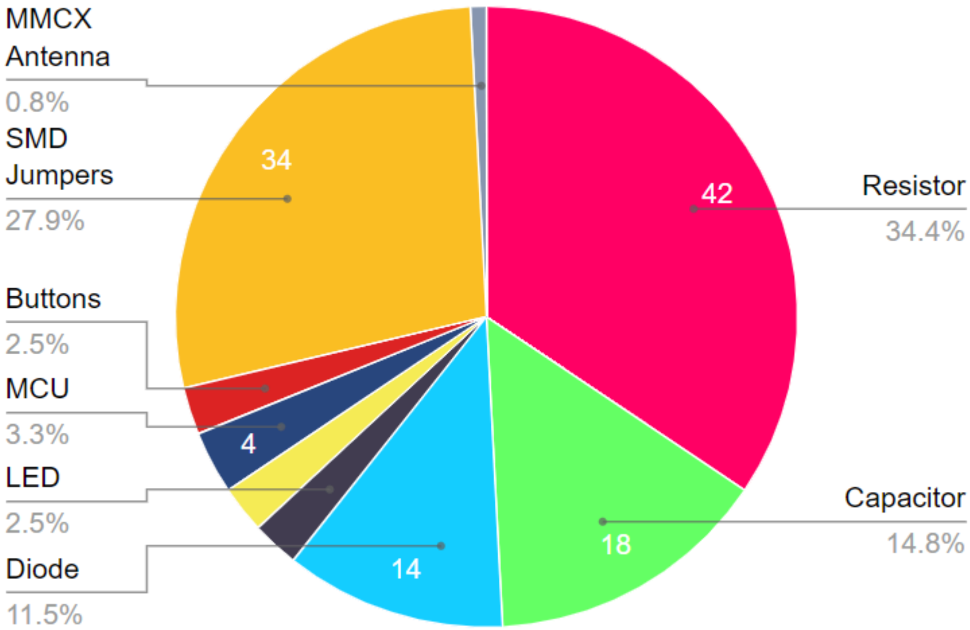

Other
3.3%
SMD Jumpers
20.7%
Buttons
1.1%
MCU
7.6%
Timer
4.3%
LED
2.2%
Resistor
30.4%
Capacitor
29.3%
3
19
28
7
4
27

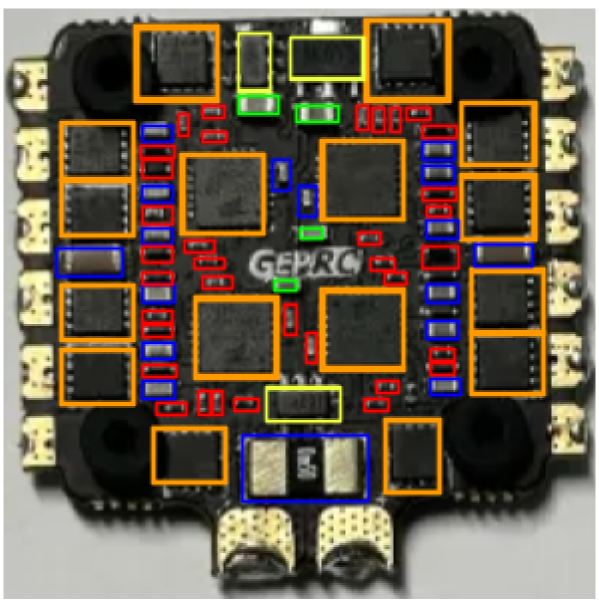
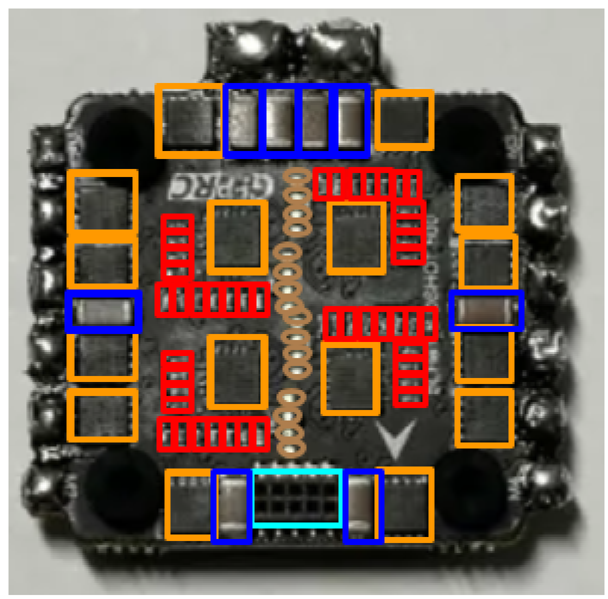
VTX


geprc.com
GEPRC


AUD
TXD
VID
GND
+5V
P/T/25/100/200/400/500mW

VTX


MMCX Antenna
0.8%
SMD Jumpers
27.9%
Buttons
2.5%
MCU
3.3%
LED
2.5%
Diode
11.5%
Resistor
34.4%
Capacitor
14.8%
34
42
4
14
18

ESC	GEPRC	

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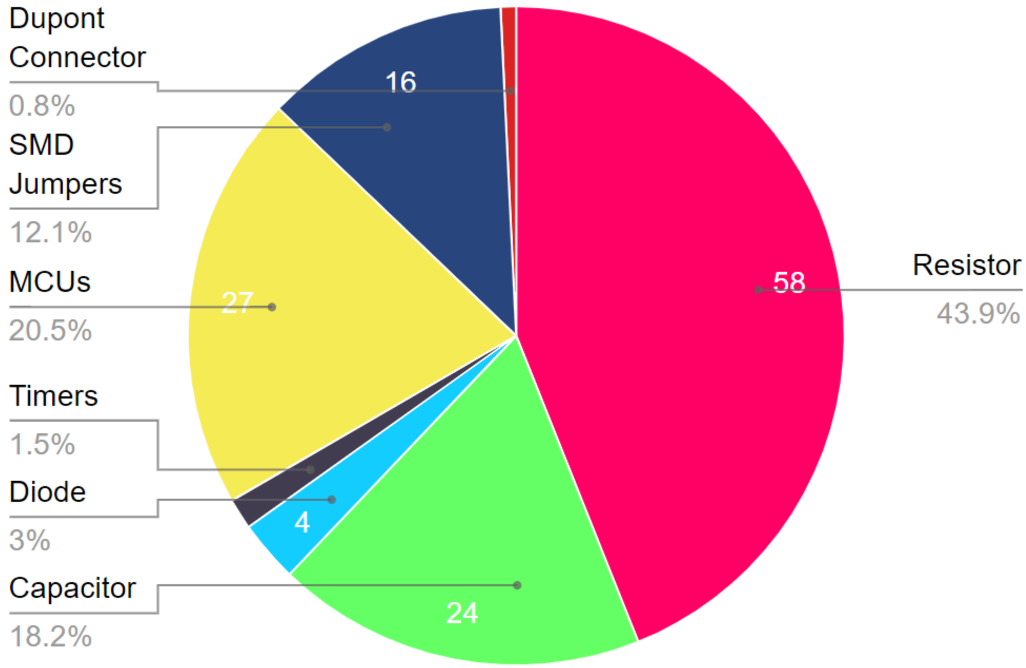
ESC



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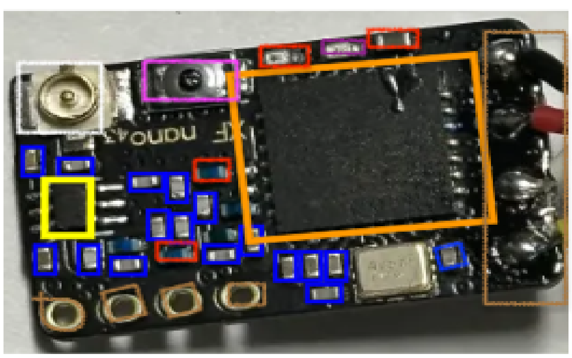
Receiver

</td><td>



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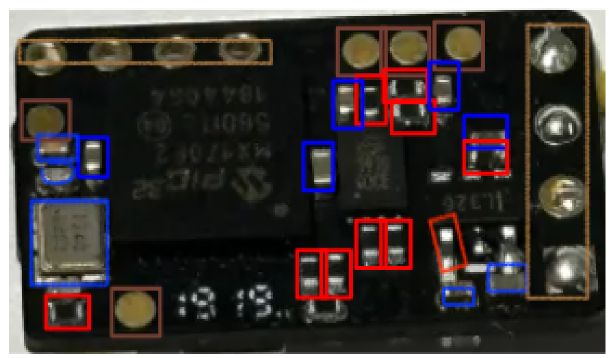

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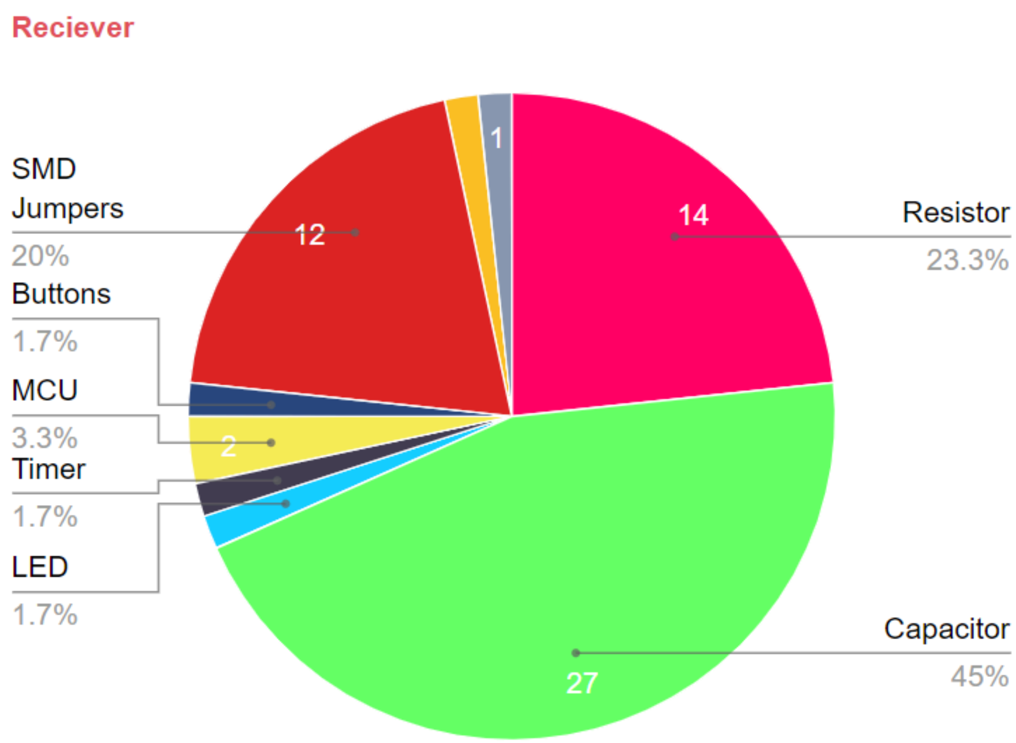
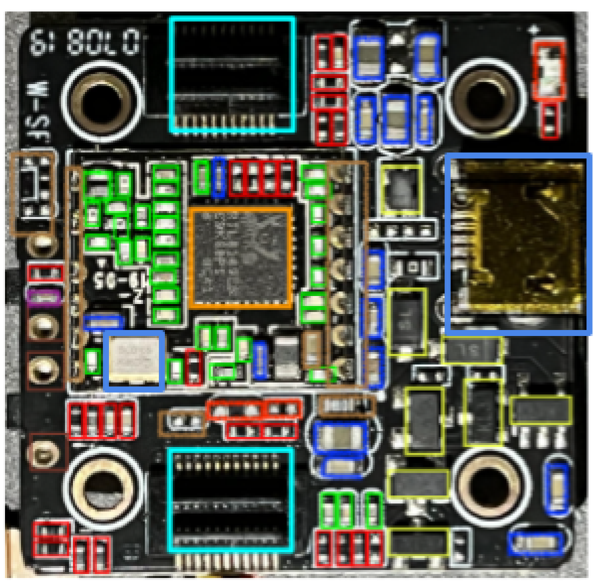
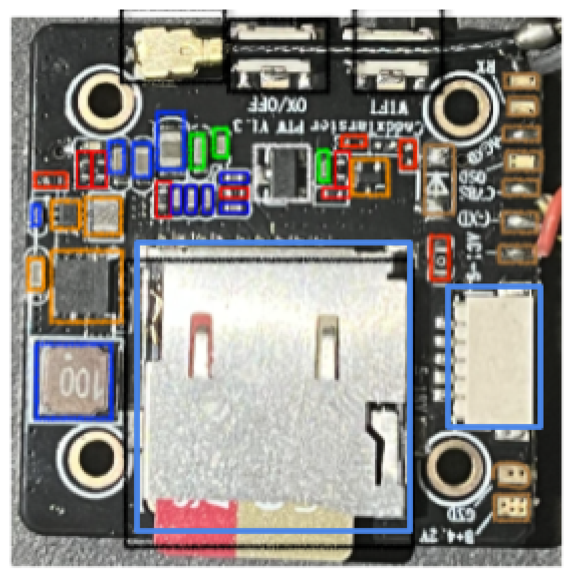
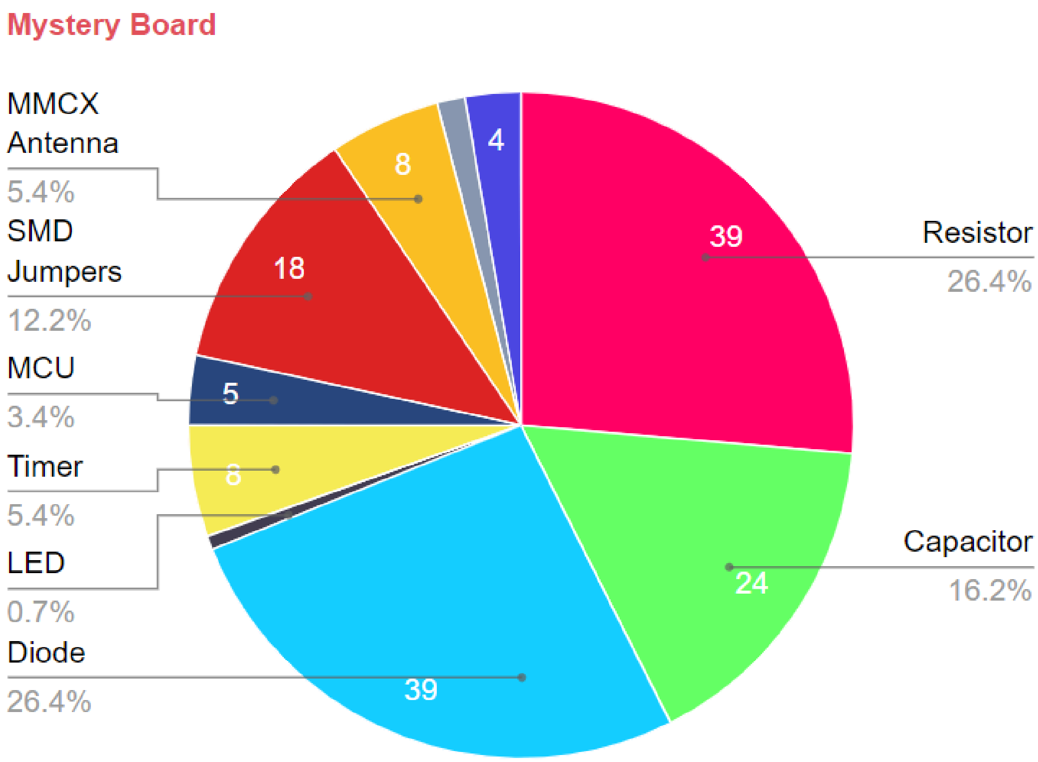

Reciever
SMD Jumpers
20%
12
Buttons
1.7%
MCU
3.3%
2
Timer
1.7%
LED
1.7%
1
14
Resistor
23.3%
Capacitor
45%
27

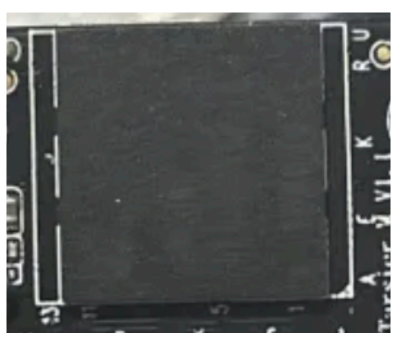
Mystery

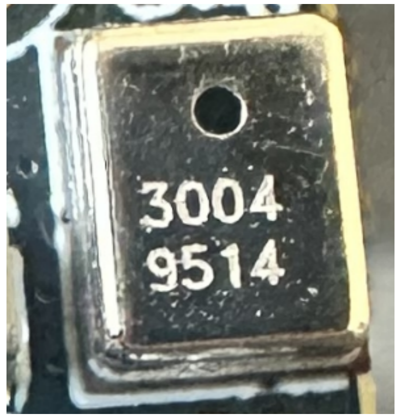
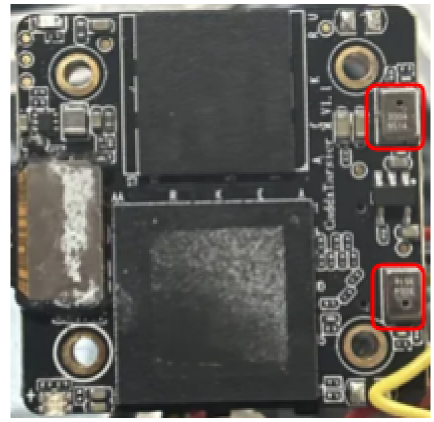
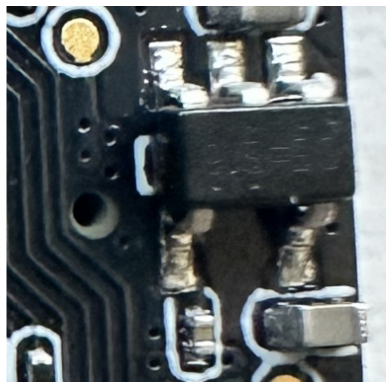
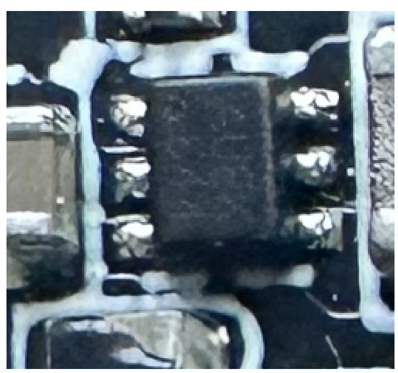
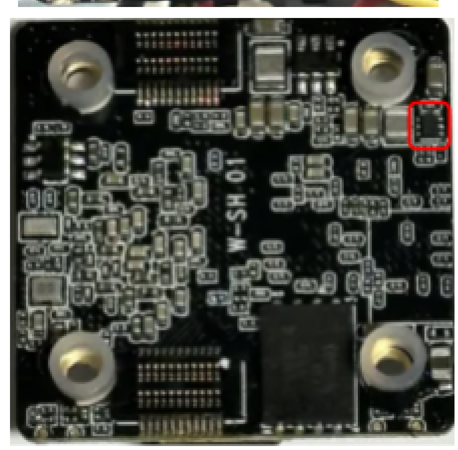






Camera PCB

[K4E4E324EE-EGCF](#) SAMSUNG LPDDR3 Series **High-speed memory transfer and storage, diverse purposes.** Quantity: 1 [Data Sheet](#)		

MEMs Microphone 3.1x2.5mm 2Vdc SMT **Electro-acoustic transducer that converts variable sound pressure to analog or digital output.** Quantity: 2 **Data Sheet**		
BZX84-B4V7 **A subset of Zener Diodes that regulates voltage and suppresses surges.** Quantity: 1 **Data Sheet**		
AUE XC6501A151MR **CMOS LDO regulator that provides stable voltage outputs.** Quantity: 2 **Data Sheet**		 

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25Q128BV1G IC Memory

8M-bit Serial Flash for code storage with low power consumption.

Quantity: 1

Data Sheet

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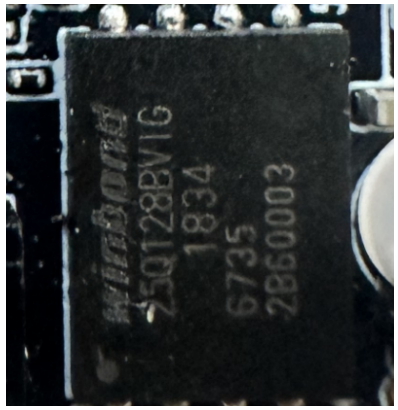

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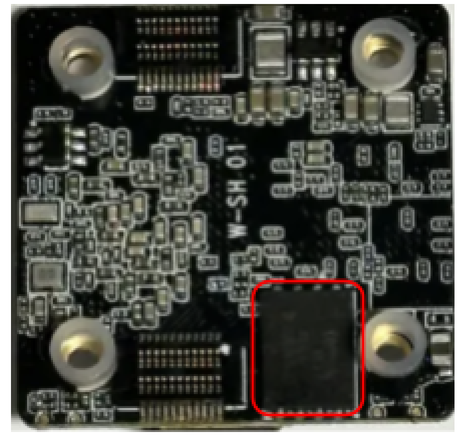

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BOG Dual High Performance 150mA

Linear Regulator: maintains a steady voltage.

Quantity: 1

Data Sheet

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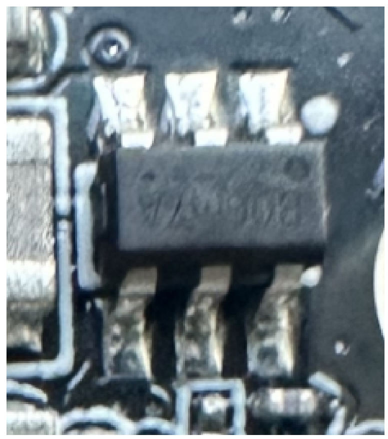

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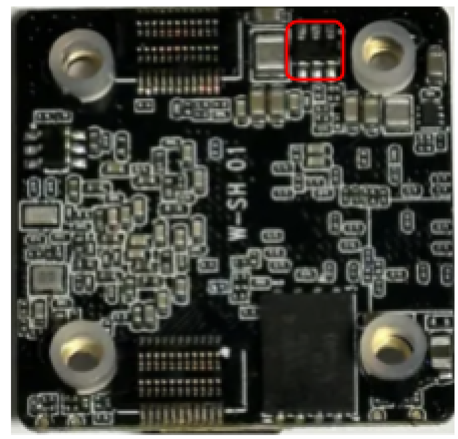

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45A FDC658P

MOSFET: controls conductivity between source and drain terminals.

