CP 301: DEVELOPMENT ENGINEERING PROJECT

CONCEPT DESIGN AND PROTOTYPE DEVELOPMENT OF A UGV-UAV TRANSFORMER

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We are also thankful to the MUSE Lab, Modular Intelligence and Robotics Lab, Design Lab, Thermo-Fluids Lab, Design Studio, Manufacturing Technology Lab and the Central Workshop for providing us access to various resources and facilities at different stages of the project. The support from these labs played a crucial role in enabling us to carry out our work efficiently and effectively.

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CHAPTER 1
INTRODUCTION

1.1 Motivation

The motivation for this project stems from the limitations of single-mode robotic systems and the growing need for adaptable autonomous solutions. Traditional UGVs struggle with obstacles,
while UAVs have limited battery life and payload capacity. A hybrid system that seamlessly transforms between ground and aerial movement offers a versatile and efficient alternative. Inspired by nature's adaptive mobility—such as birds that run and fly—we sought to develop a cost-effective, dual-purpose robot that merges the advantages of both UGVs and UAVs. This
solution is particularly beneficial for agriculture, logistics, disaster response, and industrial inspection, where a single-mode system is inefficient.

Recent advancements in robotics, AI, and automation have made multi-modal systems more viable. We were driven by the technical challenge of designing a seamless transformation
mechanism, integrating mechanical design, aerodynamics, and power efficiency into a single, functional unit.

By developing this UGV-UAV Transformer, we aim to bridge the gap between ground and aerial mobility, creating a scalable and intelligent robotic system for real-world applications.

1.2 Problem Statement

This project focuses on the design and development of a UGV-UAV Transformer, a robotic system capable of seamlessly transitioning between ground and aerial modes. This hybrid system will integrate:

- A mechanical transformation mechanism enabling mode transition.
- High-torque motors and actuators for stable UGV operation.
- Quadcopter propulsion technology for controlled UAV functionality.
- An optimized power and control system for efficient energy utilization.

1.3 Work Plan

The development of the UGV-UAV Transformer was executed in a phase-wise manner, ensuring systematic design, fabrication, and testing. The plan was structured into three main phases, each focusing on different aspects of the project.

- **Phase 1**: UGV Assembly and Ground Mobility Testing
  - Objective:
    - Construct the UGV chassis and drivetrain to establish stable ground mobility.
    - Integrate and test DC motors, servo motors, and motor drivers.
    - Ensure structural stability and weight distribution for seamless transformation.
  - Components and Tasks:
    - Assemble UGV frame using carbon fiber and lightweight materials.
    - Install and configure BLDC motors, servo motors, and motor driver

        (L298N).
        - Program ESP-32 microcontroller for basic movement control.
        - Conduct torque and traction testing to validate ground mobility.

- **Phase 2**: Transformation Mechanism and UAV Integration
    - Objective:
        - Implement the mechanical transformation system for mode switching.
        - Integrate linear actuators, servo motors, and locking mechanisms.
        - Assemble and test UAV propulsion (quad-propeller system).
    - Components and Tasks:
        - Attach linear actuators for transformation from UGV to UAV mode.
        - Install quad-propeller system and brushless motors for UAV mode.
        - Configure Electronic Speed Controllers (ESCs) and Flight Controller.
        - Conduct mode transition stability tests to ensure smooth transformation.
    - Perform flight stabilization tests for UAV functionality.
- **Phase 3**: Final Assembly, Testing, and Optimization
    - Objective:
        - Perform full-system integration of UGV and UAV functions.
        - Optimize control algorithms for seamless mode switching.
        - Conduct final performance evaluations and troubleshooting.
    - Tasks:
        - Optimize power management system for extended battery life.
        - Implement remote control functionality via a wireless receiver and remote controller.
        - Conduct real-world testing in different terrains to validate system performance.
        - Troubleshoot mechanical, electrical, and software issues.
        - Document final results and prepare project demonstration.

1.4 Expected outcomes at the end of the project

- Successfully develop a working prototype of the UGV-UAV Transformer.
- Achieve seamless transformation between UGV and UAV modes.
- Validate mechanical integrity, aerodynamics, and power efficiency.
- Demonstrate real-world applications in various industries.

CHAPTER 2
LITERATURE

2.1 Principle of Working

The UGV-UAV Transformer operates by integrating ground and aerial locomotion into a single robotic system. The primary principle behind its operation involves a seamless transition between Unmanned Ground Vehicle (UGV) and Unmanned Aerial Vehicle (UAV) modes, enabling mobility across different terrains and obstacles. This is achieved through a mechanical transformation mechanism that repurposes components for both ground and aerial movement.

