ECE445 FALL 2025

SENIOR DESIGN LABORATORY

PROJECT PROPOSAL

Omni-directional Aerial Vehicle

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1. Introduction

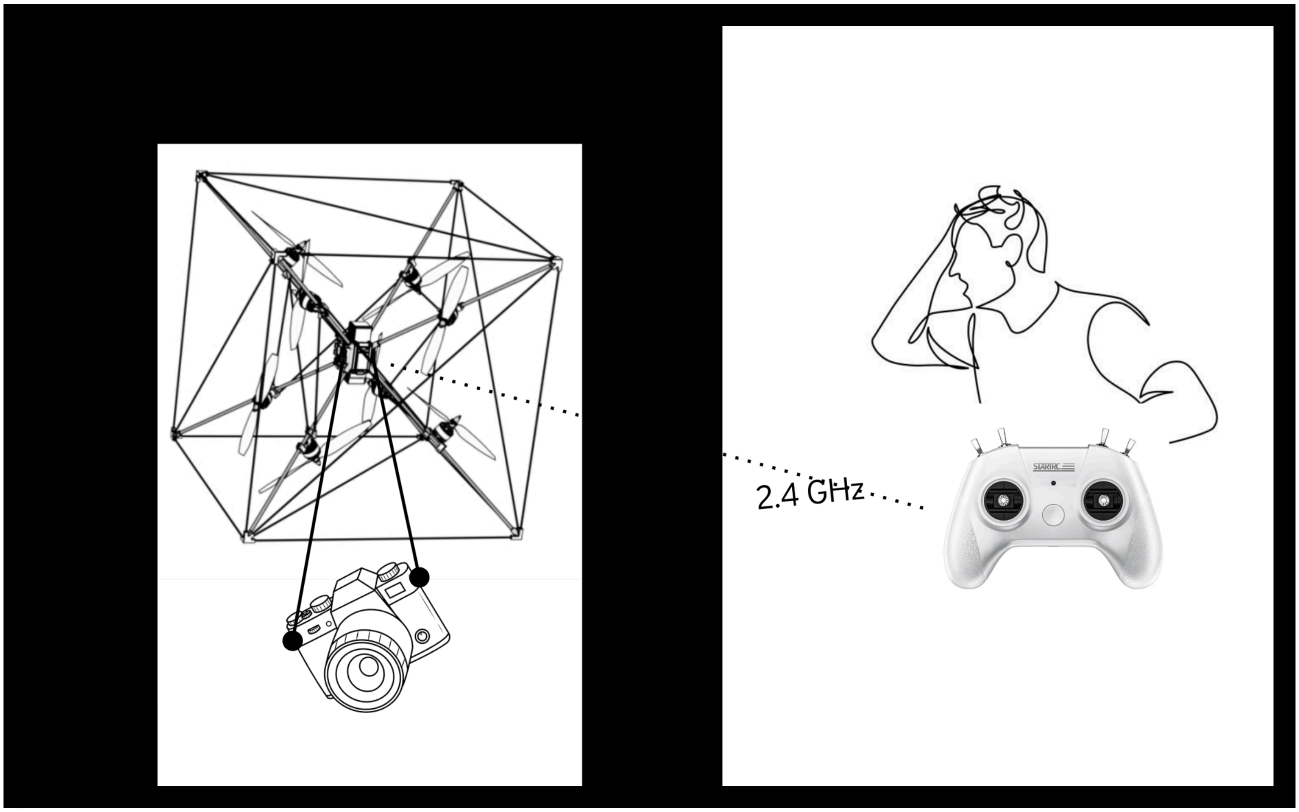
Problem

The issue of aerial maneuvering has become an increasingly important consideration in the new age of drone deliveries, drone imaging, and necessity for automation in the fields of agriculture, construction, surveying, remote monitoring, and more. The current standard of drone technology remains limited to mostly quadcopters, a technology that has matured to enough of a degree to allow for complex directional motion, and extreme speed and stability. However, these vehicles have a notable issue of a lack of movement decoupling, with the translational and rotational motions being tied together. In a lot of speed-focused applications, this issue is trivial as most movement systems can compensate to move in 6DOF space by applying different amounts of power to different motor configurations. But in precision applications or in situations that require a certain orientation to be held, decoupling the rotational and translational degrees of motion allow for the drone to have unprecedented control. For example, in an omnicopter design by ETH Zurich, their demo of catching balls using a net showed impressive results, with the drone staying motionless midair while rotating to track the ball and catch it with a net (reference). Just considering a few simple scenarios, for precise filming, construction, or especially sensitive natural or urban areas, a drone with full control over its movement means the ability to hold an angle for a shot, to apply paints at all angles and move around objects through very tight spaces, or to survey wildlife or urban areas without interfering with the natural environments. In any situation not prioritizing speed or power, an omnicopter would provide significantly improved flexibility and control.

