EE344 : ELECTRONIC DESIGN LAB

WINDOW CLEANING DRONE

TEAM ID : MON-13

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CHALLENGES IN CLEANING HIGH-RISE WINDOWS

- **Manual Effort and Risks**: Cleaning windows of high-rise buildings is labor-intensive and involves significant safety risks for workers
- **Inefficiency**: Traditional methods are time-consuming and require specialized equipment like scaffolding or suspended platforms
- **High Costs**: Employing skilled labor and safety measures increases operational expenses for building maintenance.
- **Environmental Challenges**: Cleaning in adverse weather conditions or accessing hard-to-reach windows poses additional difficulties.

PROPOSED SOLUTION

A specially designed hexacopter drone equipped with a sprayer and a continuous water supply.

MILESTONE 2

FEEDBACK FROM MILESTONE 1

1. Calculations about power, thrust should be accurate. We have addressed that by performing exhaustive calculations and analysis about all parameters which we will demonstrate in upcoming slides
2. Plan a minimum deliverable, which now we have decided to keep a fully functional flying drone with a spraying mechanism and a detailed report of calculations,simulations and software stack as a minimum deliverable
3. Have a more defined project plan, which now we have structured in a better way which we will demonstrate in updated gantt chart

DISCUSSIONS WITH PROF. SIDDHARTH TALLUR AND ANKUR SIR

Our discussions with Prof. Tallur gave us the following insights which we hope to address and incorporate in our project:

1. The battery operated drone gives a **very small flight** time and is not effectively serving the purpose of the drone. We should look into alternate modes of power supply like tethered connections which power the drone using an **SMPS** (Explained in detail later). This greatly reduces the cleaning efficiency of the drone
2. Our thrust and power calculations were assuming a flow rate of **3.5L/min**. This is a very high rate of water flow and we can achieve adequate cleaning results at much lower rates of water flow by using more **water-efficient spraying mechanisms.**

PROJECT DOCUMENTATION

Calculations and analysis

A detailed **latex report** containing all the exhaustive calculations and analysis is posted on OneNote Notebook and a brief summary is presented in this presentation as well

Simulations and results

Simulations of the drone and its spraying mechanism are conducted in Gazebo, with the setup and results summarized in this presentation. The video is also posted on OneNote.

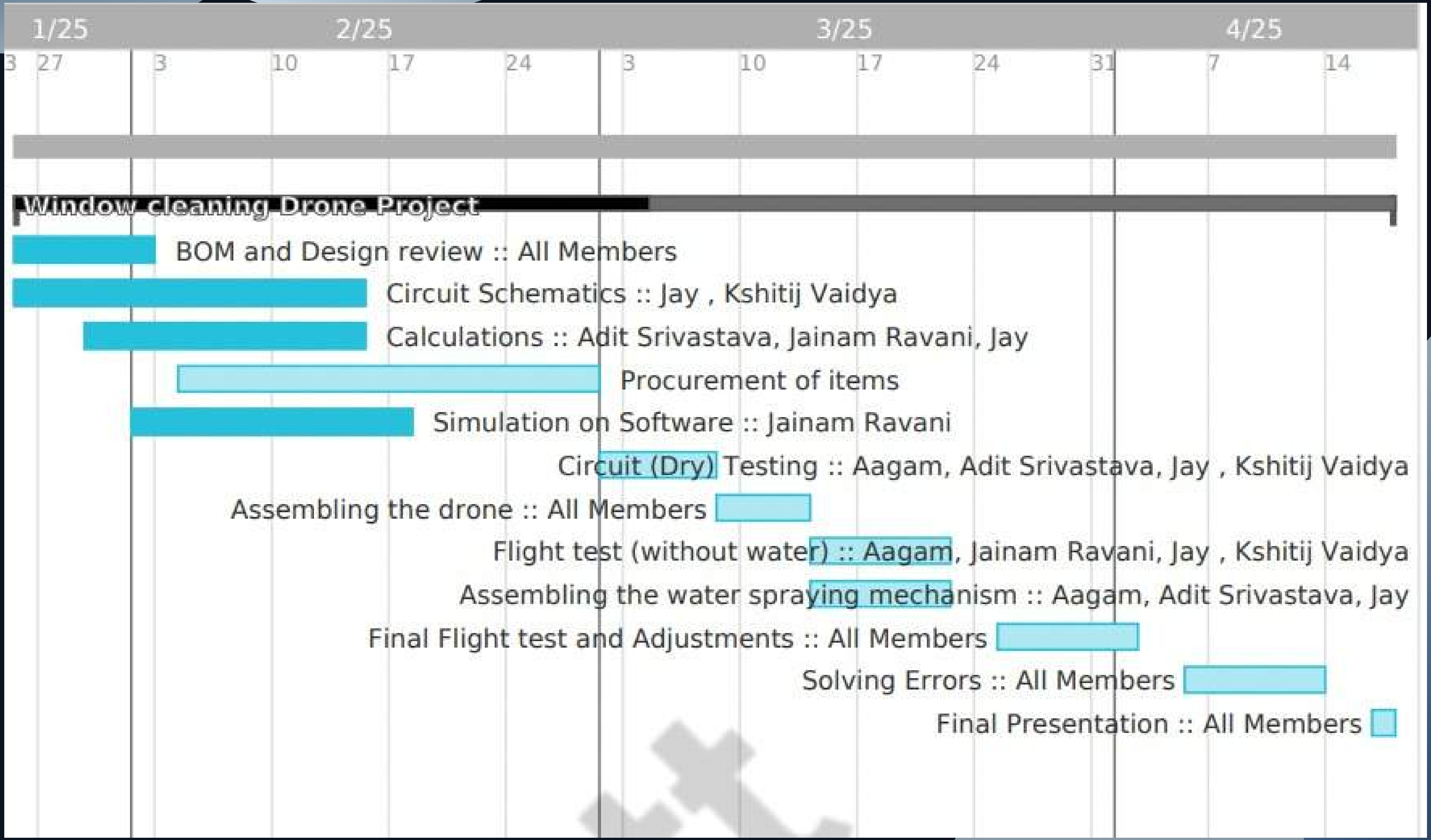
Schematics

Documents containing detailed circuit and wiring diagrams of various circuit components and whole system have been demonstrated in this presentation and is also posted on Onenote

Software Architecture

The PX4 autopilot codes have been compiled in a **GitHub repository**, and a detailed **report** explaining the software stack is available on OneNote.

UPDATED GANTT CHART



POWER & MECHANICAL

THRUST AND PUMPING ANALYSIS

OBJECTIVE

Ensure sufficient thrust for stable flight while carrying water and counteracting spray forces

Optimize pumping mechanism for efficient water delivery

KEY CHALLENGES

1. Lifting drone weight + water column in hose
2. Managing recoil force from water spray
3. Ensuring power efficiency for extended flight

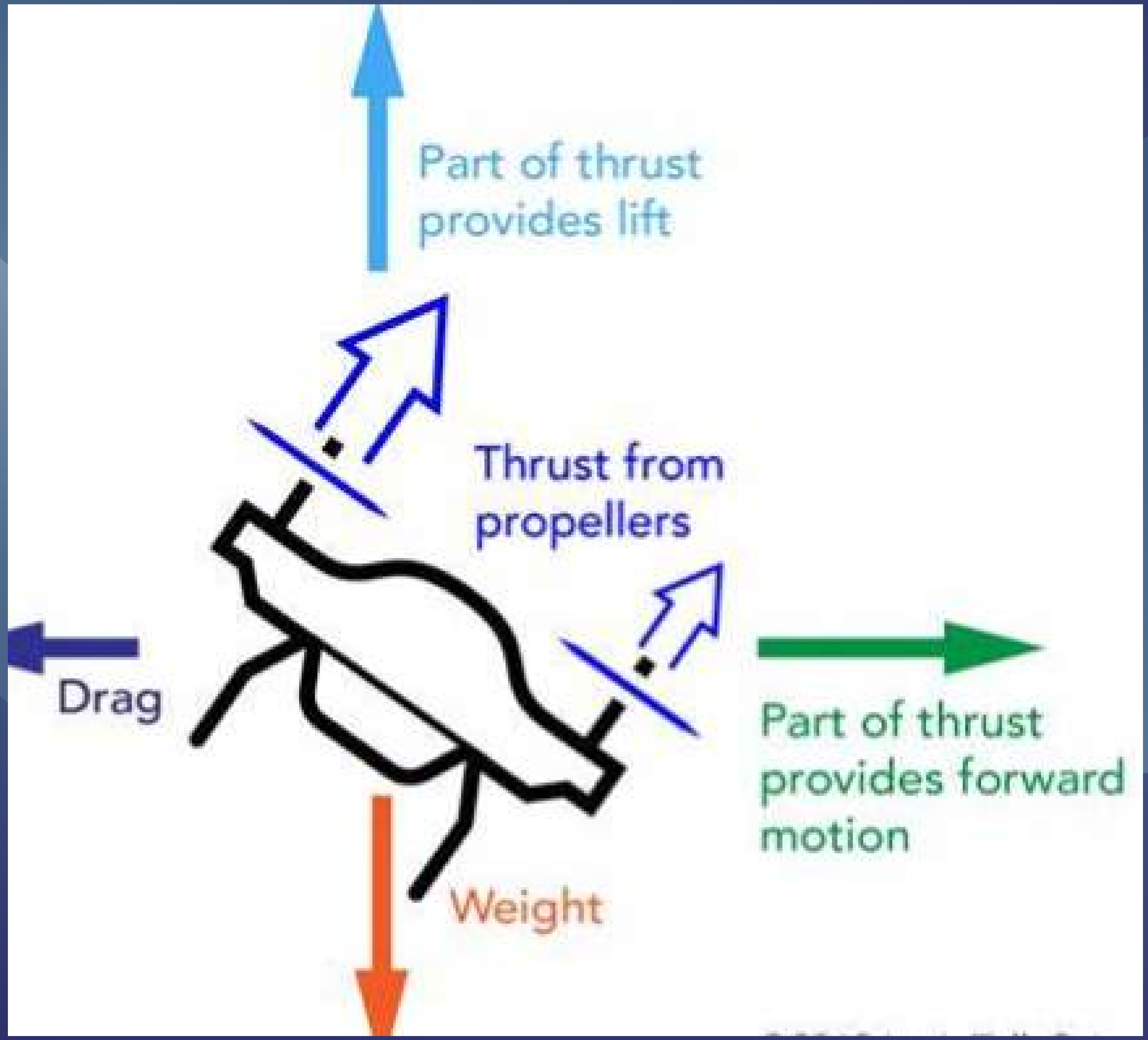
PAYLOAD AND THRUST ESTIMATION

Key Components in terms of weight:

- Chassis - 720g
- Water Column - 712g
- Battery - 260g
- BLDC Motors - 25*6 = 150g
- 12V DC Motor - 50g

Total Payload = 2.385 kg

Total Thrust required = 23.4N
Thrust per Motor = 3.9N



RPM ESTIMATION

The relation between Thrust, RPM, Pitch and Diameter of a Propeller is given by:

$$\text{Thrust} = 4.392 * 10^{-8} * \text{RPM} * \frac{d^{3.5}}{\sqrt{\text{pitch}}} * (4.233 * 10^{-4} * \text{RPM} * \text{pitch} - V_0)$$

For our propellers: Pitch = 4.7 inches

Diameter = 9 inches

RPM Required = 6652 RPM

MOTOR POWER ESTIMATION

1 *Using KV Rating of Motors*

KV Rating for a Motor is defined as the Voltage required per 1000 RPM of Motor Speed.

For 6652 RPM, Voltage required = 6.652V
Average Current drawn = 7A

Power Drawn = 46.5 W

MOTOR POWER ESTIMATION

2 *Using Datasheet of Motors*

The datasheet suggests a RPM of 6600 RPM for 9x5 Propellers requires:

- 6.7A at 7.9V

Power Drawn = 52 W

We will be using this value for further analysis

Total Power drawn = 52*6 = 312 W

TOTAL POWER ESTIMATION

The Power for each component is as follows:

1. BLDC Motors = 312 W
2. PixHawk + RPi = 15 W
3. Telemetry Module = 1 W
4. NoIR Camera = 2 W
5. 12V DC Motor = 24 W
6. Servo Motor = 2 W

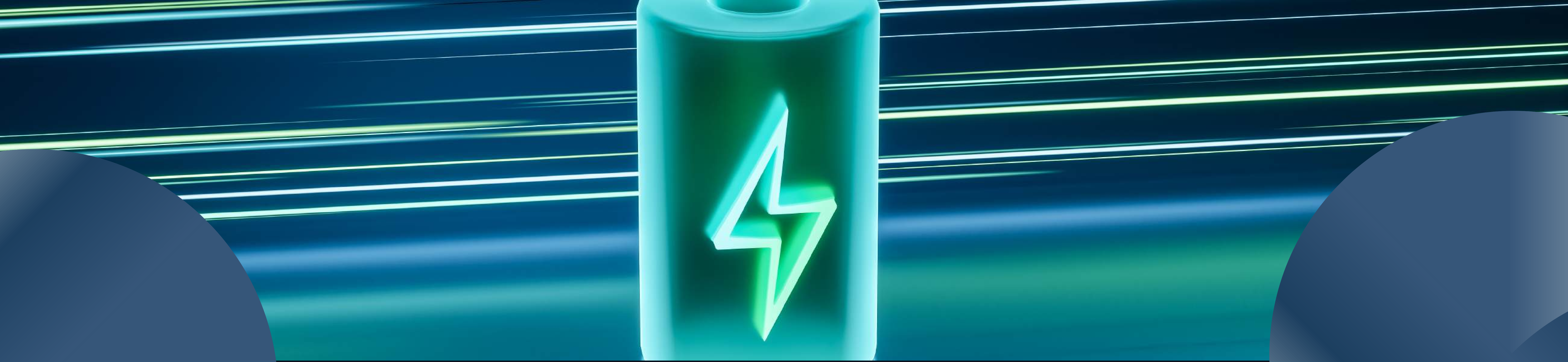
Total Power = 356 W

TOTAL POWER ESTIMATION

$$\text{Battery Life} = \frac{\text{Battery Capacity} * \text{Voltage}}{\text{Total Power}} \times \frac{60}{1000}$$

- Battery Capacity = 3300 mAh
- Voltage = 14.8 V (4S Battery)

Battery Life = 8.23 mins



BATTERY LIFE VS PERFORMANCE TRADE-OFF

The drone's 8.23-minute battery life is sufficient for demonstrations, but extending it poses challenges. A higher capacity battery increases weight, reducing the thrust-to-weight ratio, while better motors and propellers raise power consumption. Achieving the required 4-hour battery life is impractical for this size, as a larger drone would significantly increase costs. A tethered power supply removes battery constraints but limits range, adds complexity, and poses safety risks. Thus, a trade-off is necessary between battery life, performance, and feasibility.

