Full Project Proposal:
Transformer Robot

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Contents

1 Concept

1.1 Goal and Vision

We will build a simplified version of Caltech's Multi-Modal Mobility Morphobot (M4). The original M4 platform can transform between six locomotion modes; however, due to time and resource constraints, we narrow our scope to two high-impact modes:

- **Ground Mode:** Agile wheeled driving suitable for indoor environments.
- **Flight Mode:** Short-hop quadrotor flight for obstacle traversal.

Our goal is to design and build a morphing robot that can switch between these two modes. We want to learn as much as possible from this project, so we will implement the following components from scratch:

- Mechanical design and transformation mechanism
- Custom flight controller firmware
- Control system tuning
- Power distribution system

We recognize the complexity of designing these components. Building a flight controller alone requires deep understanding of control theory, sensor fusion, and embedded systems. However, this is our final year and we want to end it with a challenging project that pushes our abilities.

The vision is that by utilizing the same set of rotor-wheel appendages, we create a more versatile locomotion device capable of handling multiple scenarios. For example, the robot could drive efficiently through a building's corridors to survey damage, then switch to flight mode to cross a collapsed stairwell or navigate between floors through an open atrium.

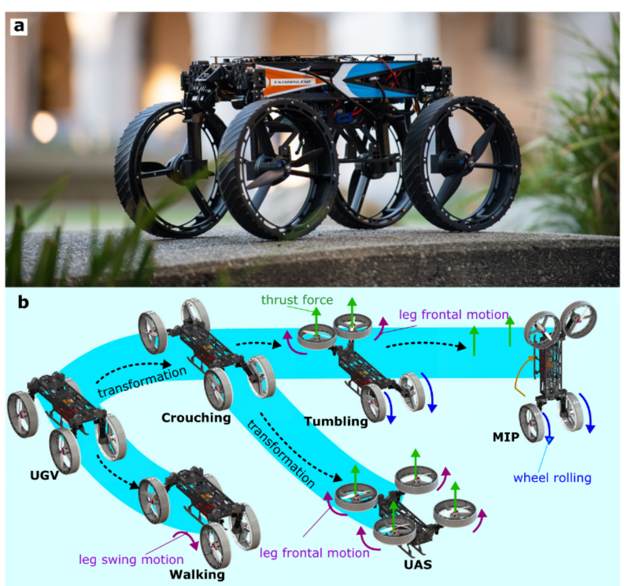

Figure 1: Caltech's M4 Robot, the inspiration for our project. The M4 demonstrates six locomotion modes through appendage repurposing.

1.2 Form Factor and Operating Concept

The robot resembles a remote-control car with four motorized wheels arranged in an "X" pattern on a central frame. What makes it special is that each wheel is part of a convertible rotor-wheel pod: essentially a propeller enclosed in a protective duct with a tire attached to its outer rim.

When driving on the ground, the pods lock flat at 0° and the motors spin the tires like a normal RC car. When the robot needs to fly (to get over obstacles or climb stairs), the four pods tilt upward to a 90° angle, the propellers spin up, and the whole system transforms into a quadcopter. Since the robot will be heavy, our goal is to provide enough flight time to hop over barriers and reach new locations, not sustained high-altitude flight.

Switching between driving and flying modes should be quick, targeting under 10 seconds. The transformation happens through motorized linear actuators that move the arms into preset positions, with Hall-effect sensors providing feedback to confirm correct positioning. An operator controls everything from an RC controller, deciding when to drive and when to take flight based on obstacles ahead.

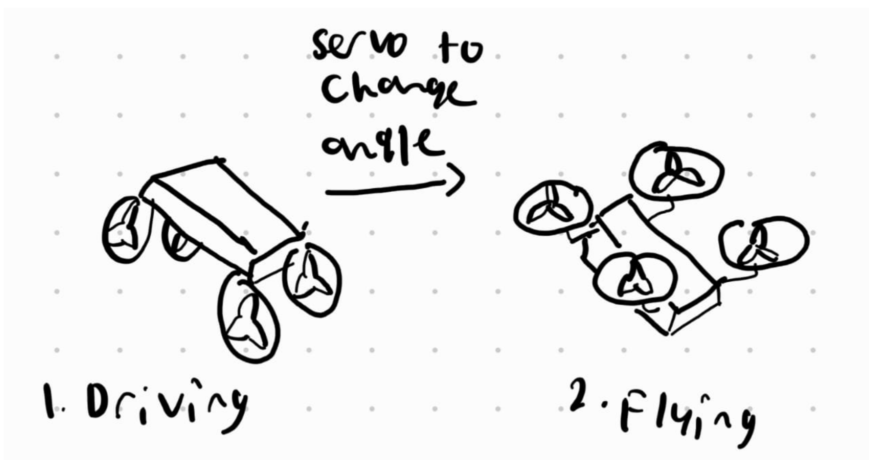

Figure 2: Conceptual sketch of the Transformer Robot in Ground Mode (left) and Flight Mode (right). The rotor-wheel pods rotate 90 degrees to switch between locomotion modes.

1.3 Conceptual Interest and Motivation

The most compelling idea is appendage repurposing, similar to how animals use their limbs for multiple functions. We must design a single electromechanical module that provides traction, thrust, and stabilization, echoing M4's research insight while staying achievable within MECH 421/423 constraints.

Both of us want to pursue further study in mobile robot navigation. Unlike typical drones or rovers whose navigation algorithms are well studied, a morphing robot presents new challenges in state estimation, control, and path planning. This project exposes us to topics we want to research in graduate school.

Finally, we think it is just cool. While this robot has practical applications in search-and-rescue, the real motivation is the challenge and learning experience. Even if the final prototype does not achieve full autonomous transitions, the process of designing the transformation mechanism, creating a working PCB, integrating control systems, and wrestling with state estimation problems will teach us more than building yet another standard quadcopter or RC car.

2 Answers to Questions from Concept Proposal

Q1: What is the value of your product to the end-user?

The added flexibility from multiple modes allows a single robot to handle various scenarios. Urban search-and-rescue teams gain a robot that can roll quietly through doorways and then quickly hop over collapsed stair segments to reach trapped occupants. The operator stays at street level, teleoperates wheeled inspection, and only flies when debris gaps appear. This approach minimizes battery use while preserving access flexibility, shortening mission timelines and reducing the number of specialized robots responders must deploy.

Beyond emergency response, this technology could find applications in space exploration (planetary rovers that can fly over obstacles), agriculture (ground surveys with aerial overviews), military reconnaissance (driving through urban environments and flying over barriers), and environmental monitoring (ground-level data collection with aerial mapping).