Solution

Our solution consists of three main components: build a robust motor drive system from scratch along with a regenerative braking solution in an omnicopter configuration, designing and 3D printing a frame with the required orientation of motors, and creating the required controls and communications to move the drone in both translational and rotational directions. The motor drive system will contain all required electronics to power and control the motors, including the ESCs, motors, current and voltage sensors, battery management system, and a central microcontroller that interfaces with the ESCs and remote controller. The system will be built to be modular, with each ESC and motor addition being its own module and being easily added to the overall electrical schematic to ensure flexibility with motor configuration, depending on power usage during testing. Within the motor drive system, the battery management system and regenerative braking feature will store away extra power produced by the large currents and wattages that spike up from the motor's inductive nature. The frame of the omnicopter will take the form of either a 6 or 8 motor configuration depending on power draw, stability, and feasibility testing after the electronics have been developed. The design will place an emphasis on easy fabrication using quick prototyping methods like FDM 3D printers, while also remaining lightweight and structurally sound. The goal here is for the drone to be easily manufacturable by hobbyists who would like a robust omni-directional drone with all required functionality and maximum tinkerability. The communications and controls side will handle reading and writing data from the drone to the remote controller, as well as converting decoupled movement signals into different motor power combinations to enable separate translational and rotational movement. The remote controller will be a simple dual-joystick system with each joystick handling either rotational and translational motion. This system also includes the inertial management unit required to track current orientation and balance the system once controls have been input, as well as the antennas required to communicate with the remote controller. Depending on time constraints, trajectory planning and more can also be explored with this side of the project by using the drone's initial position, motor velocities, and orientation. The final solution will consist of a multi-rotor drone capable of separate rotational and translational flight powered through onboard battery packs, responding to inputs from a remote controller through 2 joysticks controlling rotation and translation independently.