In UGV mode, the robot utilizes high-torque motors and a stable chassis for ground mobility, allowing it to traverse rough terrain with precise control. The wheels or tracks provide traction, while the onboard sensors facilitate navigation and obstacle avoidance. When aerial mobility is required, the system engages actuators and folding mechanisms to deploy propellers, transitioning into UAV mode. Brushless motors and electronic speed controllers (ESCs) power the propellers, lifting the system off the ground for aerial operation.

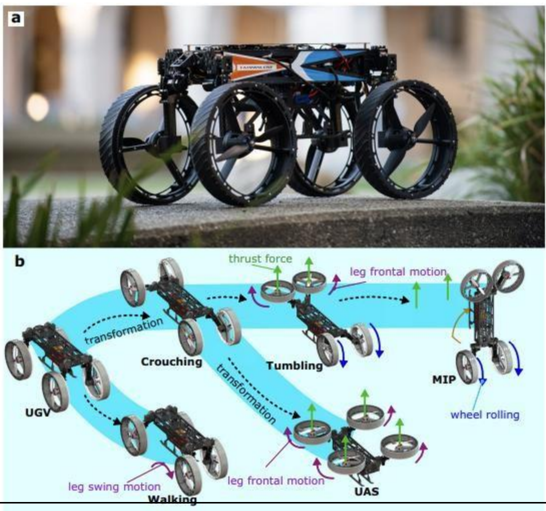
The transformation between UGV and UAV is achieved through a combination of linear actuators and servo motors that adjust the robot’s structural configuration. This design ensures minimal energy loss and optimal weight distribution, allowing efficient operation in both modes. Additionally, a centralized control system manages power allocation, stability control, and mode transitions to ensure a seamless and autonomous transformation process.

2.2 An overview of past work

- Research on hybrid UGV-UAV systems has gained significant traction in recent years, with various prototypes demonstrating multi-modal mobility. Some of them are mentioned below –

“Sihite, E., Kalantari, A., Nemovi, R. et al. Multi-Modal Mobility Morphobot (M4) with appendage repurposing for locomotion plasticity enhancement. Nat Commun 14, 3323 (2023).” – ***link***

- One of the notable works in this domain is the Multi-Modal Mobility Morphobot (M4) developed by Caltech. The M4 employs a unique appendage repurposing strategy, allowing it to roll, crawl, crouch, and fly using the same set of actuators. Inspired by biological models such as birds and quadrupeds, M4 showcases the potential of integrating multiple locomotion modes into a single platform.

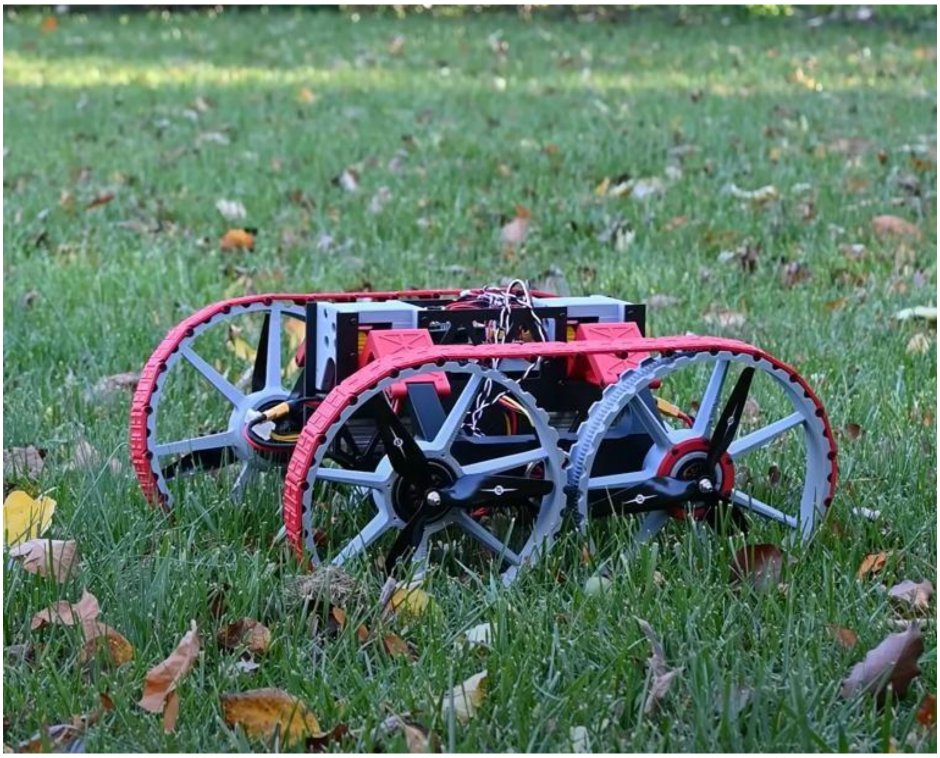


"{Chen}, Le and {Yu}, Jie and {Chen}, XingWu. et al. GuLu·XuanYuan , a biomimetic Transformer that intergrateshumanoid MIP, reptile UGV, and bird UAV." – [link]