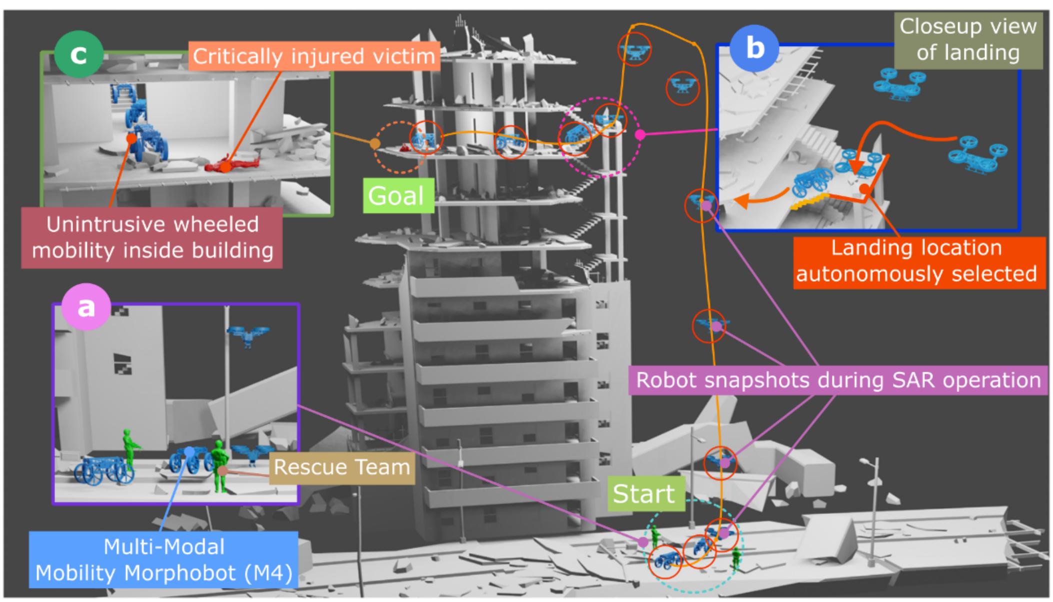

Figure 3: Search and rescue storyboard illustrating the value proposition. The robot drives through accessible areas and flies over obstacles, enabling a single device to navigate complex disaster environments.

For our demonstration, we will show that the robot can navigate through tight spaces that a typical drone cannot pass through by switching to wheeled mode.

Q2: What is the closest alternative to your product?

Since our project is inspired by Caltech's M4, their research represents the closest alternative. The M4 robot demonstrates six locomotion modes including wheeled driving, flying, walking, and tumbling.

Other academic prototypes include Caltech's ATMO (Aerially Transforming Morphobot), which uses four thrusters that double as wheels and can transform between quadcopter and ground rover modes using a single motor mechanism. Virginia Tech has developed a bistable morphing robot using shape memory alloy actuators that rapidly switches between flying and driving configurations in under 50 milliseconds.

Outside research prototypes, there is no direct commercial equivalent. The practical alternative is using two separate robots: a standard quadcopter for aerial reconnaissance and an RC car or small ground rover for close-up inspection. This is what most hobbyists and professional applications currently do, switching between devices based on terrain.

Q3: What is the metric of success for your product? How will you measure it?

We will declare success if the robot:

(i) Completes a ground-to-flight-to-ground cycle in under 20 s

(ii) Sustains 0.8 m/s average speed in drive mode for 15 m

(iii) Performs a 5 m horizontal flight hop carrying its full chassis

We will use timing gates for transformation measurements, encoder logs for ground speed verification, and visual markers or motion capture for flight distance quantification.

Q4: Pick one aspect to polish to a finished product.

The mechanical morphing mechanism and locking system will reach a polished standard. This means:

- Smooth bearing-supported hinges with minimal play
- Hidden wiring routed through the frame
- Positive locking detents that audibly click into position
- Protective covers that shield components during takeoff

A rough prototype with visible wobble, exposed wires, or detents that need hand assistance is explicitly unacceptable and will be engineered out through iterative design and cable management.

Q5: Which aspects will you not develop to a finished product?

Full autonomy will not be achieved, though we will implement enough for safe operation. We will run RC teleoperation and simple attitude stabilization, but we will not harden SLAM, obstacle avoidance, or object detection. Most movement will rely on manual operation.

Additionally, features requiring datasets and validation (such as machine learning models) will not be implemented due to time constraints and our limited experience running ML models on embedded systems.

Q6: What is your most critical module and why?

The convertible rotor-wheel pod (FC2) is most critical because it must satisfy conflicting requirements:

- Structural stiffness for fast driving over bumps
- Low mass for adequate flight performance
- Precise alignment for vibration-free hover

Failure to meet any requirement instantly degrades both locomotion modes. We will prototype this module first, run torsion and balance tests, and only then replicate it across all four corners.

Q7: What kind of data infrastructure will you need? How will you test it?

Our data infrastructure will stream wheel encoder ticks, IMU data, actuator position, current draw, and controller state vectors over serial to a logging laptop. A Python-based logging system will archive every trial with timestamps.

We will inject mock data using software simulation to ensure the telemetry pipeline handles expected bandwidth. We will then run hardware-in-the-loop bench tests where the Teensy publishes synthetic data while actuators report real motion, verifying synchronization before field trials.

3 Overview of Functional Components

The transformer robot is divided into five functional components, each addressing a specific subsystem. Table 1 summarizes each FC with effort allocation and responsible team member.

Table 1: Functional Components Overview

FC	Description	% Effort	Lead
FC1	Morphing Airframe and Transformation Mechanism	25%	Ryan
FC2	Rotor-Wheel Pod Assembly	20%	Ryan
FC3	Motor Driver and Power Electronics	20%	Gyan
FC4	Flight Controller and Sensor Fusion	20%	Gyan
FC5	Ground Station and Telemetry Interface	15%	Both

Figure 4 shows the subsystem organization, and Figure 5 shows how the functional components interact.