Visual Aid



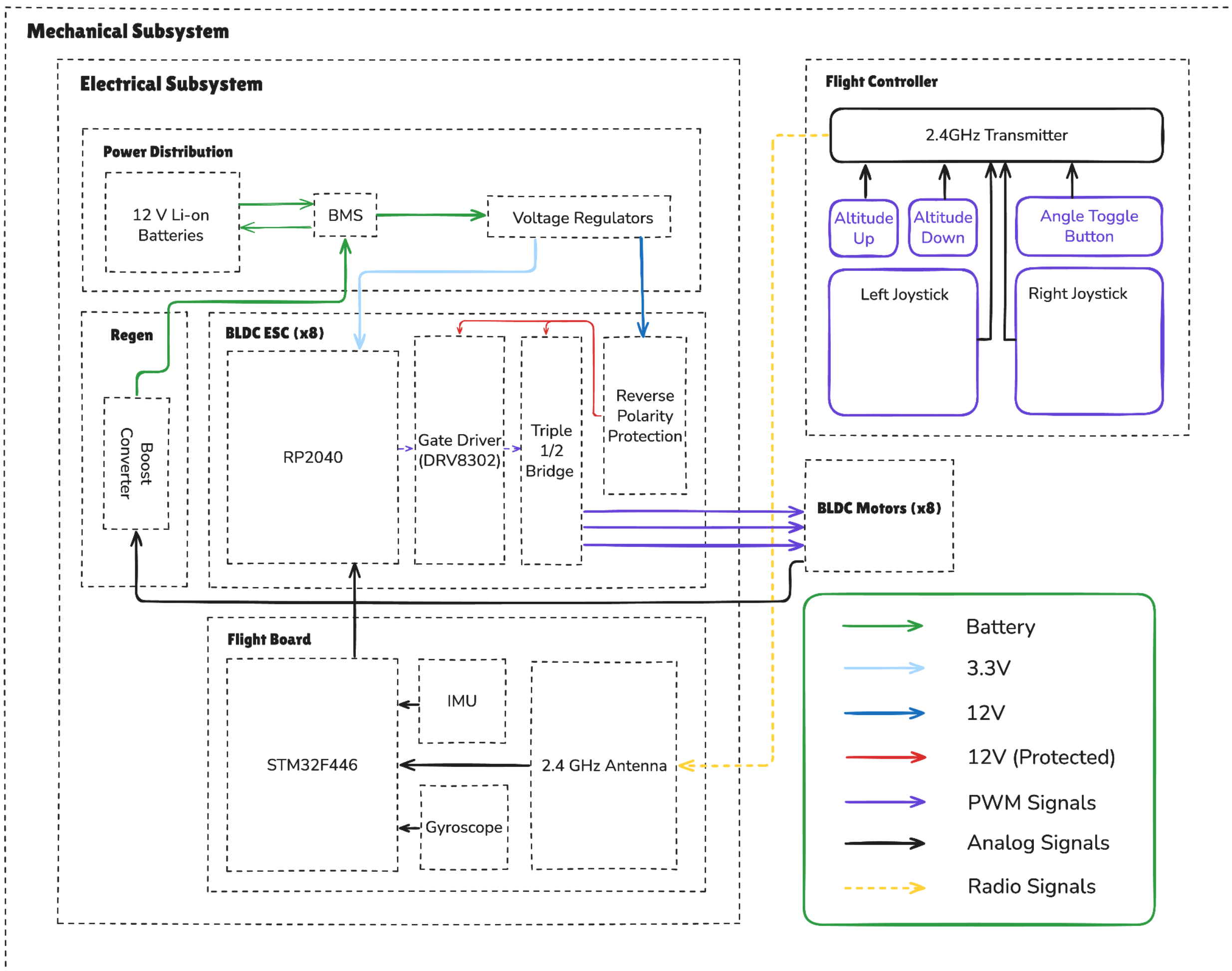
High-level Requirements

- ☐ Move (1) vertically upwards **1 meter**, and hold (2) **a fixed altitude**
- ☐ Move **1 meter to another location** without changing orientation
- ☐ Change rotational orientation **by 45°** while holding a fixed altitude

Between each of these goals, we'll have checkpoints to unit test the PCBs, power systems, antenna communications, mechanical frame, and more; for example, confirming each ESC can receive PWM signals and then output a varying motor speed

Design

Block Design



Subsystem Overview

Electrical Subsystem

The electrical subsystem will contain all required electronics to power and control the motors, including the ESCs, motors, current and voltage sensors, battery management system, and a central microcontroller that interfaces with the ESCs and remote controller. The system will be built to be modular, with each ESC and motor addition being its own module and being easily added to the overall electrical schematic to ensure flexibility with motor configuration, depending on power usage determined during testing. In specific, each ESC has:

- 6 MOSFETs in a triple half-bridge configuration connected to a main gate driver (like TI's DRV8302) to provide the required control per phase for each 3-phase BLDC motor depending on a PWM signal from the MCU.
- A sensor-less back EMF (BEMF) and phase voltage measurement system needs to be in place to approximately track the position of the rotor in each motor to know when and how much current needs to be applied to each half-bridge. This requires a voltage-divider network setup up in a wye-formation, mirroring the 3 phase setup of a BLDC motor and allowing us to measure both the individual phase voltages and also creating a "virtual" neutral point.
- 3 comparators connected to each phase voltage and the virtual neutral point to easily determine when the phase voltage has switched polarities for zero-crossing detection (ZCD); this is very important for tracking rotor position.

Within the motor drive system, the power management system handles power distribution and contains the required safety measures to protect against back energy from the motors. The main power source will be a lithium-ion battery rated at a nominal 12V, capable of outputting peak and average current values required for movement and hovering. A regenerative braking feature will store away extra power produced by the large currents and wattages that spike up from the motor's inductive nature. In specific, the power system has:

- A reverse polarity protection unit that operates using a power management chip like Analog Devices' LTC4367, which acts as a switch that closes when negative voltage is applied.
- TVS diode clamp that is placed in parallel with the battery to protect the rest of the circuit from voltage spikes resulting from the motors' inductive nature.