- This article proposes a multi habitat bio-mimetic robot, named as GuLu XuanYuan.It combines all common types of mobile robots, namely humanoid MIP, unmanned ground vehicle, and unmanned aerial vehicle. These 3 modals imitate human, bird, and reptile, separately. As a transformer, GuLu XuanYuan can transform from one modal to another. Transforming function integrates the specialized abilities of three robots into the same machine body. This simplification approach helps to reduce the total number of required robots. From another perspective, the deformation function is equivalent to creating more economic value.

"Michael Rechtin, A.A. (2024, November 18). Building a Real Life Transformer [Video]. YouTube" – [link]

- This video presents a practical implementation of a UGV-UAV transformation system, offering insights into mechanical design considerations, power optimization, and feasibility assessments.



CHAPTER 3
SYSTEM DESIGN AND INTEGRATION

In this chapter, we present a comprehensive account of the physical realization of the UGV-UAV Transformer. The complexity of this system lies not only in its individual subsystems but more importantly in the seamless integration of these distinct modules into a single, coherent, and functional unit.

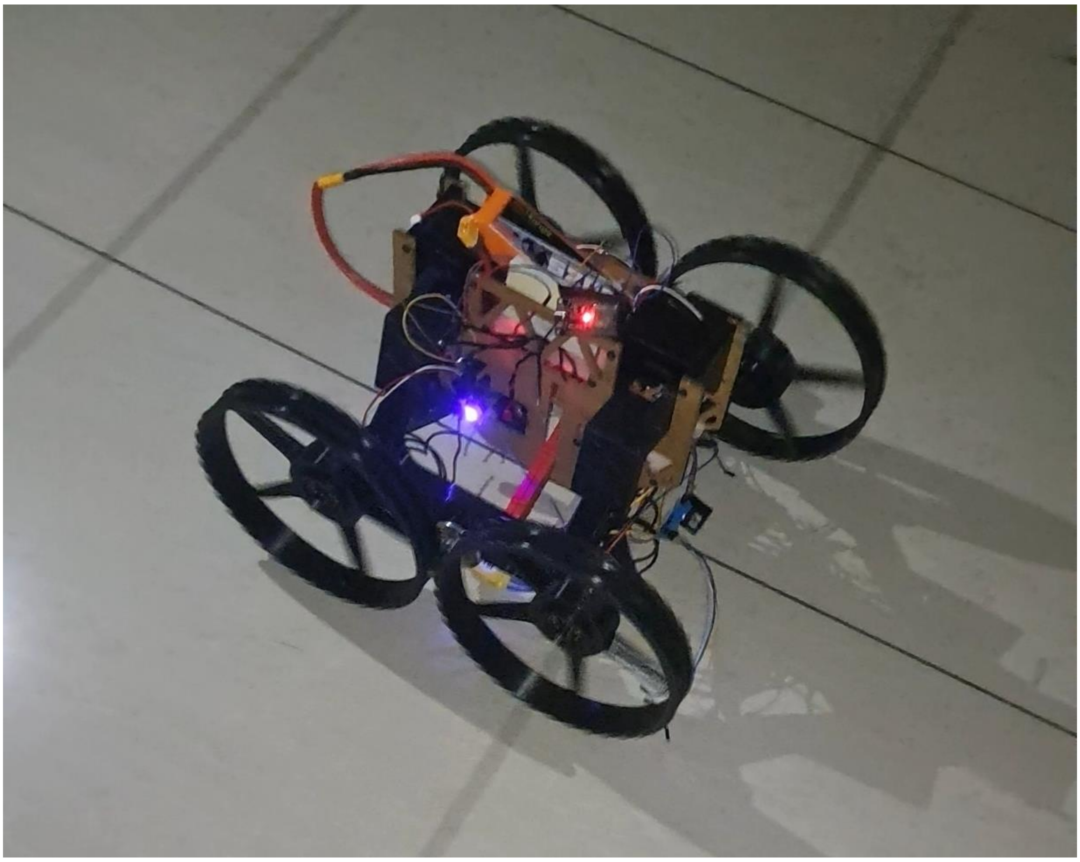
This chapter is structured into three detailed subsections, each focusing on a core segment of the system:

- The **UGV subsystem**, which forms the structural and locomotion backbone on the ground.
- The **UAV subsystem**, which enables vertical take-off, controlled flight, and aerial stability.
- The **Transformation mechanism**, which serves as the critical link between modes, allowing structural reconfiguration at runtime without compromising system integrity.