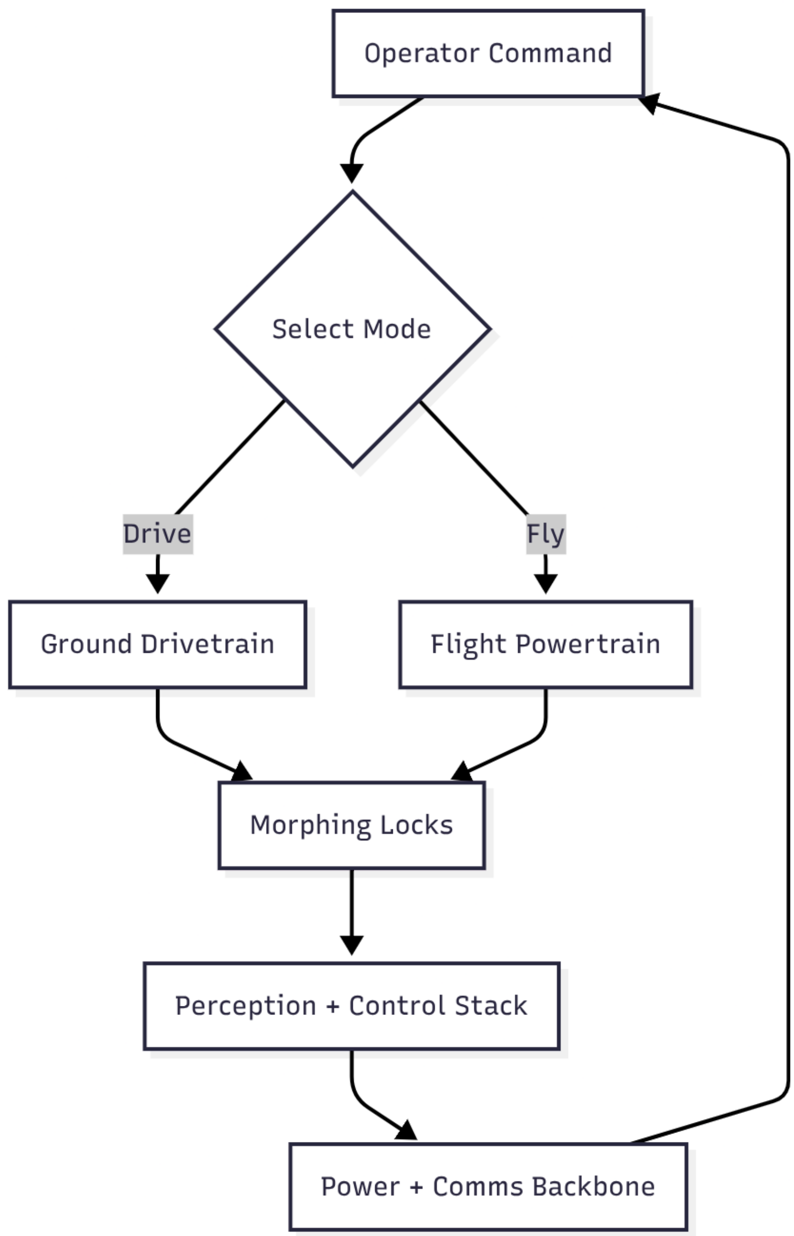

Figure 4: Subsystem flow chart showing the major components and their relationships in the Transformer Robot.

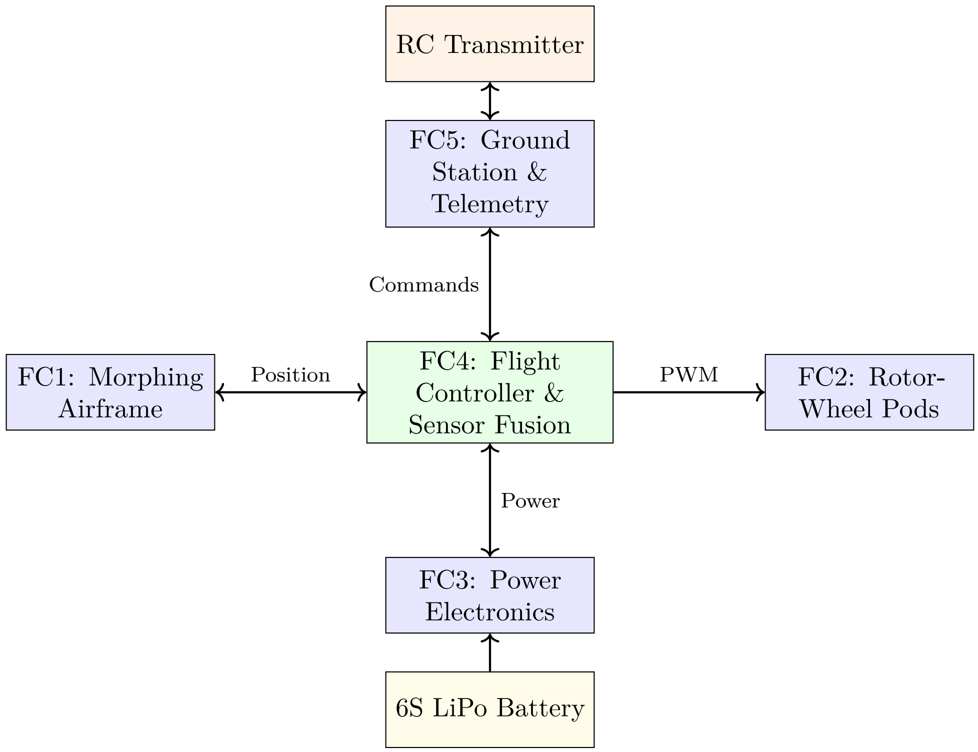

Figure 5: System Architecture Block Diagram

4 Most Critical Module

The most critical module is **FC2: Rotor-Wheel Pod Assembly**. This module faces the fundamental challenge of serving two masters: it must function as both a reliable ground wheel and an efficient aerial propulsion unit.

4.1 Challenges

Conflicting Structural Requirements: Ground driving subjects the pod to impact loads from bumps and curbs, demanding stiffness and durability. Flight requires minimal rotating mass for responsive attitude control and efficient hover. These requirements directly conflict.

Vibration and Balance: An unbalanced rotating assembly causes vibrations that degrade flight stability and accelerometer readings. The tire bonded to the propeller duct adds asymmetric mass that must be carefully balanced.

Thermal Management: Motors operating near their limits during flight generate significant heat. The enclosed duct design that protects the propeller also restricts airflow for cooling.

Manufacturing Tolerances: Four identical pods must be produced with tight tolerances. Variations in mass distribution or alignment between pods cause the flight controller to work harder to maintain stability.

4.2 Work Done So Far

We have completed preliminary CAD design of the rotor-wheel pod assembly, including:

- 3D models of the duct, hub, and tire attachment mechanism
- Structural analysis of the arm connection points
- Initial motor and propeller selection based on thrust calculations

The CAD files are located in the project repository under `/CAD/Transforming+Quadcopter/`.

4.3 Remaining Work

1. 3D print a single prototype pod for fit and function testing
2. Conduct static thrust tests to verify motor and propeller performance
3. Perform dynamic balancing using a balancing jig
4. Measure vibration spectrum during operation
5. Iterate on design based on test results
6. Replicate the final design for all four pods

Detailed development and test plans are provided in Section 6.

5 FC1: Morphing Airframe and Transformation Mechanism

5.1 Approach and Design

The morphing airframe provides the structural backbone of the robot and houses the transformation mechanism that switches between ground and flight modes.

Objective: Create a rigid yet lightweight frame that supports all components and enables reliable, repeatable transformation between locomotion modes.