- Large parallel capacitor bank to store any excess energy generated from reverse voltage effects.
- Buck converter to buck down voltage of battery to a voltage usable by the microcontroller.
- State of charge estimation through battery voltage tracking and battery thermal tracking for safety reasons.

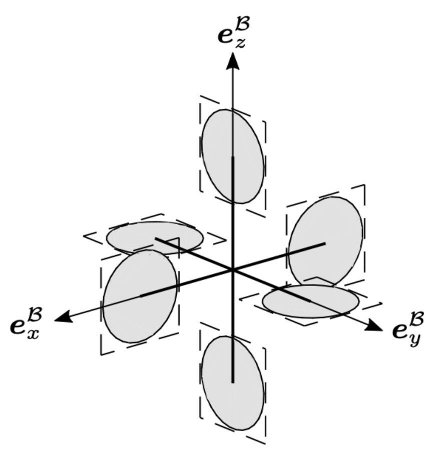
Regarding regenerative braking, as an optional addition, there are a few things that need to be changed or considered before implementing it with the rest of our electrical subsystem. In particular:

- In our case, the energy generated by each motor when slowing down is not proportional to the total weight of the drone; the motor is only connected to a singular rotor, so the energy generated is limited to being less than the energy required to spin the rotor up to its initial speed.
- In contrast to cars and trains, speeding up requires a large proportion of energy while maintaining velocity is related to frictional losses, which is relatively small unless at high velocities. For drones, the amount of energy required to spin up a single rotor is relatively small compared to the amount of energy constantly consumed to hover.
- A boost converter to increase the voltage of the reverse voltage from the motors, allowing current to flow back into the batteries (or potentially run MOSFET bridge as boost converter)
- Since all rotors will be running off the same battery packs, the battery cannot be charged and discharged simultaneously. The best solution here is to have 2 batteries in parallel, with a switching circuit that routes regenerative charging through only one battery at one time while the other battery powers the rest of the circuitry. A dedicated 3.3V battery may likely also be required for sensitive electronics that require stability.

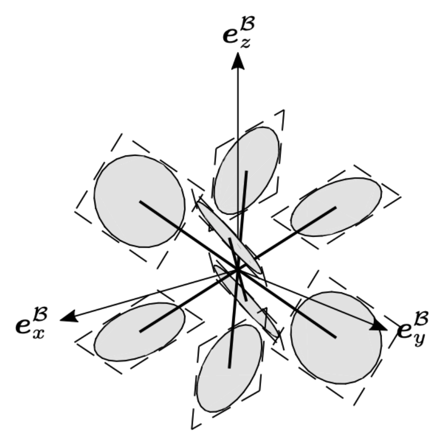
However, if using the 3-phase MOSFET as a boost converter, no extra hardware is required to externally test the feasibility of regenerative braking. If the power produced is too minimal in comparison to the complexity/instability of adding a switching circuit, we can disable the MOSFET bridge converter, and the capacitor bank and RPP will handle the reverse voltage from the motors. Considering the motor number and frequent motor speed changes in order to switch orientations, we are willing to investigate if any energy savings can be made.

Mechanical Subsystem

The overall mechanical design focuses on the design of the frame and configurations of the motors. The frame of the omnicopter will take the form of either a 6 or 8 motor configuration depending on power draw, stability, and feasibility testing after electronics development. We're placing an emphasis on minimum weight and maximum strength while maintaining easy fabrication through quick prototyping methods like 3D printers. Regarding motor configurations, we've already found existing research papers that document optimal motor placements for 6 and 8 motor omnicopter designs as well as the physics for powering these motors in various orientations. Example orientations for both 6 motor and 8 motor configurations are listed below:



(a) $N = 6$, $r_{\max} = 1.41$



(b) $N = 8$, $r_{\max} = 2.31$

Utilizing the given dimensions and angles, an overall structure for this drone can be constructed. The frame can be split into 3 major parts:

- A central hub containing the control electronics and electrical subsystem, and 6 or 8 arms that hold each motor at a given angle. The central hub can be kept as simple as possible for weight savings. Mounting holes for all the PCBs and simple brackets to hold the batteries will be enough for the central hub.
- 6 or 8 arms, each with a mounting point for the motor, positioned at an angle that matches optimal configurations, as mentioned in the paper. Each arm also must be long enough for the motors to be detached from the central hub, i.e. the rotors shouldn't be able to touch the central hub. For maximum weight savings, each arm will be constructed primarily from carbon fiber rods. Parts requiring custom design, like attachment points and connectors can be constructed out of sturdy material blends, like Tough 2000 from Formlabs' material lineup, while using medium infill percentages (30-50%) for weight savings.
- An external cage connecting each arm and providing structural rigidity to the overall frame. This cage also gives the drone some protection against crashes, as well as a landing platform. The cage can also be made of majority carbon fiber rods with 3D printed connectors.