The selection of components was guided by performance requirements, weight constraints, and energy efficiency considerations.

Brushless motor (x4)
Servo Motor(x2)
DC Motor(x2)
Linear Actuator(x2)
LiPo battery(x1)
Flight Controller
ESCs (4 in 1)
Motor Driver(x1)
Voltage regulators
ESP 32
Propellers(x4)
Acrylic sheet
Wires, Remote Controller
PLA

3.1 UGV



UGV Mode

The Unmanned Ground Vehicle (UGV) module serves as the foundational locomotion unit of the hybrid transformer system. It is designed to operate effectively over rugged terrain and provide a stable base for take-off and landing in UAV mode. The UGV's structural design prioritizes **mechanical robustness, torque-optimized mobility, and lightweight construction**, ensuring reliable operation even under variable loads and transformation-induced stresses.

To achieve this, the UGV incorporates **high-torque BLDC motors** that drive the rear wheels through a geared transmission system. The selected motors (IDUINO 5010-360KV) are capable of delivering a post-gearing torque of 3.41 Nm, thus ensuring that the vehicle can overcome resistive forces and surface friction.

$$Total\ mass\ of\ the\ robot\ =\ 4kg\ (conservative)$$

$$No\ of\ driven\ wheels\ =\ 4$$

$$Wheel\ radius\ =\ 0.125m$$

$$Coefficient\ of\ rolling\ friction\ (PLA\ on\ smooth\ ground)$$

$$=\ 0.03 - 0.05\ (conservative)$$

$$Frolling =\ \mu r \cdot m \cdot g =\ 0.04 * 1 * 9.81\ =\ 0.3924\ N$$

$$Tmin,\ total = Frolling \cdot r\ =\ 0.04905\ Nm$$

$$Tmin\ per\ wheel\ =\ 0.04905/4\ =\ 0.0122625\ Nm$$

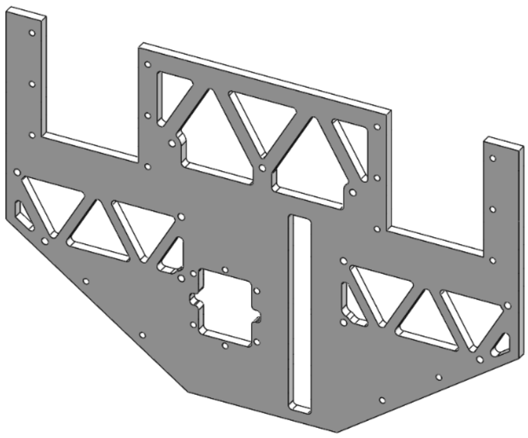
$$The\ no.of\ teeth\ on\ each\ wheel\ is\ 240\ and\ the\ no.of\ teeth\ on\ the\ BLDC\ motor\ is\ 20.$$

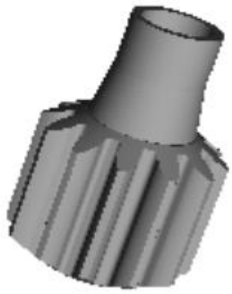
$$Gear\ Ratio\ =\ Teeth\ on\ the\ wheel\ gear/\ Teeth\ on\ the\ motor\ =\ 20:1$$

$$This\ means\ the\ wheel\ turns\ once\ for\ every\ 20\ rotations\ of\ the\ motor, but\ torque\ is\ multiplied\ by\ \times.$$

$$\begin{aligned}
&The\ torque\ which\ can\ be\ provided\ by\ the\ motor\\
&= 3.41\ Nm\ , this\ means\ that\ the\ torque\ received\ by\ each\ of\ the\ wheels\\
&= 20 * 3.41/2\\
&= 34.1\ Nm — significantly\ above\ the\ minimum\ required\ torque\ per\ wheel.
\end{aligned}$$

The UGV’s frame has been fabricated using **acrylic sheets**, chosen for their strength-to-weight ratio and structural rigidity. Lightweight yet durable, the frame supports not only the locomotion elements but also houses the transformation system and UAV propulsion components without compromising maneuverability.





Side Plate Motor Gear

The **motor driver (L298N)** interfaces with an **ESP32 microcontroller**, which handles PWM-based speed regulation, direction control, and wireless communication.