Frame Construction: The main chassis consists of two carbon fiber plates (2 mm thickness, 300x200 mm) forming top and bottom decks connected by aluminum standoffs. This sandwich construction provides excellent stiffness-to-weight ratio.

Transformation Mechanism: Each rotor-wheel pod is mounted on a pivoting arm. Linear actuators drive the arms between two positions:

- Ground mode: Arms horizontal (0 °)
- Flight mode: Arms vertical (90 °)

Position Feedback: Hall-effect sensors at each pivot detect magnets embedded in the arms, providing binary feedback for locked positions. This allows the controller to verify successful transformation before enabling the appropriate control mode.

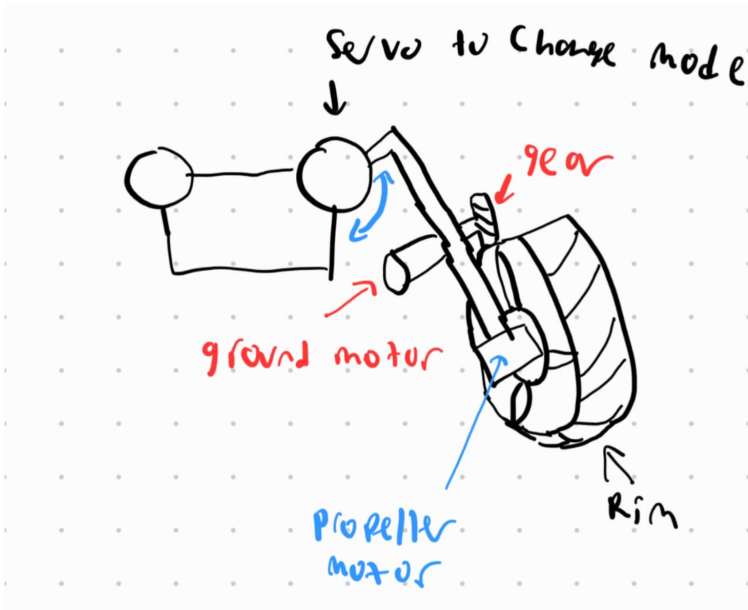

Figure 6: Preliminary concept sketch of the transformation mechanism showing the pivot arm and actuator arrangement.

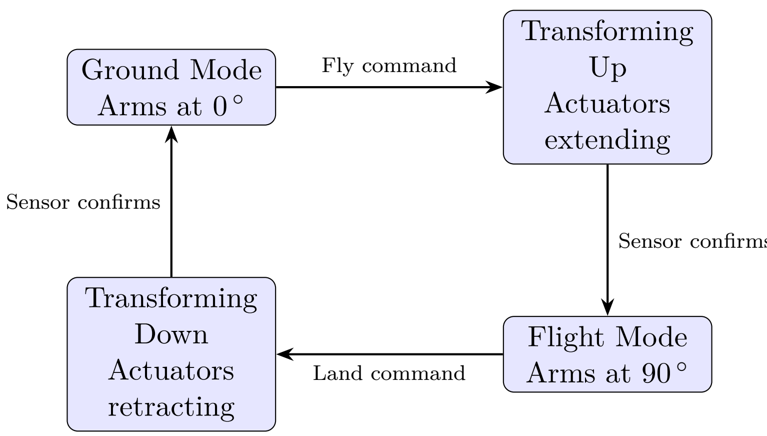

Figure 7: Transformation State Machine

[PLACEHOLDER: CAD Isometric View of Full Assembly]
Insert rendered image of complete robot assembly

Figure 8: CAD Model: Isometric View of Transformer Robot Assembly

5.2 Inputs and Outputs

Table 2: FC1 Inputs and Outputs

Signal	**Type**	**Range**	**Description**
Inputs			
Transform_Cmd	Digital	0/1	Command to initiate transformation
Target_Mode	Digital	0/1	0 = Ground, 1 = Flight
Outputs			
Actuator_PWM	PWM	0–100%	Drive signal to linear actuators
Actuator_Dir	Digital	0/1	Direction control (extend/retract)
Feedback			
Hall_Ground	Digital	0/1	Ground position detected
Hall_Flight	Digital	0/1	Flight position detected
Current_Sense	Analog	0–5 V	Actuator current for stall detection

5.3 Parameters

- **Ground angle:** 0° (horizontal arms)
- **Flight angle:** 90° (vertical arms)
- **Actuator stroke:** 100 mm
- **Actuator force:** 150 N minimum (upgraded from initial 60 N)
- **Actuator speed:** 15 mm/s
- **Transformation timeout:** 10 s maximum
- **Hall sensor threshold:** Digital with 5 mm magnet proximity

The actuator force was increased from 60 N after preliminary calculations showed the original specification was marginal for lifting the pod mass against gravity during transformation.

5.4 Development Plan

1. Finalize frame CAD and generate DXF files for carbon fiber cutting
2. Order carbon fiber plates and have them CNC cut
3. 3D print mounting brackets and actuator housings in PLA
4. Assemble frame with standoffs and verify dimensional accuracy
5. Mount linear actuators and wire to DRV8871 drivers
6. Install Hall-effect sensors and calibrate detection positions
7. Write transformation control routine and integrate with main controller
8. Conduct transformation cycle testing

5.5 Test Plan

Table 3: FC1 Test Plan

Test	**Method**	**Success Criteria**
Transformation Time	Stopwatch timing	< 10 s full cycle
Lock Engagement	Visual inspection	Audible click, no wobble
Position Accuracy	Protractor measurement	$\pm 2^\circ$ of target
Cycle Fatigue	100 transformation cycles	No mechanical degradation
Sensor Reliability	50 detection tests	100% correct detection

6 FC2: Rotor-Wheel Pod Assembly

6.1 Approach and Design

The rotor-wheel pod is the defining feature of the transformer robot, serving as both wheel and propulsion unit.

Objective: Create a module that provides ground traction when horizontal and aerial thrust when vertical, using shared mechanical components.

Pod Construction: Each pod consists of:

- **Brushless motor:** 2812 Pro 1100 KV mounted at the center
- **Propeller:** 8-inch or 9-inch propeller attached to motor shaft
- **Duct:** 3D-printed shroud surrounding the propeller for protection and efficiency
- **Tire:** Rubber tire bonded to the outer rim of the duct
- **Hub:** Central hub connecting the pod to the pivot arm

Operating Modes:

- **Ground mode:** Motor spins the entire pod assembly; tire contacts ground for traction
- **Flight mode:** Motor spins only the propeller; pod body remains stationary

A clutch mechanism (or separate drive motors) may be needed to decouple the propeller from the duct during ground operation. Initial prototypes will test both approaches.