ALTERNATE POWER SUPPLY: SMPS

We have also planned for an alternate method for powering the drone to improve the flight time of the drone and also eliminate the need for rechargeable onboard batteries

SMPS is an AC-DC Power Source that operates at a high efficiency and with minimal heat dissipation.

A Switching Mode Power Supply stationed on the ground can be used to power the drone via a tethered connection. This improves the flight time because of a continuous power supply for the drone

UHP-750-12

- The SMPS selected for this method is UHP-750-12 by Meanwell.

Power Rating	**750 W**
Voltage	12 V
Current Rating	62.5 A

- These specifications cover the steady state and the take off operation.

PROBLEMS WITH SMPS

SAFETY HAZARD

Using an SMPS and the tethered connection adds the potential risk of a hanging cable carrying a high current thus the flight operations of the drone need to be as stable as possible.

INCREASE IN PAYLOAD

Also, the wire adds a significant weight to the drone increasing the payload requirements of the drone and the onboard motors.

WATER SUPPLY MECHANISMS

- Our initial proposal was to supply water using a ground-stationed motor that would pump water up to the drone at a constant rate. This ensures a continuous and high rate of water supply to the drone.

- Upon further discussion, the water flow rate and motor specifications decided by us were more than the requirements of the projects and so we have to look into alternate options with lesser water supply capacities.

ON-BOARD TANK

Proposal

Small 0.5-1L On-board Tank

- The tank can be refilled as and when required.
- For this to be a viable solution, however, the spraying and cleaning mechanisms used by the drone must be very efficient in their water usage to ensure that the water capacity of the drone is not a limiting factor in effective and consistent cleaning results.

POSSIBLE COMPLICATIONS

- Using a tank removes the hazard of adding a water pipe and also eliminates the need for a ground-stationed motor. This however adds a payload of the tank weight and the water in holds on the drone. Thus the capacity of the tank must be chosen appropriately to ensure that it does not add excessive thrust strain on the motors while allowing for an appropriate quantity of water to clean the surfaces properly.
- Adding a water tank also requires careful consideration of the centre of gravity of the drone and carefully managing the weight distribution of the drone to ensure that it can operate stably. We can also have multiple tanks and a simple fitting mechanism that makes the refilling and replacement of the water tank faster to improve the overall efficiency of the drone.

MAX THRUST ANALYSIS

Max RPM from datasheet

9660 RPM

Corresponding max thrust per motor

8.225 N

Max Total Thrust

49.35 N

Thrust to weight ratio

2.11

HORIZONTAL THRUST ESTIMATION

- 12V DC Motor can provide a maximum pressure of 4.8 bar
- We assume pressure difference of 2 bar since we don't want the motor to run at maximum capacity at all times

$$\text{Exit velocity} = \sqrt{\frac{2 * \Delta P}{\text{Density}}}$$

- Using the above formula, we get Exit Velocity around 20 m/s
- Horizontal Thrust = Mass Flow x Exit Velocity

Horizontal Thrust = 1.166 N

GROUND PUMP ANALYSIS

Upward Pressure required for 15m height including friction

2-3 bar

Ground Pump Power Needed

250-300 W

Mass Flow

0.0583 kg/s

Area of pipe

71.26 mm^2

Velocity

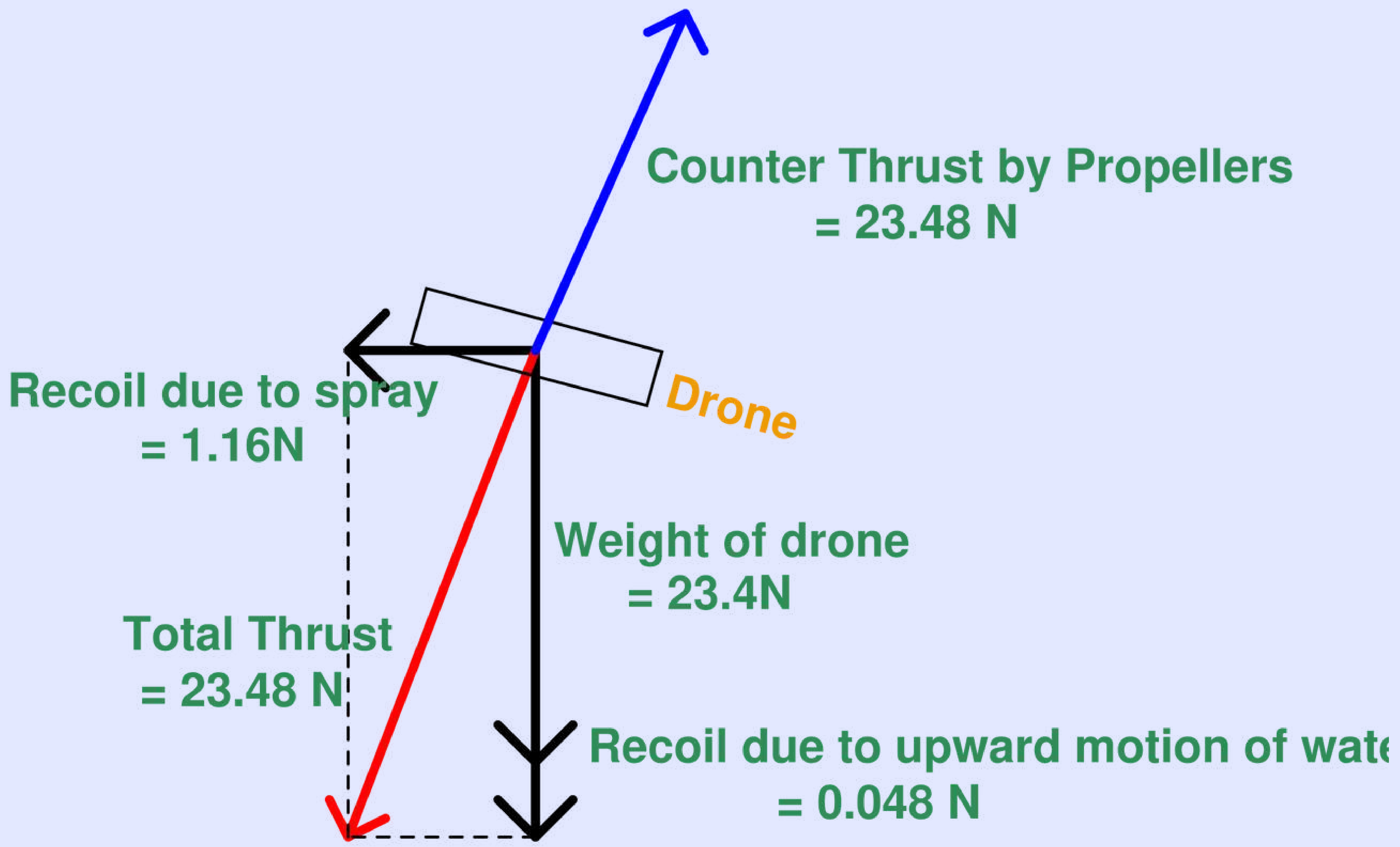
0.818 m/s

Upward Thurst Required = Mass Flow* Velocity

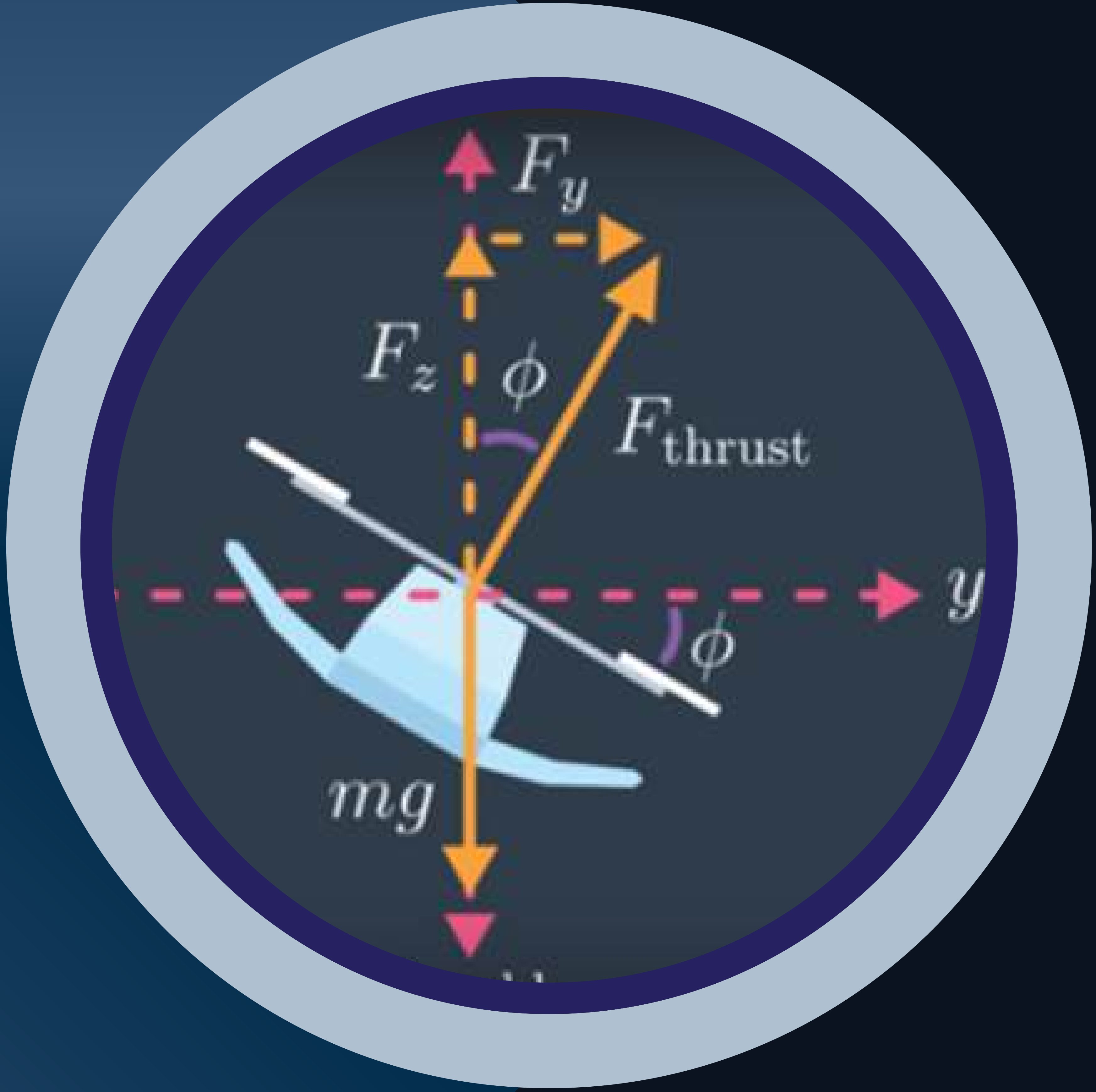
0.0477 N

VECTOR DIAGRAM OF ALL THRUSTS

- The calculated tilt angle of the drone is 2.38 degrees. This angle is well within achievable limits for the drone.
- The tilt is needed to counter the horizontal thrust.



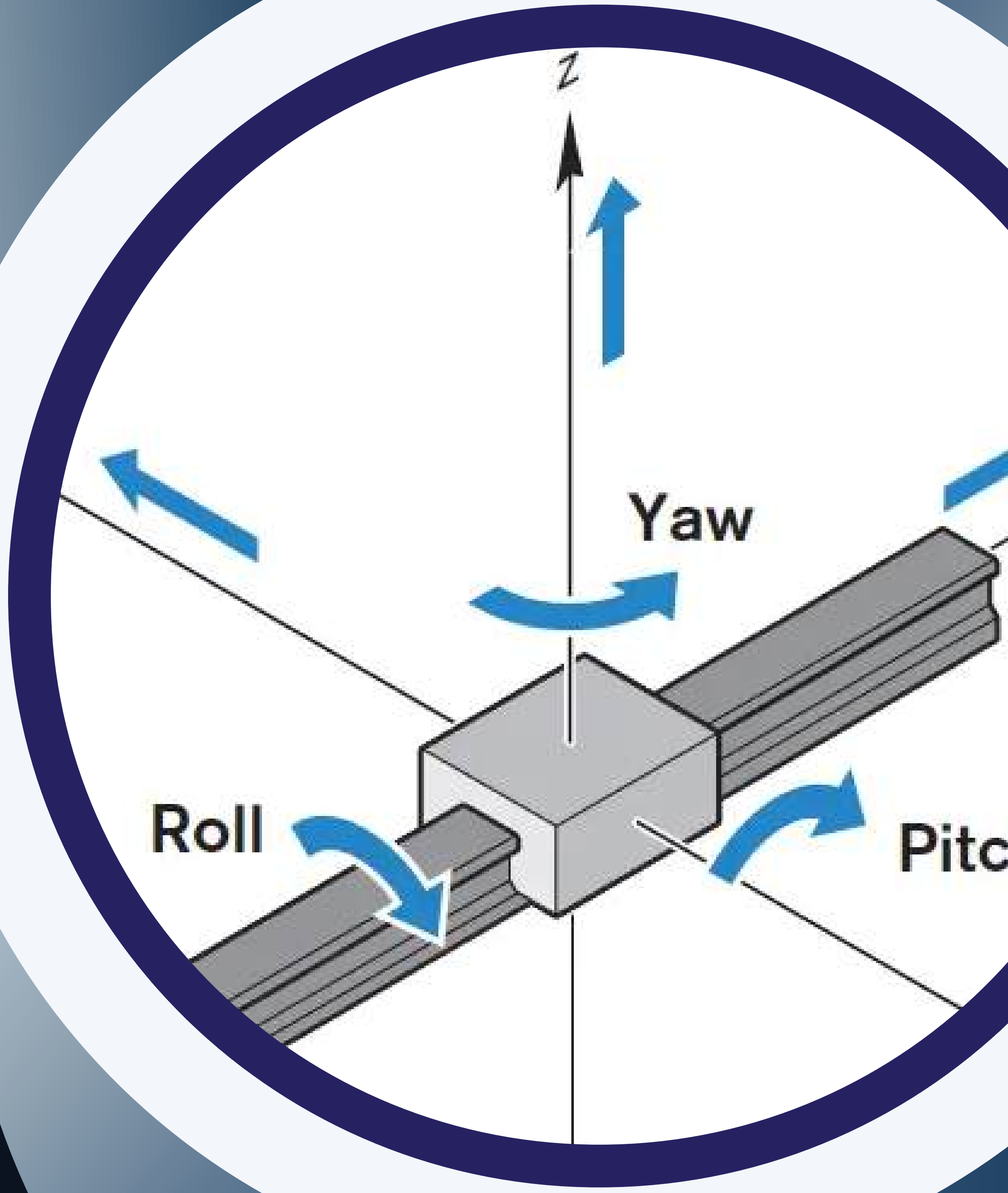
VEHICULAR DYNAMICS



HEX-ROTOR DYNAMICS

SOME NOTATIONS:

- World (inertial) frame, {W} : $\{x_W, y_W, z_W\}$
- Body frame, {B}: $\{x_B, y_B, z_B\}$
- COM position in {W}: $r = [x, y, z]^T$
- Roll-Pitch-Yaw in {B}: (ϕ, θ, ψ)
- Angular rates in {B}: (p, q, r)

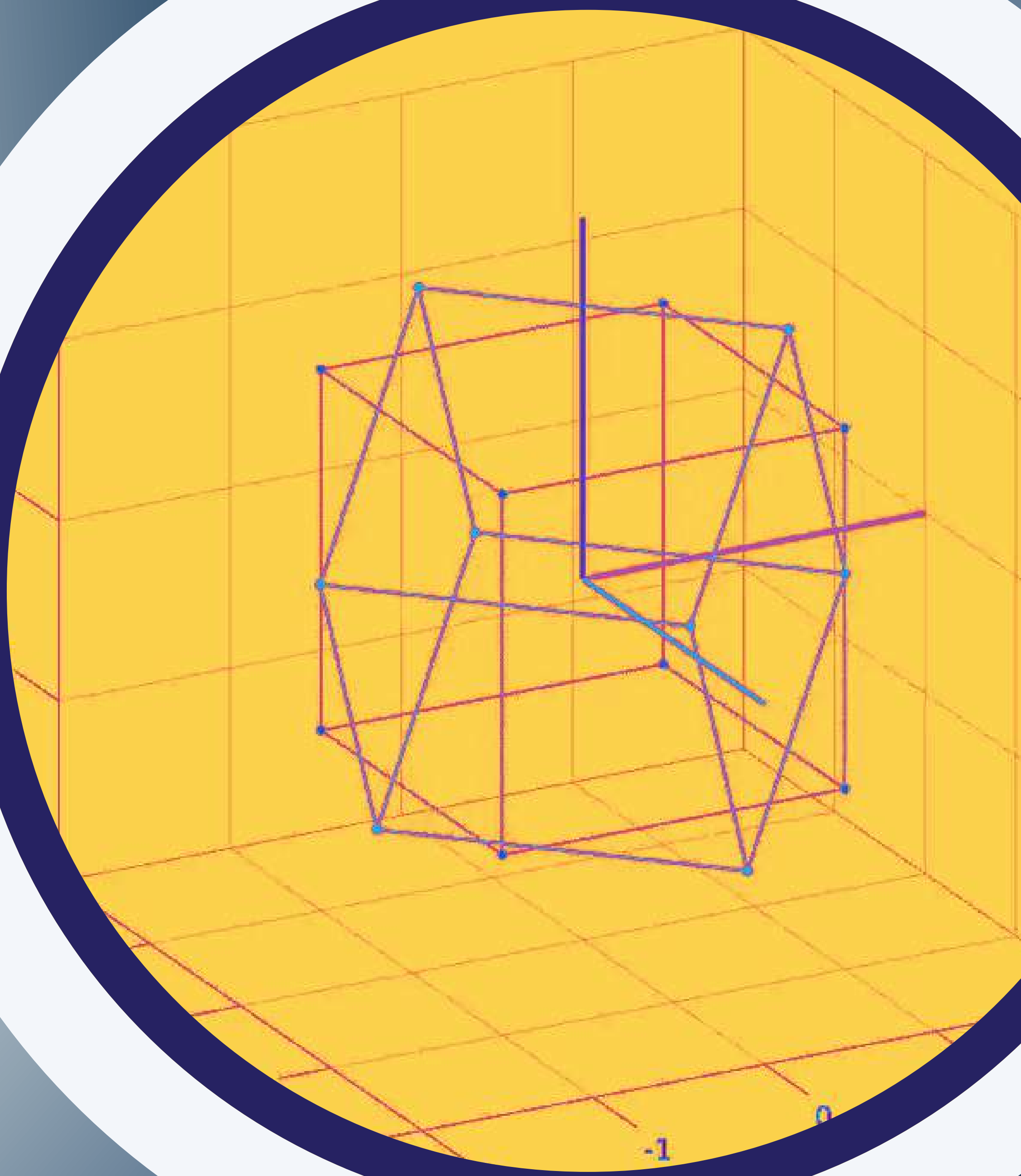


ROTATION MATRIX AND EULER ANGLES

{B} to {W}

$$R(\phi,\theta,\psi) = \begin{bmatrix} c\psi\, c\theta - s\phi\, s\psi\, s\theta & -c\phi\, s\psi & c\psi\, s\theta + c\theta\, s\phi\, s\psi \\ c\theta\, s\psi + c\psi\, s\phi\, s\theta & c\phi\, c\psi & s\psi\, s\theta - c\psi\, c\theta\, s\phi \\ -c\phi\, s\theta & s\phi & c\phi\, c\theta \end{bmatrix}$$

$$c\alpha = cos\alpha \qquad s\alpha = sin\alpha$$



TRANSLATIONAL DYNAMICS

$$\mathbf{T}_b = \begin{bmatrix} 0 \\ 0 \\ \sum_{i=1}^{6} F_i \end{bmatrix} \quad \text{(in the body frame)}$$

$$F_i = \text{Thrust from rotor i,each towards} + z_B$$

Including gravity, we get:

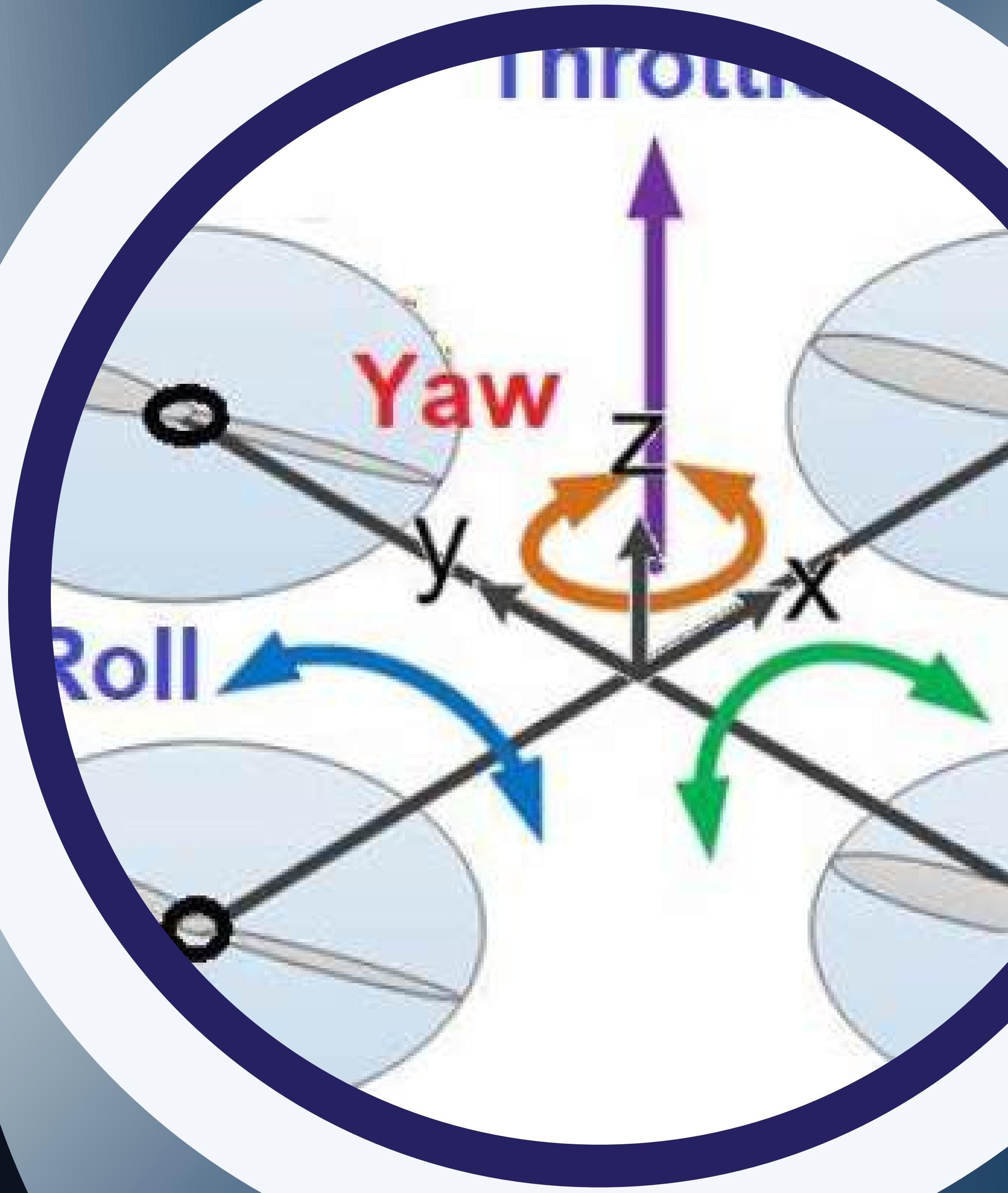
$$m\,\ddot{\mathbf{r}} = m \begin{bmatrix} 0 \\ 0 \\ -g \end{bmatrix} + R\,\mathbf{T}_b$$

Here R is as defined in previous slide and g = acceleration due to gravity

ROTATIONAL DYNAMICS

Relation of (p, q, r) with rate of change of roll-pitch-yaw angles:

$$\boldsymbol{\omega}^B = \begin{bmatrix} p \\ q \\ r \end{bmatrix} = \begin{bmatrix} c\theta & 0 & -c\phi\, s\theta \\ 0 & 1 & s\phi \\ s\theta & 0 & c\phi\, c\theta \end{bmatrix} \begin{bmatrix} \dot{\phi} \\ \dot{\theta} \\ \dot{\psi} \end{bmatrix}$$



ROTATIONAL DYNAMICS

Moments and Euler's Equations:

Inertia in {B}: $I = \mathrm{diag}(I_{xx},\ I_{yy},\ I_{zz})$

M_i : Torque about z_B from rotor i

Each rotor exerts a thrust F_i at some position r_i in x_B - y_B plane

$$\boldsymbol{\tau}^B = \sum_{i=1}^{6}\left(\mathbf{r}_i^B \times [0,\ 0,\ F_i]^T\right) + \sum_{i=1}^{6}[0,\ 0,\ \pm M_i]^T$$

Euler's rigid-body equations:

$$I\,\dot{\boldsymbol{\omega}}^B = \boldsymbol{\tau}^B - \boldsymbol{\omega}^B \times \left(I\,\boldsymbol{\omega}^B\right)$$

PROPELLER THRUST AND MOTOR DYNAMICS

$$F_i = k_F\,\omega_i^2, \quad M_i = k_M\,\omega_i^2$$

where omega_i is the rotor speed and k_F, k_M are empirically determined constants.

Half the rotors spin CW and other half spin CCW so sum of their torques can cancel in hover.

$$\dot{\omega}_i = k_m\left(\omega_{\mathrm{cmd},i} - \omega_i\right)$$

where omega_cmd,i is the commanded speed and k_m is a motor constant

SMALL-ANGLE CONTROL

Many Hex-rotor and Quad-rotor controllers assume the vehicle remains stable during hover. Under small angles, one can linearise the dynamics. Hence we can break it into two control loops:

1. Outer (position) loop: Runs at a lower frequency and uses position/velocity feedback to set desired roll, pitch, thrust
2. Inner (attitude) loop: Runs at a higher frequency, uses onboard Gyros/Accelerometers to stabilise roll, pitch and yaw.