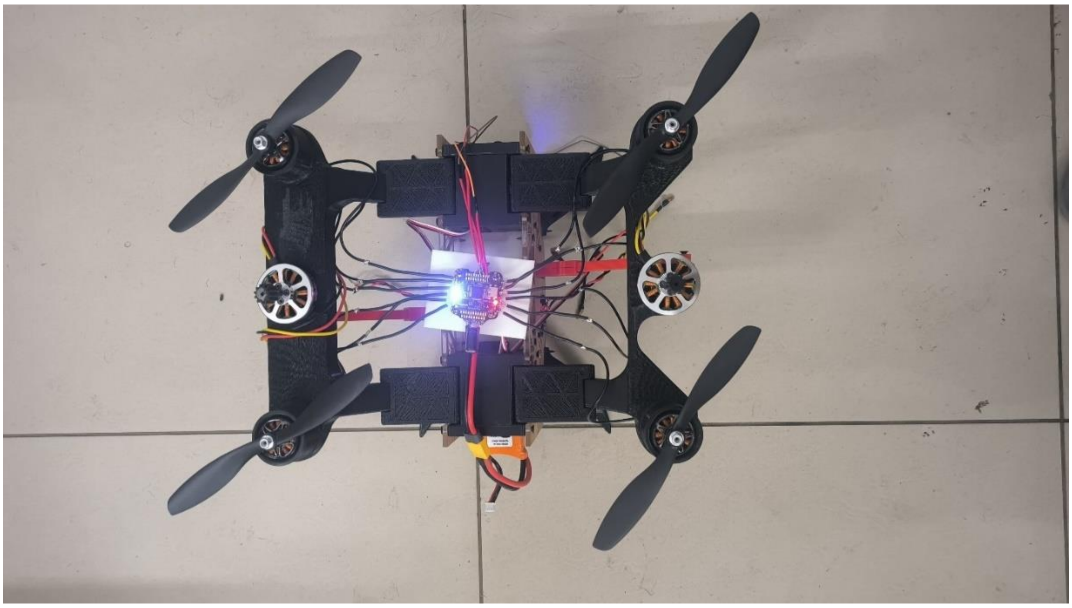
The UGV is controlled via a multi-channel PWM signal system, where four channels are assigned to different subsystems. These signals are received through a dedicated receiver and interpreted by the onboard **ESP32 microcontroller**, which serves as the local control hub for the UGV. The ESP32 then reads the PWM values from **four active channels** and converts them into appropriate control commands for the wheel motors, steering logic, servo-driven linkages, and DC-powered linear actuators. The PWM signal's pulse width varies between 1 ms (minimum) and 2 ms (maximum), representing the desired control level for each actuator. This setup provides precise, real-time remote control over both locomotion and transformation functions.

The differential drive control strategy allows the UGV to perform turning maneuvers smoothly. **3D printed wheels**, optimized for weight and traction, form the contact interface with the ground and were customized using PLA to match both the mechanical profile and aesthetic integration of the overall system.

SolidWorks Model of the wheel 3D Printed Wheel

Collectively, the UGV subsystem functions as a rugged ground mobility platform, offering precision control, power efficiency, and structural versatility, while also serving as the mechanical scaffold for the aerial system.

3.2 UAV



UAV Mode

The UAV subsystem is designed to provide **vertical lift, aerial navigation, and hover stabilization**, extending the operational scope of the robot beyond what terrestrial mobility can achieve. This capability is essential for applications in environments with **terrain discontinuities, elevation changes, or inaccessible regions**, where flight becomes the only viable mobility option.

At the heart of the UAV module are **four 2215 1100KV brushless motors**, mounted inside the rotor arms of the transformer. These motors offer a high thrust-to-weight ratio, capable of lifting the entire integrated structure with enough margin to account for battery drain and aerodynamic drag. The KV rating (RPM per volt) of 1100 strikes a balance between lift force and current draw, ensuring energy-efficient flight.

Each motor is paired with **8045 propellers**, chosen for their aerodynamic performance and compatibility with the motor shaft specifications.