[**PLACEHOLDER: Exploded View of Rotor-Wheel Pod**]
Insert CAD exploded view showing motor, propeller, duct, tire, and hub

Figure 9: CAD Model: Exploded View of Rotor-Wheel Pod Assembly

6.2 Inputs and Outputs

Table 4: FC2 Inputs and Outputs

Signal	**Type**	**Range**	**Description**
Inputs (from FC4)			
Motor_PWM	PWM	1000 μs–2000 μs	Throttle command to ESC
Outputs (mechanical)			
Thrust (flight)	Force	0–10 N	Vertical thrust per pod
Torque (ground)	Torque	0–0.5 Nm	Drive torque at wheel
Feedback			
RPM (optional)	Frequency	0–15000 RPM	Motor speed from ESC telemetry

6.3 Parameters

- **Motor KV rating:** 1100 KV (RPM per volt)
- **Propeller size:** 8x4.5 or 9x5 inches (diameter x pitch)
- **Tire outer diameter:** 100 mm
- **Duct inner clearance:** 2 mm tip gap
- **Pod total mass:** Target $<$ 300 g

- **Static thrust:** Target > 800 g per pod at full throttle

Propeller pitch affects both thrust and efficiency. Higher pitch provides more thrust but requires more power. We will test multiple propeller options to find the best balance.

6.4 Development Plan

1. Finalize single pod CAD design
2. 3D print duct and hub components
3. Assemble prototype with motor and propeller (without tire initially)
4. Conduct static thrust test on test stand
5. Add tire and repeat thrust test to measure impact
6. Perform dynamic balancing using a balancing jig
7. Measure vibration spectrum with accelerometer
8. Iterate design based on results
9. Produce four matched pods for final assembly

6.5 Test Plan

Table 5: FC2 Test Plan

Test	**Method**	**Success Criteria**
Static Thrust	Load cell test stand	> 800 g per pod
Vibration	Accelerometer FFT	No dominant peaks > 0.5 g RMS
Balance	Balancing jig	< 1 g-cm imbalance
Thermal	Thermocouple on motor	< 80 °C after 60 s hover
Ground Traction	Tow force measurement	> 2 N traction force

7 FC3: Motor Driver and Power Electronics

7.1 Approach and Design

The power electronics subsystem manages energy distribution from the battery to all motors and provides regulated power for control electronics.

Objective: Deliver reliable power to all actuators while protecting against overcurrent, undervoltage, and reverse polarity conditions.

Components:

- **Flight ESCs:** 4-in-1 45 A ESC stack for the four flight motors
- **Drive ESCs:** Two 35 A bidirectional ESCs for ground drive motors (5010 360 KV)
- **Actuator drivers:** Two DRV8871 H-bridge modules for linear actuators
- **Voltage regulators:** Buck converters for 5 V (logic) and 12 V (actuators)

- **Power distribution:** Custom PCB with XT60 connectors

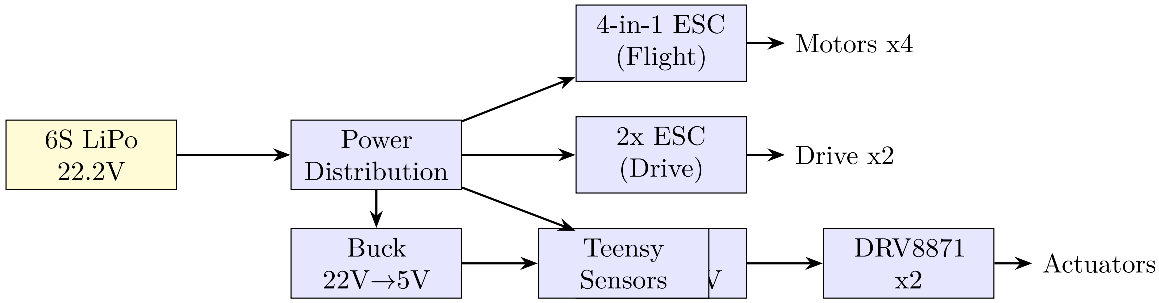

Figure 10: Power Distribution Diagram

[PLACEHOLDER: Power Distribution Schematic]
Insert detailed circuit schematic showing all power connections

Figure 11: Circuit Schematic: Power Distribution Board

7.2 Inputs and Outputs

Table 6: FC3 Inputs and Outputs

Signal	Type	Range	Description
Power Inputs			
Battery_V	DC	18.5 V–25.2 V	6S LiPo voltage range
Control Inputs (from FC4)			
Flight_PWM[4]	PWM	1000–2000 μs	Four flight motor commands
Drive_PWM[2]	PWM	1000–2000 μs	Two drive motor commands
Act_PWM[2]	PWM	0–100%	Two actuator speed commands
Act_Dir[2]	Digital	0/1	Actuator direction
Power Outputs			
Rail_22V	DC	22.2 V	Main battery rail
Rail_12V	DC	12 V regulated	Actuator supply
Rail_5V	DC	5 V regulated	Logic supply
Feedback			
V_Sense	Analog	0–3.3 V	Battery voltage (divided)
I_Sense	Analog	0–3.3 V	Total current draw

7.3 Parameters

- **ESC PWM frequency:** 400 Hz standard, 32 kHz if DShot used
- **ESC timing:** Auto or medium-high (motor dependent)
- **Current limit:** 45 A per flight motor, 35 A per drive motor
- **Low voltage cutoff:** 3.3 V per cell (19.8 V for 6S)
- **Buck converter efficiency:** $> 90\%$ expected

7.4 Development Plan

1. Bench test each ESC with motor on test stand
2. Verify bidirectional operation of drive ESCs
3. Build power distribution board (or use off-the-shelf PDB)
4. Integrate buck converters and verify output voltages under load
5. Wire DRV8871 modules and test with linear actuators
6. Calibrate voltage and current sensing
7. Perform thermal testing under simulated load
8. Integrate complete wiring harness

7.5 Test Plan

Table 7: FC3 Test Plan

Test	Method	Success Criteria
Voltage Regulation	Multimeter under load	5 V ± 0.1 V, 12 V ± 0.5 V
Current Capacity	Ammeter during operation	Sustained 60 A without trip
Thermal	IR thermometer	< 70 °C on ESCs
Failsafe	Disconnect signal wire	Motors stop within 1 s
Reverse Operation	Command negative throttle	Drive motors reverse smoothly

8 FC4: Flight Controller and Sensor Fusion

8.1 Approach and Design

The flight controller is the brain of the robot, processing sensor data and generating motor commands for stable flight and controlled ground driving.

Objective: Implement attitude estimation and closed-loop control for both flight and ground modes.