Quantity: 1

Data Sheet

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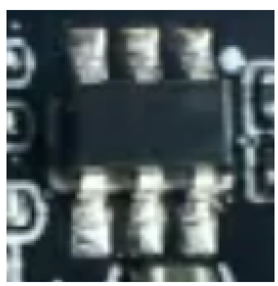

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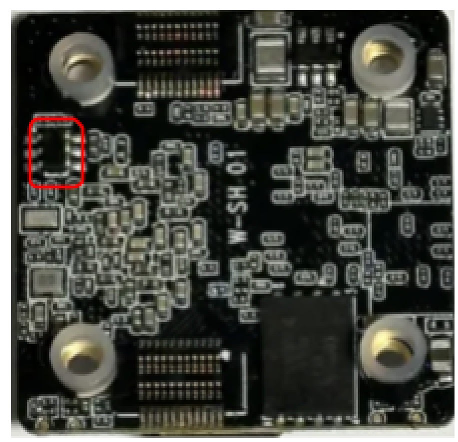

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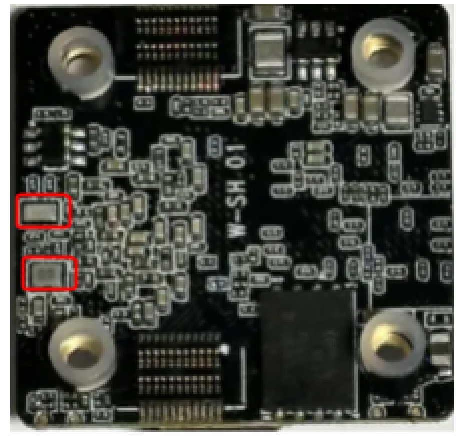
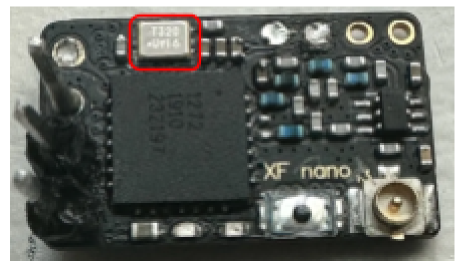
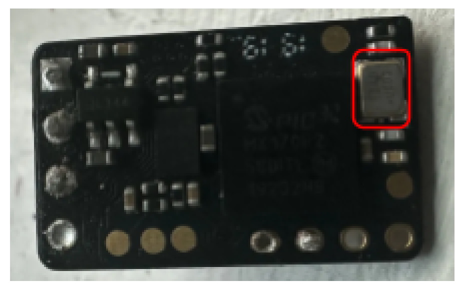
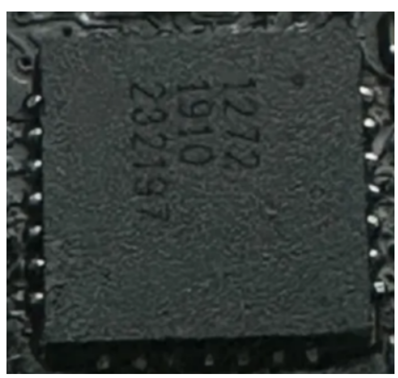
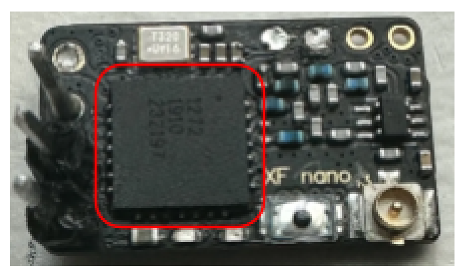
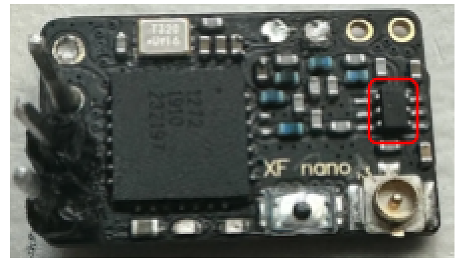
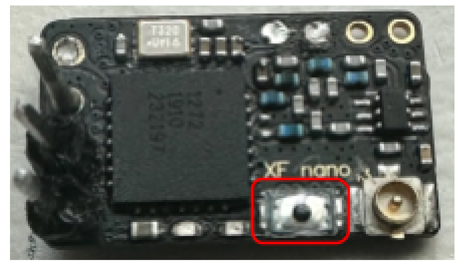
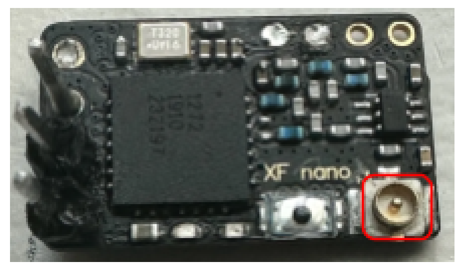
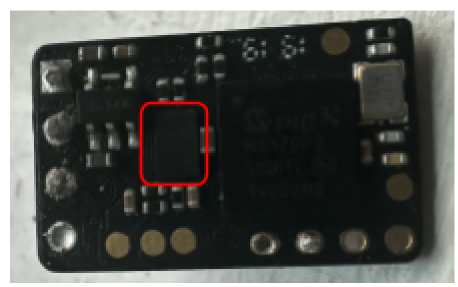
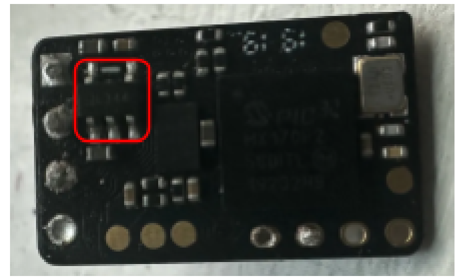
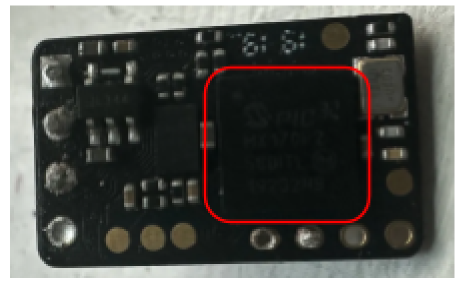
NX2016SA-26M-STD-CZS-2 **Passize Quartiz Crystal component that increases stability using the crystal's piezoelectrical effect.** Quantity: 2 Data Sheet		

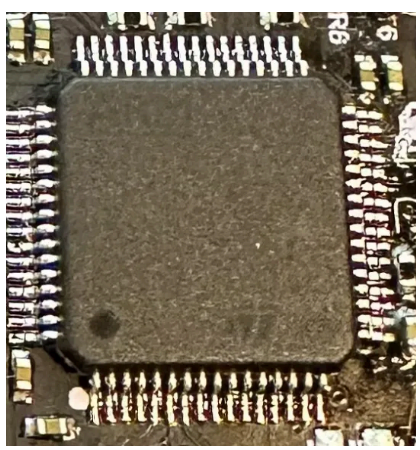
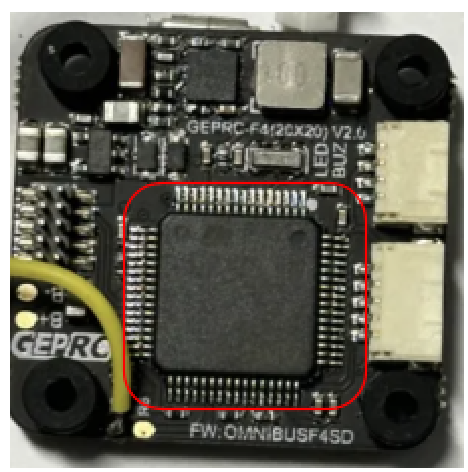
Receiver

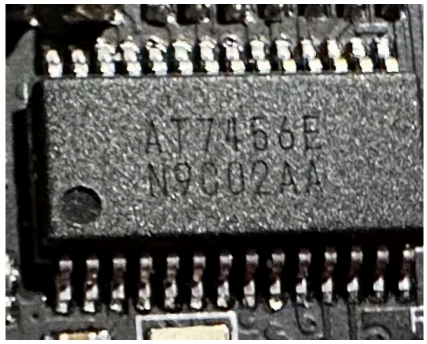
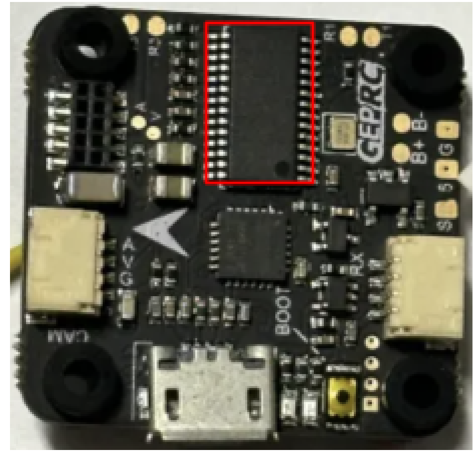
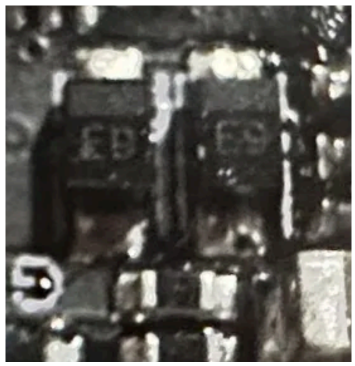
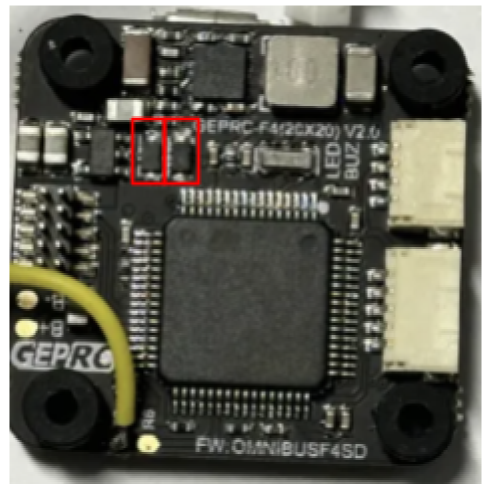
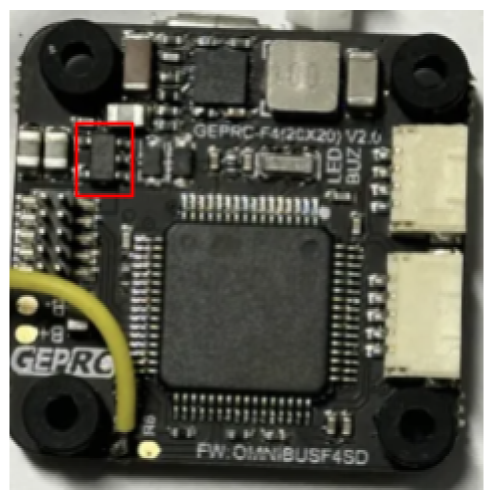
3225 High-Precision SMD Crystal Oscillators **Does precise timing and frequency stability for receiving** Quantity: 2		 
SX1272 **Allows for ultra-long range communication with high interference protection.** Quantity: 1 Data Sheet		

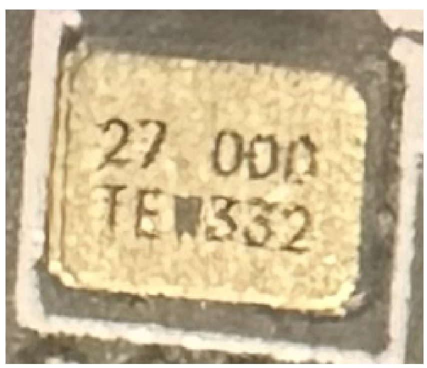
45A FDC658P **MOSFET: controls conductivity between source and drain terminals.** Quantity: 1 **Data Sheet**		
FPV Drone Bind Button **Allows drone and controller to bind through a unique, shared number.** Quantity: 1		
UFL SMT Connector **Industry standard connector for antennas.** Quantity: 1		
PIC10F200T-I/OT **Flash CMOS Microcontroller for data storage/hardware processing** Quantity: 1 **Data Sheet**		

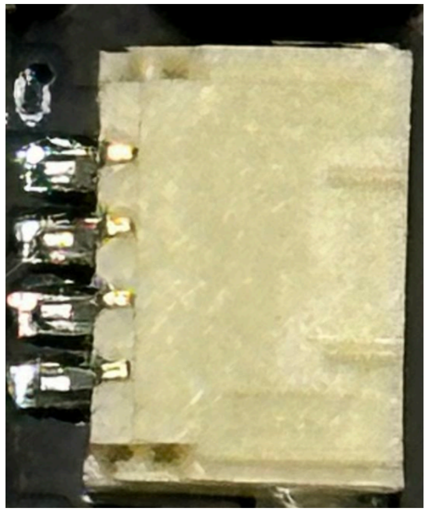
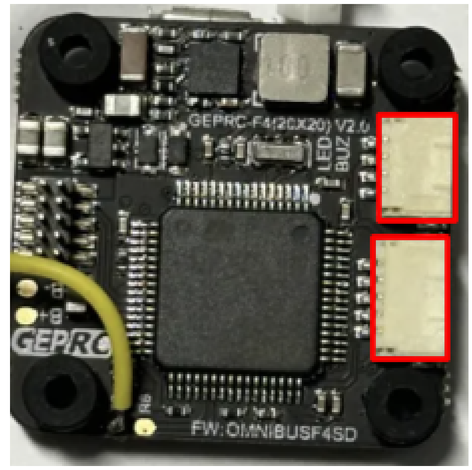
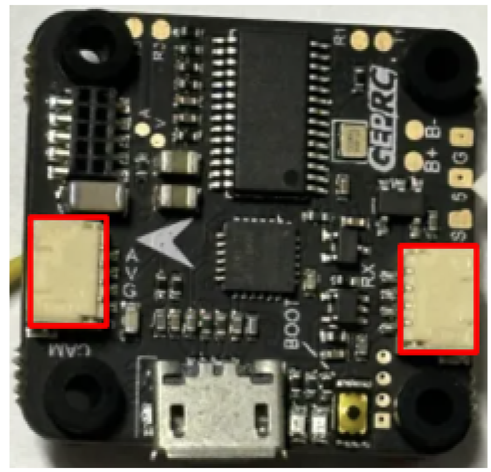
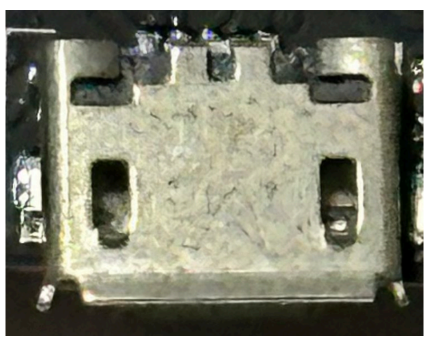
Microchip MIC5504-3.3YM5-TR **Regulates voltage to safeguard other electrical components.** Quantity: 1 Data Sheet		
PIC32MX170F256D **32-Bit Microcontroller** Used for processing user config data/smart features Quantity: 1 Data Sheet		

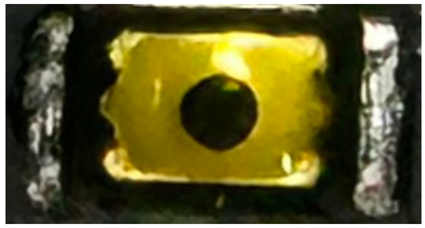
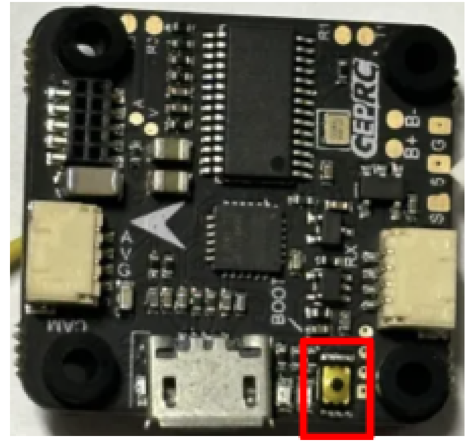
Flight Controller (FC):

STM32F405 processor **Processor which responds to interruptions with low resource consumption.** Quantity: 1 Data Sheet		

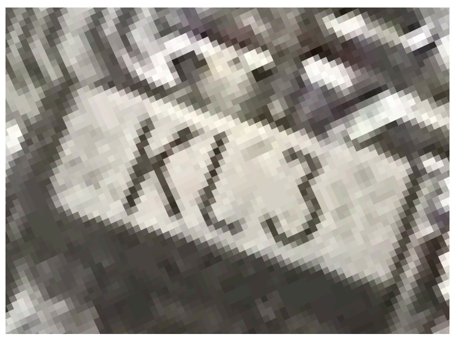
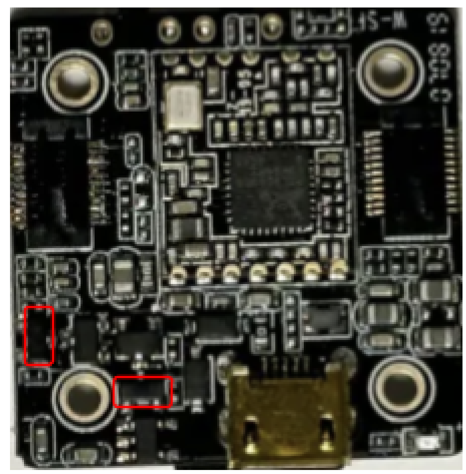
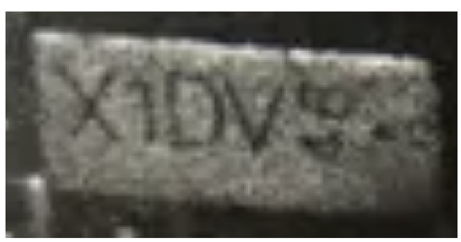
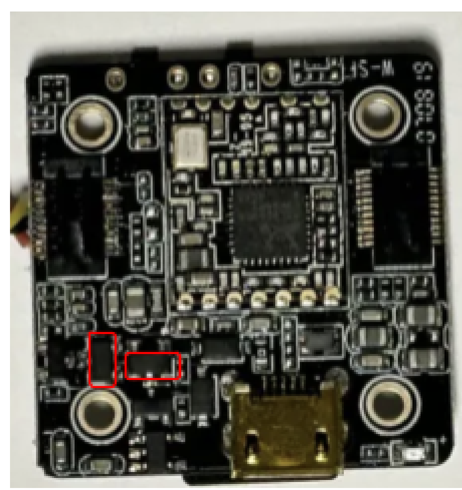
AT7456E **OSD chip which provides on-screen statistics.** Quantity: 1 **Data Sheet**		
AP8821C-49GC **Voltage detectors in the CMOS protocol which safeguard circuit.** Quantity: 2 **Data Sheet**		
S-1315A14- M5T1U3 **Voltage regulator which maintains a fixed voltage output.** Quantity: 1 **Data Sheet**		

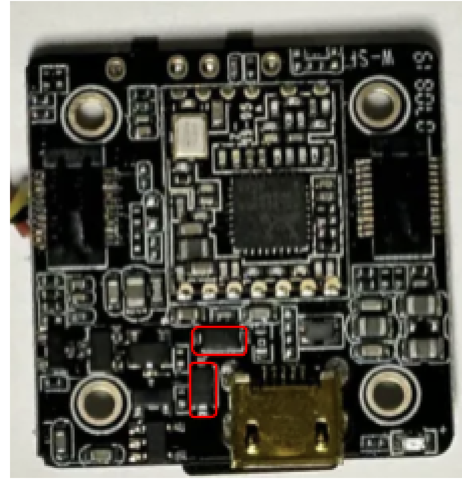
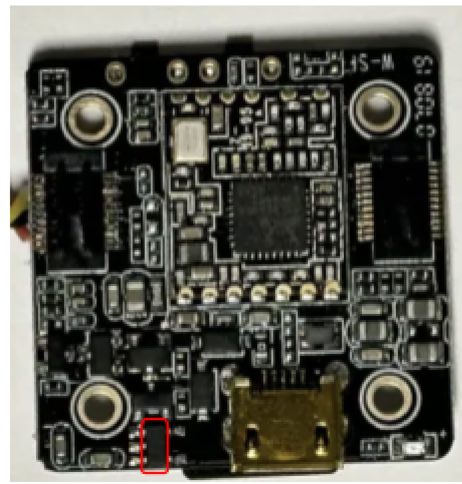
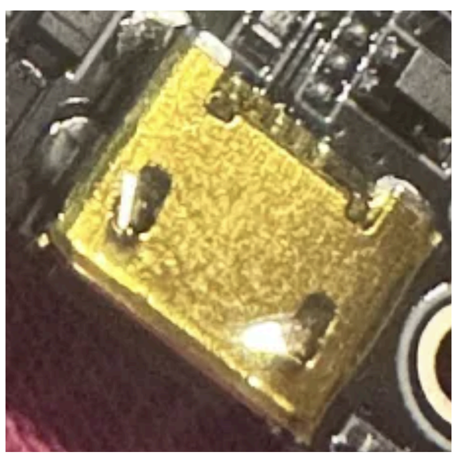
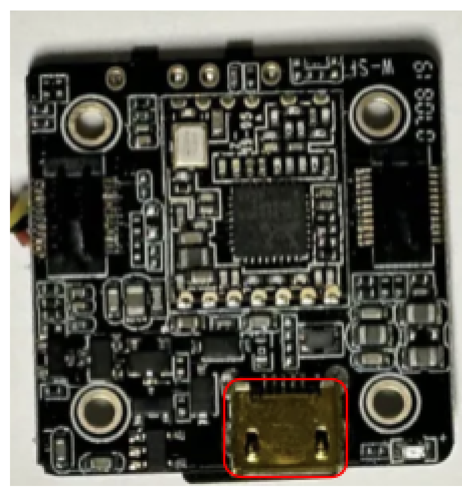
[74AHCT1G86GW](#) **2 input exclusive-or gate where one input determines actions on second input** Quantity: 1 **[Data Sheet](#)**		
[2SK2742](#) **N-channel Mosfet which changes voltage to switch between states** Quantity: 1 **[Data Sheet](#)**		
[Fuse](#) **Protects from overvoltage** Quantity: 1 Data Sheet N/A		

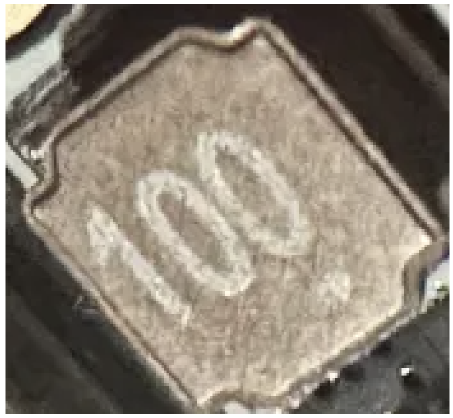
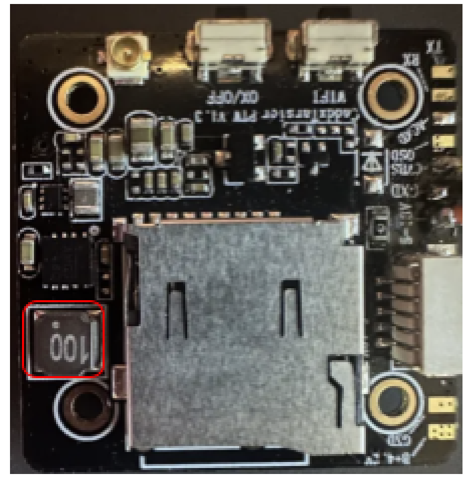
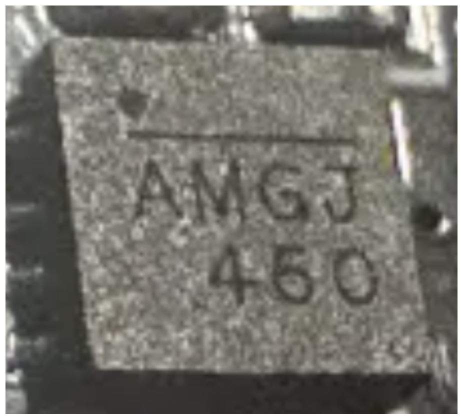
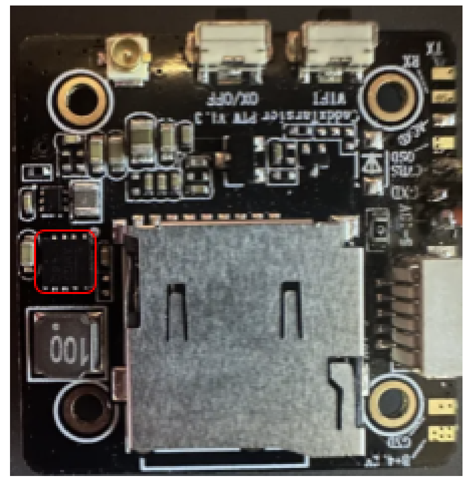
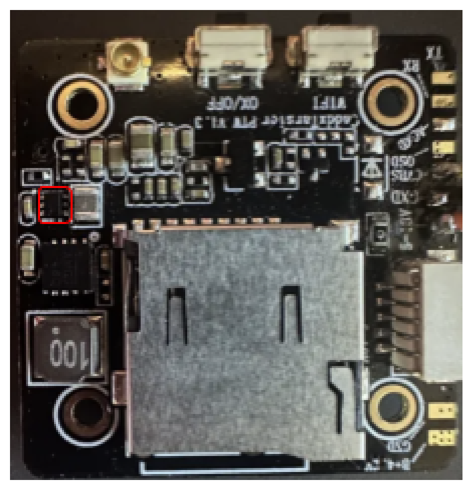
JST Connector **Connects external components to each other.** Quantity: 4		
Micro-USB Connector **Port for Micro USB cable.** Quantity: 1		

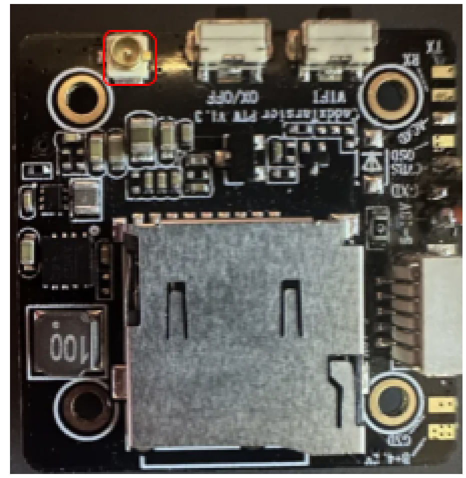
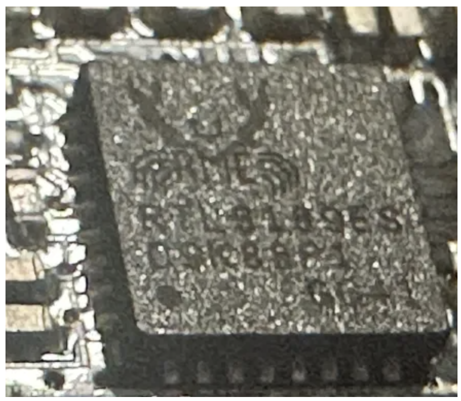
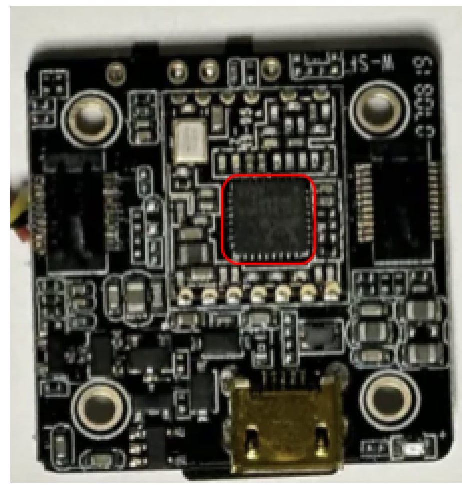
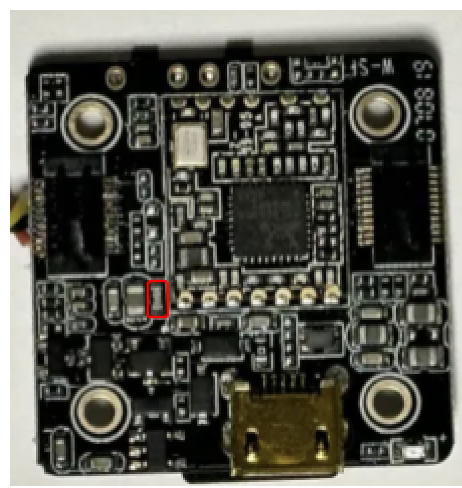
Mini Pushbutton **Electrically close/open circuits when pressed/released.** Quantity: 1		

Mystery Board:

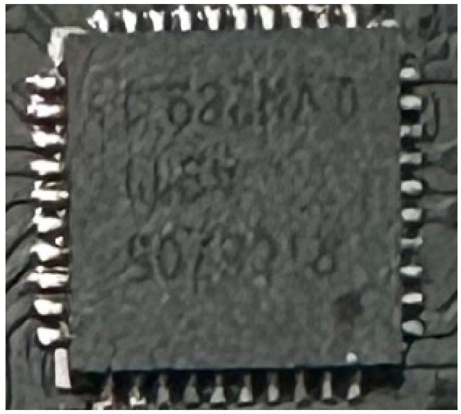
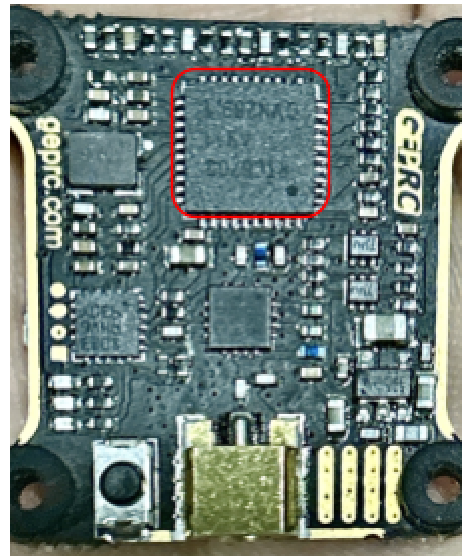
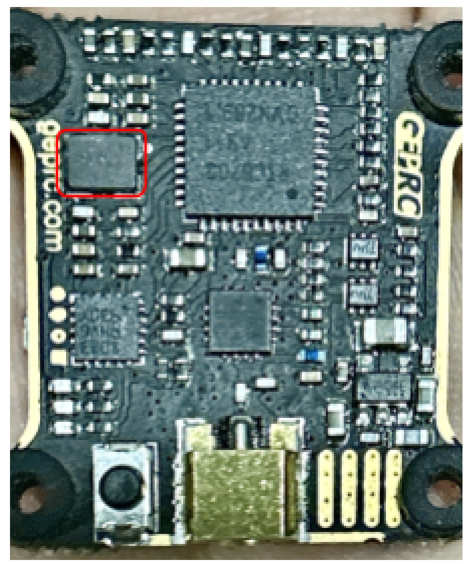
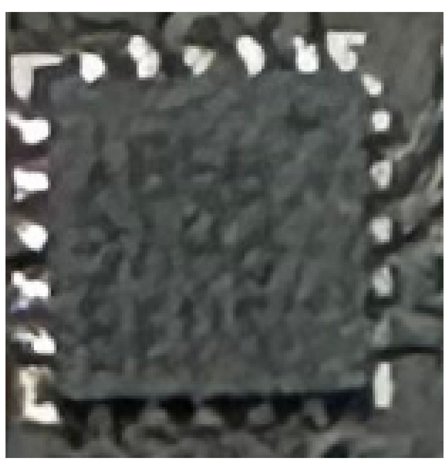
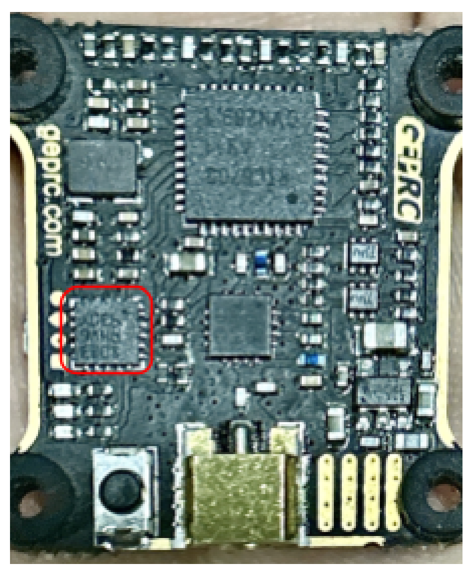
2SK2731 **MOSFET: controls conductivity between source and drain terminals.** Quantity: 2 **Data Sheet**		
RN1108 **NPN transistors which amplify and switch electrical signals.** Quantity: 3 **Data Sheet**		

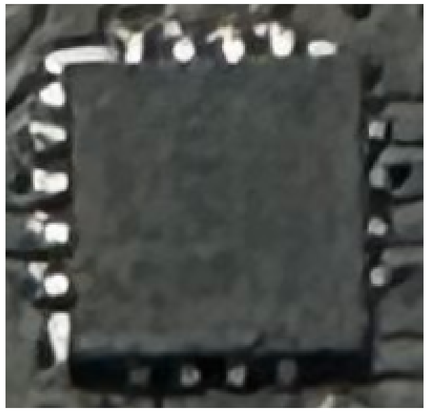
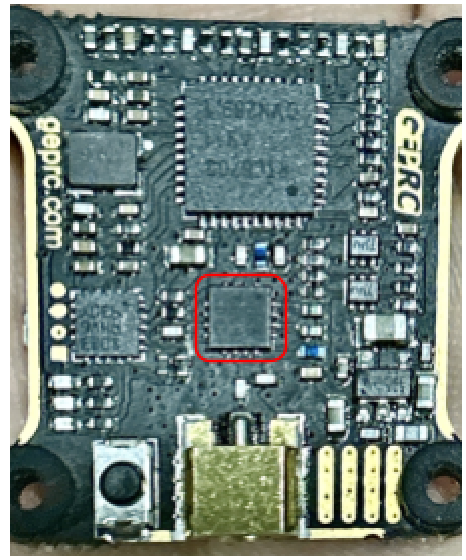
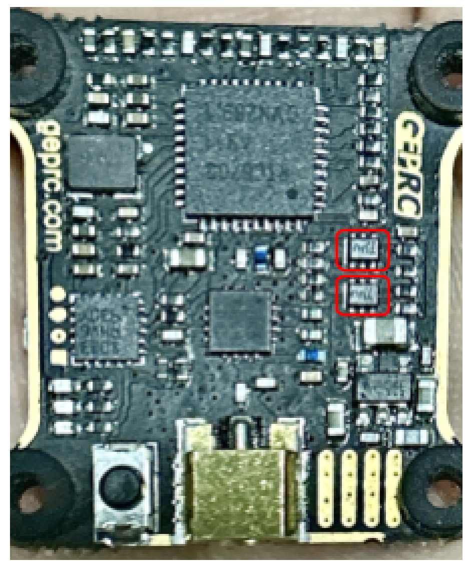
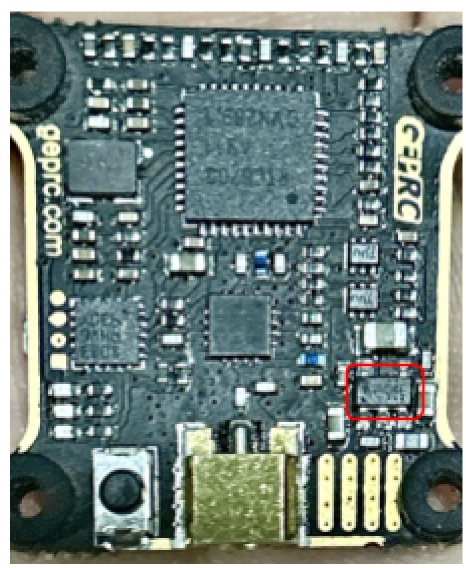
1N5819 **A diode with a low forward voltage drop and high switching speed.** Quantity: 2 **Data Sheet**		
LTH7 **Used for single-cell lithium battery charging.** Quantity: 1 **Data Sheet**		
Micro-USB Connector **Port for Micro USB cable.** Quantity: 1		

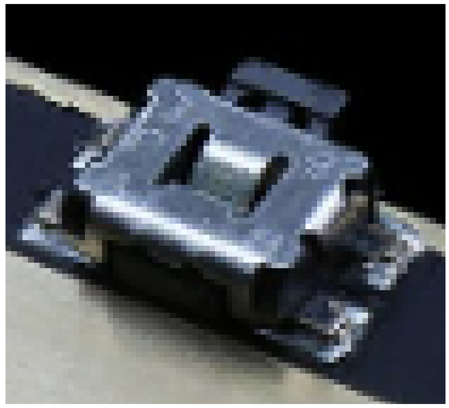
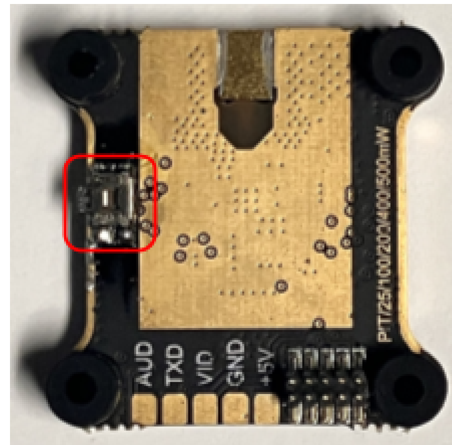
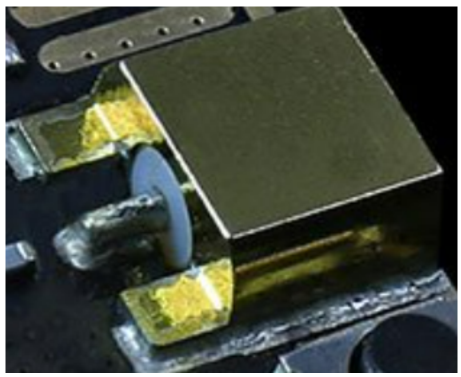
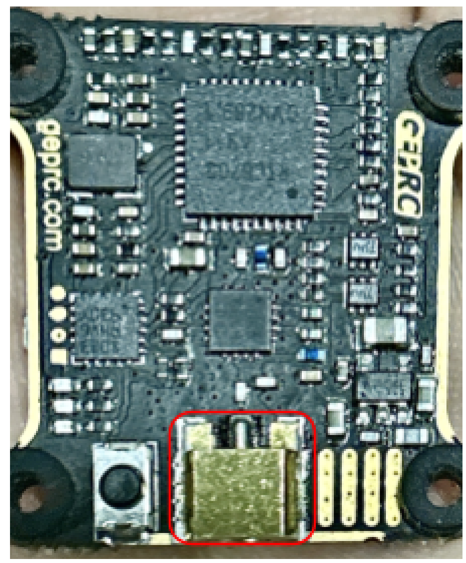
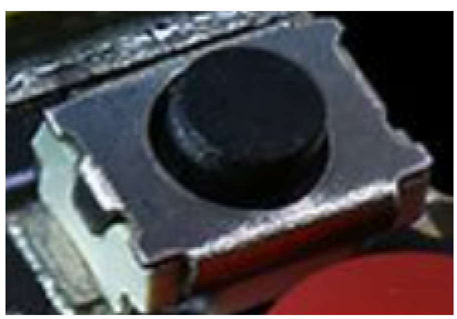
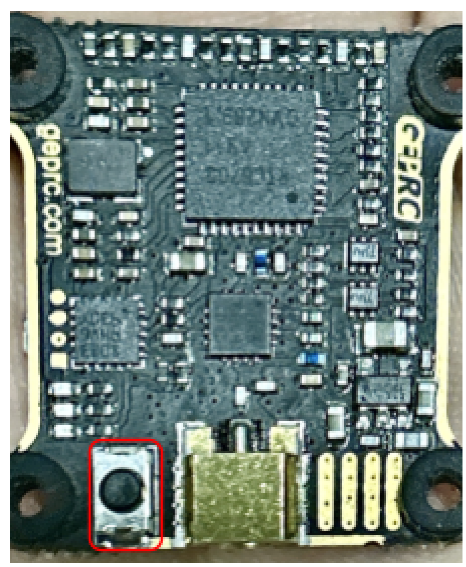
LQH3C 100µ Inductor **Filters noise from power and signal lines.** Quantity: 1 **Data Sheet**		
AM460 - Industrial Amplifier and Voltage-to-Current Converter IC **Amplifies weak signals and converts voltage inputs into current outputs.** Quantity: 1 **Data Sheet**		
2SA2014 **Bipolar (BJT) Transistor** Quantity: 1 **Data Sheet**		

UFL SMT Connector **Industry standard connector for antennas.** Quantity: 1		
RTL8189ES **Integrated single-chip network SDIO interface controller** Quantity: 1 **Data Sheet**		
B10 **Single chip platform with fully integrated 5G modem.** Quantity: 1 **Data Sheet**		

VTX:

RTC6705 **Wide-band FM transmitter intended for 5.8GHz bands.** Quantity: 1 **Data Sheet**		
BGSC2341ML10E6327XTSA1 **Antenna transmission device, includes LC filtering.** Quantity: 1 **Data Sheet**		
ATTINY85-20MU **Manages functions like channel selection, power output adjustment and pit testing modes.** Quantity: 1 **Data Sheet**		

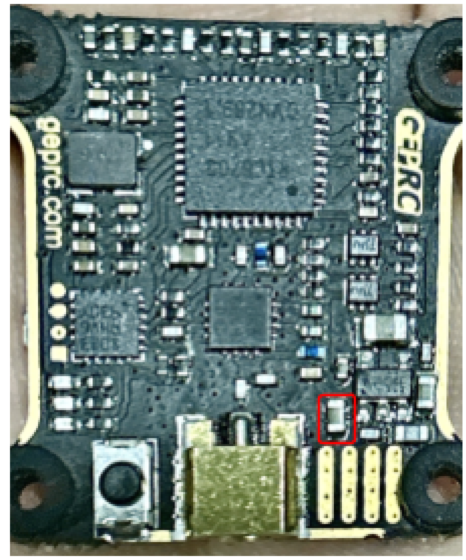
PIC16F15223-I/MG **Processes input signals from camera.** Quantity: 1 **Data Sheet**		
S47BKB **Manages specific signal processing tasks like encoding, decoding and modulation of the video feed.** Quantity: 2 **Data Sheet**		
MCP6001T-I/OT **Signal conditioning tasks including amplifying, filtering, and buffering the video signal before it is modulated and transmitted, ensuring a clear and stable video feed.** Quantity: 1 **Data Sheet**		

SMT Side Switch **Simple user GUI input for switching modes channels power, etc.** Quantity: 1		
MMCX Connector **Extends antenna range.** Quantity: 1 **Data Sheet**		
SMT Button **Easily switch modes and low level settings.** Quantity: 1 **Data Sheet**		

<table>
<tr>
<td>Y201510K0000T9L

Vishal foil resistor used in high current systems.

Quantity: 1

Data Sheet</td>
<td></td>
<td>
</td>
</tr>
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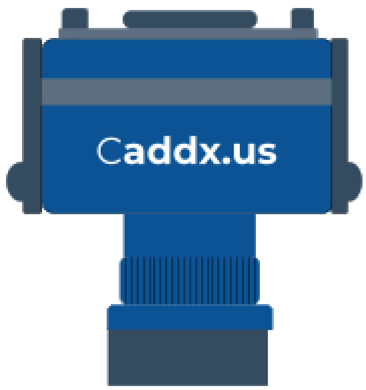
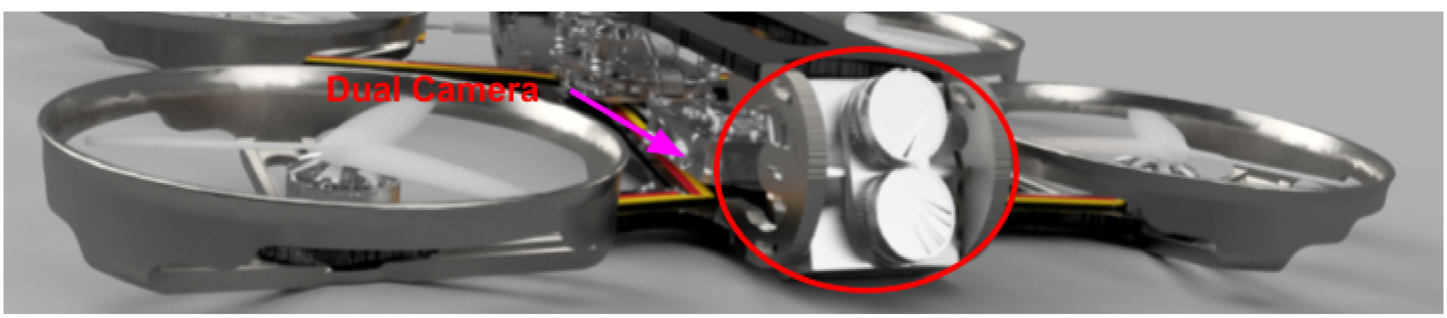
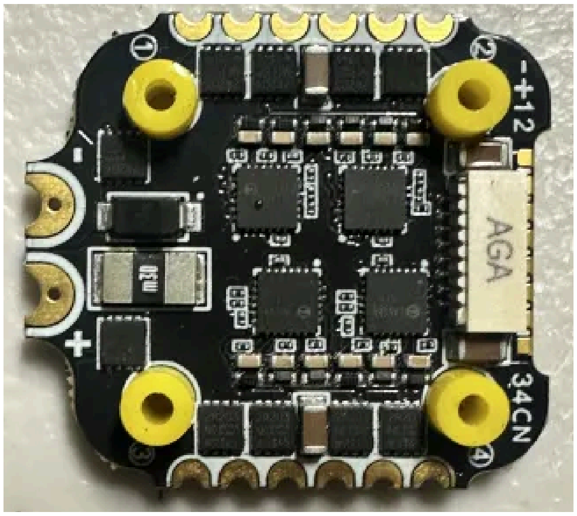
<table>
<tr>
<td rowspan="2"></td>
<td colspan="2">Analog HD Dual Camera:</td>
</tr>
<tr>
<td>
</td>
<td>Records video in HD and Analog which is transmitted using VTX.

Caddx Tarsier V2 4K

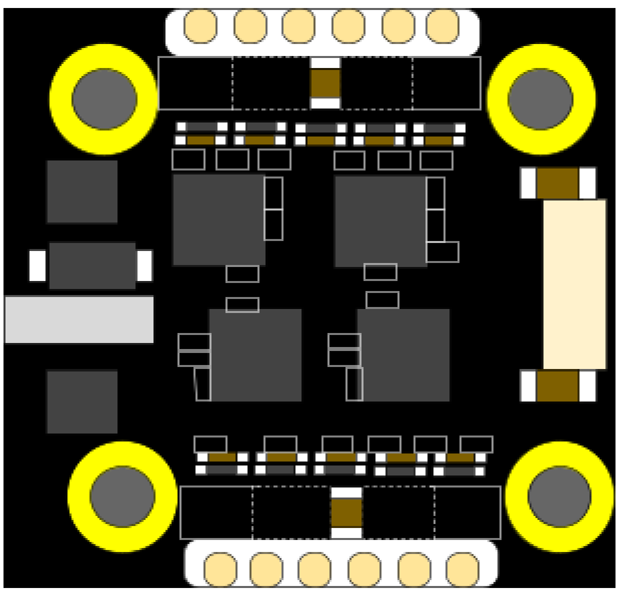
Quantity: 1</td>
</tr>
</table>

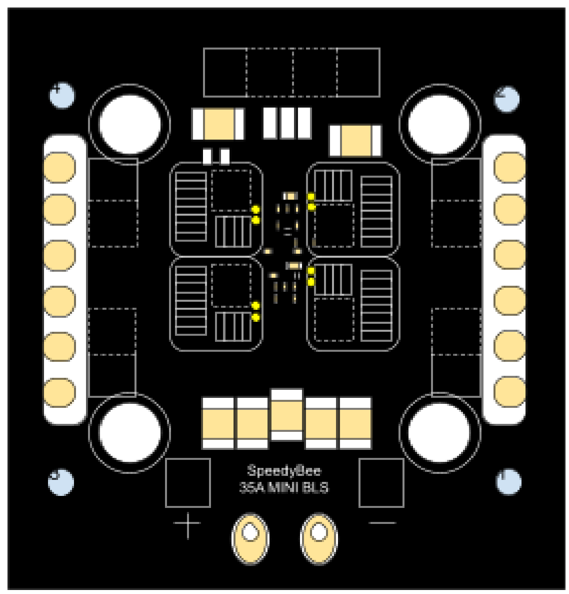


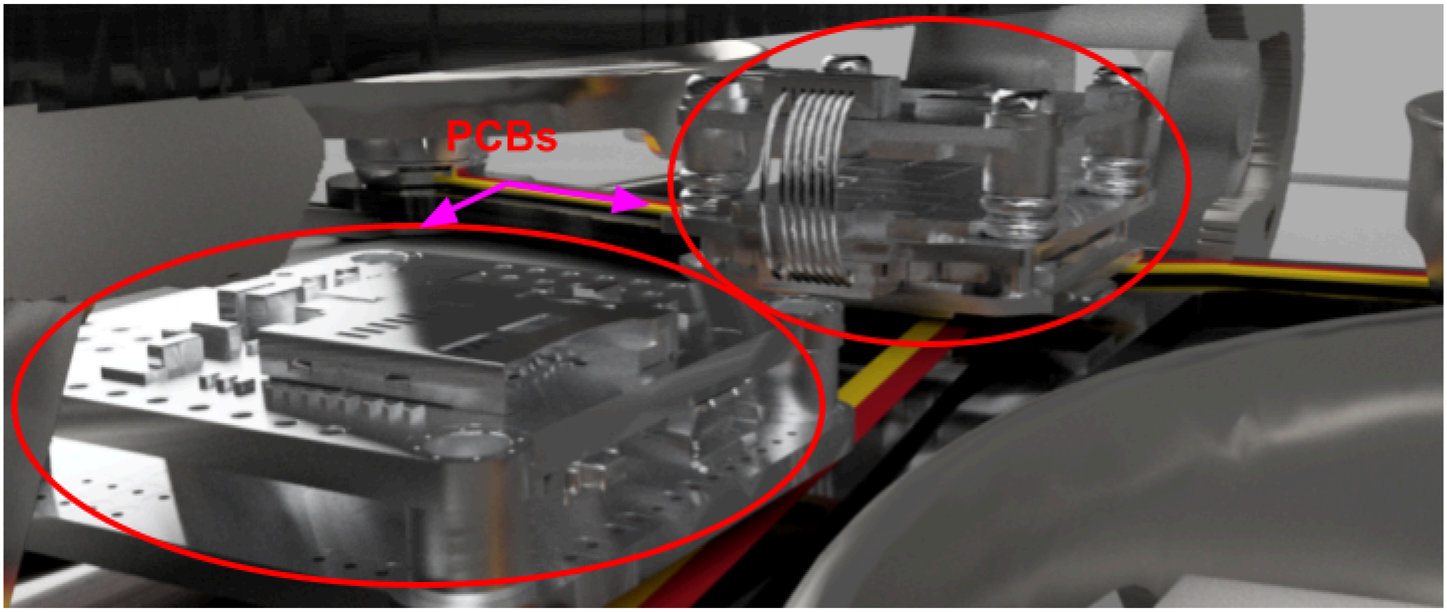
Electronic Speed Controller (ESC): NEW



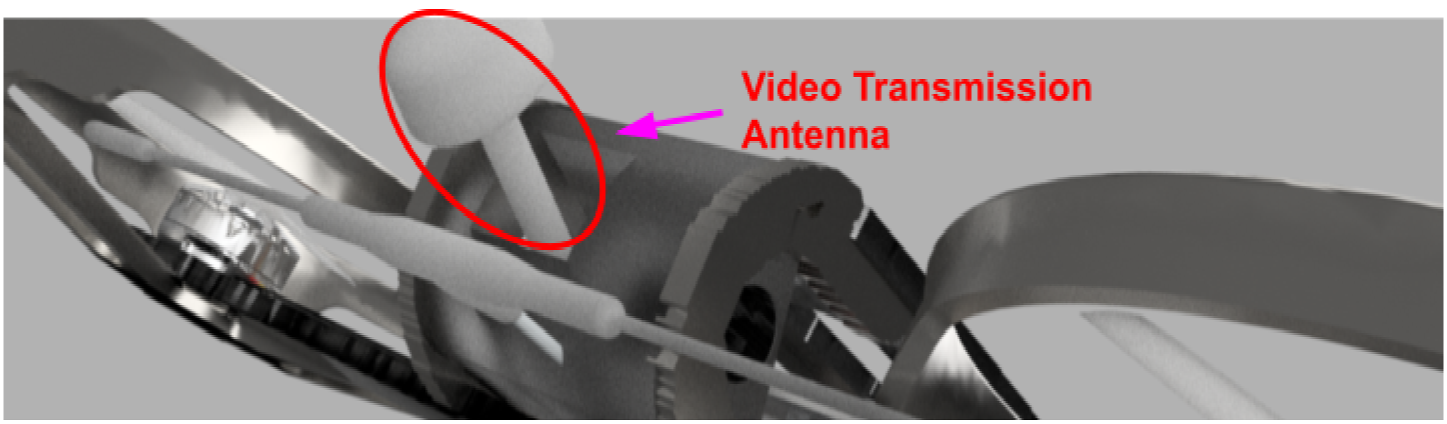
The ESC was broken, so we had to buy our own and replace it.

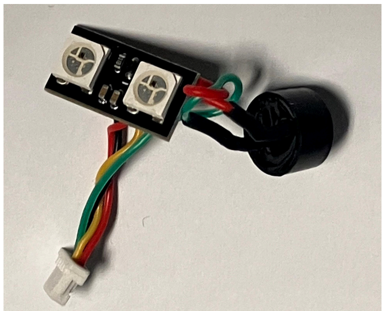


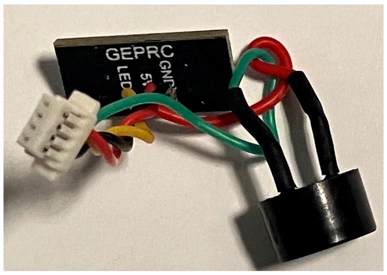




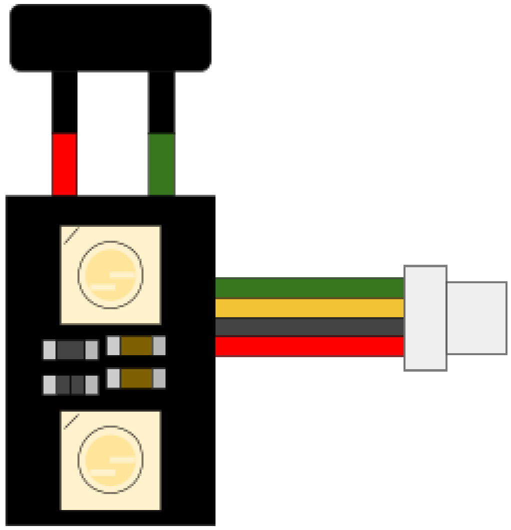
	Video Transmission Antenna: Momoda 5.8G	
		**Connects to receiver** through radio frequency. [Product Link] Quantity: 1







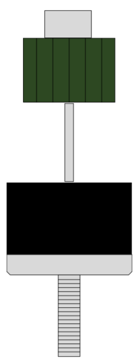
LED & RGB:



Lights up when it receives power or a certain signal.

Quantity: 1

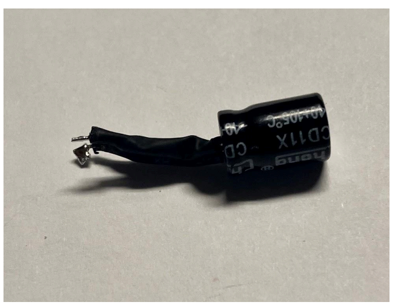
3600KV Motors: GEP-GR1206



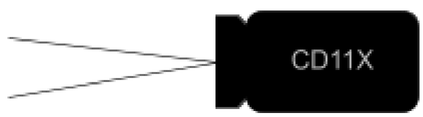
Converts electrical energy to mechanical energy through rotation.

3600 KV = 3600 Kilovolts

Quantity: 4



Capacitor:



Protects electronics from voltage spike.

Quantity: 1

Battery Cable:

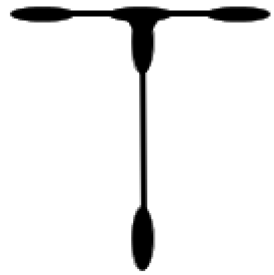
Transfers energy to drone from battery.