$The\ thrust\ generated\ by\ a\ propeller\ is\ governed\ by: T = CT \cdot \rho \cdot n2 \cdot D4$

- $T\ =\ Thrust\ (N)$
- $CT\ =\ Thrust\ coefficient\ (depends\ on\ prop\ shape\ \&\ pitch)$
- $\rho\ =\ Air\ density\ (\sim 1.225\ kg/m^3\ at\ sea\ level)$
- $n\ =\ Propeller\ rotation\ speed\ (rev/s)$
- $D\ =\ Propeller\ diameter\ (in\ meters)$

$$\boldsymbol{Diameter\ D}\ =\ 8\ inches\ =\ \boldsymbol{0.2032\ m}$$

$$\boldsymbol{Pitch}\ =\ 4.5\ inches$$

- $\boldsymbol{CT\ (Thrust\ coefficient)}\ \approx\ 0.1\ (typical\ for\ slow - fly\ props\ like\ 8045)$
- $\boldsymbol{Air\ density\ \rho}\ \approx\ 1.225\ kg/m^3\ (at\ sea\ level)$

$$\boldsymbol{Motor\ speed\ n}\ =\ RPM/60 For\ a\ \mathbf{2215\ 1100}\boldsymbol{KV}\ motor\ on\ a\ \mathbf{3}\boldsymbol{S\ battery}\ (\mathbf{11.1}\ \boldsymbol{V}):$$

$$RPM\ =\ KV * V = 1100 \cdot 11.1 = 12210\ \Rightarrow\ n\ \approx\ 12210/60 = 203.5\ rev/s$$

$$T = 0.1 \cdot 1.225 \cdot (203.5)2 \cdot (0.2032)4\ =\ 8.68N$$

$$TTotal\ =\ 8.68 * 4\ =\ 34.72$$

$The\ mass\ of\ the\ system$
$=\ 3.5\ Kg\ which\ means\ the\ thrust\ required\ is\ 35\ Kg\ which\ is\ closely\ matching\ our$

$$calculated\ thrust\ of\ \sim 34.72\ N.$$
$$This\ confirms\ the\ adequacy\ of\ our\ propulsion\ system\ for\ lift\ and\ short - duration\ hover.$$

To reduce wiring complexity and increase synchronization during high-speed operations, we employed **a 4-in-1 Electronic Speed Controller (ORION 35A.**

The **4-in-1 ESC** consolidates the function of four individual ESCs into a single, compact board. Each channel of the ESC independently controls a brushless motor by generating **precise PWM or DSHOT signals** based on input from the flight controller. It regulates voltage and current to the motors, ensuring that they spin at the desired RPM based on throttle commands, while also providing **telemetry feedback** (e.g., temperature, voltage, RPM) back to the flight controller. This real-time motor feedback enables more accurate control and advanced flight features like **current limiting and dynamic braking**. The compact integration of four motor controllers in a single PCB not only saves space but also improves heat dissipation and electromagnetic compatibility. Our ESC supports **continuous current ratings of up to 35A per channel**, with bursts of up to 40A, which is more than sufficient for our 2215 1100KV motors driving 8045 propellers. Additionally, the use of a 4-in-1 ESC eliminates the complexity of synchronizing separate ESCs, ensuring all motors respond uniformly, thus enhancing **stability during hover and rapid transitions**. The board is mounted directly beneath the flight controller in a stack configuration, with **BLHeli_S firmware** for easy configuration via Betaflight passthrough.

Central flight control is managed by a dedicated **flight controller (SpeedyBee F405 V3)**, equipped with an Inertial Measurement Unit (IMU) for dynamic orientation sensing and onboard stabilization algorithms.

The **Speedybee F405 V3** is a high-performance flight controller built on the **STM32F405** microcontroller, offering fast processing capabilities, low-latency signal handling, and extensive connectivity options. It integrates a **6-axis IMU**, **barometer**, **OSD**, and **blackbox logging**, all of which are essential for maintaining stable flight and for post-flight analysis.

- **6-axis IMU:** The 6-axis IMU is a sensor module that combines a **3-axis gyroscope** (measuring angular velocity) and a **3-axis accelerometer** (measuring linear acceleration). It allows the flight controller to determine the drone's **orientation** (roll, pitch, yaw) and detect changes in motion. This real-time motion sensing is essential for maintaining flight stability, executing smooth maneuvers, and recovering from disturbances during flight or transformation.

- **Barometer:** The barometer measures **atmospheric pressure** to estimate the drone's altitude above sea level. It enables features like **altitude hold**, smoother takeoff/landing, and height-based navigation. Unlike GPS, the barometer provides fast and fine-grained altitude feedback, which is especially important for low-altitude hovering and indoor flight stability.

- **OSD (On-Screen Display):** The On-Screen Display overlays critical flight data (battery voltage, altitude, flight time, RSSI, etc.) onto the FPV (first-person view) camera feed. This lets the pilot monitor real-time telemetry without needing separate ground station equipment, improving situational awareness and safety during manual control or testing.

- **Blackbox Logging:** Blackbox logging records real-time flight data such as gyro readings, PID outputs, motor responses, and receiver inputs. This data can be reviewed post-flight to analyze performance, identify causes of instability, or fine-tune PID gains. It is a powerful tool for debugging complex behaviors, especially during mode transitions and dynamic transformations.