ATTITUDE CONTROL

Assumptions near hover: $I_{xx} \approx I_{yy}, \quad \dot{\psi} \approx r$

PD laws for each axis:

$$
\begin{aligned}
u_\phi &= K_{p,\phi}(\phi_{\text{des}} - \phi) \; + \; K_{d,\phi}(p_{\text{des}} - p), \\
u_\theta &= K_{p,\theta}(\theta_{\text{des}} - \theta) \; + \; K_{d,\theta}(q_{\text{des}} - q), \\
u_\psi &= K_{p,\psi}(\psi_{\text{des}} - \psi) \; + \; K_{d,\psi}(r_{\text{des}} - r).
\end{aligned}
$$

$(u_\phi, u_\theta, u_\psi)$: Moments about body axes

u_1 : Total Thrust

MIXER EQUATION

$$\mathbf{u} = \begin{bmatrix} u_1 \\ u_\phi \\ u_\theta \\ u_\psi \end{bmatrix}, \quad \boldsymbol{\omega}^2 = \begin{bmatrix} \omega_1^2 \\ \omega_2^2 \\ \vdots \\ \omega_6^2 \end{bmatrix}, \quad \mathbf{u} = M\,\boldsymbol{\omega}^2$$

Representative M matrix for a particular Hex-rotor layout

$$M = \begin{bmatrix} b & b & b & b & b & b \\ -\frac{b\,l}{2} & -b\,l & -\frac{b\,l}{2} & \frac{b\,l}{2} & b\,l & \frac{b\,l}{2} \\ -\frac{b\,l\sqrt{3}}{2} & 0 & \frac{b\,l\sqrt{3}}{2} & \frac{b\,l\sqrt{3}}{2} & 0 & -\frac{b\,l\sqrt{3}}{2} \\ -d & d & -d & d & -d & d \end{bmatrix}$$

b = k_F (force constant), d = k_M (moment constant), l = vehicle center to rotor distance.

Inverting or pseudo-inverting M determine omega_i for particular u

POSITION CONTROL

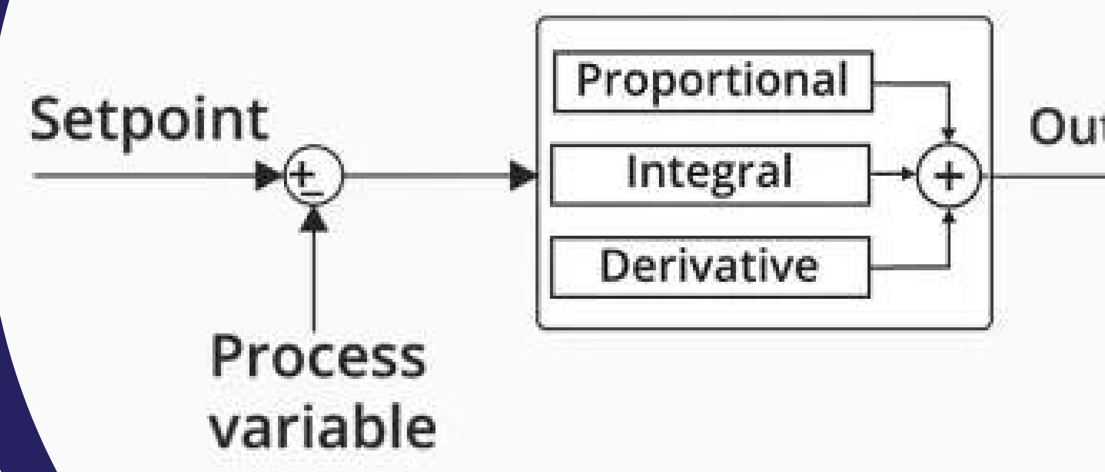
We control (x, y, z) in this loop. Near hover, ignoring drag we have:

$$\ddot{x}_{\text{des}} \approx g\,(\theta_{\text{des}}\,\cos\psi + \phi_{\text{des}}\,\sin\psi)$$
$$\ddot{y}_{\text{des}} \approx g\,(\theta_{\text{des}}\,\sin\psi - \phi_{\text{des}}\,\cos\psi)$$
$$\ddot{z}_{\text{des}} \approx \frac{u_1}{m}$$

Thus:

$$\phi_{\text{des}} = \frac{1}{g}\Big(\ddot{x}_{\text{des}}\,\sin\psi - \ddot{y}_{\text{des}}\,\cos\psi\Big)$$
$$\theta_{\text{des}} = \frac{1}{g}\Big(\ddot{x}_{\text{des}}\,\cos\psi + \ddot{y}_{\text{des}}\,\sin\psi\Big)$$
$$u_1 = m\,\ddot{z}_{\text{des}}$$

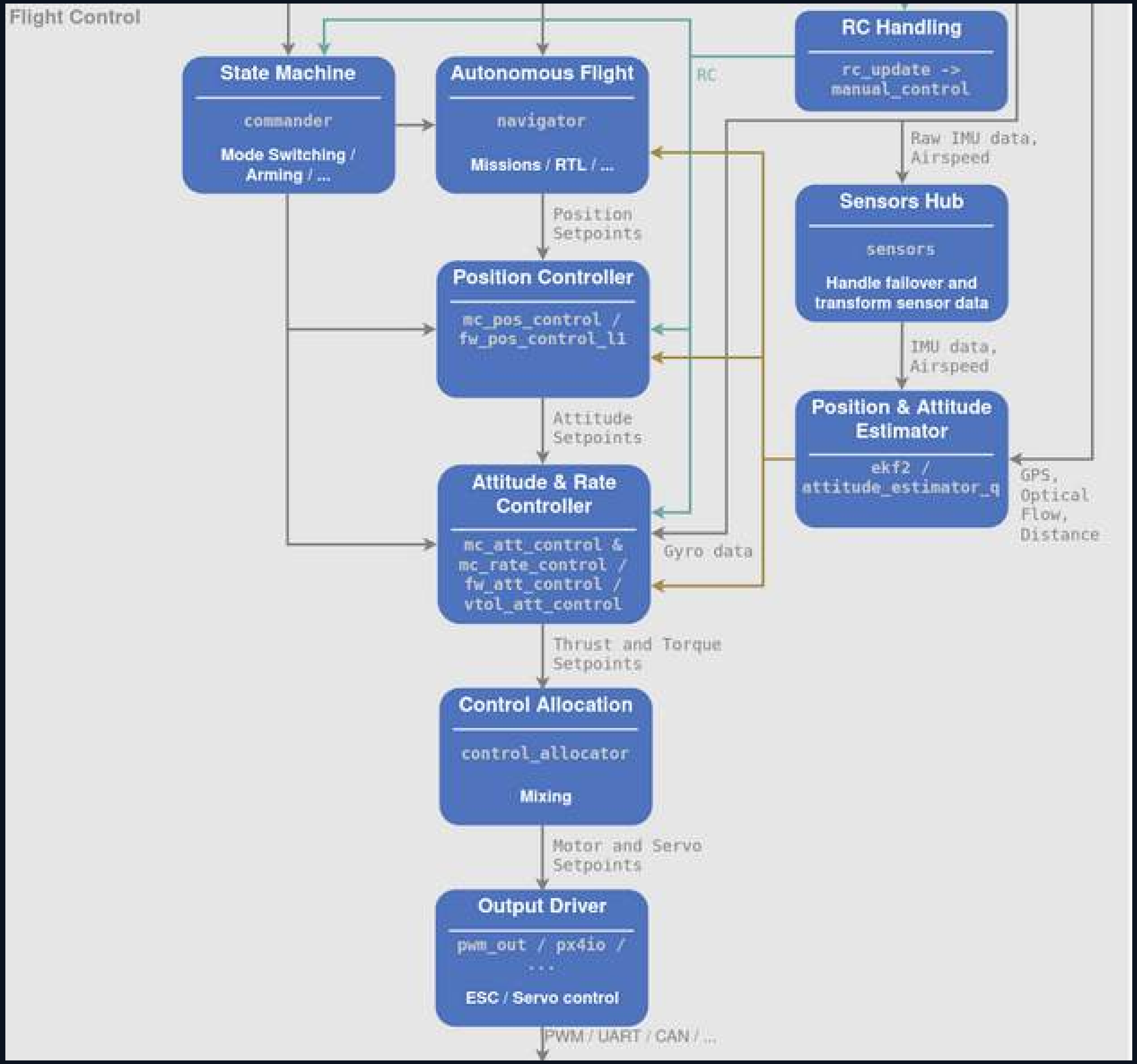
These commands are fed into the inner attitude controller, ensuring the vehicle follows the desired trajectory in position.



SOFTWARE ARCHITECTURE

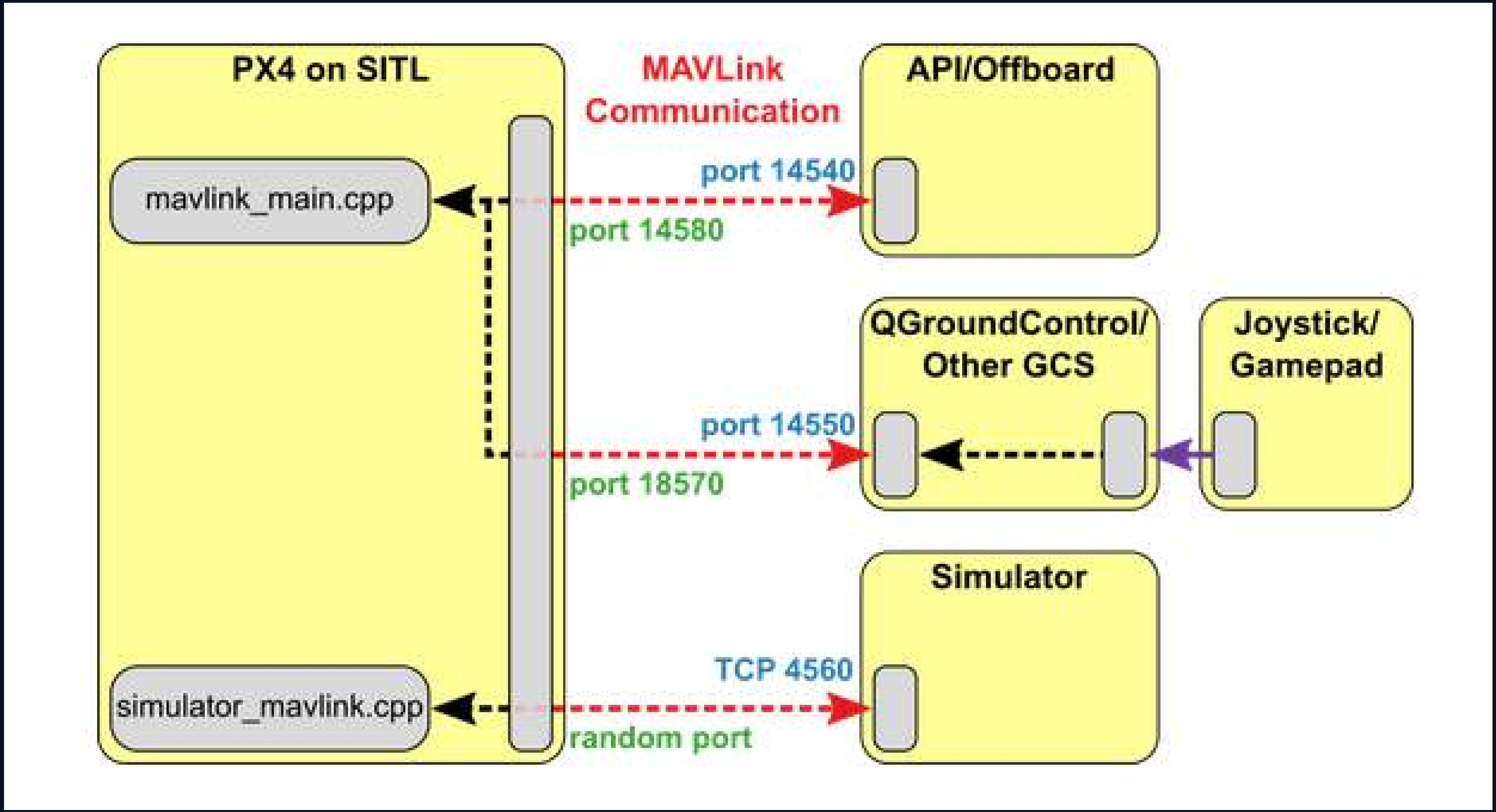
PX4 SOFTWARE STACK

- PX4 Autopilot is widely used for flight control due to its modular architecture, compatibility with various flight controllers, and intuitive uORB communication bus.
- For our implementation, minimal changes will be made to the core control stack since its operation has already been validated in simulation.
- If a custom controller is required, an alternative pipeline has also been proposed.



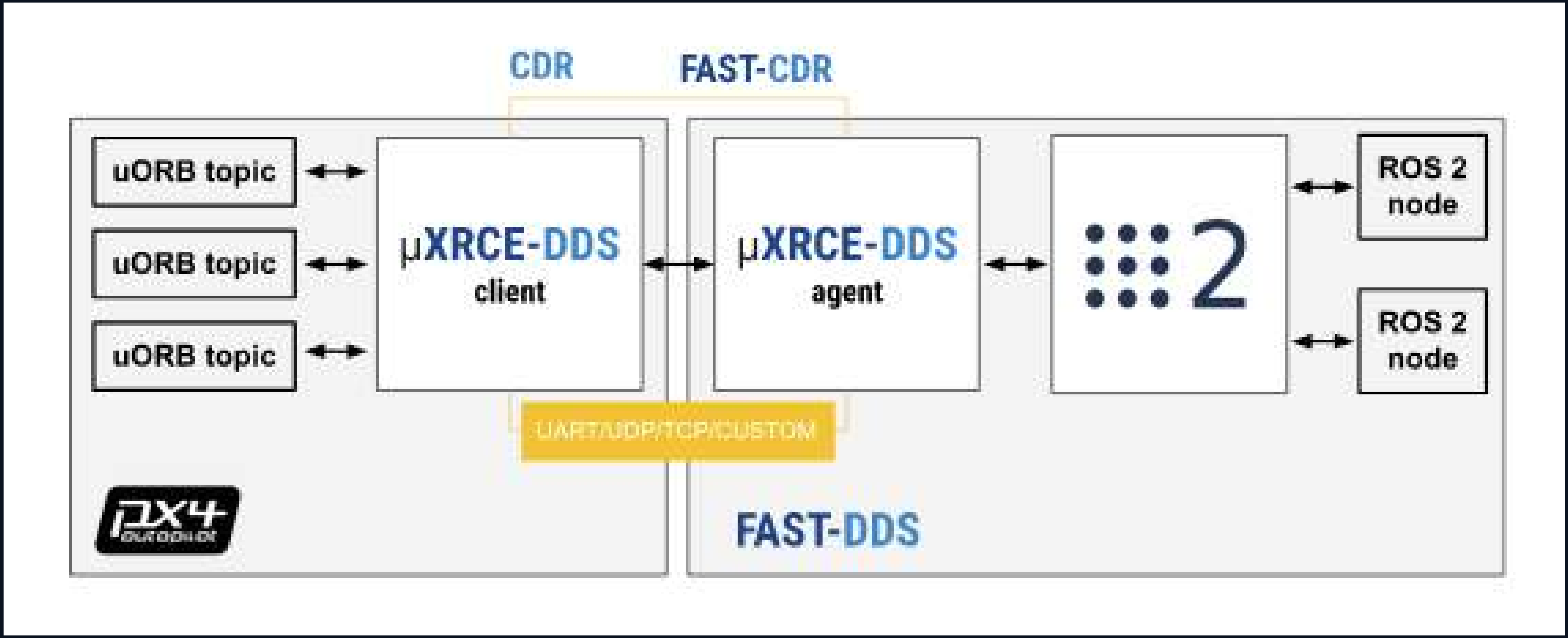
INTERFACING

Gazebo-ROS Interface



INTERFACING

ROS-PX4 Interface



GAZEBO SIMULATION

INERTIAL PARAMETERS

Component	Dimsensions	Mass	MoI (Ix)	MoI (Iy)	MoI (Iz)
Chassis	0.67 x 0.67 x 0.15	0.997	0.039	0.039	0.075
Camera	0.01 x 0.01 x 0.01	0.011	1.83e-7	1.83e-7	1.83e-7
Landing Legs	0.01 x 0.03 (r x h)	0.1	7.54e-4	7.54e-4	7.45e-3
Rotors	0.128 x 0.005 (r x h)	0.024	9.83e-5	9.83e-5	1.97e-4
Nozzle	0.05 x 0.12 (r x h)	0.05	0.07	0.07	0.07