Flight Control + Telemetry

The controls and communications side will handle reading and writing data from the drone to the remote controller, as well as converting movement signals into different motor power combinations to enable separate translational and rotational movement. To do this conversion, we will write our own custom firmware that reads motion data and motor feedback from the drone to dictate the output PWMs for each individual motor. The parts involved in this subsystem are as follows:

- 9 axis IMU to track translational motion and rotational motion
- 2.4 GHz antenna and receiver

- 2.4 GHz remote controller will be a simple dual-joystick system with each joystick handling either rotational and translational motion, as well as auxiliary buttons to control up and down motion
- STM32F446 microcontroller receives signals from the remote controller and transforms it into output motor PWM signals that are sent to the gate driver on each of the ESCs.

Subsystem Requirements

Electrical Subsystem

- [ ] 12 V Battery
    - [ ] Capable of outputting at a nominal 12V
    - [ ] Capable of power draw up to $8 \cdot 150W = 1200W$
    - [ ] Capable of powering flight time of around 5 minutes, approximately an energy capacity of $8 \cdot 30$ W/12V $\cdot$ 1/12 hour = 240/144 Ah = 1667 mAh
- [ ] Microcontroller Buck Converter
    - [ ] Capable of outputting a steady 3.3V from a 12 V input
    - [ ] Capable of current draw up to 160 mA
    - [ ] Capable of outputting 3 different PWM channels at 100 KHz
- [ ] MOSFET Bridge
    - [ ] MOSFETs capable of switching at 100 KHz
    - [ ] MOSFETs capable of handling VDS as high as 30V
- [ ] Gate Drivers
    - [ ] Driver capable of handling input PWM frequencies of 100 KHz
- [ ] BLDC Motors
    - [ ] Motors run at 12V

Mechanical Subsystem

- [ ] Central Hub
    - [ ] Dimensions large enough to holding 12V lithium
- [ ] Arms

- ☐ Long enough that rotors do not touch each other and that they don't interfere with the rotors' airstream, around 0.15m according to the paper

Flight Control + Telemetry

- ☐ STM32f446ZE
  - ☐ Powered by 3.3V digital input from power management board
  - ☐ Capable of SPI, I2C and UART communications
  - ☐ Clock rates of ~32MHz
- ☐ SX1280IMLTRT
  - ☐ RF encoder that takes digital signals and converts to 2.4GHz radio signals
    - ☐ Frequency accuracy: ±10–20 ppm (depends on crystal)
    - ☐ TX output power tolerance: ±1.5–2 dB
    - ☐ RX sensitivity tolerance: ±2 dB
    - ☐ Phase noise: –100 dBc/Hz @ 100 kHz offset (typical)
- ☐ 9 axis IMU
  - ☐ Accelerometer (IMU)
    - ☐ Zero-g offset: ±40–100 mg
    - ☐ Sensitivity error: ±1–3%
    - ☐ Noise density: ~100–300 µg/√Hz
  - ☐ Gyroscope (IMU)
    - ☐ Zero-rate offset: ±1–5 °/s
    - ☐ Sensitivity error: ±1–3%
    - ☐ Noise density: ~0.005–0.02 °/s/√Hz

Tolerance Analysis

Geometry:

The ETH Zurich team [1] determined rotor positions and orientations by framing the problem as an optimization problem, where the goal is to maximize the inner sphere radius r_{max} while enforcing symmetry and isotropy. The rotor positions were constrained to the vertices of regular polyhedrons, so that the inertia tensor is isotropic, meaning the moment of inertia stays the same across each direction. They cast the design as $\underset{P,N}{\text{maximize}} \arg\max_{r} \left\{r : \{v \in \mathbb{R}^6 \mid \|v\|_2 \le r\} \subseteq \mathcal{V}\right\}$, where P is the position of the rotors, N is the disk normals, and $\mathcal{V}$ is the set of all attainable thrusts and torques. After using MATLAB's fmincon and numerically solving for optimal rotor orientation, they chose to go with a cube orientation as it was the best balance of capability and practicality. To maximize torque, they align each rotor's disk normal perpendicular to its position vector (so the torque arm is largest). But to satisfy isotropy (equal singular values), they slightly rotate the normals (e.g. π/6 about z-axis) so that the final configuration balances thrust and torque equally. The result is a set of 8 thrust vectors (the columns of N) that are evenly spread out in 3-D space and matched to the cube vertices.