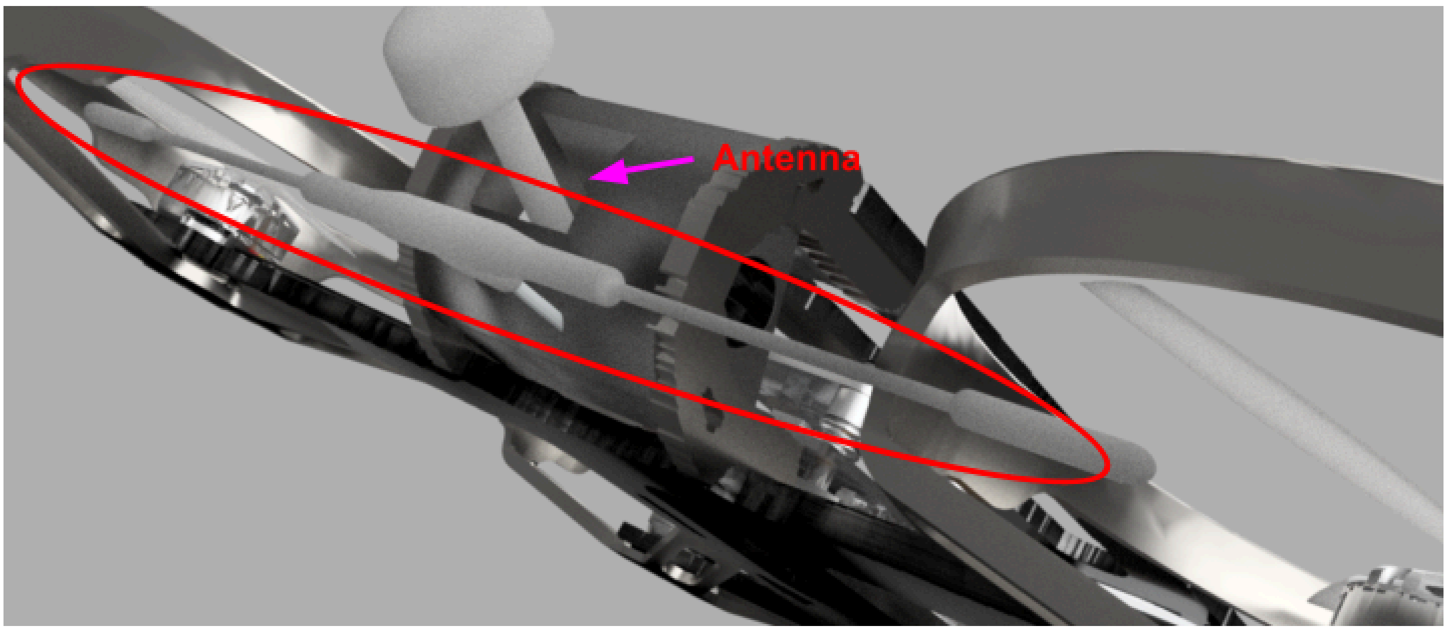
Quantity: 1

Mystery Wire:

Purpose **unclear** *(was not connected to anything)*.

Quantity: 1

	Antenna:	
		**Transmits radio waves** to controller. Quantity: 1



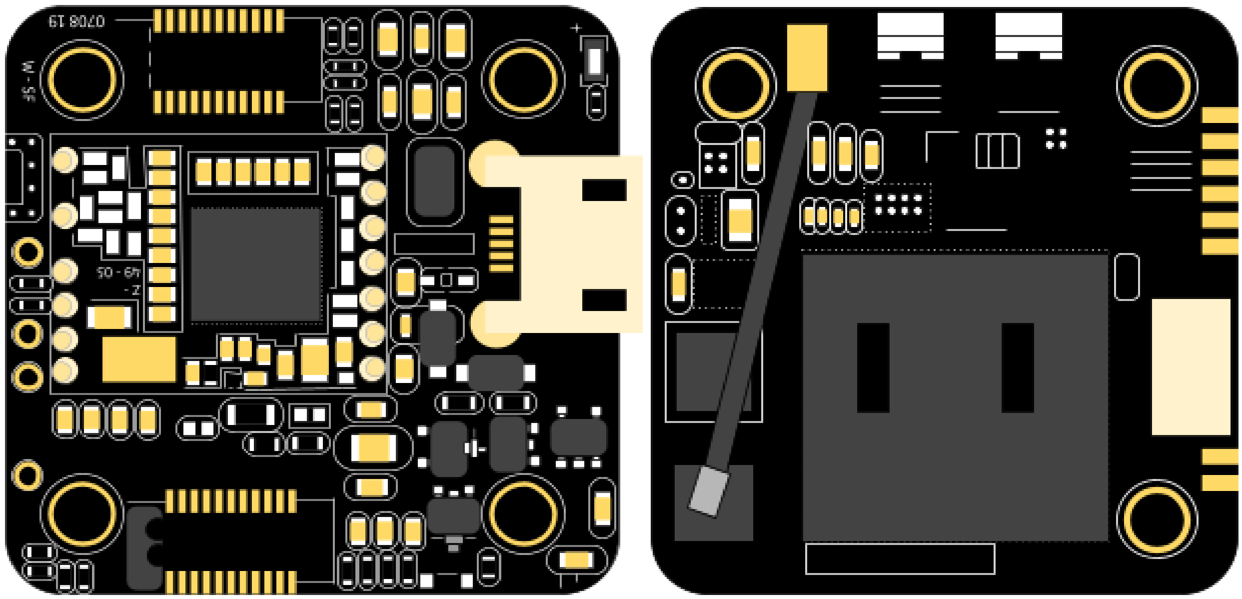
Electrical Components- Overall Labeling

<u>Vulnerability</u>: The memory cards in the drone store sensitive information that can be accessed by external parties who possess the drone, creating a massive security threat.

4.3 Hypothesis: Mystery Board

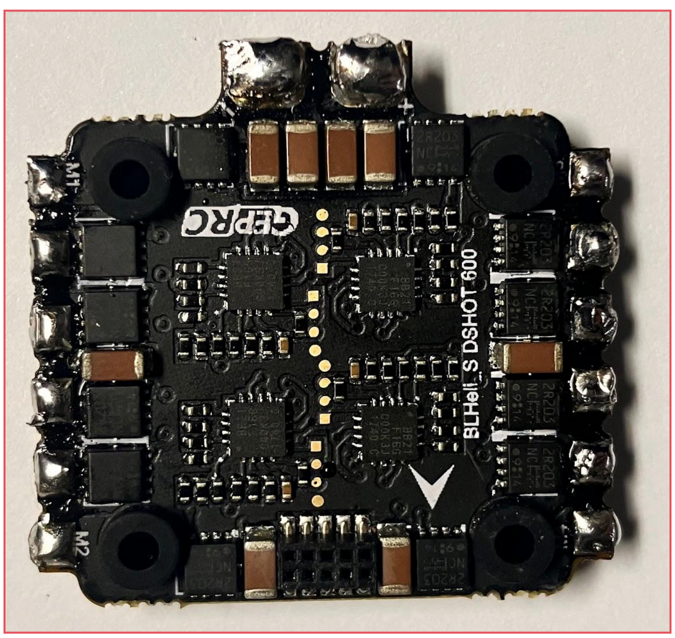
We found an electrical board that we did not recognize, which we believe functions as part of the drone's **camera system**.

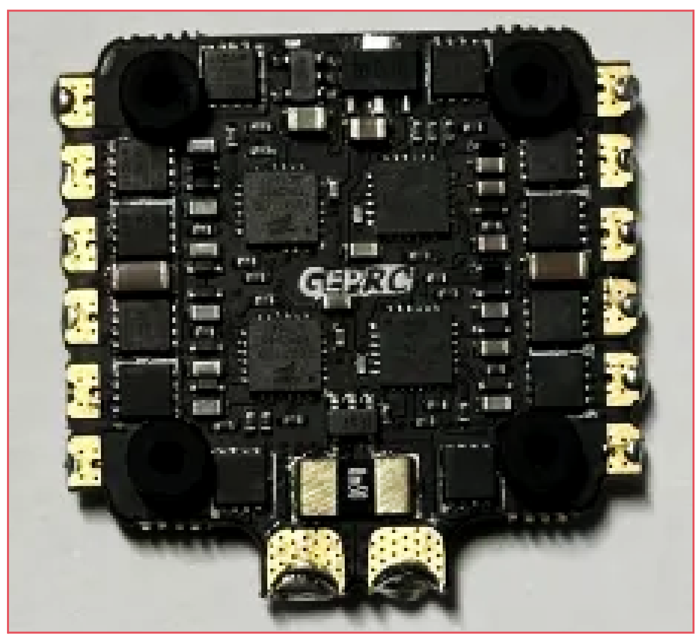
We hope to learn more about this mysterious PCB as we continue working through this challenge.



4.4 A Step Further

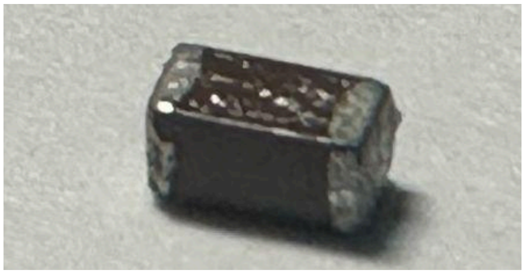
To go deeper, we disassembled the broken ESC.



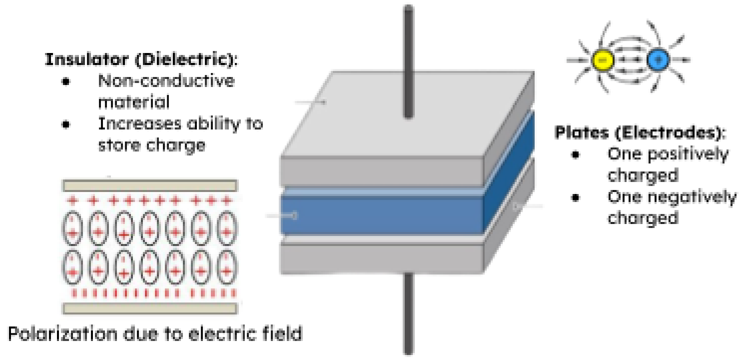


,

Capacitors:

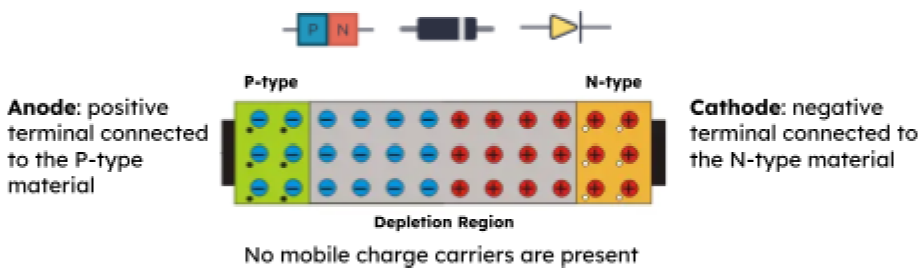


Quantity: 16x

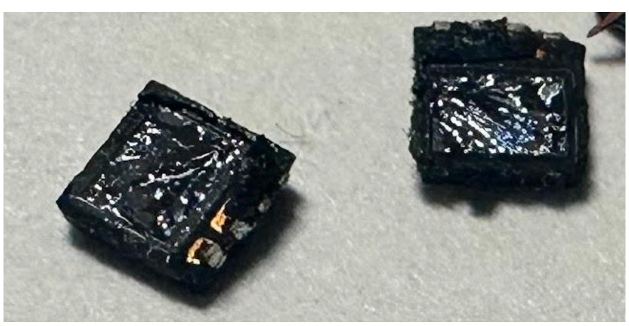


Diodes:

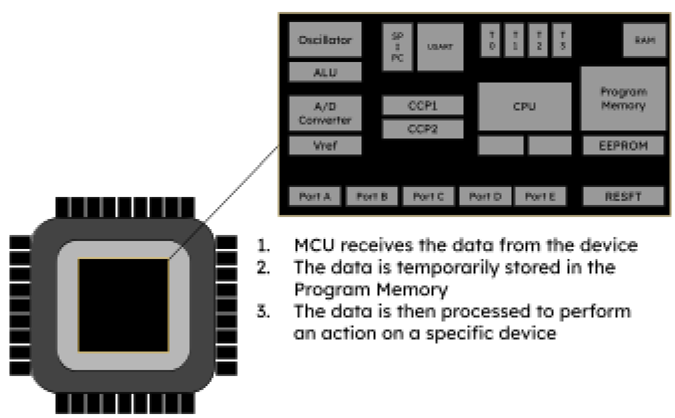
Quantity: 10x



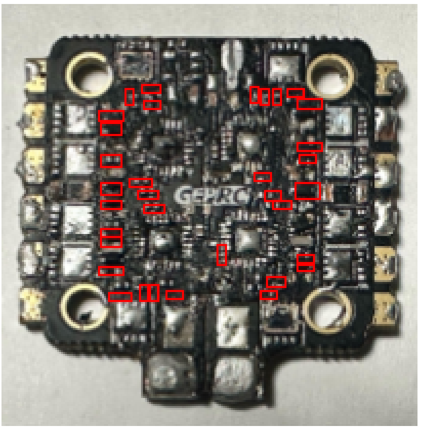
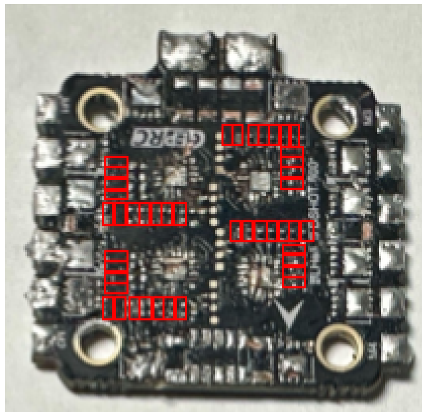
MCUs:



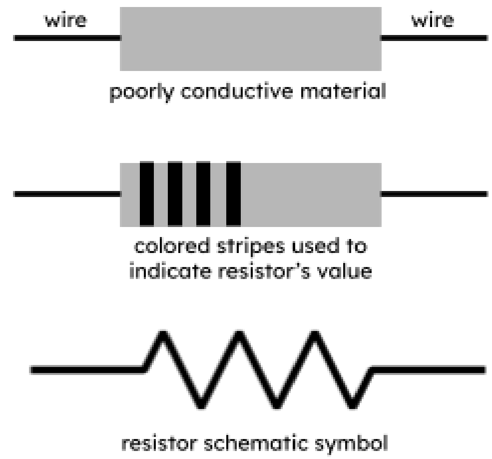
Quantity: 15x



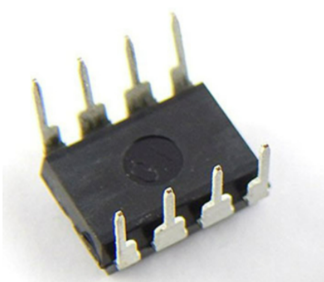
Resistors:

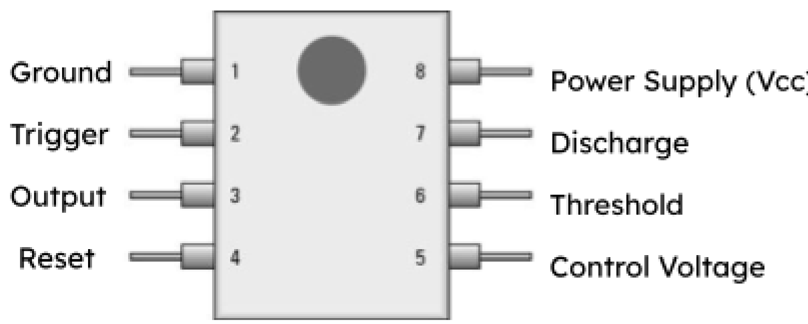
Quantity: 78x

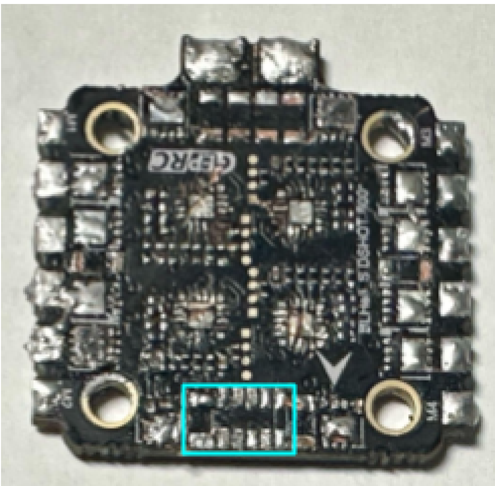
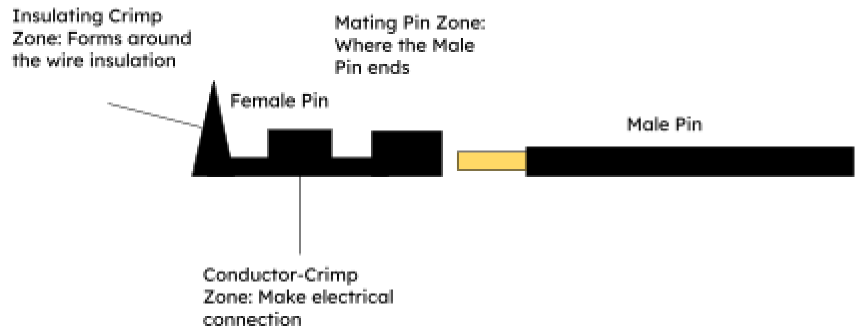


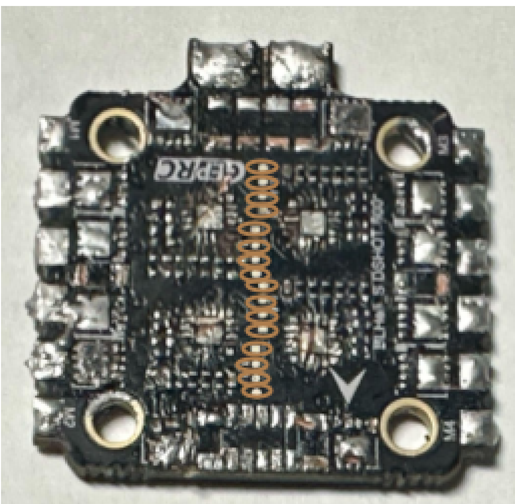
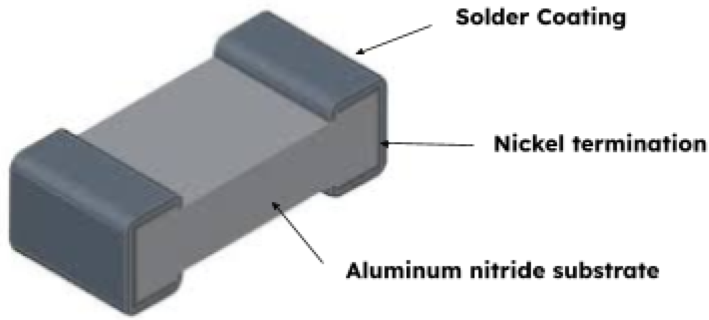
Timer:



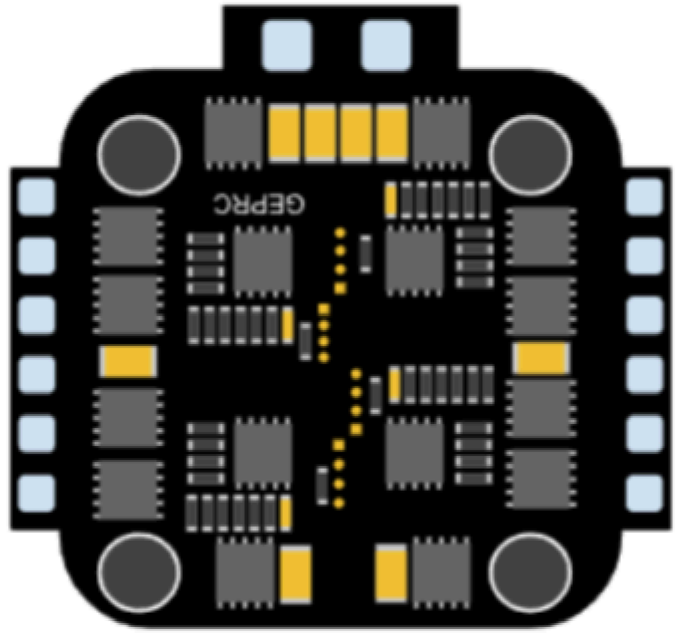
Quantity: 3x



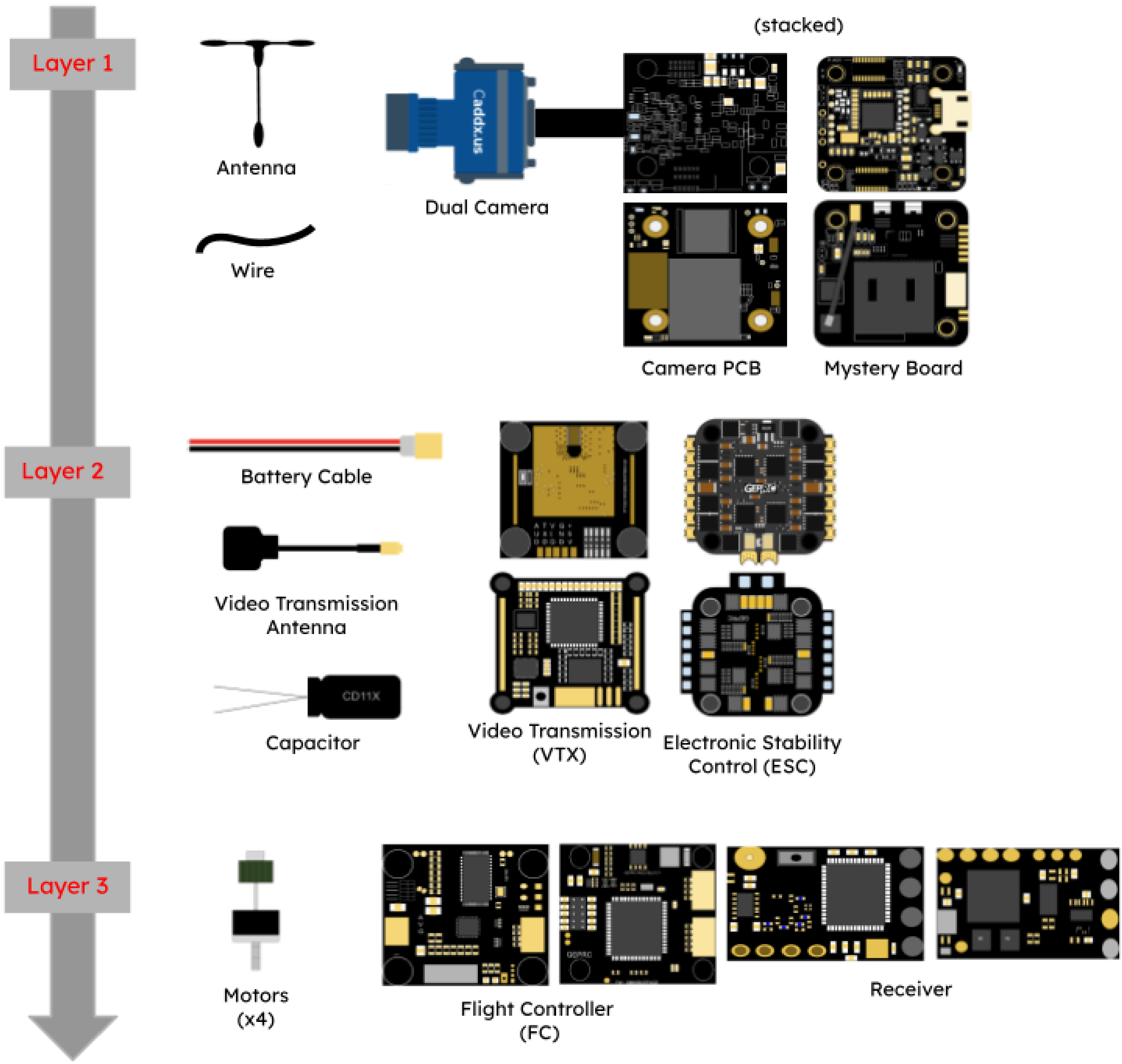
Dupont Connector:	
 Quantity: 1x	

SMD Jumper:	
 Quantity: 16x	 ***These materials have a low heat capacity, allowing heat to be transferred to different parts of the ESC or dissipated***


GEPRC



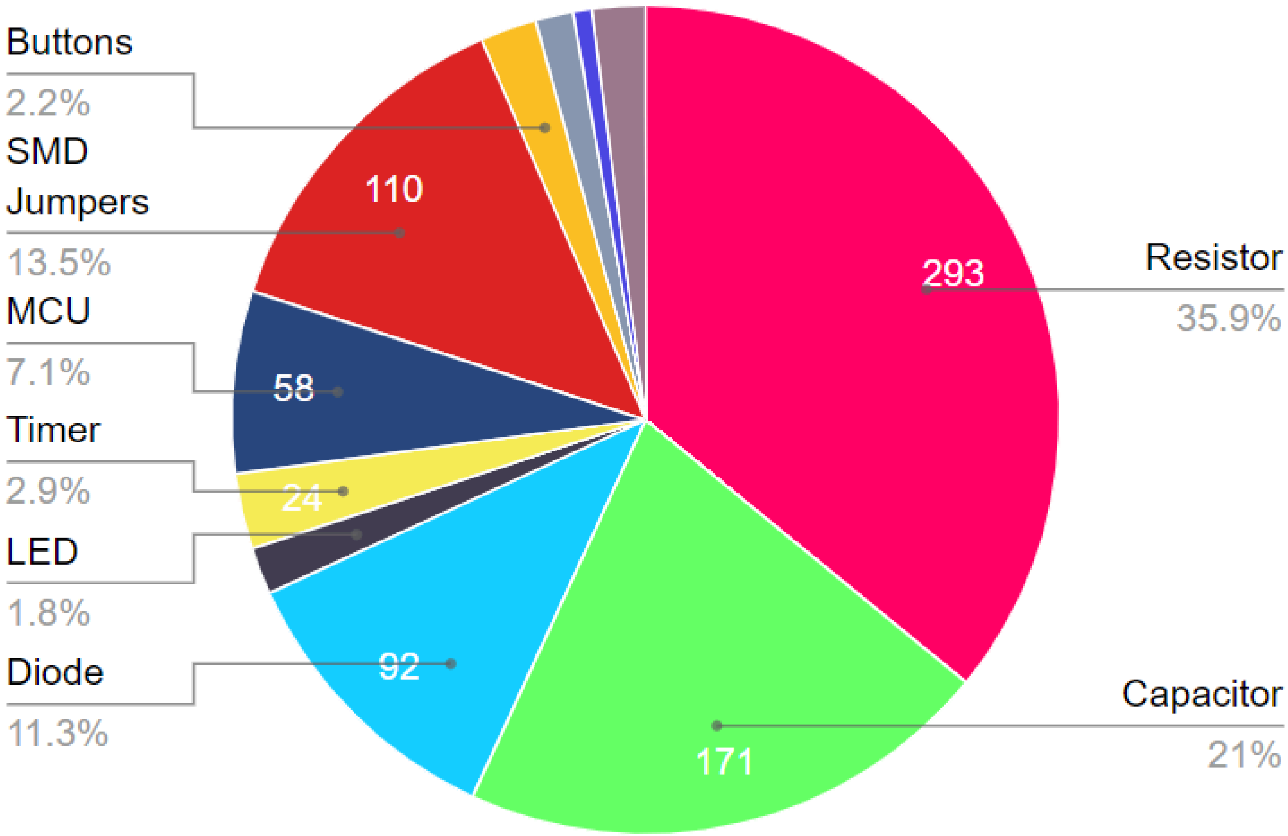
4.5 Component Overview



Electrical Anatomy Created From Scratch in Google Drawings

Vulnerability: Hobbyist drones can be tapped into using radio frequency sensors, revealing the location of the pilot.