The controller is compatible with **Betaflight** even though it has its own SpeedyBee Firmware, allowing extensive tuning of PID parameters, flight modes, and failsafe behavior. With its built-in support for **SBUS, UARTs, and PWM/DSHOT outputs**, it serves as the central node of the UAV's control system, interpreting signals from the receiver and sensors, and dynamically adjusting motor outputs to ensure precise stabilization in real-time. This controller also receives remote inputs via a telemetry receiver to allow manual override and flight path adjustments.

The **SBUS (Serial BUS)** signal is used to interface the receiver with the **Speedybee F405 V3** flight controller. SBUS is a digital serial protocol capable of carrying 16 channels of control data through a single wire, offering high signal resolution and low latency. This compact and efficient communication method is critical for reducing wiring clutter and ensuring reliable transmission of real-time control commands to the flight controller. The SBUS signal is decoded by the flight controller and used to update motor outputs via the ESC, enabling precise multirotor control.

This aerial subsystem transforms the UGV into a fully functional quadcopter, making it capable of navigating vertically and laterally through the air, providing critical enhancements in speed, adaptability, and reach.

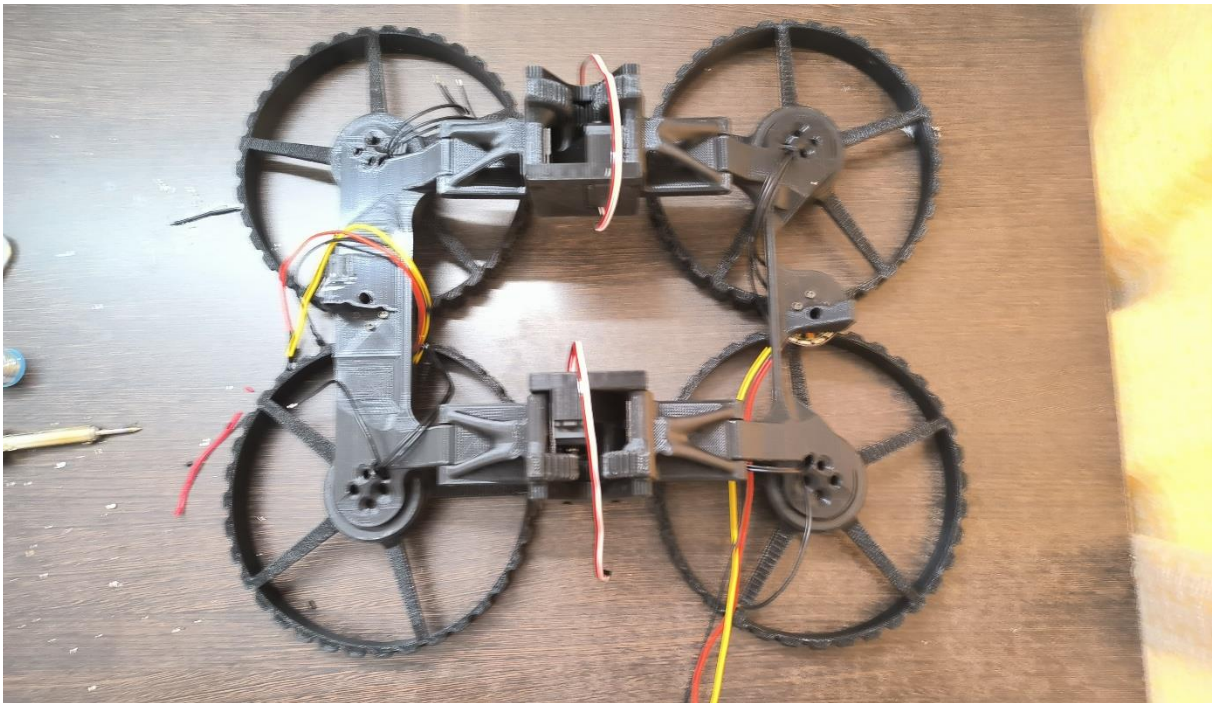
3.3 TRANSFORMATION

The transformation subsystem lies at the heart of our hybrid robotic design, enabling the vehicle to dynamically shift between its UGV and UAV configurations. The primary components facilitating this transformation are **two high-torque servo motors** and **two linear actuators**, which work in tandem to reposition the UAV rotor arms from a stowed ground configuration to a flight-ready state. Upon receiving PWM signals from the transmitter (via the ESP32), the servo motors initiate the transformation by **lifting the central rotor arms** upward. These servo motors are rated at **25 kg·cm**, providing sufficient torque to overcome gravitational and structural resistance during lifting.