Thrust:

In [1], the authors build a 6-D wrench map from rotor thrusts to vehicle torque, they then optimize geometry and report a normalized insphere radius, $r_{max} = 2.31$. Here normalized means per-rotor thrust is normalized to $f_{max} = 1$, and rotor positions lie on the unit sphere. This means, if each rotor could deliver unit thrust, the vehicle could guarantee any combined wrench $\begin{bmatrix} f \\ \tau \end{bmatrix}$ whose Euclidean norm ≤ 2.31. Real fixed-pitch motors can't go to zero, they need a minimum RPM. In [1], they handle this with $f_{max}^{eff} = f_{max} - 2f_{min}$ an "effective" per-motor bound, . Scaling this normalized radius by our per-motor limit gives us our guaranteed 6-D wrench radius, $r_{wrench} = r_{max} f_{max}^{eff}$. Using this, for our drone to be able to hover at any given direction, we are going to need to satisfy the requirement $r_{wrench} \ge S_f mg$, where S_f is a safety factor, and m is the weight of our drone. Since r_{wrench} is for force and torque, meeting this should be sufficient for the force that our motors will need to generate in order to guarantee omnidirectionality.

The motors we intend to use in the design are MRM Titan 2208-1100KV. Based on the datasheet of the motor, each motor can provide a thrust of 6.25N using 5cm rotors. When multiplying the individual thrust with the insphere radius, we get a max symmetrical thrust of 14.4375 N. This thrust provides us with a weight budget of 1473g.

Frame:
We intend to use a 3D printer along with 3D modeling software to design and fabricate the frame for our omnicopter. A critical aspect of the design is maintaining geometric symmetry. The more symmetrical the frame is, the more generalizable and predictable our control algorithms will be across different orientations of the drone. However, perfect symmetry is difficult to achieve because components such as the battery and flight controller introduce unavoidable asymmetries due to their uneven weight distribution.

Since we are using eight identical motors and ESCs, the propulsion system itself remains largely symmetrical. The main challenge lies in compensating for the mass imbalance introduced by the heavier subsystems. To address this, we deliberately orient these components in directions where the motors are capable of producing thrust well above the critical minimum required for stable flight. While some orientations of the drone inherently allow for higher maximum thrust output than others, strategically biasing the weight distribution toward these stronger thrust directions allows us to effectively calibrate the system. This approach enables the drone to behave more like a pseudo-symmetrical system, improving control performance without requiring a perfectly balanced frame.

Battery:
Based on our motors and their theoretical draw, we can expect a maximum of 1864W from the battery. We plan to use a 4s LiPo battery for our design and by using the

formula P = IV, this comes out to a maximum current draw of 155A across all 8 motors or 20A per motor. The maximum current draw of a LiPo battery is given by $I_{max} = C_{rating}$ * Energy. Where the C_{rating} is a LiPo-specific parameter corresponding to the battery's current draw. The energy here is in Ah. Then, for example a 3100 mAh battery would need to be around 50C to provide the needed current. For our design, we're planning on using a 3300 mAh battery rated for 60C. This battery gives us critical leeway in potential cases where certain motors might require extra current draw to account for unbalanced weight distribution and propeller imperfections.

Weight Budget:
Our total weight budget is 1473g. This weight needs to include the battery, motors, frame and electronics. The heaviest of these components are going to be the motors and batteries. The current battery weight is 318g and total motor weight 448g. As such, we have a total electronics and frame budget of 707g. We're aiming to have a total frame and electronics weight of 500g to provide extra tolerance in weight load.