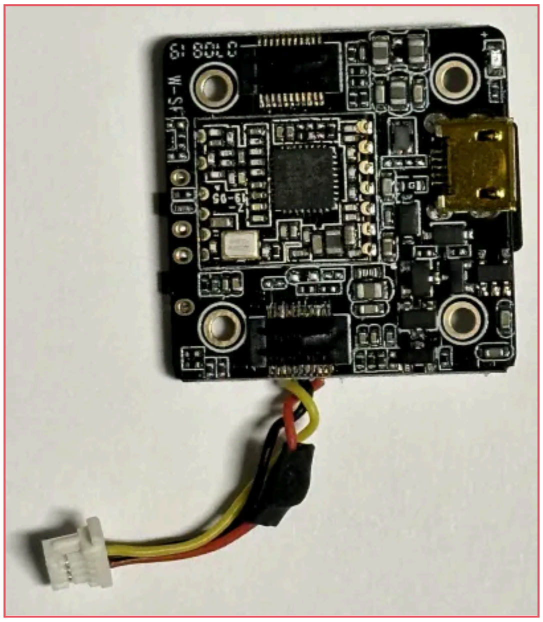
Total Components

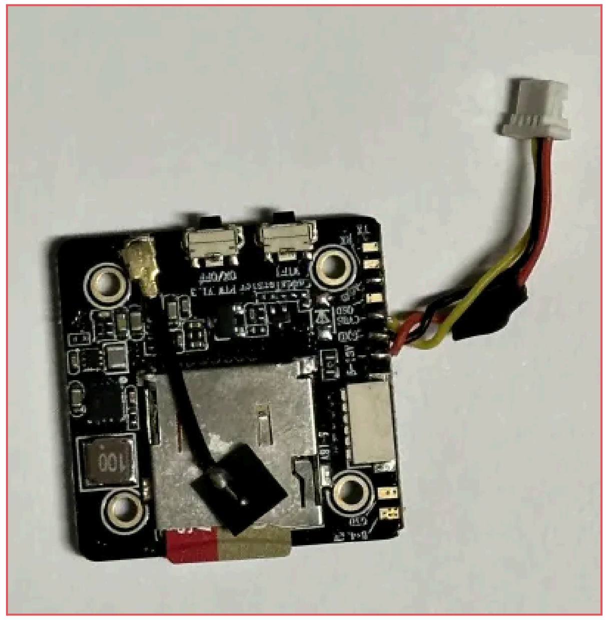


5. Findings

5.1 The Mystery Board: Demystified

After researching the components, we believe this is the **DVR**, responsible for **recording and storing video** on the drone.

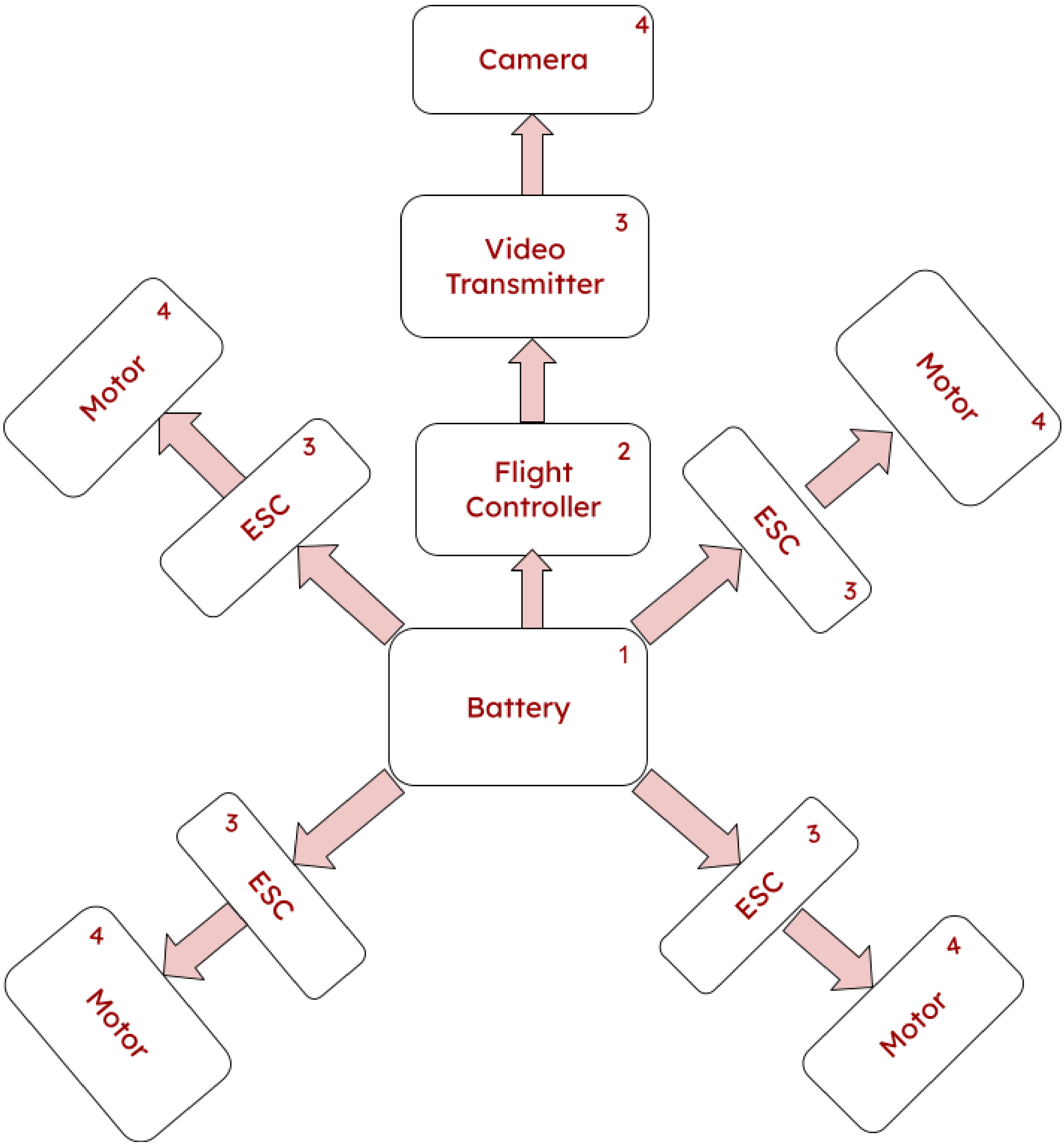




CADDXFPV DVR Turtle 2

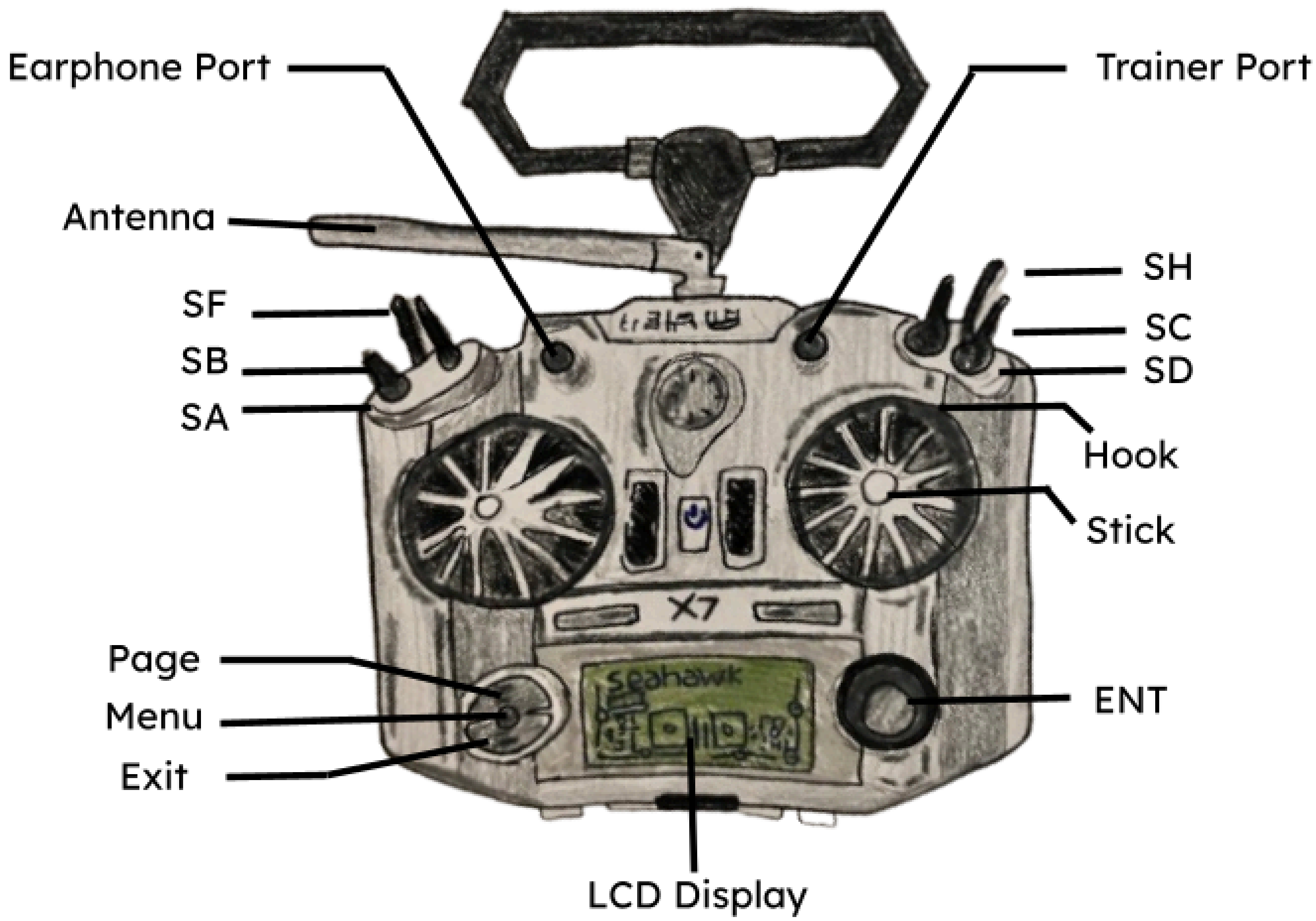
5.2 Power Flow

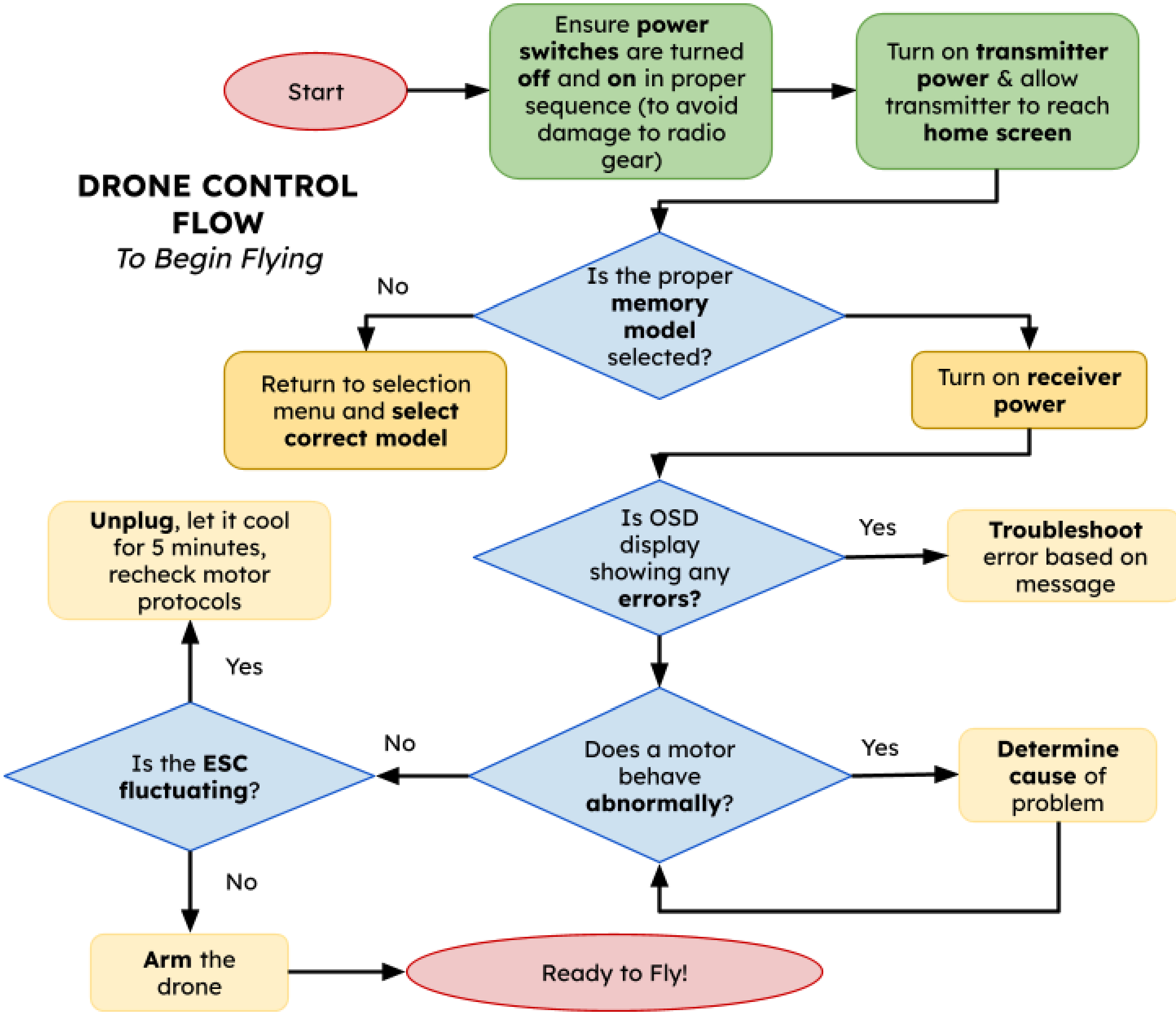
Here's a high-level diagram of how we believe power flows throughout the drone:



5.3 Control Flow

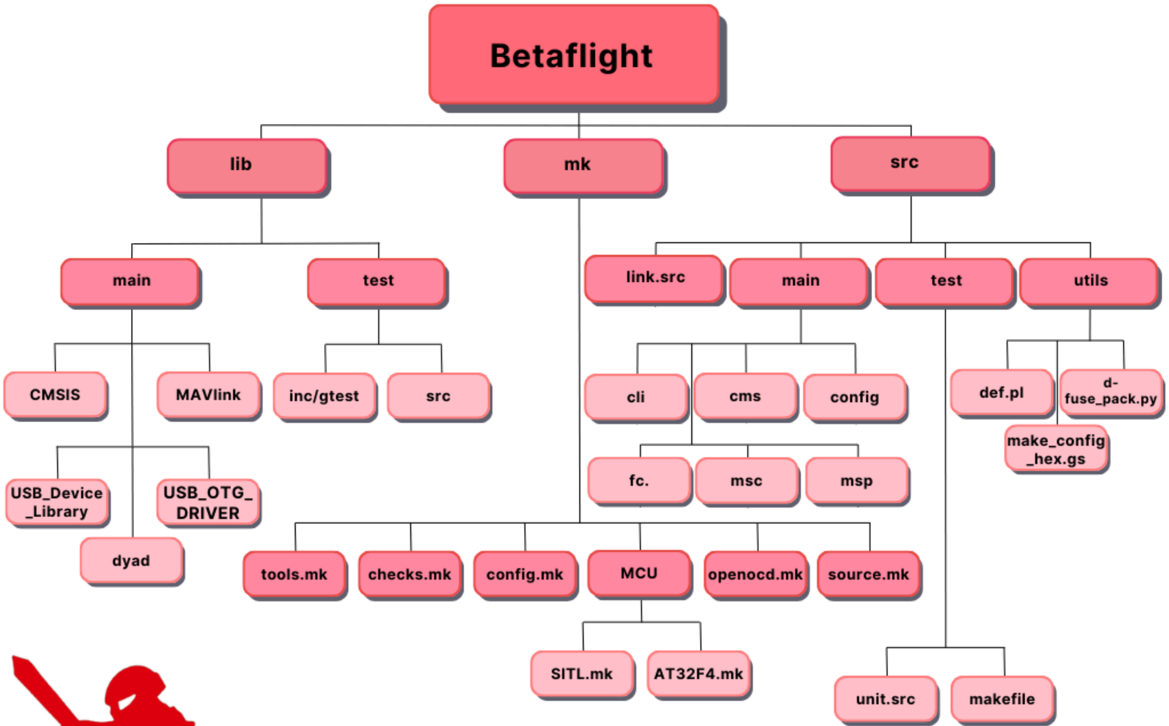
Control Flow Component Overview




Start
Ensure power switches are turned off and on in proper sequence (to avoid damage to radio gear)
Turn on transmitter power & allow transmitter to reach home screen
DRONE CONTROL FLOW
To Begin Flying
Is the proper memory model selected?
No
Return to selection menu and select correct model
Turn on receiver power
Is OSD display showing any errors?
Yes
Troubleshoot error based on message
Unplug, let it cool for 5 minutes, recheck motor protocols
Yes
Is the ESC fluctuating?
No
Does a motor behave abnormally?
Yes
Determine cause of problem
No
Arm the drone
Ready to Fly!

5.3 Betaflight Software

[Betaflight](#)



We reverse engineered our drone's live multi-rotor flight control software (Betalight), which we pulled from the FC.

These are the ESC files, which control the motors and enable flight:

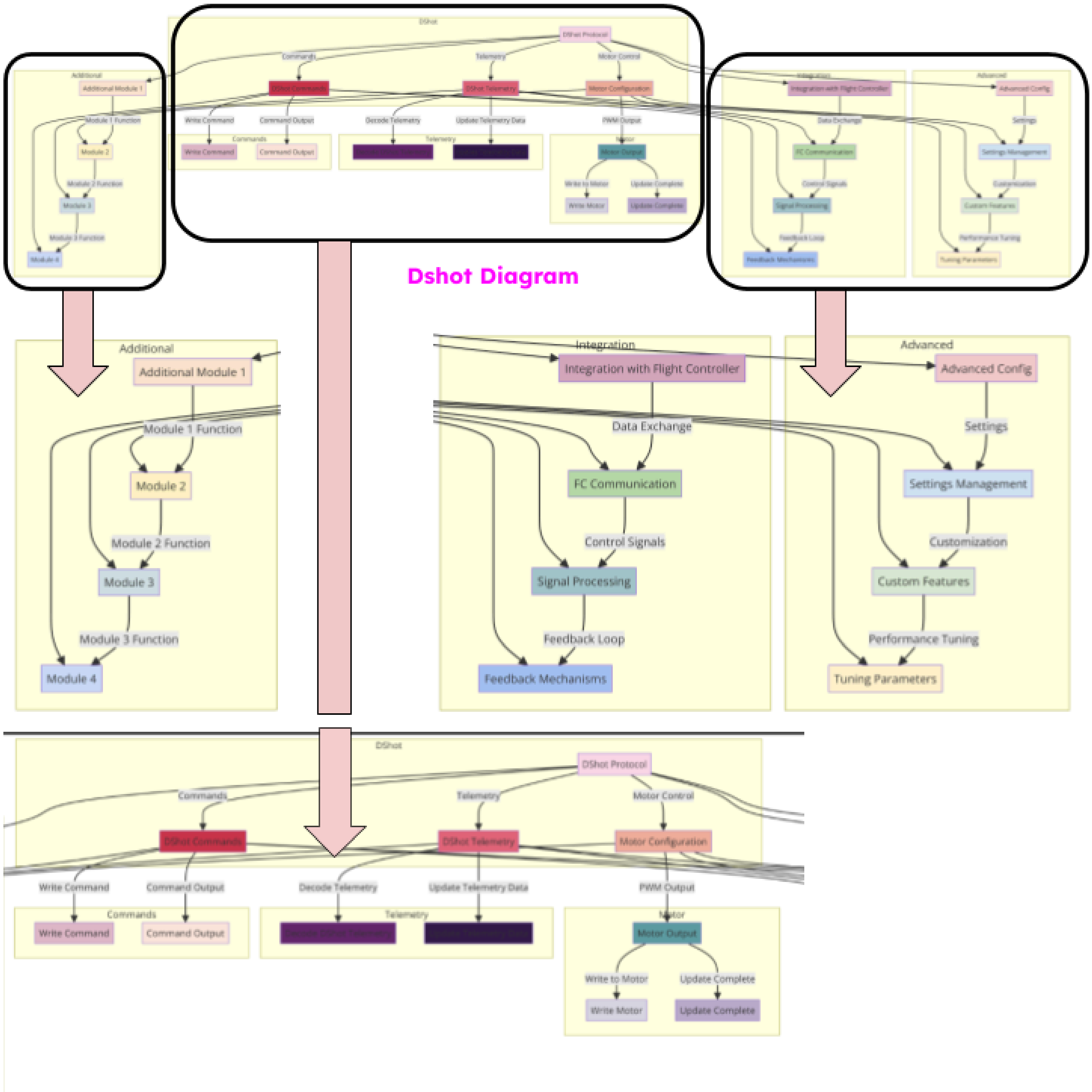
dshot.c: sets up DShot protocol configurations, processes motor commands

dshot_bitbang_decode.c: decodes ESC telemetry data

dshot_command.c: manages DShot command queuing and timing, ensuring synchronization with the motor control loop

dshot_dpwm.c: initializes motor devices, configuring timers and DMA for efficient DShot transmission.

Together, these components enable precise motor control and real-time telemetry, enabling stable and responsive flight dynamics.



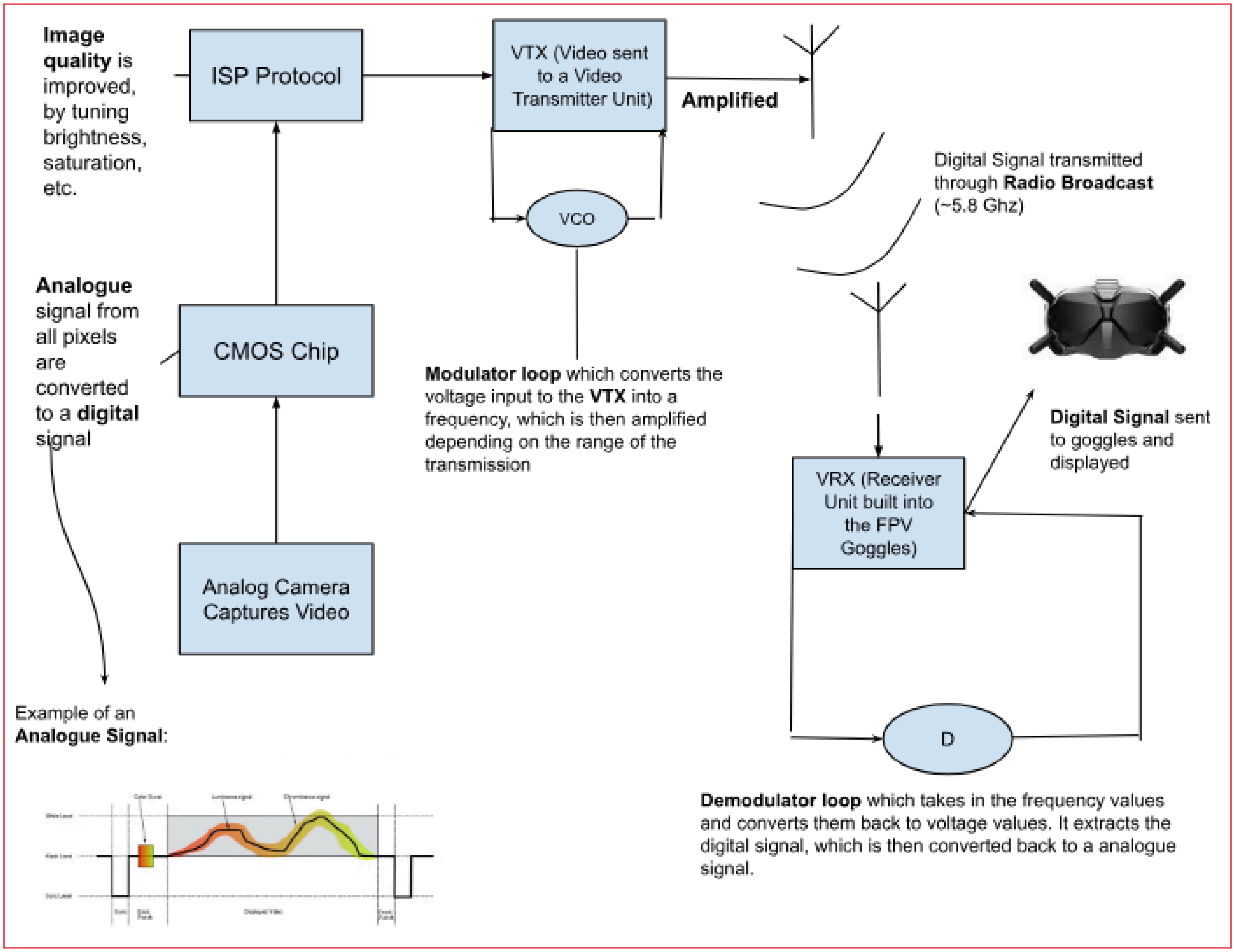
Full Betaflight Software Reverse Engineering

[Link to Live Diagram]

[Betaflight Software Explanation Video]

5.4 FPV Analog Transmission

We also took apart the drone's video transmission system.