Hardware:

- **Microcontroller:** Teensy 4.0 (600 MHz ARM Cortex-M7)
- **IMU:** MPU6050 or ICM-20948 (accelerometer + gyroscope)
- **RC Receiver:** Standard PWM or SBUS receiver
- **Optional:** Barometer for altitude hold, GPS for position

Software Architecture:

- Sensor reading at 1 kHz
- Complementary filter for attitude estimation
- Cascaded PID control (rate loop at 1 kHz, angle loop at 500 Hz)
- Motor mixing for quadrotor configuration

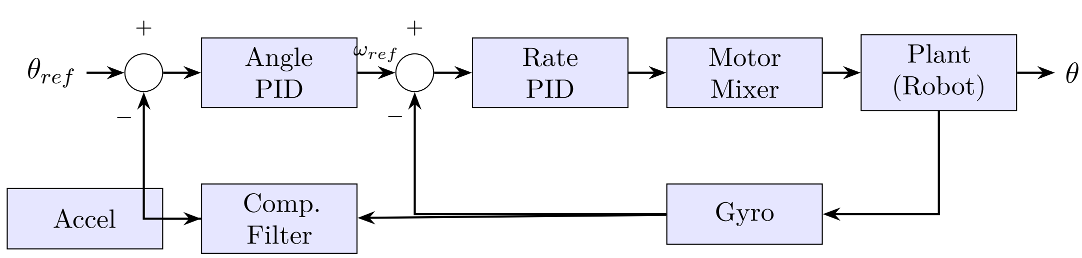

Figure 12: Flight Control Loop Block Diagram

8.2 Inputs and Outputs

Table 8: FC4 Inputs and Outputs

Signal	Type	Range	Description
Sensor Inputs			
Accel_XYZ	I2C/SPI	$\pm 16\,\mathrm{g}$	3-axis acceleration
Gyro_XYZ	I2C/SPI	$\pm 2000\,°/\mathrm{s}$	3-axis angular rate
RC Inputs			
RC_Throttle	PWM	1000 – 2000 μs	Throttle command
RC_Roll	PWM	1000 – 2000 μs	Roll command
RC_Pitch	PWM	1000 – 2000 μs	Pitch command
RC_Yaw	PWM	1000 – 2000 μs	Yaw command
RC_Mode	PWM	1000 – 2000 μs	Mode switch
Control Outputs			
Motor_PWM[4]	PWM	1000 – 2000 μs	Flight motor commands
Drive_PWM[2]	PWM	1000 – 2000 μs	Drive motor commands
Status Outputs			
Telemetry	UART	115200 baud	State data to ground station

8.3 Parameters

Attitude Estimation:

- Complementary filter alpha: 0.98 (gyro weight)
- Gyro calibration offset: Measured at startup
- Accelerometer calibration: 6-point calibration

PID Gains (initial estimates, require tuning):

- Roll rate: $K_p = 0.5$, $K_i = 0.3$, $K_d = 0.05$
- Pitch rate: $K_p = 0.5$, $K_i = 0.3$, $K_d = 0.05$
- Yaw rate: $K_p = 1.0$, $K_i = 0.5$, $K_d = 0.0$
- Roll angle: $K_p = 4.0$, $K_i = 0.0$, $K_d = 0.0$
- Pitch angle: $K_p = 4.0$, $K_i = 0.0$, $K_d = 0.0$

Control Loop Rates:

- Sensor read: 1000 Hz
- Rate PID: 1000 Hz
- Angle PID: 500 Hz
- Telemetry: 50 Hz

8.4 Development Plan

1. Set up Teensy development environment (Arduino IDE or PlatformIO)
2. Read IMU data over I2C and verify values
3. Implement complementary filter and verify attitude estimation
4. Implement rate PID controller
5. Test rate control on single-axis gimbal jig
6. Implement angle PID controller
7. Implement motor mixing for X-quad configuration
8. Integrate RC receiver input
9. Conduct tethered flight tests
10. Tune PID gains through flight testing

8.5 Test Plan

Table 9: FC4 Test Plan

Test	**Method**	**Success Criteria**
IMU Accuracy	Compare to reference IMU	$< 2°$ error
Attitude Estimation	Rotate by known angles	$< 5°$ drift over 60 s
Rate Response	Step input on gimbal	Settling time < 0.5 s
Angle Response	Step input on gimbal	Settling time < 1 s
Hover Stability	Tethered hover test	Maintains $\pm 10°$ for 30 s

9 FC5: Ground Station and Telemetry Interface

9.1 Approach and Design

The ground station provides the operator interface and data logging capability.

Objective: Enable remote monitoring and control of the robot with real-time data display and logging.

Components:

- **RC Transmitter:** Standard 6+ channel transmitter (e.g., FlySky, FrSky)
- **Telemetry Radio:** Serial link (433 MHz or 915 MHz) or USB cable for testing
- **Ground Station Software:** Python GUI using PyQt or tkinter

Display Features:

- Real-time attitude display (artificial horizon)
- Battery voltage and current
- Motor outputs

- Transformation state
- Data logging to CSV files

[PLACEHOLDER: Ground Station GUI Screenshot]
Insert screenshot of telemetry display software

Figure 13: Ground Station Software Interface

9.2 Inputs and Outputs

Table 10: FC5 Inputs and Outputs

Signal	**Type**	**Format**	**Description**
Incoming (from robot)			
Telemetry_Packet	Serial	See below	State data packet
Outgoing (to robot)			
Command_Packet	Serial	See below	Configuration commands

Telemetry Packet Format (20 bytes):

```
Byte 0-1:   Header (0xAA 0x55)
Byte 2-3:   Roll angle (int16, 0.01 deg/LSB)
Byte 4-5:   Pitch angle (int16, 0.01 deg/LSB)
Byte 6-7:   Yaw angle (int16, 0.01 deg/LSB)
Byte 8-9:   Battery voltage (uint16, mV)
Byte 10-11: Current draw (uint16, mA)
Byte 12:    Mode (0=Ground, 1=Flight, 2=Transforming)
Byte 13-16: Motor outputs (4x uint8, 0-255)
Byte 17-18: Timestamp (uint16, ms)
Byte 19:    Checksum (XOR of bytes 2-18)
```

9.3 Parameters

- **Baud rate:** 115200 baud

- **Telemetry rate:** 50 Hz
- **Log file format:** CSV with timestamp
- **Display update rate:** 30 Hz

9.4 Development Plan

1. Define serial packet format
2. Implement packet encoding on Teensy
3. Write Python serial receiver
4. Create basic text display of received data
5. Add graphical attitude indicator
6. Implement data logging to CSV
7. Add real-time plotting capability
8. Test range and reliability with telemetry radio

9.5 Test Plan

Table 11: FC5 Test Plan

Test	**Method**	**Success Criteria**
Packet Integrity	Send known data	0% packet loss over 1000 packets
Latency	Timestamp comparison	< 50 ms end-to-end
Range	Increase distance	> 50 m reliable link
Logging	Review saved files	All data recoverable from log

10 Data Infrastructure Development

The data infrastructure enables information flow from sensors to the operator and supports development debugging.