Ethics and Safety

Public and Operator Safety:

Our omni-directional drone features high-speed rotating propellers and a Li-ion battery pack, which pose risks of injury, fire, or electrical failure. To mitigate these risks, all testing will initially be conducted in restricted environments such as netted indoor flight spaces or designated outdoor zones, in line with University of Illinois Laboratory Safety Protocols for Unmanned Aircraft Systems (UAS). Early flights will use tethers to reduce potential crash energy, and propeller guards will be installed during development. An emergency kill switch will be implemented to immediately cut motor power in case of malfunction.

Electrical and Battery Safety:

Lithium-ion batteries can overheat or catch fire if improperly charged or discharged. We will follow the U.S. Consumer Product Safety Commission (CPSC) guidelines for lithium-ion batteries and adhere to UIUC's Electrical and Computer Engineering (ECE) lab policies on handling rechargeable cells. Specific measures include reverse polarity protection, fuses, TVS diodes, and capacitor banks to absorb back-EMF from motors. Charging will be supervised using manufacturer-recommended chargers, batteries will be stored in fire-retardant containers, and regular inspections will be documented to monitor swelling or damage.

Material and Manufacturing Safety:

When working with 3d printing, solder, and carbon fiber, there are specific safeguards that need to be taken to avoid accidental ingestion of harmful materials.

Mechanical Integrity and Pre-Flight Checks:

Drone crashes present hazards to people and property. Following UIUC Drone Safety Guidelines and general UAS operational best practices, each flight will be preceded by a structured inspection protocol: ensuring frame integrity, checking for loose screws or connectors, and verifying propeller attachment. MOSFET and motor thermal checks will be conducted during operation to prevent overheating. These procedures will be consolidated into a written Safety Manual that details pre-flight inspection, propeller installation, battery handling, and emergency response.

Ethical Use and Privacy:

We recognize that drones can be misused in ways that compromise privacy or disturb the environment. Following the ACM Code of Ethics, sections 1.2 (Avoid Harm) and 1.6 (Respect Privacy), we commit to using this vehicle only for academic and research purposes. No visual or audio data unrelated to flight performance will be collected, and we will responsibly recycle or dispose of all batteries and electronic waste to minimize environmental harm.

RF Exposure and Communication Safety:

Our project uses a 2.4 GHz wireless remote controller and telemetry module to transmit and receive flight commands. These components fall under unlicensed operation limits defined by the FCC Part 15 Subpart C rules for intentional radiators in the 2.4 GHz ISM band. To ensure compliance, we will use only FCC-certified transceiver modules that meet the maximum effective isotropic radiated power (EIRP) limits ($\leq$ 1 W) and comply with specific absorption rate (SAR) limits for RF exposure. Since the modules are low-power consumer-grade devices designed for hobbyist and research use, the expected RF exposure is well below harmful thresholds.

Interference is another consideration, as 2.4 GHz is a crowded spectrum used by Wi-Fi, Bluetooth, and other wireless devices. We will mitigate this risk by operating in designated lab or field test areas where wireless traffic is controlled, and by following UIUC Laboratory UAS Operation Guidelines to avoid interference with nearby research equipment. Should interference or connectivity issues arise, testing will be halted until safe communication is reestablished.

Fabrication Safety (3D Printing, Soldering, and Machining):

When working with 3D printing, solder, and carbon fiber, there are specific safeguards that need to be taken to avoid accidental ingestion of harmful materials. Additively manufactured parts, such as those made from nylon or resin, can release fine particulates during post-processing, therefore sanding or trimming should be performed with gloves and masks in accordance with UIUC Laboratory Safety Guidelines for Additive Manufacturing. Soldering exposes operators to flux fumes and molten metal, therefore all soldering will be performed in well-ventilated areas or under fume extraction hoods, and eye protection will be worn to prevent burns from solder splatter.

Carbon fiber machining introduces the risk of inhaling fine dust that is harmful to lungs and skin. Cutting or sanding carbon fiber will be done in controlled environments with protective equipment, including N95 (or higher-rated) respirators, safety goggles, and gloves, following OSHA guidelines on composite material handling. All debris will be collected with HEPA-filter vacuums and properly disposed of to prevent secondary exposure.

For general machining (e.g., drilling or cutting aluminum brackets), we will comply with the Grainger College of Engineering machine shop safety rules, which require training, the use of personal protective equipment (PPE) such as safety glasses and closed-toe shoes, and never operating machines unattended.

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