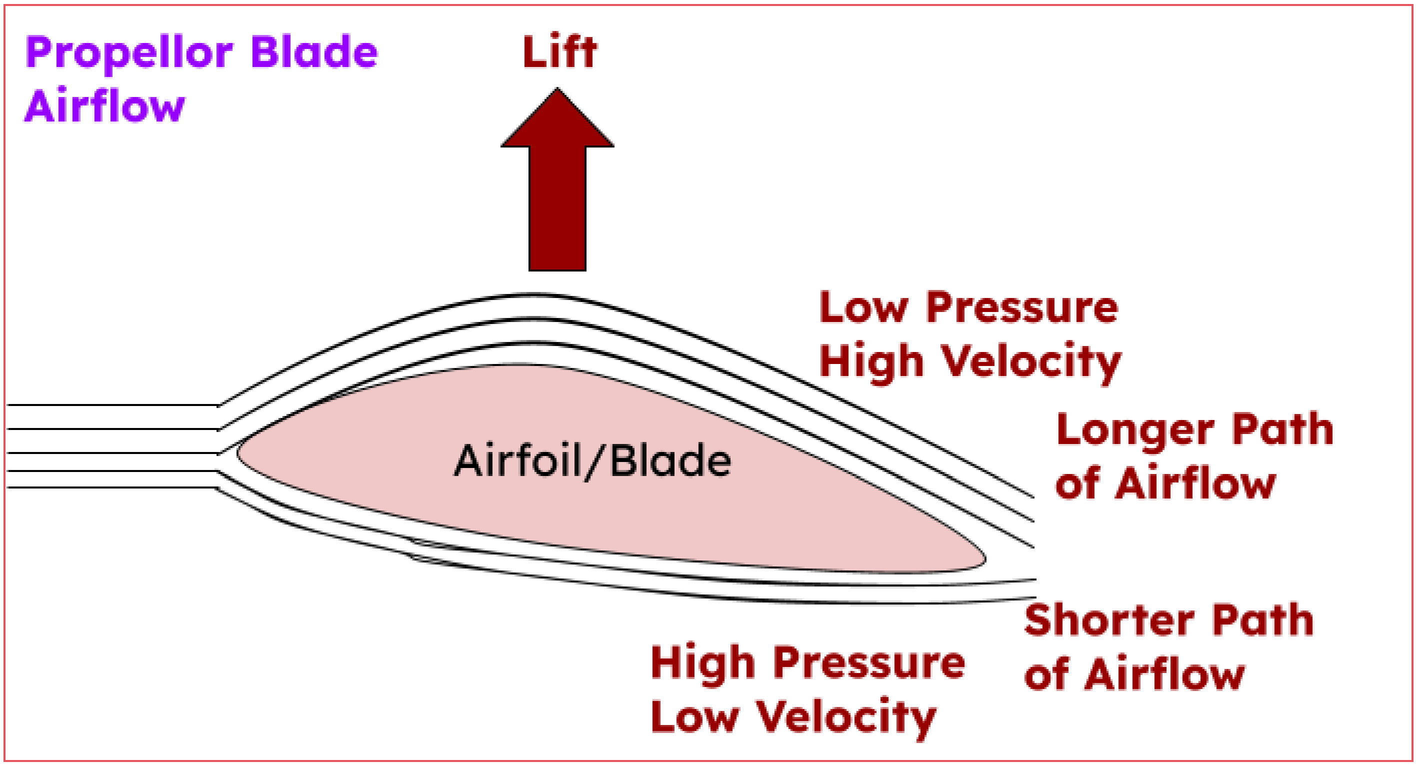


Summary: FPV Analog Transmission

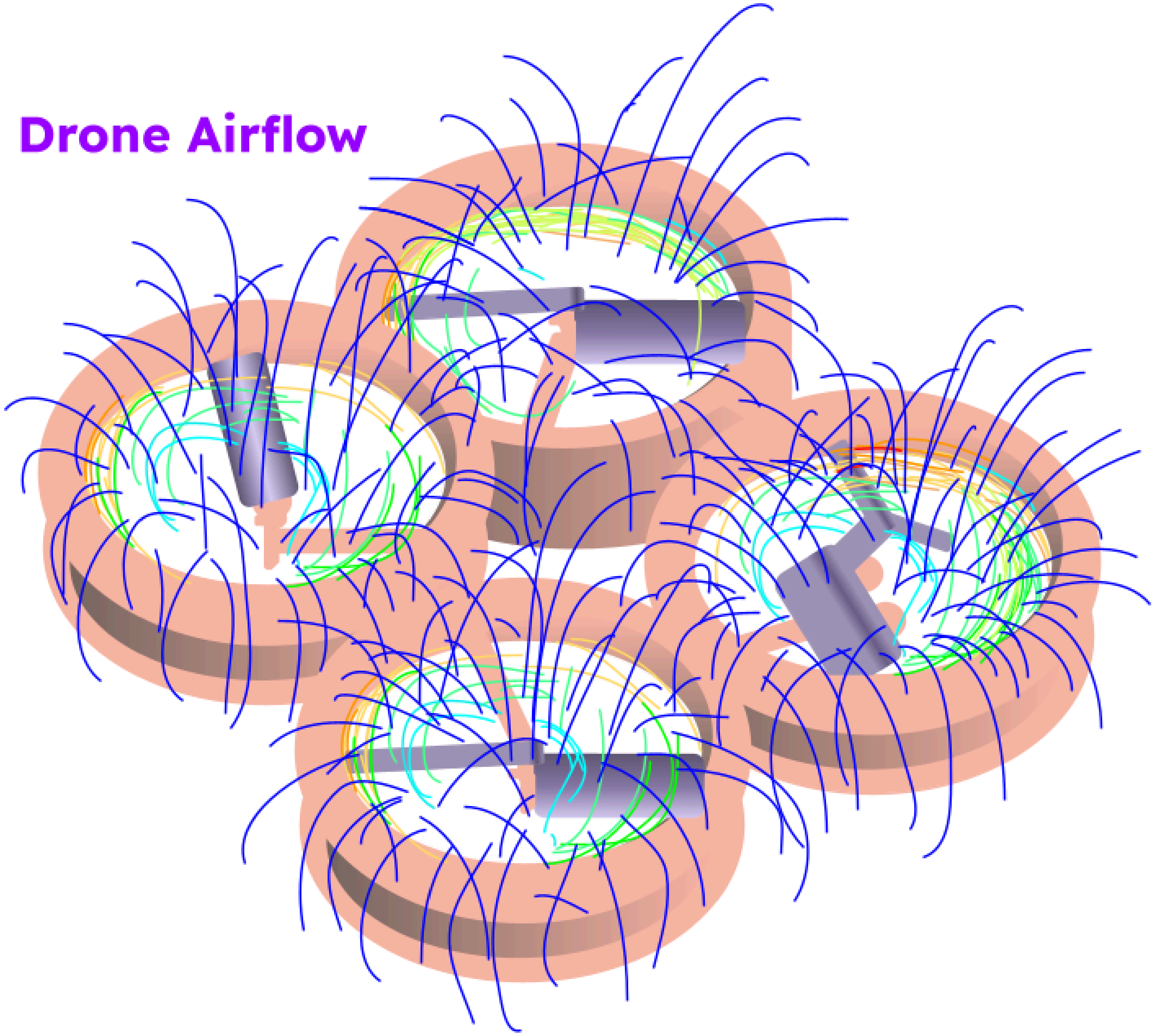
Vulnerability: External parties can tap into a drone's exact frequency and send powerful signals, scrambling the drone's RF and communication systems, causing it to crash.

5.5 Air Flow

Systems outside a machine are often as crucial as those inside it.



Drone Airflow



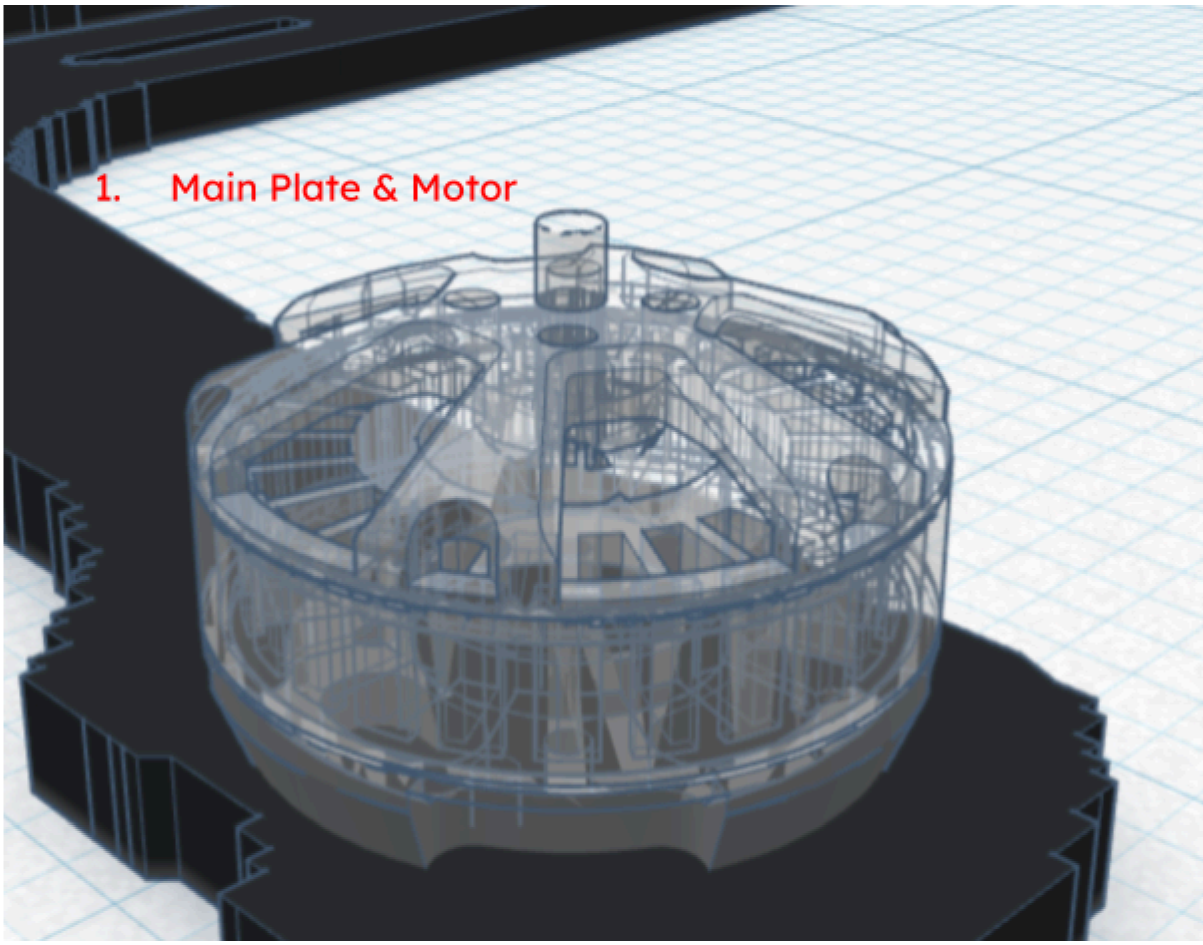
We know it’s not pretty, but that’s truly how the airflow looks!

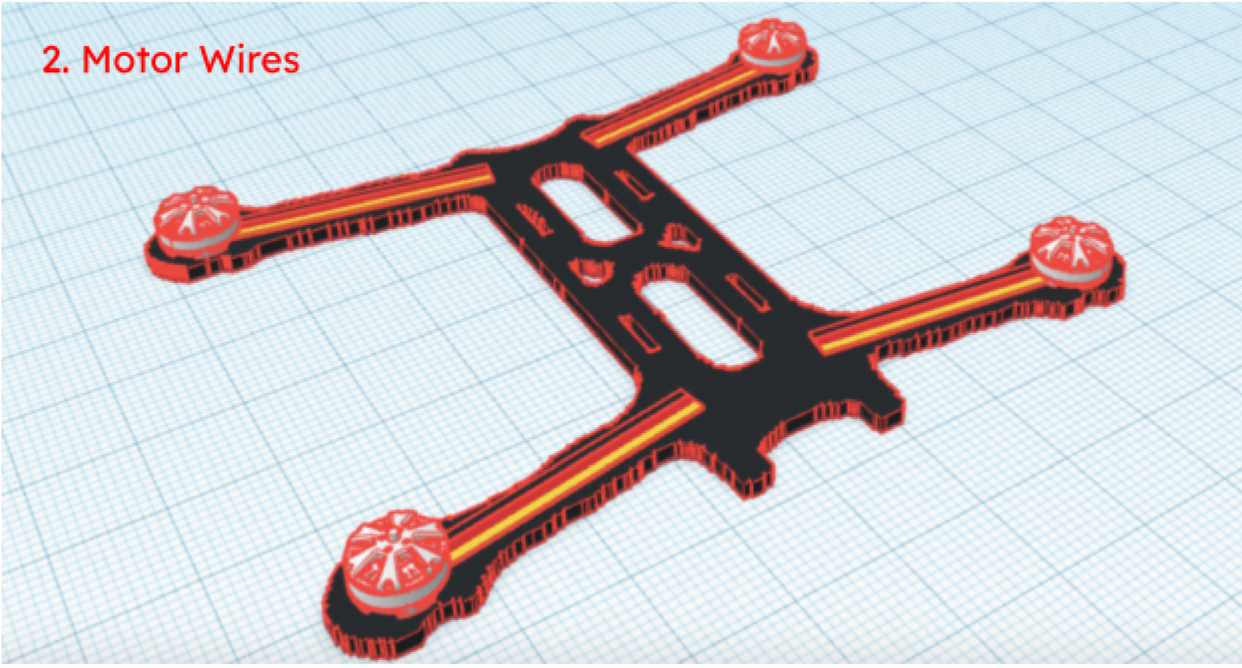
5.6 CAD

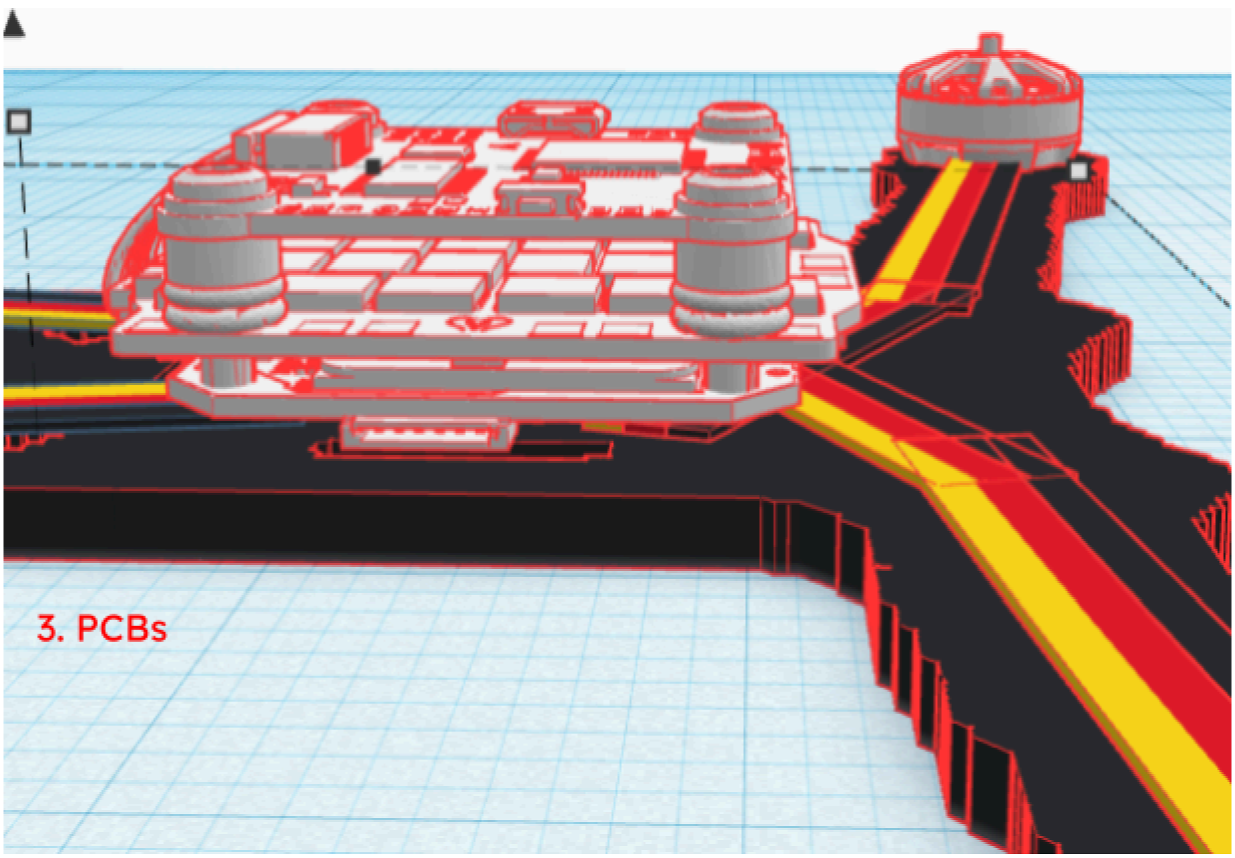
CAD Renders

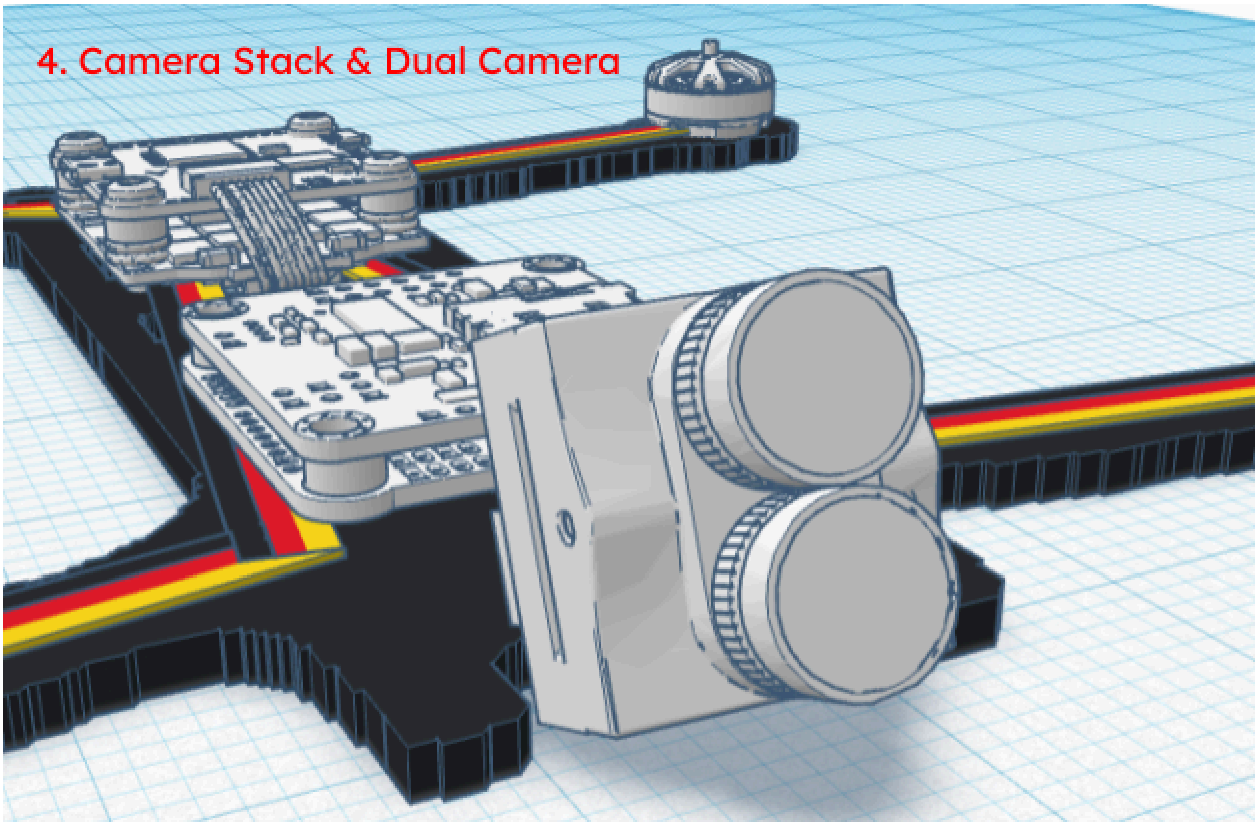
Applying VEX skills, we crafted a CAD model of the drone from scratch, allowing us to test our understanding of its intricate components and their roles in the overall system.

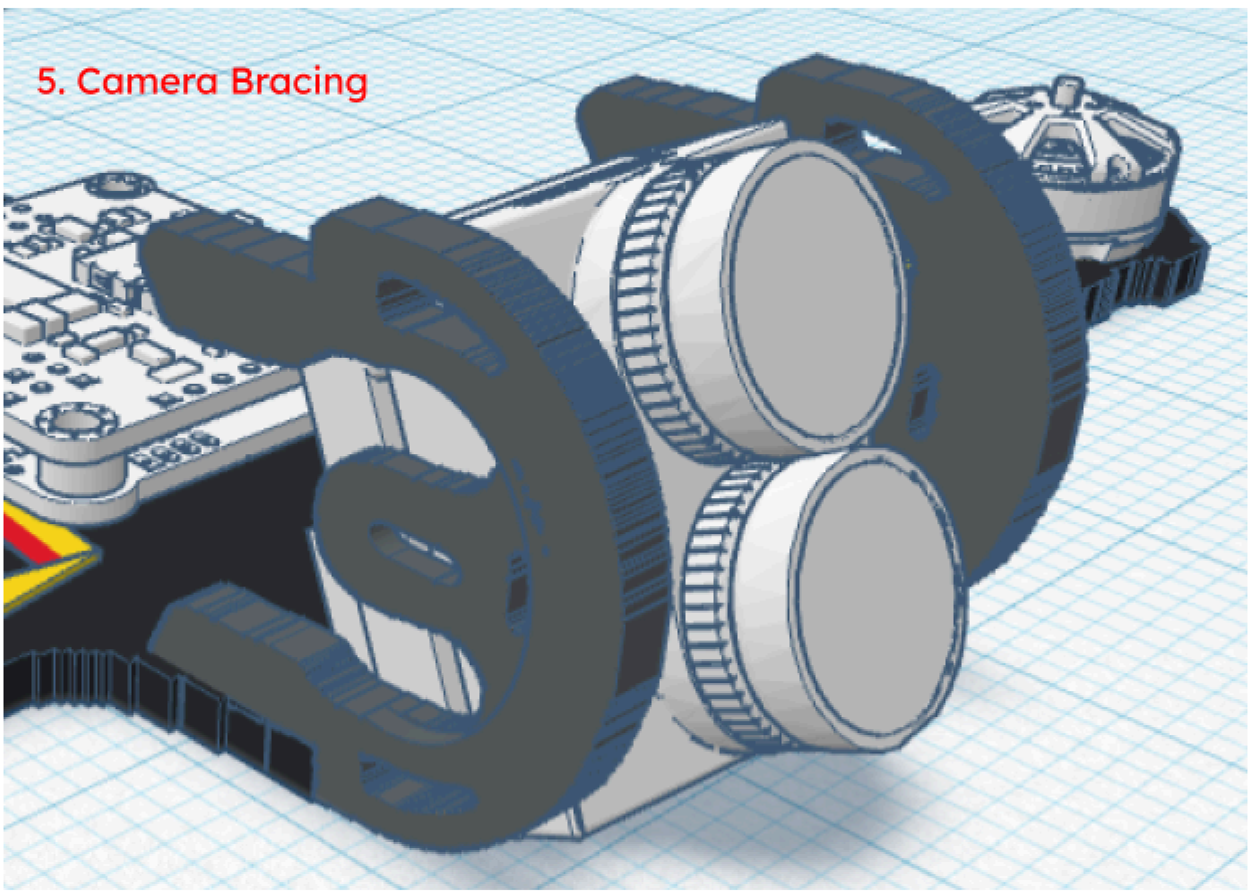
Steps to CAD:



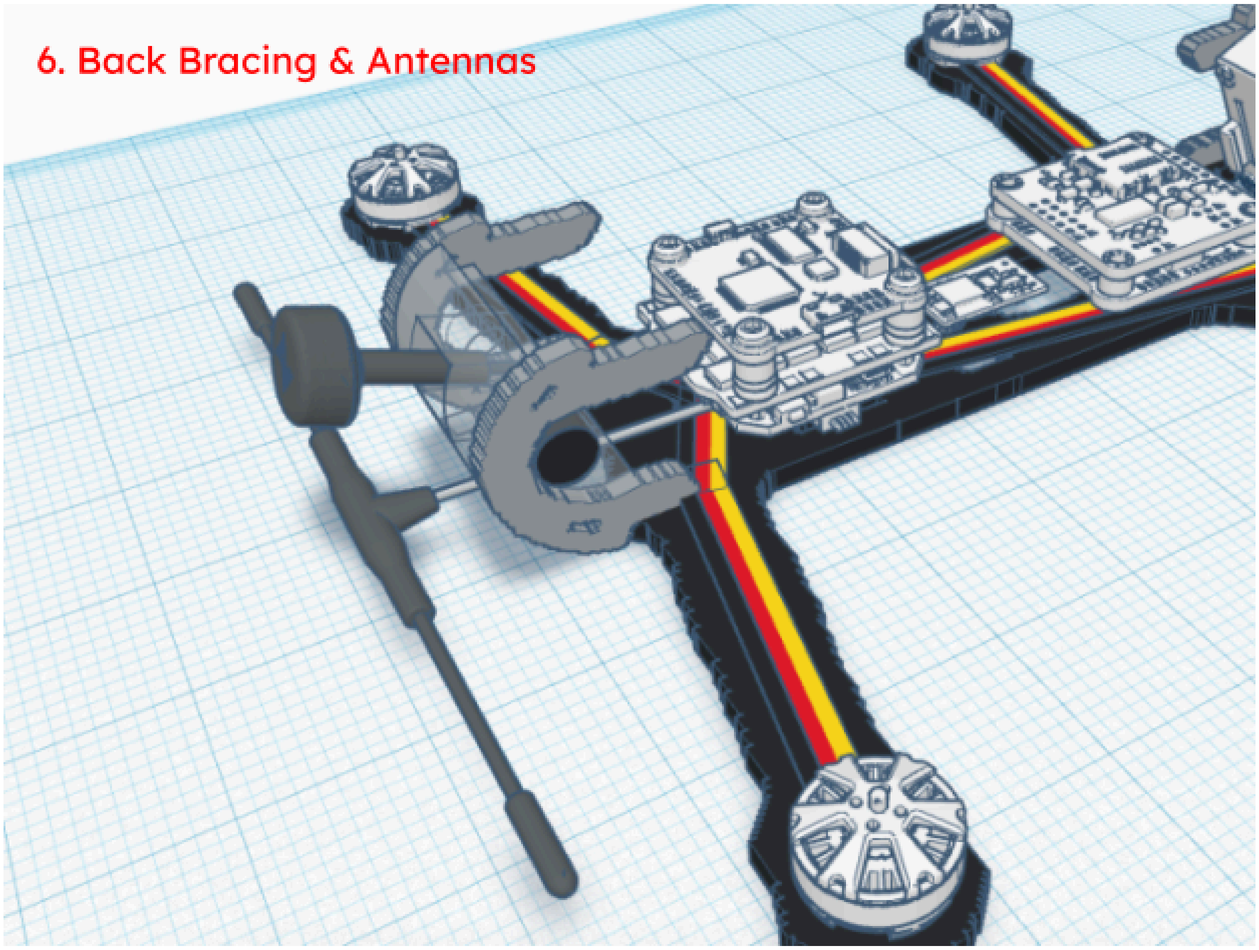

2. Motor Wires


3. PCBs

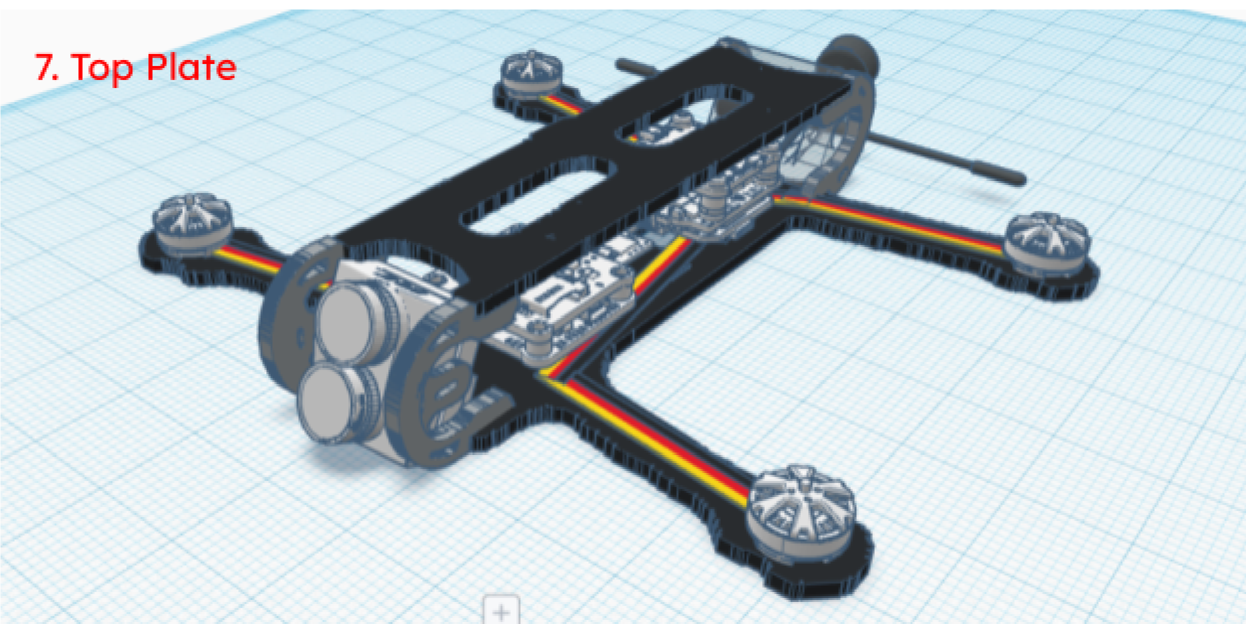

4. Camera Stack & Dual Camera

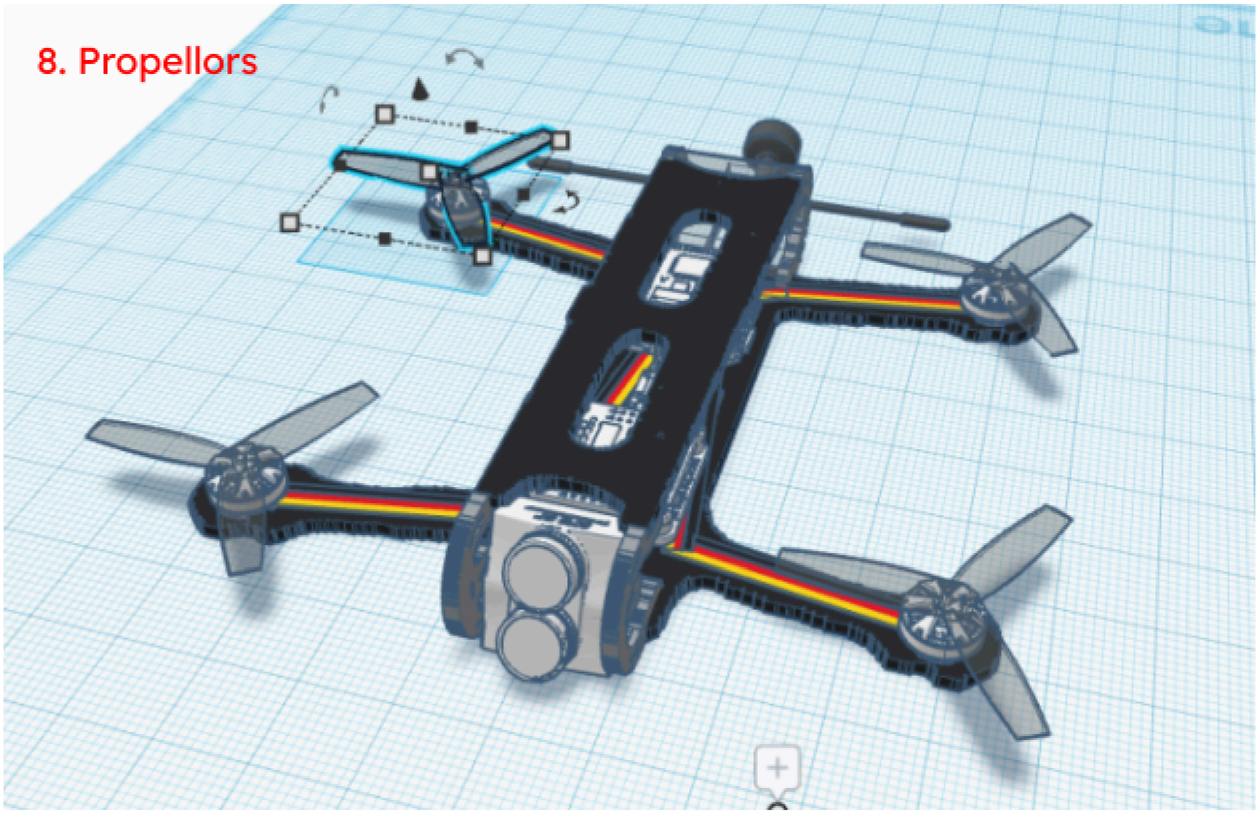

5. Camera Bracing

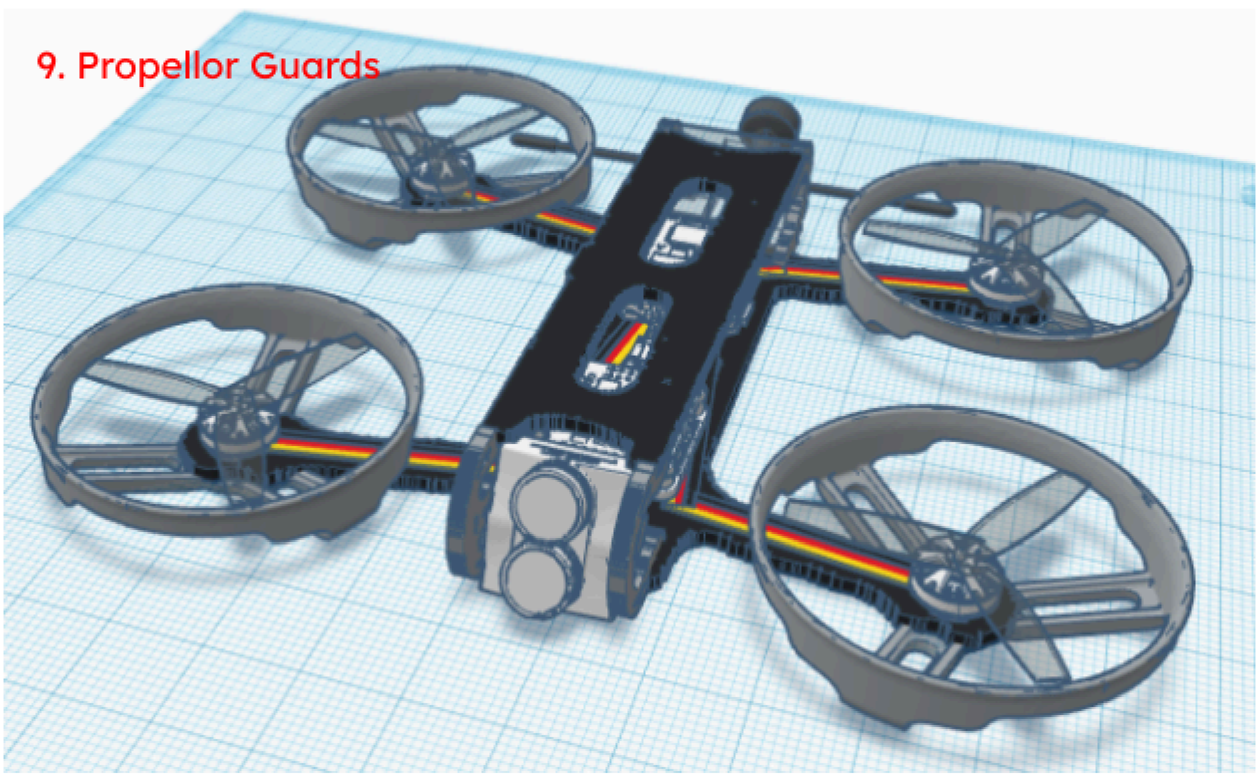
6. Back Bracing & Antennas



7. Top Plate







[CAD Model Walkthrough Link]

Our model is open-source so other students can use it to learn: TinkerCAD Live Model Link (360 viewable)

5.7 Mathematical Representation

We also attempted to derive the drone's most fundamental form: math.

① Positional

x, y, z } 3-D coords

ψ - Yaw

θ - Pitch

ϕ - Roll

Body Fixed Reference Frame:

$$W_b = \begin{bmatrix} W_{bx} \\ W_{by} \\ W_{bz} \end{bmatrix} = \begin{bmatrix} 1 & 0 & -\sin\theta \\ 0 & \cos\phi & \cos\theta\sin\phi \\ 0 & -\sin\phi & \cos\phi\cos\theta \end{bmatrix} \begin{bmatrix} \dot{\phi} \\ \dot{\theta} \\ \dot{\psi} \end{bmatrix}$$

② Velocities

$\dot{x}$, $\dot{y}$, $\dot{z}$ } translational velocity

$\dot{\phi}$, $\dot{\theta}$, $\dot{\psi}$ } angular velocity

Kinetic Energy:

$$T = \frac{1}{2}m\left((\dot{x})^2 + (\dot{y})^2 + (\dot{z})^2\right) + \frac{1}{2}\left(I_x W_{bx}^2 + I_y W_{by}^2 + I_z W_{bz}^2\right)$$

$m \rightarrow$ mass; I_x → interia on each axis

Potential Energy:

$V = mgz$ $\quad$ $V \rightarrow$ potential energy $\quad$ $g \rightarrow$ acceleration from gravity ($9.81\ m/s^2$)

Lagrangian Equation:

$L = T - V$ (tracks motion through a set of matrices)

③ $$\frac{d}{dt}\left(\frac{dL}{d\dot{q}_j}\right) - \frac{dL}{dq_j} = \Gamma_j$$ ← external forces

$$q = \{x, y, z, \phi, \theta, \psi\}$$

$$\Gamma = \begin{bmatrix} f_{ext} \\ \tau_{ext} \end{bmatrix}$$ ← net external force

$k \rightarrow$ lift constant
$b \rightarrow$ drag factor

$$\tau_{ext} = \begin{bmatrix} \tau_x \\ \tau_y \\ \tau_z \end{bmatrix} = \begin{bmatrix} \tau_\phi \\ \tau_\theta \\ \tau_\psi \end{bmatrix} = \begin{bmatrix} kl(\omega_4^2 - \omega_2^2) \\ kl(\omega_3^2 - \omega_1^2) \\ b(\omega_1^2 - \omega_2^2 + \omega_3^2 - \omega_4^2) \end{bmatrix}$$

conversion matrix (R); damping constants (A)

$$F_{ext} = R(\text{Thrust}) - \text{Drag}$$

$$= R \begin{bmatrix} 0 \\ 0 \\ k(\omega_1^2 + \omega_2^2 + \omega_3^2 + \omega_4^2) \end{bmatrix} - \begin{bmatrix} A_x V_x \\ A_y V_y \\ A_z V_z \end{bmatrix}$$

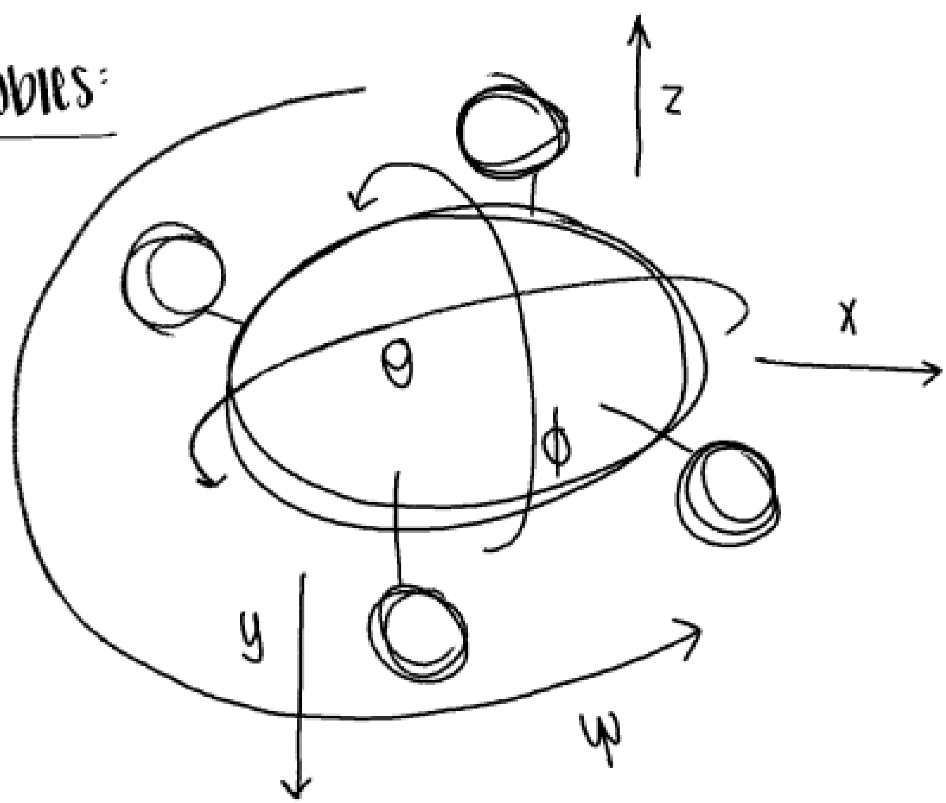
↑ R converts this world frame representation to body frame

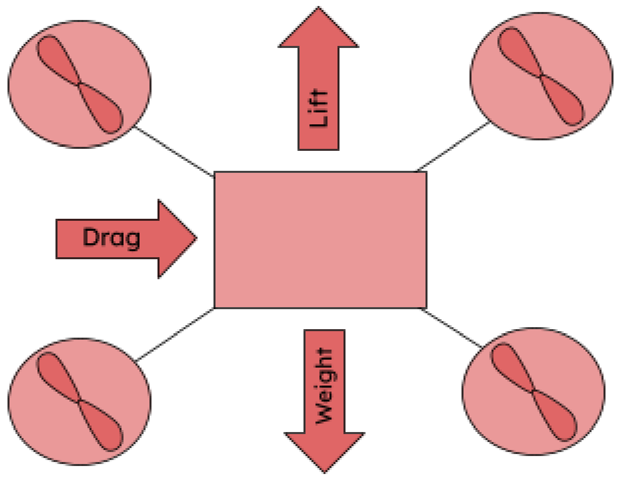
(4) simplify to $AX = B$

$$X = [\ddot{x}, \ddot{y}, \ddot{z}, \ddot{\phi}, \ddot{\theta}, \ddot{\psi}]$$

A - 6x6 linear Matrix
B - 6x1 Matrix
↓
contains:
centrifugal forces
gravity
external forces
coriolis forces
drag

Variables:





Lift:

$$F_{L_{net}} = 4T - W$$

$F_{L_{net}}$ → net lifting force
T → thrust (multiplied by 4 for each motor)
W → weight

Thrust:

$$T = C_T \cdot \rho \cdot A \cdot V^2$$

T → thrust
C_T → thrust coefficient
ρ → "rho"; density of fluid
(atmospheric density @ sea level = 1.3 kg/m³)
A → rotor disc area
V → velocity of air

Weight:

$W = F_g$ ←
(weight equals the force of gravity)

$F = ma$

$F_g = m \cdot g$

g → acceleration due to gravity

$g = 9.81\ m/s^2$ (on earth)

$F_g = 9.81m$

m → mass

Drag:

$$D = 0.5 \cdot C_D \cdot \rho \cdot V^2 \cdot SA$$

D → drag
C_D → drag coefficient
SA → surface area
V → speed of air
ρ → density of air (rho)

Weight:

$W = F_g$

$F_g = mg$

$F_g = 9.81\ \frac{m}{s^2} \cdot 140.7\ / g$

$\therefore W = .138037\ \frac{kg\ m}{s^2}$

Lift:

$F_{Lnet} = 4T - W$

$F_{Lnet} = 4(2.76\ N) - 1.38037\ \frac{kgm}{s^2}$

$\therefore F_{Lnet} = 9.65963\ N$

Thrust:

$T = C_T \cdot \rho \cdot A \cdot v^2$

A = rotor disc area

$A = \pi r^2$

r = length of propellor blade

$A = \pi (1.35\ m)^2$

$A = \pi (0.03429\ m)^2$

$2.76\ N = C_T \left(\frac{1.3\ kg}{m^3}\right)\left((0.03429)^2\ m^2\ \pi\right)\left(\frac{0.01\ m^2}{s^2}\right)$

$\therefore C_T = 0.249632255$ *approximation

Drag:

$D = 0.5 \cdot C_D \cdot \rho \cdot v^2 \cdot SA$

Surface Area (SA) rough approximate = frame

$SA = 2 \cdot (0.003m \cdot 0.18034m) + 2((0.119838)(0.08636) - (10,059.69)(0.06096)) + 2(0.11938 \cdot 0.1103))$

$\approx 0.0152193346\ m^2$

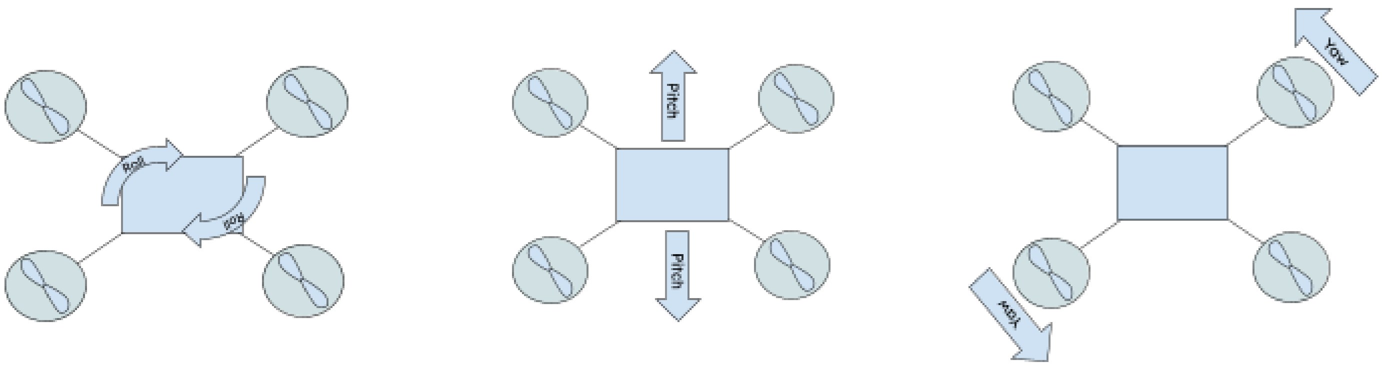
$C_D = + C_T$

$D = 0.5(0.2496322\pi)\left(\frac{1.3\ kg}{m^3}\right)\left(\frac{0.01\ m^2}{s^2}\right)(0.0152193346\ m^2)$

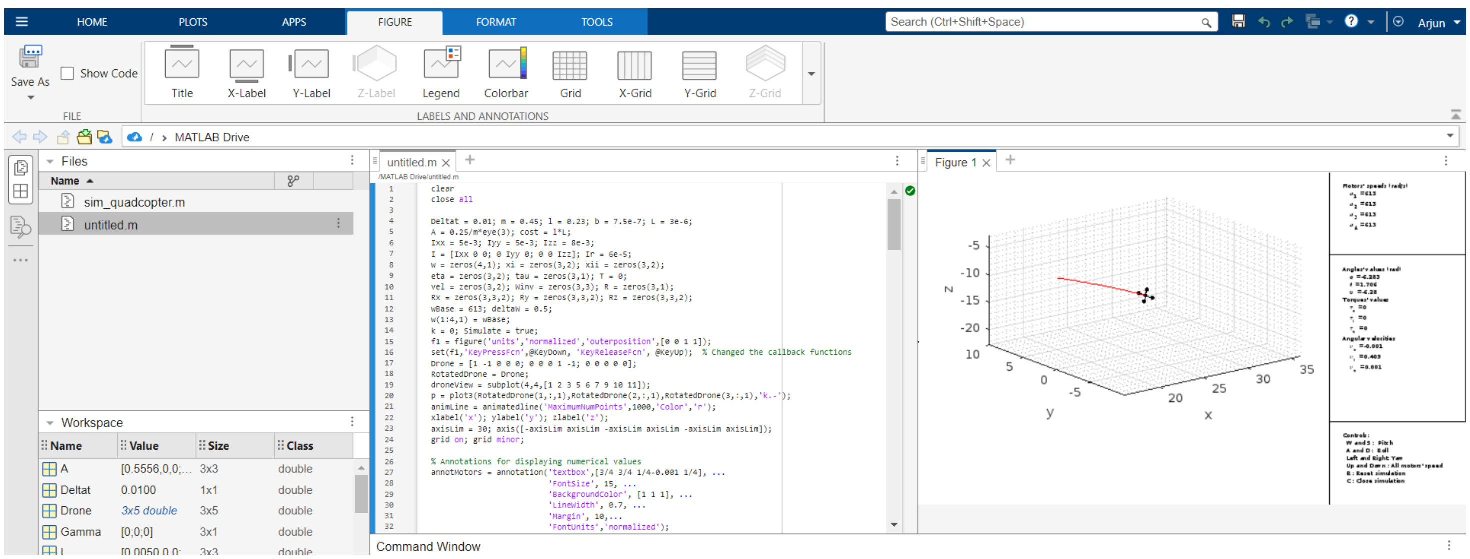
$= 2.4695 \times 10^{-5}\ N$ *approximation

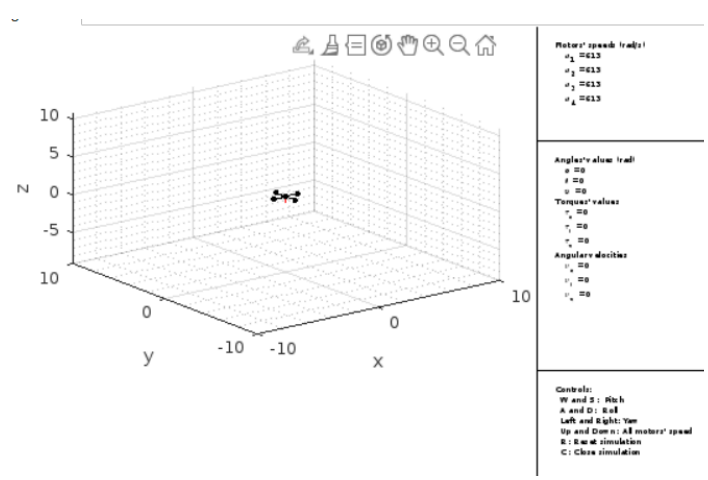
5.8 Digital Simulation

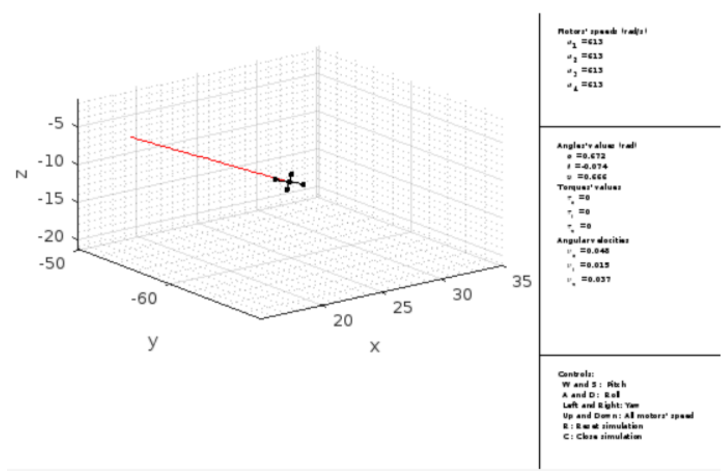
We programmed a simulation specific to our drone based on calculations in the previous section: CineQueen Quadcopter Values



[Simulation Demo Video]



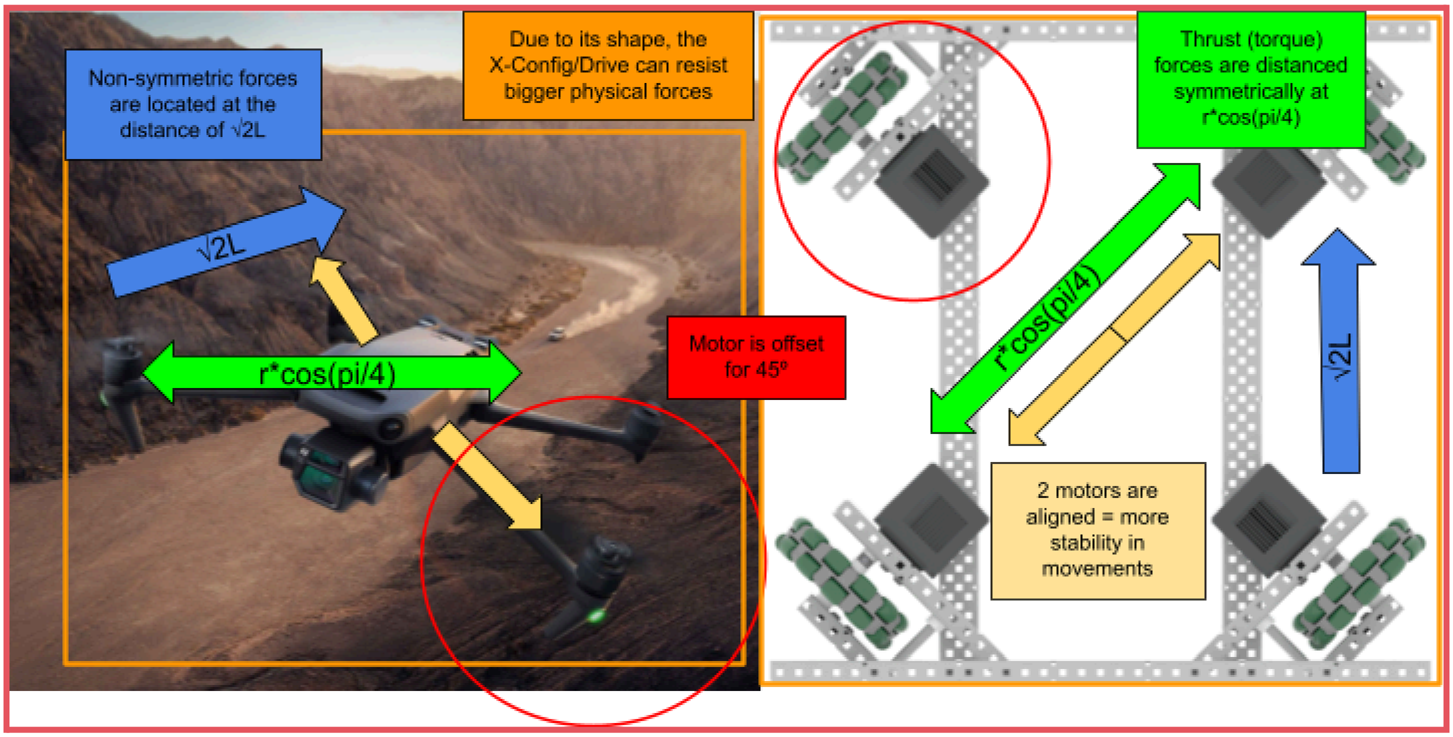




5.9 Holonomic Configuration

Quadcopters use the X-Configuration, where thrust is applied at a distance of r*cos(pi/4), using torque from all 4 motors.