MOTOR PARAMETERS

Parameters	Value
Time Constant (s)	0.0125
Max Speed (rad/s)	1240
Max Speed (RPM)	11840
Motor Constant (N · s^2/rad^2)	8.038e-6
Moment Constant (N · m · s^2/rad^2)	9.55e-3
Rotor Drag Constant	0.09637
Rolling Moment Coefficient	1e-6

SIMULATION ENVIRONMENT

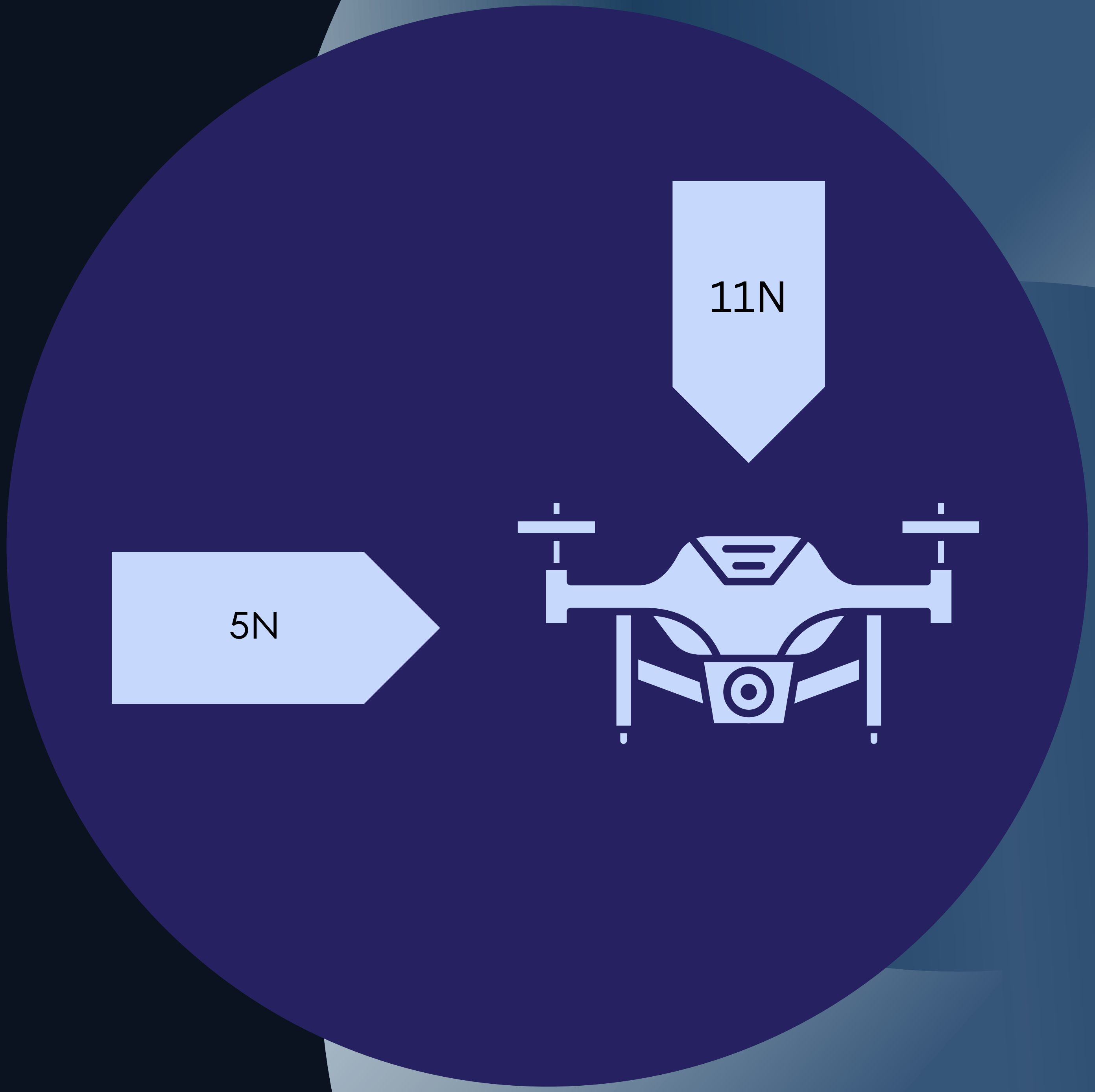
Simulator	***Gazebo classic***
Drone Model	***Typhoon H480***
Autopilot	***PX4 v1.14***
Middleware	***ROS2 with MicroXRCE bridge***

SIMULATION SETUP

Objective

- Take off the drone and maintain a constant altitude for 10s.
- To start spraying water in the specified direction.
- To ascend upwards by some distance while spraying water and then stabilizing at its original altitude

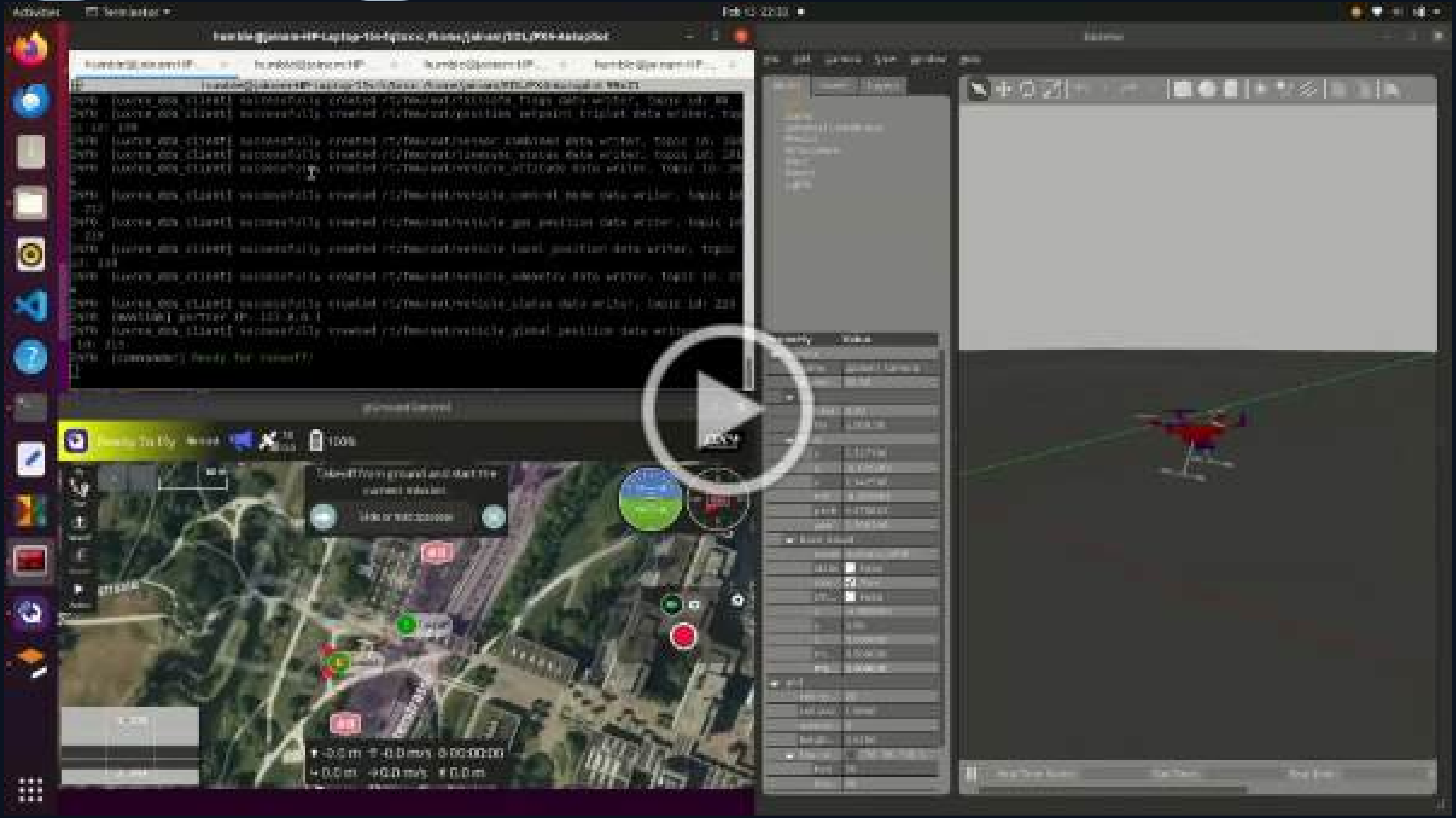
→ For spraying mechanism, we have tried to simulate weight of water column by applying forces as shown



Note

The simulation results obtained at the current takeoff altitude can be extrapolated to any other altitude since the air density and pressure is uniform throughout the simulation