10.1 Data Flow Architecture

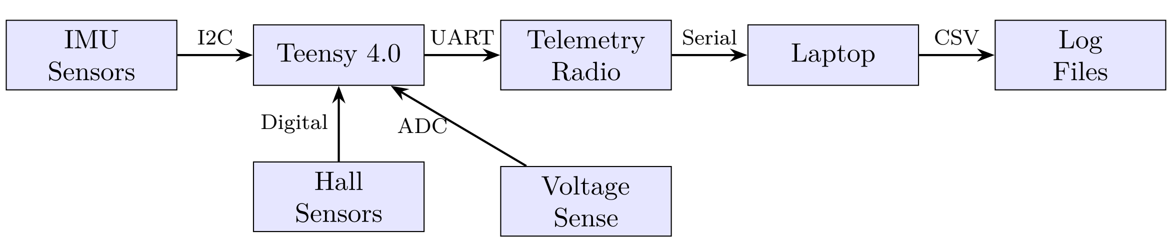

Figure 14: Data Flow Diagram

10.2 Data Rates and Bandwidth

Table 12: Data Rate Requirements

Data Source	Sample Rate	Bytes/sec
IMU (6-axis)	1000 Hz	12,000
Hall sensors (4)	100 Hz	400
Battery voltage	10 Hz	20
Motor commands (6)	500 Hz	3,000
Telemetry output	50 Hz	1,000

At 115200 baud, the serial link supports approximately 11.5 kB/s, which is sufficient for the 1 kB/s telemetry stream with margin for overhead.

10.3 Mock Data Testing

Before hardware is available, we will test the data pipeline using mock data:

1. Generate synthetic IMU data with known motion profiles
2. Inject synthetic data into the processing pipeline
3. Verify attitude estimation produces expected results
4. Test telemetry encoding/decoding with generated packets
5. Verify logging and playback functionality

10.4 Hardware-in-the-Loop Testing

Once hardware is available:

1. Connect Teensy to sensors and verify raw data quality
2. Stream real sensor data to laptop and verify reception
3. Compare real data statistics to expected ranges
4. Test under vibration and electromagnetic interference

11 System-Level Test Plan

System-level tests evaluate the complete integrated robot against the success metrics defined in Section 2.

11.1 Test 1: Transformation Cycle Time

Objective: Verify transformation between modes completes within target time.

Setup: Robot on flat ground, fully charged battery, operator with RC controller.

Procedure:

1. Start in ground mode with all sensors indicating ground position
2. Command transformation to flight mode
3. Record time from command to flight-ready indication
4. Command transformation back to ground mode
5. Record time from command to ground-ready indication

Success Criteria: Full ground-to-flight-to-ground cycle $< 20\,\mathrm{s}$

Metrics Recorded:

- Transformation time (each direction)
- Actuator current during transformation
- Hall sensor state transitions

11.2 Test 2: Ground Drive Performance

Objective: Verify ground mode drive speed and control.

Setup: Robot in ground mode on smooth floor, 15 m marked course.

Procedure:

1. Position robot at start line
2. Command forward drive at 75% throttle
3. Record time to cross 15 m finish line
4. Repeat 5 times for consistency

Success Criteria: Average speed $\geq 0.8\,\mathrm{m/s}$

Metrics Recorded:

- Transit time
- Motor current draw
- Any steering corrections required

11.3 Test 3: Flight Hop Performance

Objective: Verify flight mode can achieve horizontal distance.

Setup: Robot in flight mode, outdoor area with markers at 5 m intervals.

Procedure:

1. Position robot at start marker
2. Arm motors and command takeoff
3. Fly horizontally toward 5 m marker
4. Land and measure actual distance traveled

5. Repeat 3 times

Success Criteria: Achieves $\geq 5\,\text{m}$ horizontal displacement

Metrics Recorded:

- Flight distance
- Flight duration
- Battery consumption
- Maximum altitude reached

11.4 Test 4: Polished Aspect Evaluation (Transformation Mechanism)

Objective: Evaluate the finish quality of the transformation mechanism.

Criteria Checklist:

- ☐ Hinges move smoothly without binding
- ☐ No visible wobble in locked positions
- ☐ Wiring is hidden from view
- ☐ Locking detents click audibly
- ☐ No hand assistance needed for transformation
- ☐ Consistent transformation time ($\pm 1\,\text{s}$)
- ☐ Mechanism survives 100 cycles without degradation

11.5 Test 5: Full Mission Scenario

Objective: Demonstrate complete operational capability.

Scenario: Simulate navigating through a doorway (ground mode), encountering an obstacle, transforming to flight mode, hopping over the obstacle, landing, and transforming back to ground mode.

Setup: Indoor space with simulated obstacle (0.5 m height).

Procedure:

1. Start in ground mode, drive 5 m toward obstacle
2. Stop and command transformation to flight mode
3. Take off and fly over obstacle
4. Land on opposite side
5. Transform back to ground mode
6. Drive 5 m away from obstacle

Success Criteria: Complete mission without manual intervention.

12 Engineering Calculations

This section presents the engineering calculations that justify our component selections.

12.1 Mass Budget

Table 13: Estimated Mass Budget

Component	**Mass (g)**	**Notes**
Carbon fiber frame	200	Two 300x200x2mm plates
Rotor-wheel pods (x4)	1200	300g each including motor
Linear actuators (x2)	200	100g each
Batteries (x2)	400	200g each (6S 2200mAh)
Electronics	150	Teensy, ESCs, PDB, wiring
Servos and misc	100	DS3225 x2 plus hardware
Total	**2250**	

Design margin: Target $< 2.5\,\text{kg}$ total mass.

12.2 Motor Thrust Calculation

For stable hover, total thrust must exceed weight. For agile flight, we target a thrust-to-weight ratio of 2:1.

Required total thrust:

$$T_{total} = 2 \times m \times g = 2 \times 2.5\,\text{kg} \times 9.81\,\text{m/s}^2 = 49.1\,\text{N} \tag{1}$$

Required thrust per motor:

$$T_{motor} = \frac{T_{total}}{4} = \frac{49.1\,\text{N}}{4} = 12.3\,\text{N} \approx 1250\,\text{g} \tag{2}$$

Selected motor analysis:

The 2812 Pro 1100 KV motor with 8-inch propeller produces approximately 800 g thrust at full throttle according to manufacturer data. This gives:

$$\text{T/W ratio} = \frac{4 \times 800\,\text{g}}{2500\,\text{g}} = \frac{3200}{2500} = 1.28 \tag{3}$$

This is below our target of 2.0. **Mitigation options:**

1. Upgrade to 9-inch propellers (estimated 1000 g/motor) → T/W = 1.6
2. Reduce total mass through design optimization
3. Accept lower agility for initial prototype

For the initial prototype, we will proceed with T/W = 1.28 and verify hover stability before considering upgrades.