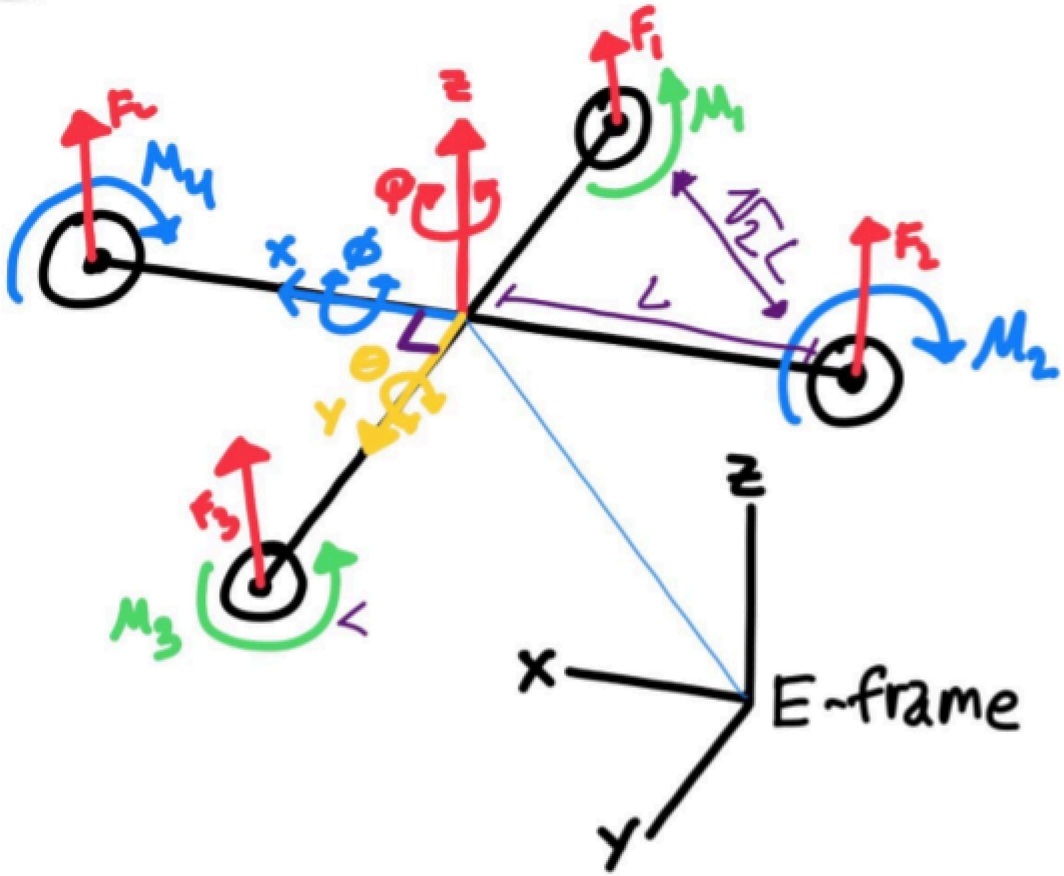
Interestingly, the popular VRC X-Drive base also demonstrates the holonomic configurations, albeit in 2 dimensions:



The algorithms to calculate movement for both configurations are below, utilizing vector arithmetic and translational/rotational kinematics.

Plus - Configuration

*Comparable to a Tank Drive

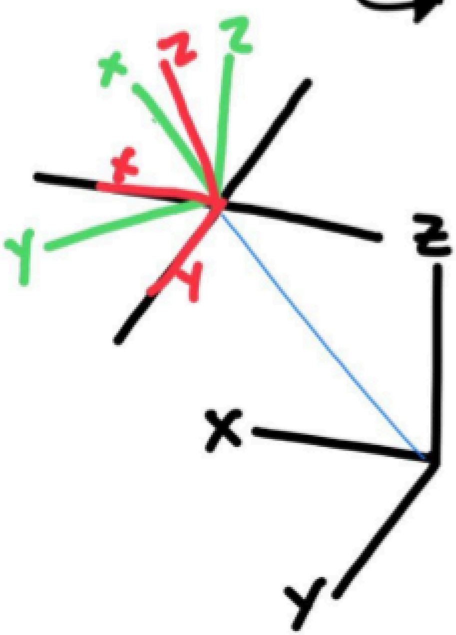


E - frame = Earth Inertial frame (fixed coordinate plane on Earth)

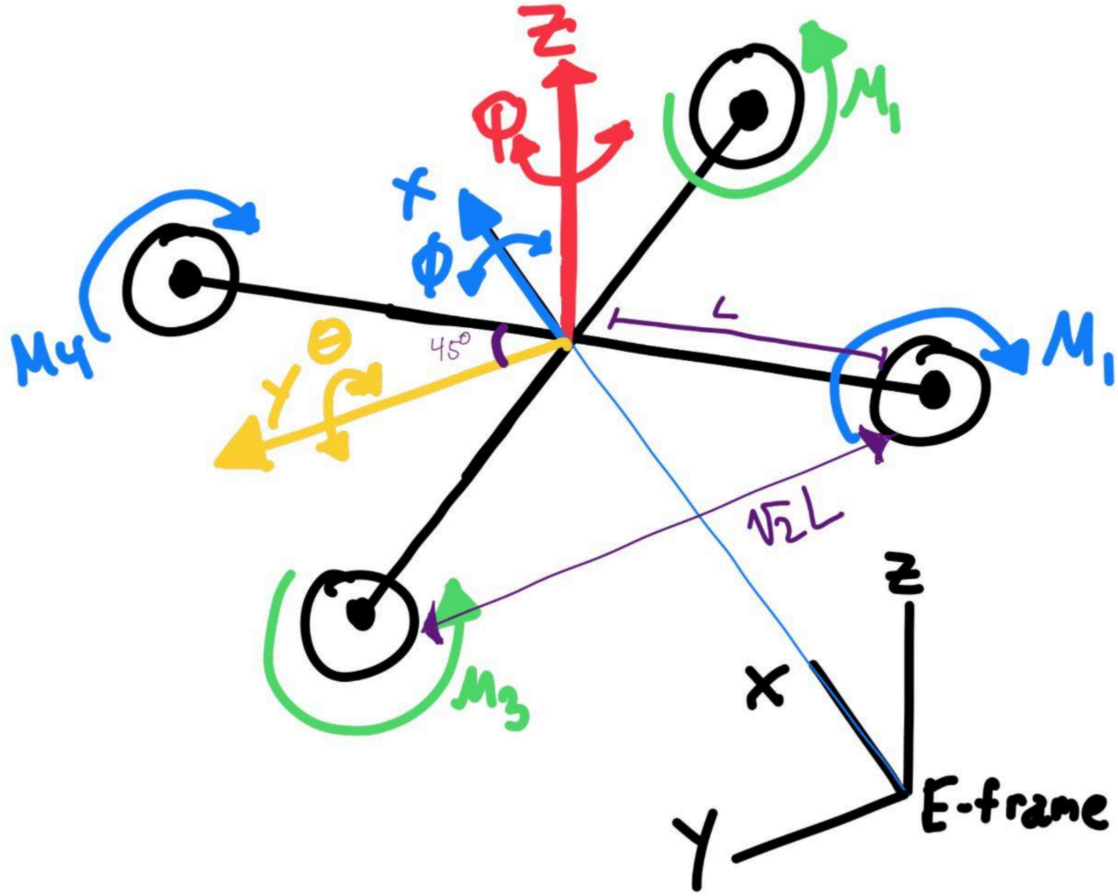
used with V-frame and B-frame

Vehicle Inertial Frame
(located on quadcopter's center of mass, in line with E-frame)

Fixed Body Frame
(initially same as V-frame, moves with Yaw-Pitch-Roll)



X-configuration



Translation motions

Newton's 2nd Law

$$F_d = K_d \cdot \dot{r}^2$$

F_d = difference between thrust force & gravity

K_d = drag force constant (dependent on outside area of quadcopter & air density)

$\dot{r}$ = time derivative of position vector

$$\ddot{r} = \begin{bmatrix} \ddot{r}_x \\ \ddot{r}_y \\ \ddot{r}_z \end{bmatrix}$$

$\ddot{r}$ = acceleration of quadcopter from E-frame

Calculating non-gravitational forces on quadcopter

$$M_B = \begin{bmatrix} M\phi \\ M\theta \\ M\varphi \end{bmatrix}$$

refer to diagrams above

M_B: mass moments on inertia relative to body frame

Moments of inertia can be calculated in terms of acceleration as:

$$m \begin{bmatrix} \ddot{r}_x \\ \ddot{r}_y \\ \ddot{r}_z \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ -mg \end{bmatrix} + R_v^b \begin{bmatrix} 0 \\ 0 \\ F_{th} \end{bmatrix} - F_d$$

$-mg$ → force of gravity

F_{th} → total thrust in z-axis

R_v^b → rotational matrix

→ Note: calculation is done assuming drone is in a steady-state condition (force on x and y axis is negligible)

If the mass of both the X-configuration and +-configuration drones are the same, as well as the amount of rotation and the total thrust, the only factor that sets the two configurations apart is the difference between total thrust force and gravity (F_d).

F_d can be calculated with the equation above ($F_d = K_d \cdot \dot{r}^2$). If the time derivative of position vector is equal for both configurations, the difference in the configurations lies in the drag force (K_d).

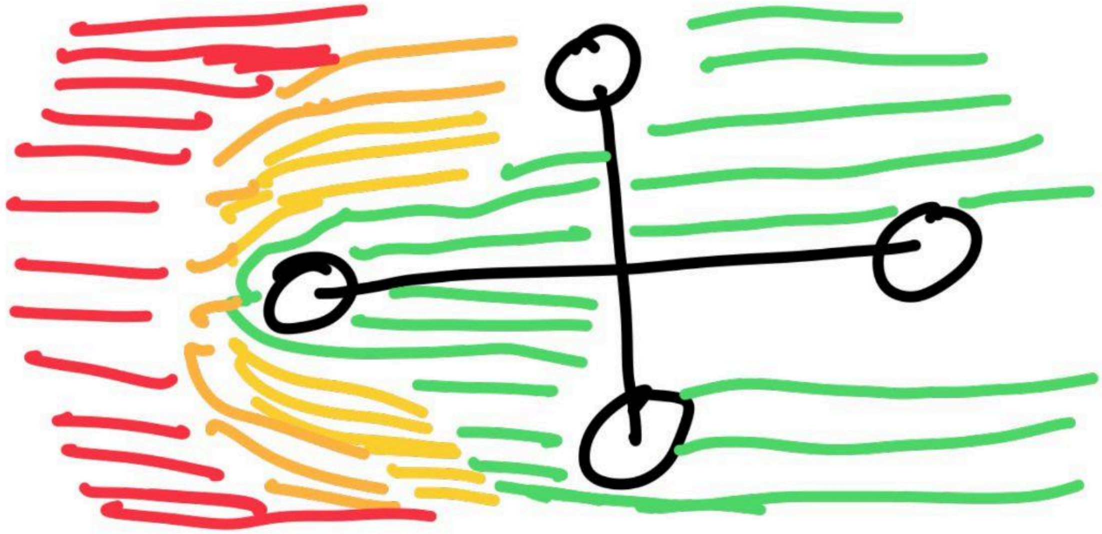
$$K_d = \frac{1}{2} \rho C_D A$$

- C_D → aerodynamic drag coefficient
- A → effective area
- ρ → air density (constant)

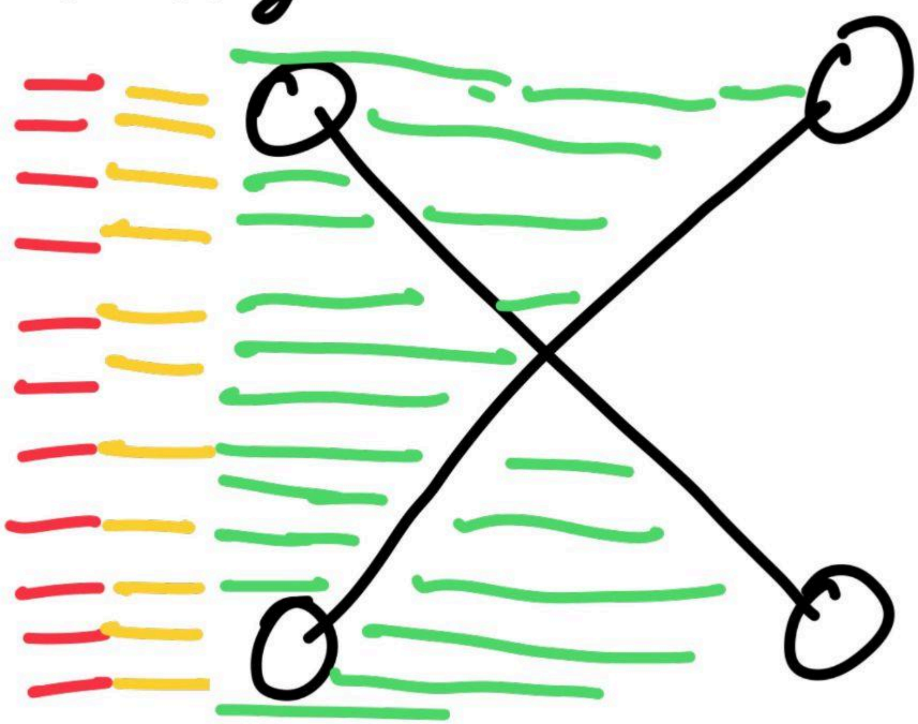
∴ effective area is the primary factor in the difference in maneuverability of the two configurations

The air flow diagram below shows that the X-configuration is optimal for maneuverability as less airflow comes in contact with the frame, decreasing drag force.

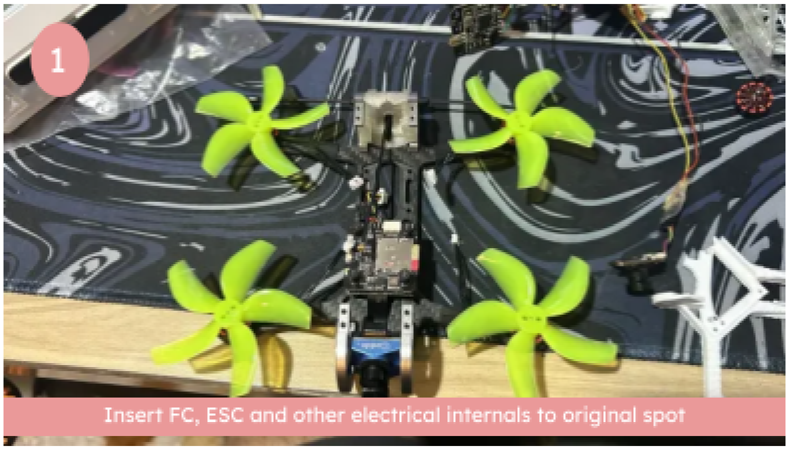
plus-configuration



X-configuration

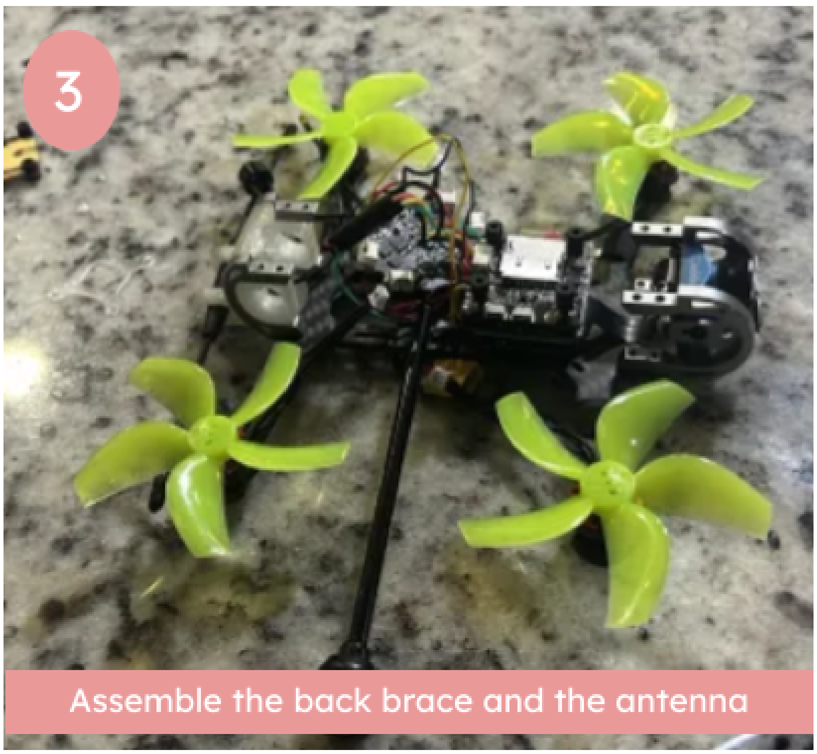


6. Reconstruction

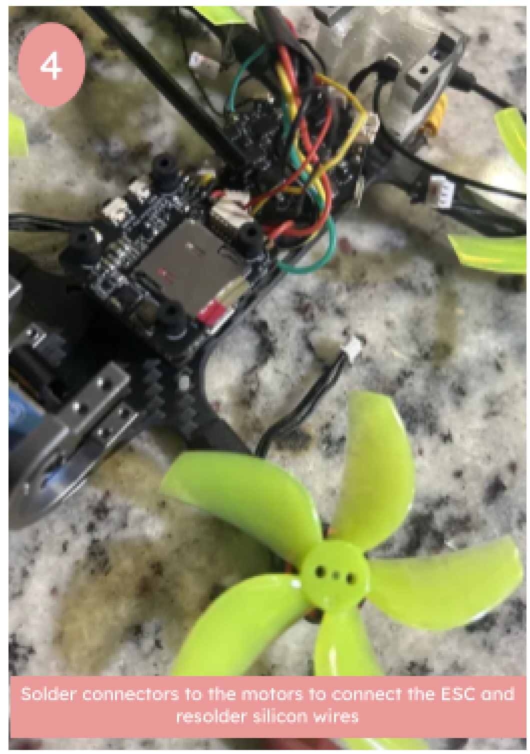


Insert FC, ESC and other electrical internals to original spot

Solder Camera PCB and ESC to secure into place



Assemble the back brace and the antenna



Solder connectors to the motors to connect the ESC and resolder silicon wires

5

Cut off motor wire and connect it to the camera stack at the back of the drone

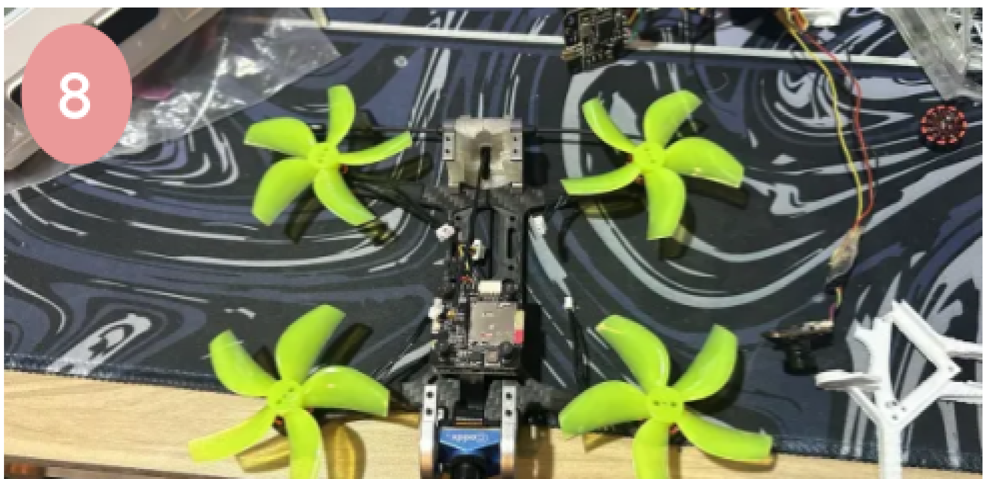
6

Put electrical tape over wires

7

Solder in the receiver

8



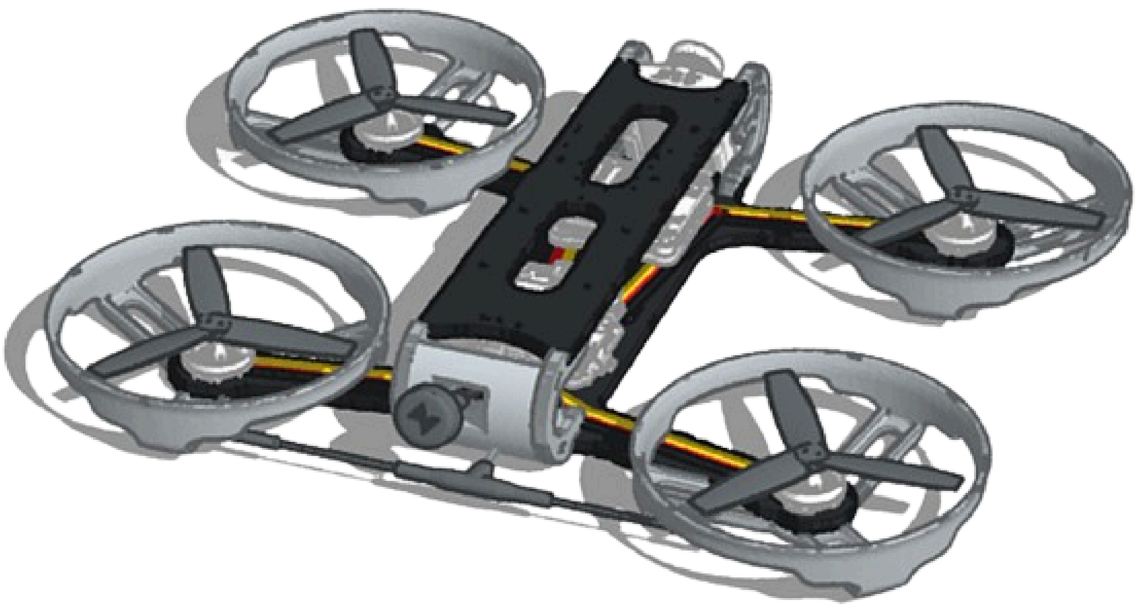
Add in the plate and battery

6.1 Back in the Air

After hours of effort, we successfully reconstructed the drone and restored video transmission.

Final Flight Test Video

7. Conclusion



One takeaway we gained from this project is that even a machine as small as a drone is incredibly complex. By looking at the data sheets, we learned that each component is carefully designed by huge teams of engineers and countless hours of work and rigorous documentation. It’s truly astonishing how machines with components from hundreds of companies are able to seamlessly operate. It expanded our insight on the standard of quality that engineering demands, and only solidified our excitement and awe of the field.

This project provided a unique chance to move beyond our typical VEX environment and apply our skills to a real-world scenario. We studied a commercial FPV drone by researching its deconstructed parts and delving into electrical engineering, math and physics behind its functions. We condensed this information into comprehensive diagrams, CADs, and simulations which demonstrated how the subcomponents work together. Our analysis revealed vulnerabilities within such FPV drones, exposing the dangers of misusing technology in warfare.

Our journey working on this project over the past several months only reinforced our commitment to engineering as a force of good and taking a stand against the harmful misuse of technology.

> *"I sincerely hope nobody else experiences the suffering that the war brings, which me and millions of other Ukrainians are, sadly, going through right now…"*
>
> \- Klymentti Zhyliaiev

7.1 Skills Learned

[What We Learned Video]

While working on this project, we overcame challenges and gained valuable skills along the way, listed here.

Skills Developed and Topics Learned

- **Soldering**
  - Used to replacing the broken ESC in the drone with a new one
  - Learned to create conductive connections between components and PCBs
- **CAD Modeling**
  - Modeled each component of the drone using Tinkercad to have a visual model to refer to once drone was reconstructed
- **3D Simulations**
  - Learned complex programming techniques to partially recreate a simulation to represent quadcopter flight dynamics
  - Gained ability to replicate drones (and other aircrafts) digitally in 3-Space (x, y, z)
    - Applied math to a practical demonstration
  - Able to study drone forces without interference from environmental variables (discussed below in Physics of Flight)
- **Designing Diagrams**
  - Created through tools like Google Drawing to model different components of each component

8. All References linked on doc