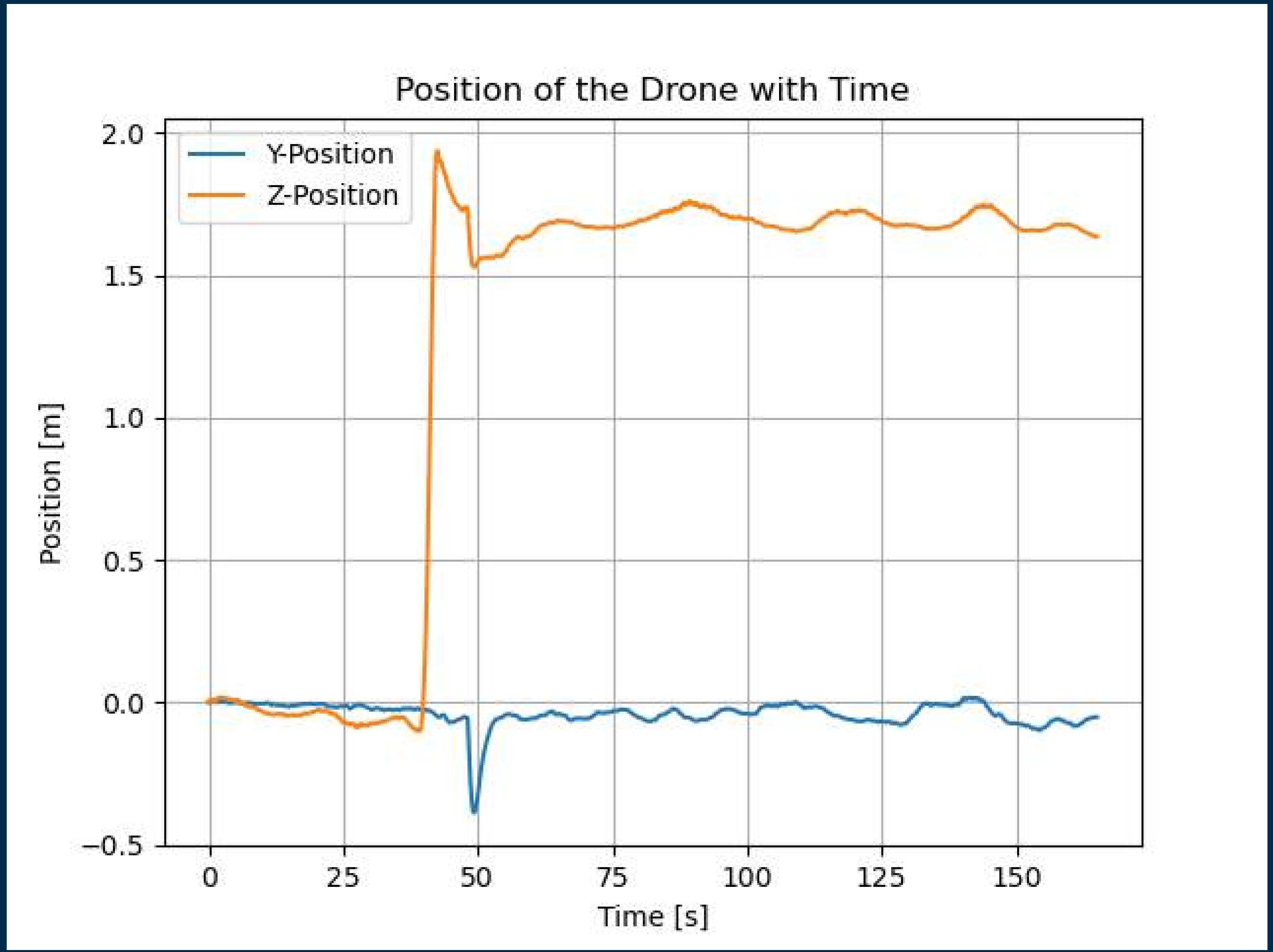
SIMULATION VIDEO



SIMULATION RESULTS

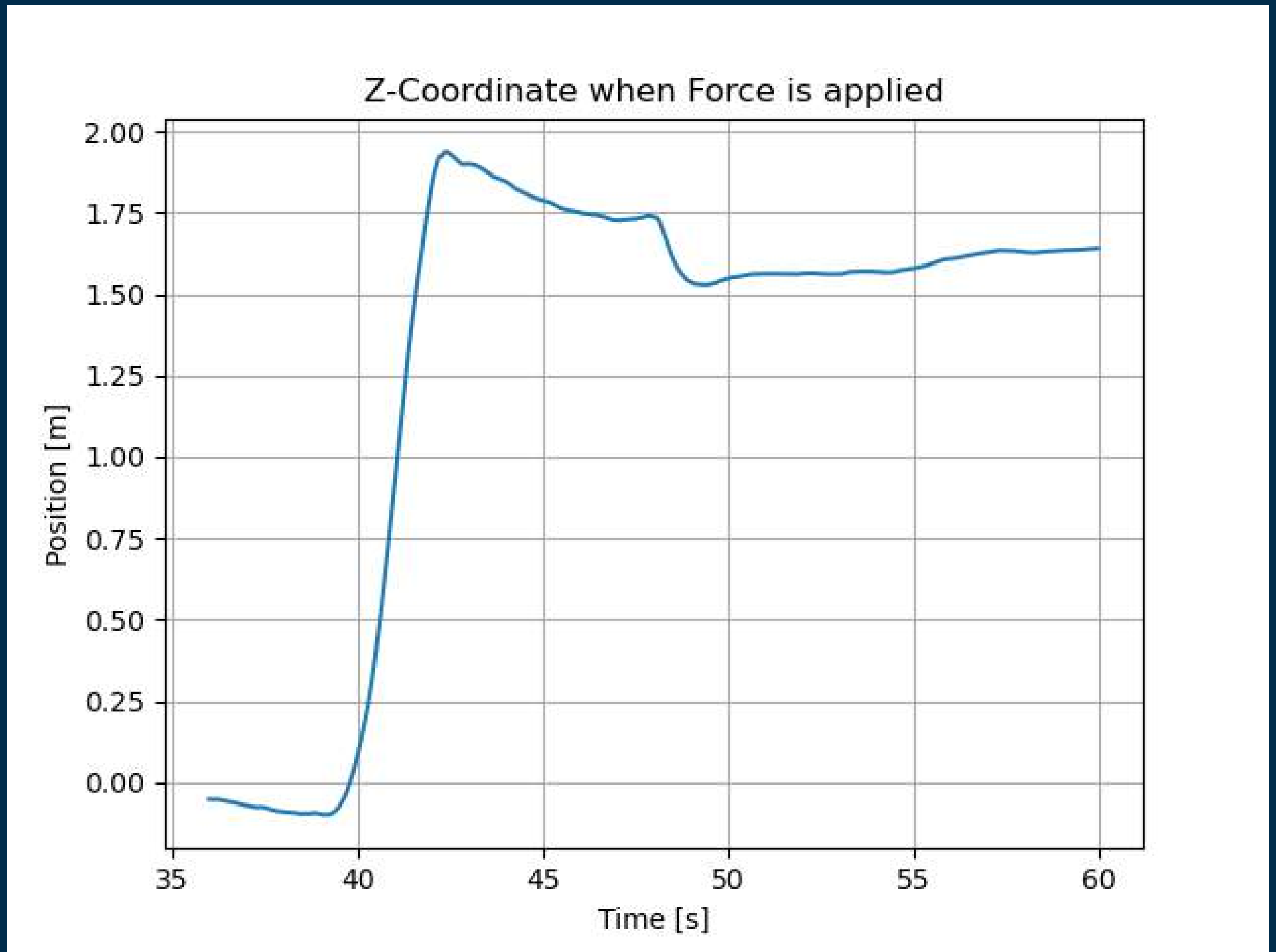
Position Plot

- The drone takes off at T=40s and attains a stable altitude thereafter.
- At T=47s, the spraying mechanism is enabled which leads to a recoil force of 10N in the Y direction and an additional downward force of 11N in the Z direction.
- This subsequently leads to a perturbation of around 0.3m in the Y direction and a drop in altitude of around 0.2m.
- The drone then eventually stabilises at its nominal position.