12.3 Servo Torque Calculation

The transformation servos must lift the rotor-wheel pod mass against gravity.

Pod mass: $m_{pod} = 300\,\text{g} = 0.3\,\text{kg}$

Arm length to center of mass: $r = 150\,\text{mm} = 0.15\,\text{m}$

Required torque (worst case, arm horizontal):

$$\tau = m_{pod} \times g \times r = 0.3\,\text{kg} \times 9.81\,\text{m/s}^2 \times 0.15\,\text{m} = 0.44\,\text{Nm} \tag{4}$$

Converting to kg-cm:

$$\tau = 0.44\,\text{Nm} \times \frac{100\,\text{cm}}{1\,\text{m}} \times \frac{1\,\text{kg}}{9.81\,\text{N}} = 4.5\,\text{kg-cm} \tag{5}$$

Selected servo: DS3225 rated at 25 kg-cm

Safety factor:

$$SF = \frac{25}{4.5} = 5.5 \tag{6}$$

This provides excellent margin for dynamic loads during transformation.

12.4 Linear Actuator Force Calculation

The linear actuators assist the servos in transformation. We analyze the force required.

Assuming the actuator pushes on the arm at a 45° angle to the pivot:

Mechanical advantage: Approximately 1.5 based on geometry

Required actuator force:

$$F_{act} = \frac{m_{pod} \times g}{MA} \times SF = \frac{0.3\,\text{kg} \times 9.81\,\text{m/s}^2}{1.5} \times 2 = 3.9\,\text{N} \tag{7}$$

The original 60 N actuator would seem sufficient, but this calculation ignores:

- Friction in the pivot bearings
- Dynamic loads from acceleration
- Stall force derating

The BOM notes recommend upgrading to 150 N or higher for reliable operation. We will use 150 N actuators.

12.5 Battery Sizing Calculation

Flight power consumption (estimated):

- Each motor at hover: 10 A (estimated from motor specs)
- Total flight current: $4 \times 10\,\text{A} = 40\,\text{A}$

Battery capacity: 6S 2200 mAh = 2.2 Ah

Hover time (80% usable capacity):

$$t_{hover} = \frac{0.8 \times 2.2\,\text{Ah}}{40\,\text{A}} \times 60\,\text{min/hr} = 2.6\,\text{min} \tag{8}$$

This is sufficient for short hop maneuvers. With two batteries, we have 5.2 minutes total hover time.

Battery discharge rate verification:

Peak current (full throttle, 4 motors): $4 \times 25\,\text{A} = 100\,\text{A}$

Required C-rating:

$$C = \frac{100\,\text{A}}{2.2\,\text{Ah}} = 45C \tag{9}$$

Selected battery: 150C rating → Max discharge = $150 \times 2.2\,\text{A} = 330\,\text{A}$

This provides excellent margin for peak demands.

12.6 Structural Analysis

Carbon fiber plate bending:

For a simply supported plate with center load:

$$\sigma_{max} = \frac{6 \times P \times L}{b \times t^2} \tag{10}$$

Where:

- $P = 25\,\text{N}$ (point load from battery)
- $L = 150\,\text{mm}$ (half span)
- $b = 200\,\text{mm}$ (width)
- $t = 2\,\text{mm}$ (thickness)

$$\sigma_{max} = \frac{6 \times 25 \times 0.15}{0.2 \times 0.002^2} = 28.1\,\text{MPa} \tag{11}$$

Carbon fiber tensile strength: $> 500\,\text{MPa}$

Safety factor: > 17 (more than adequate)

13 Bill of Materials

Table 14 presents the complete bill of materials for the transformer robot.

Table 14: Bill of Materials

Component	Description	Qty	Unit	Total	Source
Actuators					
Servo DS3225	25kg torque, 180 deg	2	€14.39	€28.78	AliExpress
Motor 2812 Pro	1100KV brushless	4	€11.00	€44.00	AliExpress
Motor 5010	360KV brushless (drive)	2	€17.29	€34.58	AliExpress
Linear Actuator	12V, 100mm, 150N	2	€17.70	€35.40	AliExpress
Motor Control					
4-in-1 ESC	45A brushless	1	€30.00	€30.00	GetFPV
Bidirectional ESC	35A brushless	2	€10.29	€20.58	Amazon
DRV8871	H-bridge driver	2	€3.15	€6.30	Amazon
Flight Components					
Propellers	8x4.5 or 9x5 (CW/CCW)	4	€0.92	€3.68	Amazon
Structure					
Carbon Fiber Plate	2mm, 300x200mm	2	€80.00	€160.00	Amazon
Bearings	MR128-2RS, 12x8x3.5mm	6	€1.20	€7.20	Amazon
3D Printed Parts	PLA filament	1	€20.00	€20.00	Local
Power					
6S LiPo Battery	2200mAh, 150C	2	€25.00	€50.00	Amazon
Buck Converter	22V to 5V	1	€2.00	€2.00	AliExpress
Buck Converter	22V to 12V	1	€2.00	€2.00	AliExpress
Electronics					
Teensy 4.0	Microcontroller	1	€30.40	€30.40	PJRC
Custom PCB	Power distribution	1	€8.31	€8.31	JLCPCB
XT60 Connectors	Power connectors	10	€2.00	€20.00	Amazon
IMU (MPU6050)	6-axis sensor	1	€5.00	€5.00	Amazon
Misc Electronics	Wire, headers, etc.	1	€15.00	€15.00	Various
			Total (EUR)	**€523.23**	
			Total (CAD, approx)	**$760**	

Budget Notes:

- Course budget: $200 CAD from Digikey/McMaster/Amazon
- Remaining cost: $560 CAD (personal funds)
- Carbon fiber plates are the largest expense; alternatives include aluminum or 3D printed frames
- Some components may be available from the parts library

14 Preliminary Design

This section provides placeholder figures for CAD and circuit documentation.

[**PLACEHOLDER: Transformation Sequence Diagram**]
Insert sequence of images showing ground-to-flight transformation

Figure 15: Transformation Sequence: Ground Mode to Flight Mode

[**PLACEHOLDER: Signal Routing Schematic**]
Insert circuit schematic showing signal connections between Teensy, sensors, and ESCs

Figure 16: Circuit Schematic: Signal Routing

[PLACEHOLDER: PCB Layout]
Insert PCB layout image from KiCad/JLCPCB

Figure 17: Custom PCB Layout for Power Distribution

References

1. E. Sabree et al., "Multi-Modal Mobility Morphobot (M4) with appendage repurposing for locomotion plasticity enhancement," *Nature Communications*, 2023.
2. Caltech Autonomous Systems and Technologies, M4 Robot Project Documentation.
3. EMAX Motor Specifications, 2812 Pro Series Datasheet.
4. Teensy 4.0 Technical Reference Manual, PJRC.