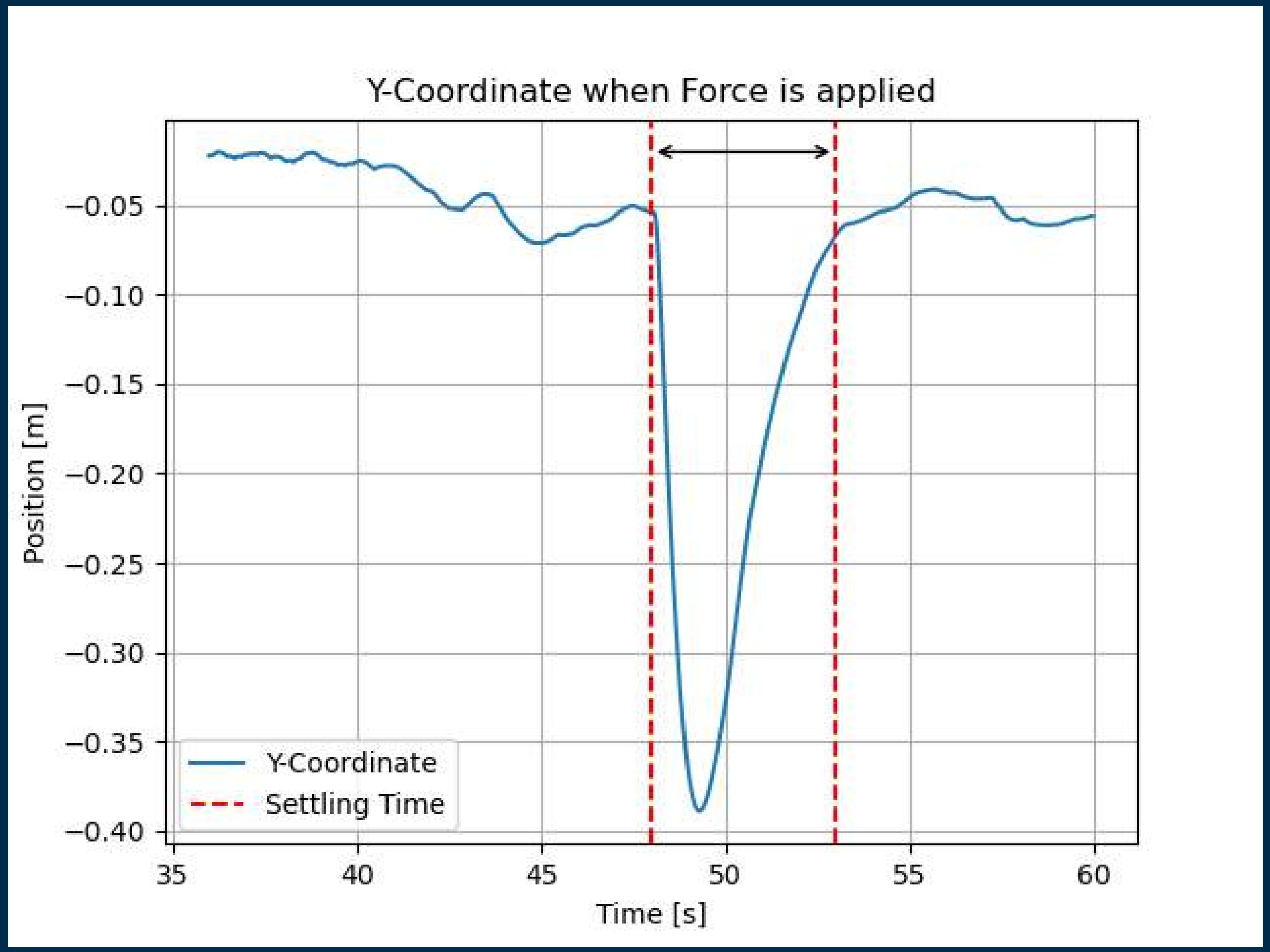


SIMULATION RESULTS

Y coordinate plot



Settling time = 5s

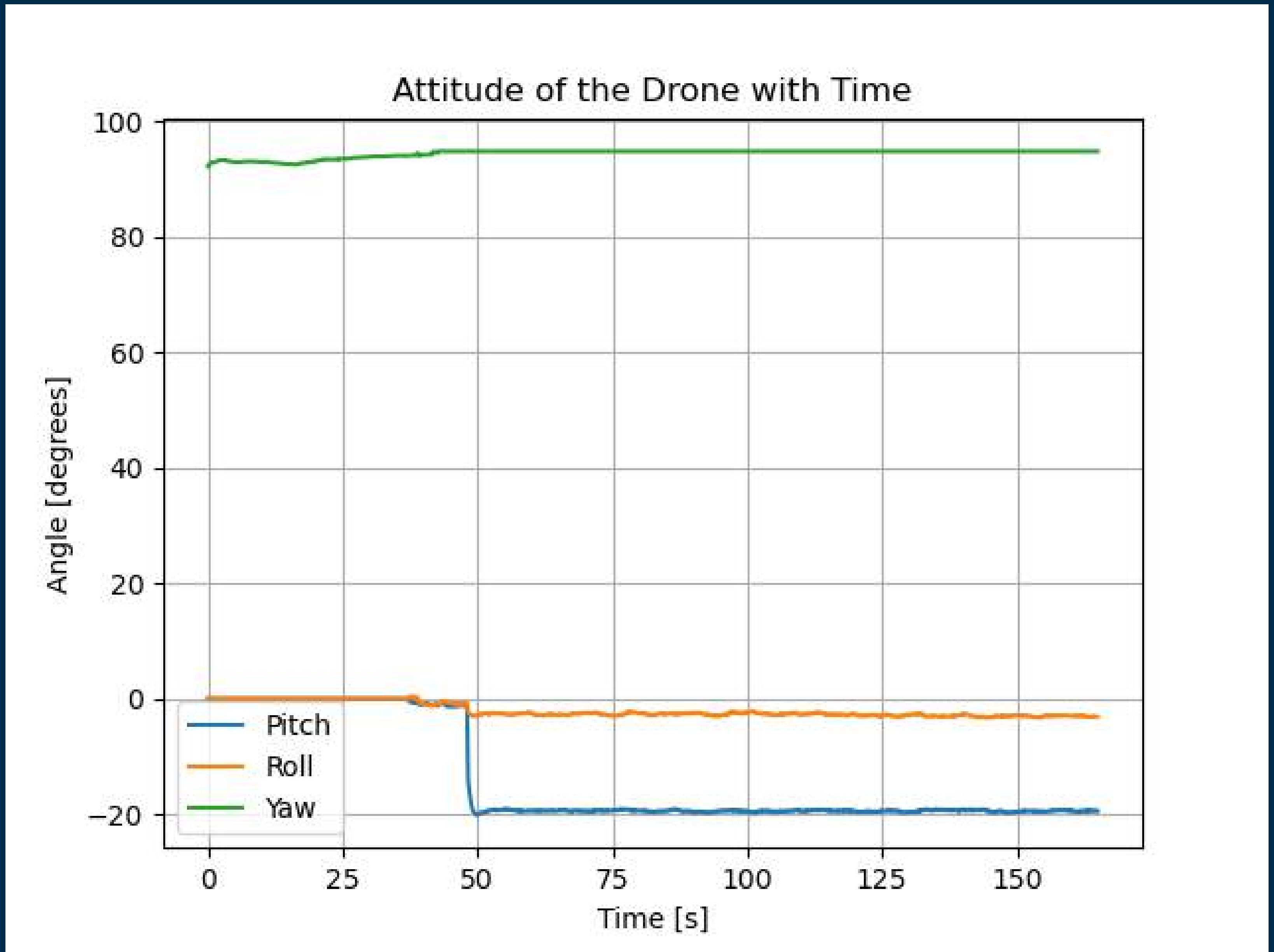


Z coordinate plot

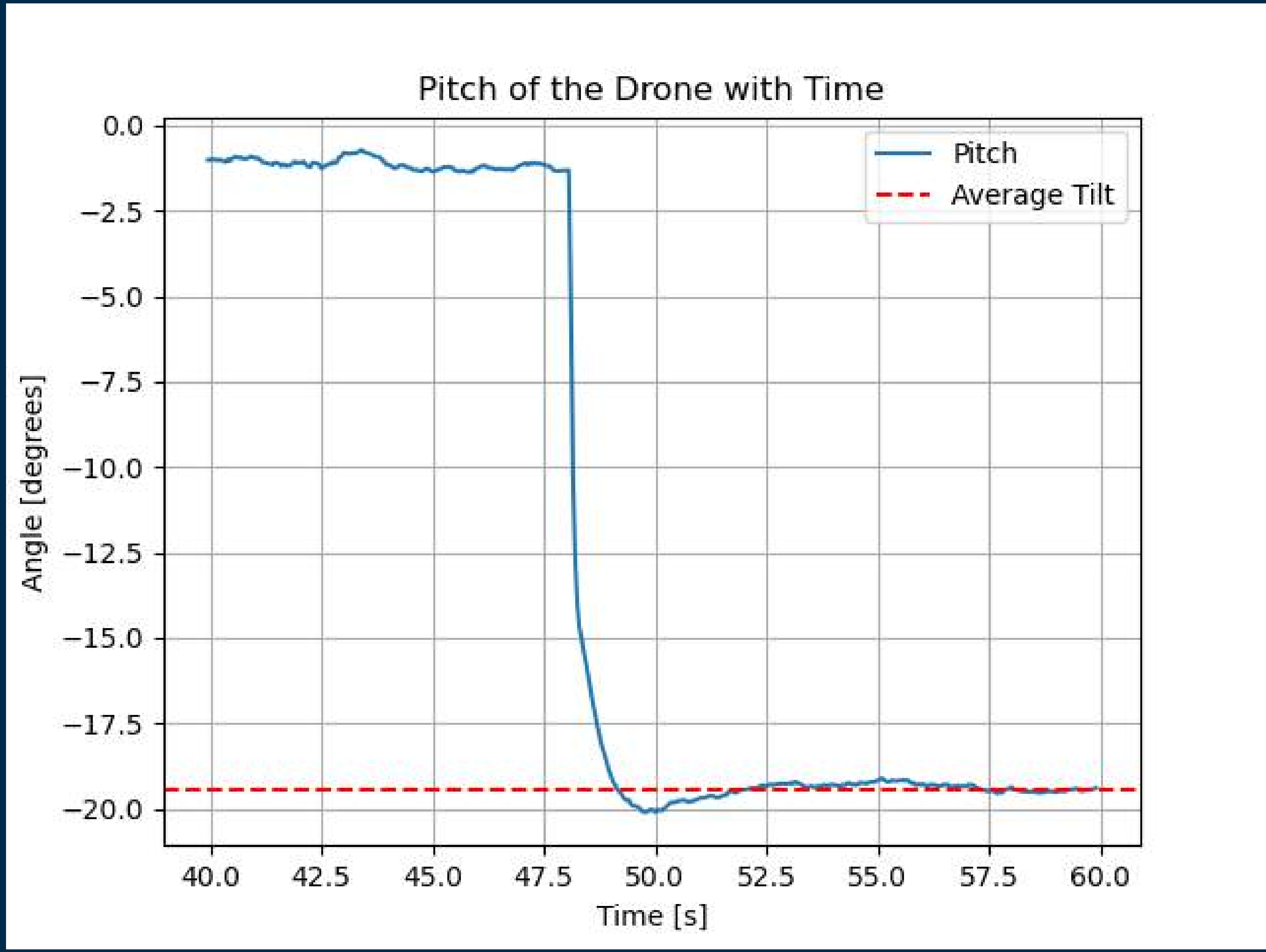
SIMULATION RESULTS

Attitude plot

- The drone maintains a stable roll and yaw angle throughout the mission.
- The pitch angle increases slightly after T=47s to counter the recoil force and the additional weight of the water column.



SIMULATION RESULTS



Pitch plot

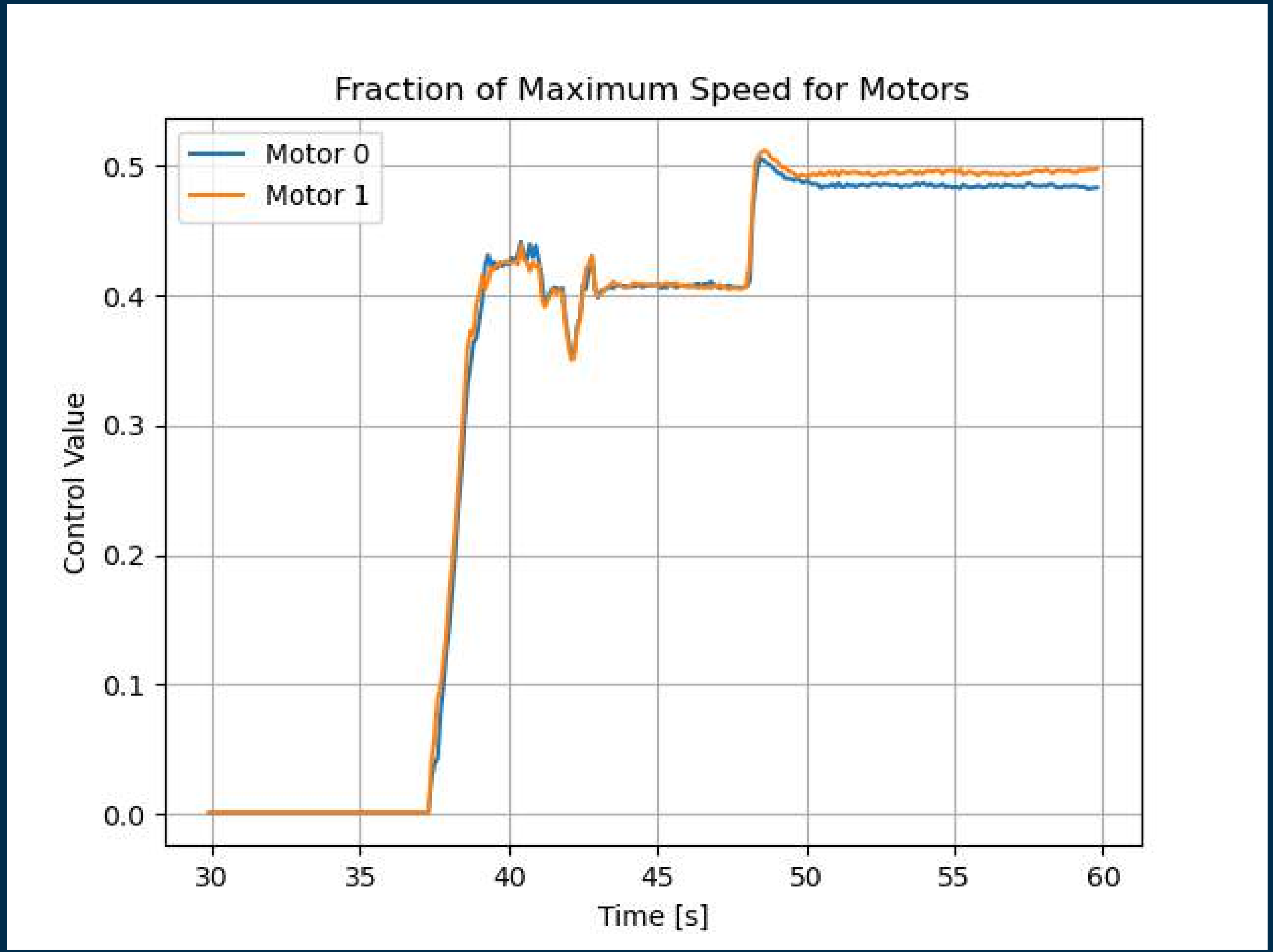
- The drone stabilises with a slight tilt in orientation.
- The drone maintains this orientation throughout the spraying process.
- The tilt can be described by a Pitch angle which is around 20 degrees.

SIMULATION RESULTS

Motor control plot

The Control Value is the fraction of the maximum speed of the motor of the model which is 1240 rad/s or 11840 RPM.

Time Duration	Control Value	RPM
40-47s	0.4	4720
47s onwards	0.5	5900

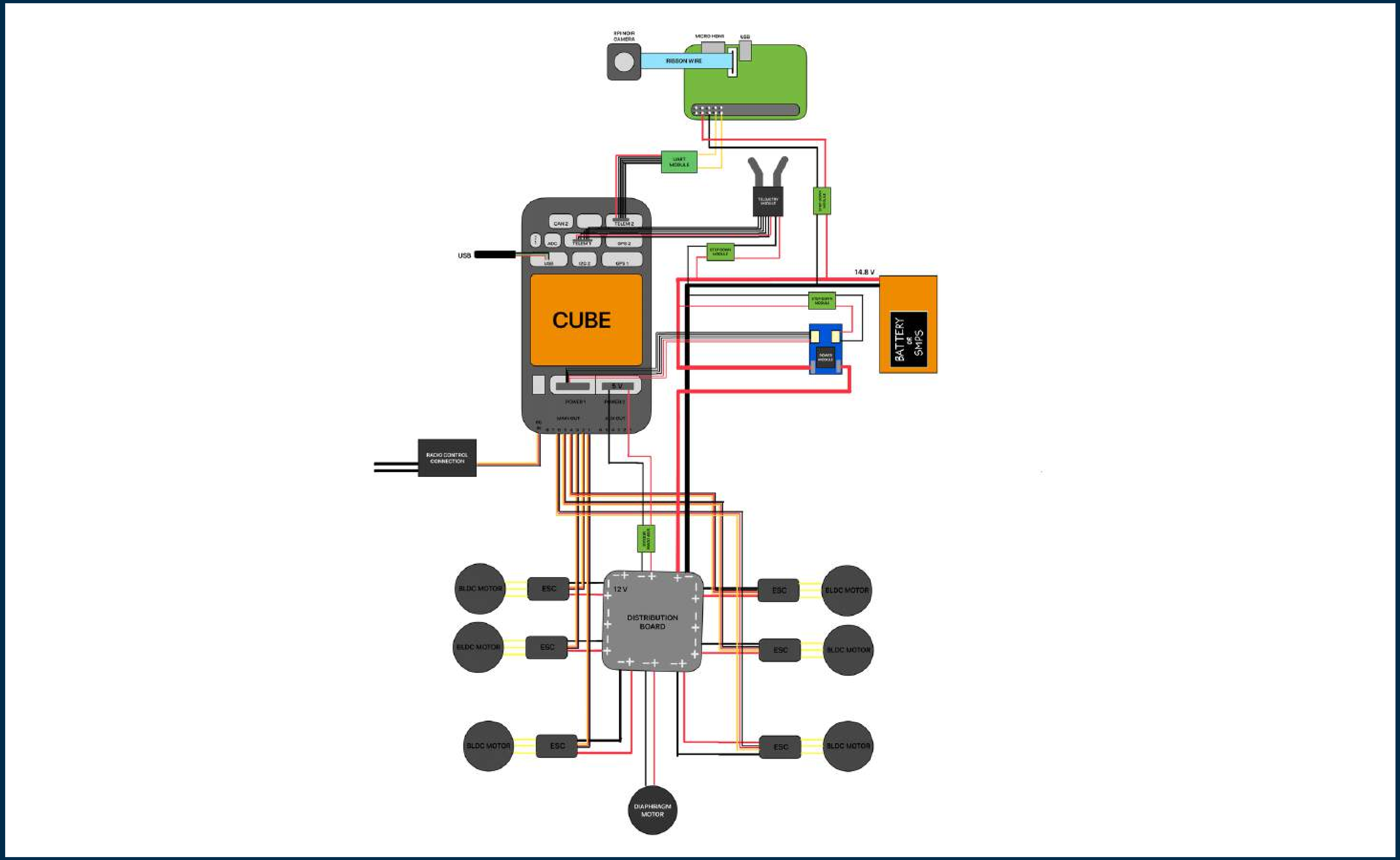


CIRCUIT DIAGRAMS

OVERALL DIAGRAM

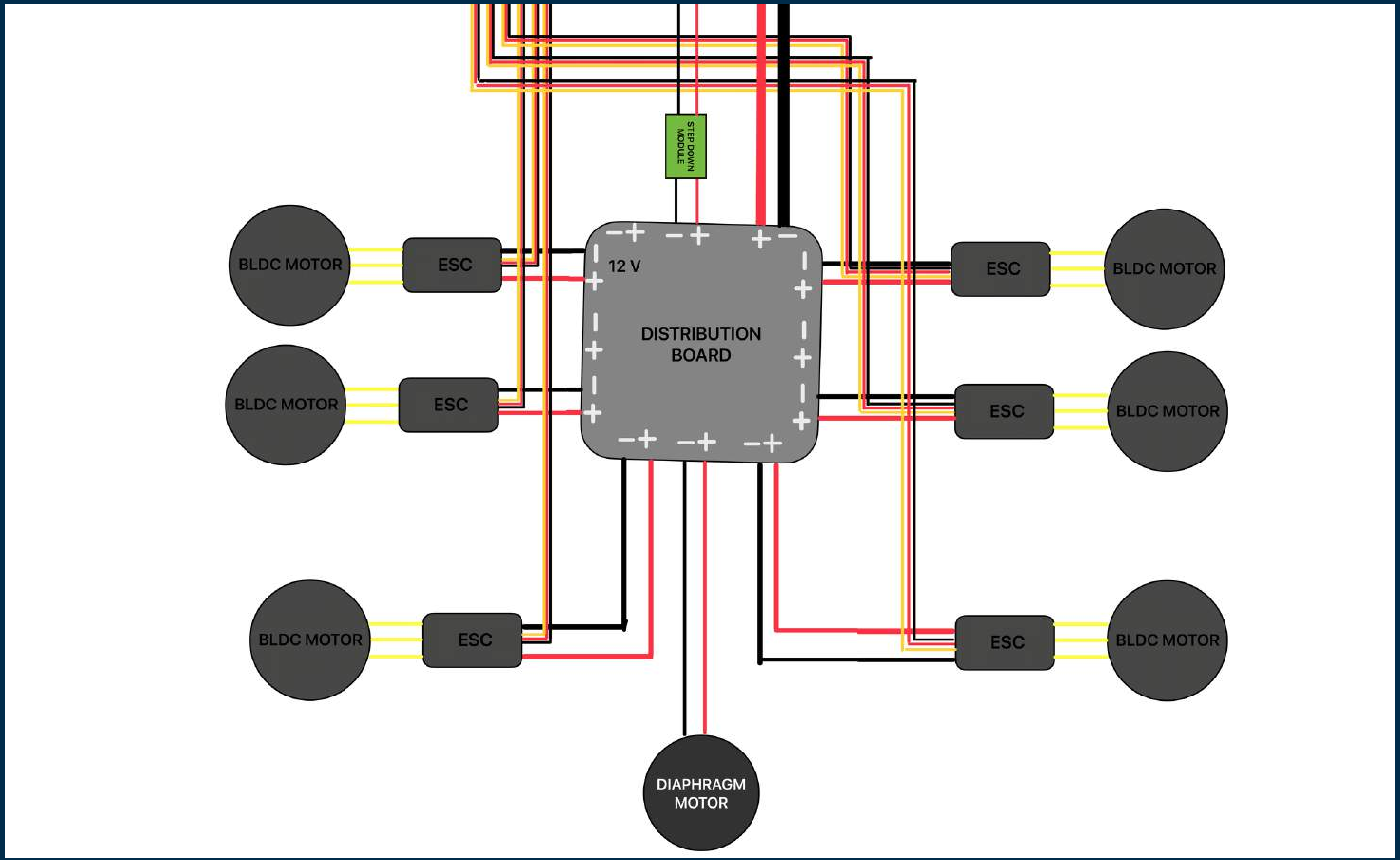
This is the overall diagram of the circuitry and how the components will be connected to each other.

Each sub-part is shown in detail on following slides



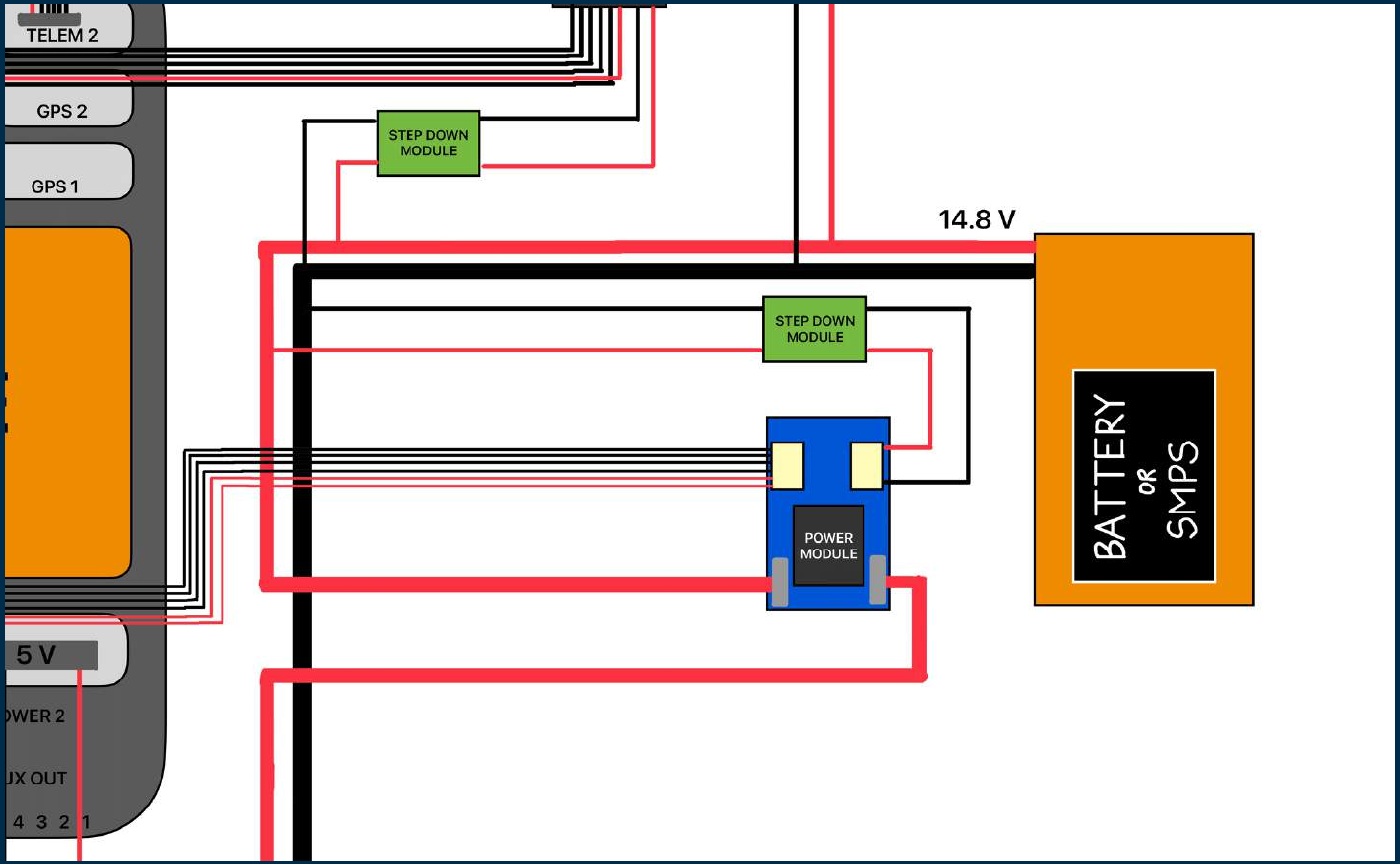
POWER DISTRIBUTION BOARD (PDB)

The Chassis comes with an in-built PDB, which we can use to route power to each BLDC Motor using an ESC. The Diaphragm Motor is also powered using this. The PixHawk and RPi are also powered through the PDB with a BEC to step down voltage.



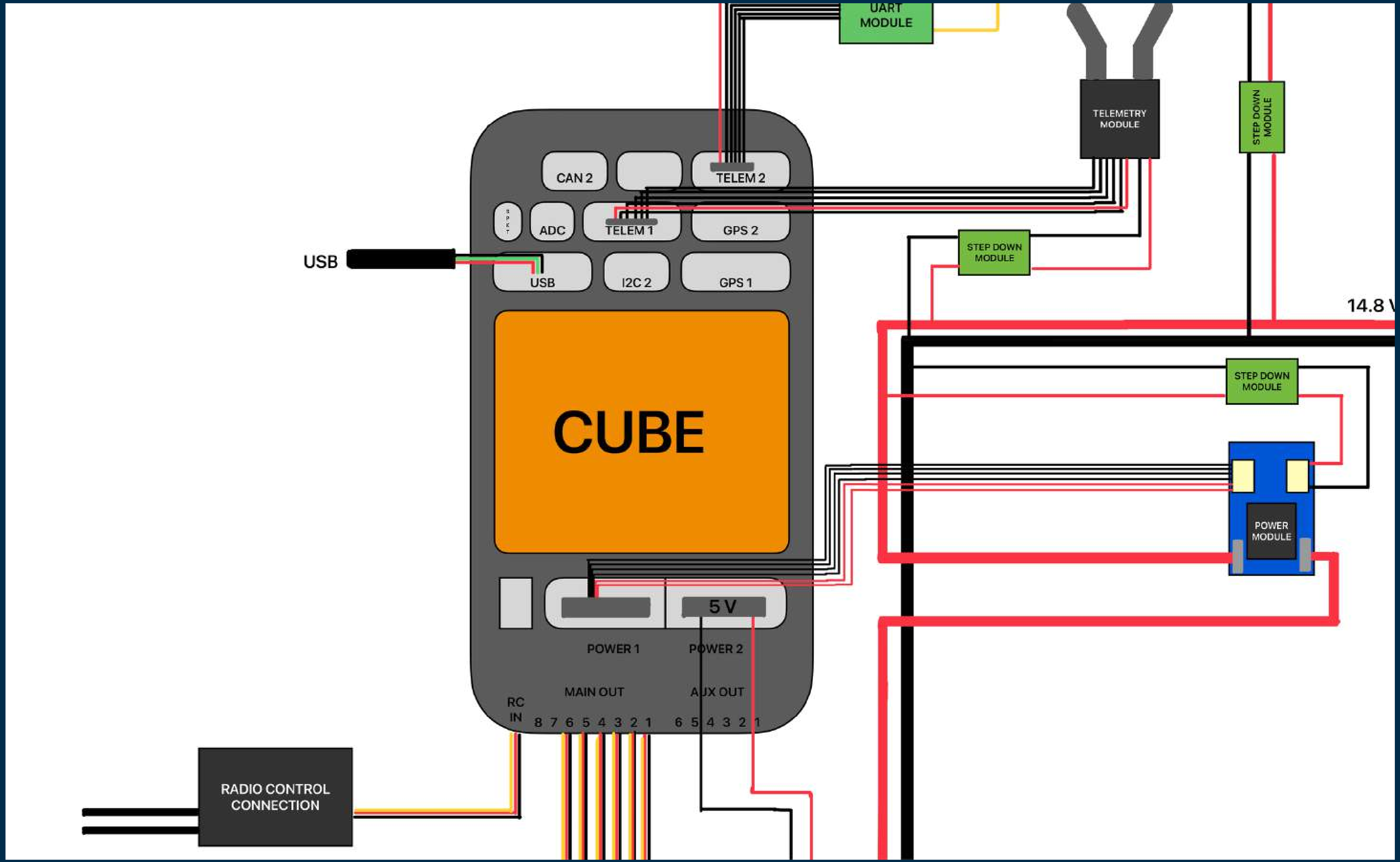
BATTERY/SMPS

The powering of the Drone will be through an SMPS or a Rechargeable Battery. The drone chassis comes with a power module which is used to isolate the power supply from the components. The Step-down Modules are essentially the BECs.



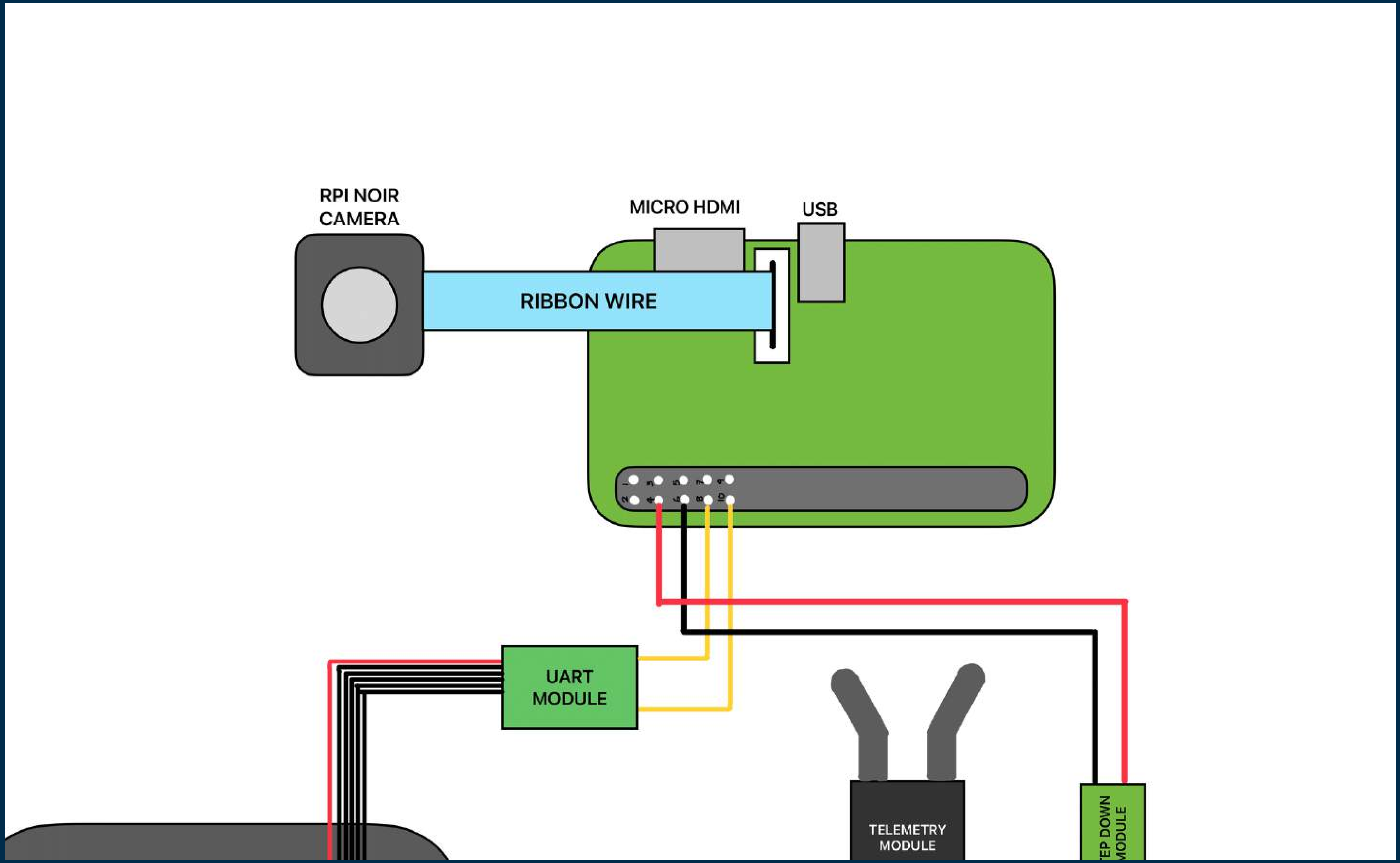
PIXHAWK CONNECTIONS

The PixHawk Cube is the centerpiece of the drone which will control the flight as well as communications. The RC Rx, Telemetry Modules, ESCs for Motors, RPi are all connected to the Cube using appropriate connections.



RASPBERRY PI-4 CONNECTIONS

The Raspberry Pi-4 is essentially on-board to serve as a video broadcasting method. The NoIR Camera is connected to the RPi. The camera feed will be relayed to the ground station using WiFi.



TESTING PLAN

PRELIMINARY TESTING

1 SITL Testing

Simulate the drone operation on Gazebo Simulator using model parameters of the hardware drone.

2 HITL Testing

Simulate the drone operation on Gazebo Simulator using the actual flight controller for a more accurate representation of real-world behavior.

3 Power and Flight Analysis

Analyze the log files generated by the simulator to compare the estimated power and state values with the simulated values.

INTERMEDIATE TESTING

SMPS

Evaluate it's current and voltage output and adjust the regulation till it reaches the desired value.

Pumping Mechanism

Using a ground pump, note the speed and volume of water dispensed

ESC+BLDC motors

For various values of the PWM input and power input from the SMPS evaluate the motor speed and estimate the thrust generated

Nozzle Control

Using the pumping mechanism, ensure that the servo controlled valve operates as desired.

Communi-cation

Test the RC, Telemetry and Video Streaming modules seperately

FINAL TESTING

Altitude Hold

Ensure that the drone can maintain a stable altitude of 10m for the flight duration with reliable communication with GCS

Waypoint Travesal

Ensure that the drone accepts high level setpoints from the GCS and smoothly navigates to the desired position.

Recoil Tolerance

On enabling the spraying mechanism, ensure that the drone suffers minimal perturbation and eventually stabilizes

Effectiveness of cleaning

Test the system on an unclean window and ensure that the drone can effectively clean a window pane

THANK YOU !