Once the arms reach their threshold angle, the **linear actuators** extend forward to **lock the rotor arms into their final position**, providing rigid structural support for stable quadcopter operation. Each actuator features a **stroke length of 100 mm** and a thrust force capacity of approximately **60 N**, ensuring the system remains stable even under vibration or wind disturbances during flight. This two-stage transformation—first rotational via servos, then translational via actuators—ensures smooth, coordinated motion without causing imbalance or stress on the frame.

In order to transition from ground mode to flight mode, a **mode-switching step is also performed on the receiver**. The receiver, initially operating in **PWM mode for UGV control**, must be switched to **SBUS mode** to interface with the **Speedybee F405 V3** flight controller. This is achieved by enabling **binding mode** on the transmitter and re-binding the receiver to configure it for SBUS output. This change allows the UAV to receive high-speed, multiplexed control data required for flight stabilization and precise motor control via the flight controller. The entire transformation—both mechanical and signal-level—occurs wirelessly and in real time, enabling the robot to adapt seamlessly to operational demands.

Differential Drive Wheel Assembly-



CHAPTER 4

CONSTRUCTION OF THE LINEAR ACTUATOR

The linear actuator used in this project was designed to convert rotary motion into linear motion, using a lead screw mechanism housed within a cylindrical casing. The actuator consists of multiple segments fabricated to ensure structural integrity and ease of assembly. Mounting flanges and bolt holes were incorporated into the design to facilitate attachment to other mechanical subsystems. The core components include a motor housing, screw assembly, guide rails, and a sliding shaft that transfers the output force.

The system is powered by an N20 micro metal gear motor (600 RPM, 6V), chosen for its compact form factor and sufficient torque output for the actuator's intended load conditions. A lead screw with a pitch of 1.25 mm was used, ensuring precise control by converting every motor revolution into a 1.25 mm linear displacement. This configuration provides a good balance between speed and positioning accuracy.

For the prototype, PLA (Polylactic Acid) material was used due to its ease of 3D printing and sufficient mechanical strength for moderate load applications. However, for simulation purposes, the geometry was analyzed using ABS (Acrylonitrile Butadiene Styrene) properties in the software to evaluate stress distribution, deformation, and strain under applied loads. The structure was meshed using triangular elements for accurate representation of stress concentration around curves and holes.

Finite Element Analysis (FEA) was performed on the designed linear actuator to evaluate its structural performance under applied loads. The simulation considered a fixed support at one end and a downward force at the extended arm tip, replicating realistic working conditions.

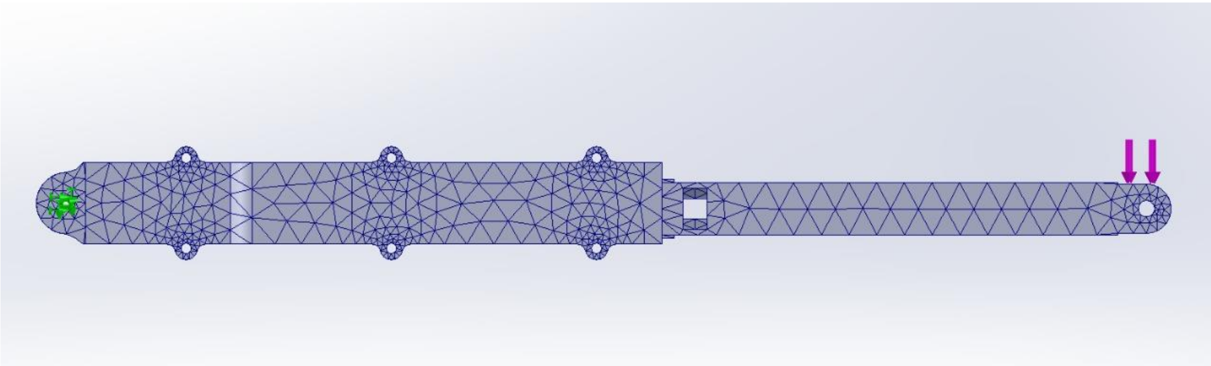
The Von Mises stress distribution showed that the maximum induced stress remains below 23 MPa, which is significantly lower than the typical yield strength of PLA (~60 MPa). This indicates that the design operates within the elastic limit of the material and is structurally safe under the applied loading condition.

Total displacement analysis revealed a maximum deflection of approximately 9 mm at the tip of the actuator arm. Given the load direction and the cantilever configuration, this displacement is acceptable for non-precision applications, especially considering the inherent flexibility of PLA. It also highlights the need to account for stiffness in future iterations if higher accuracy is required.

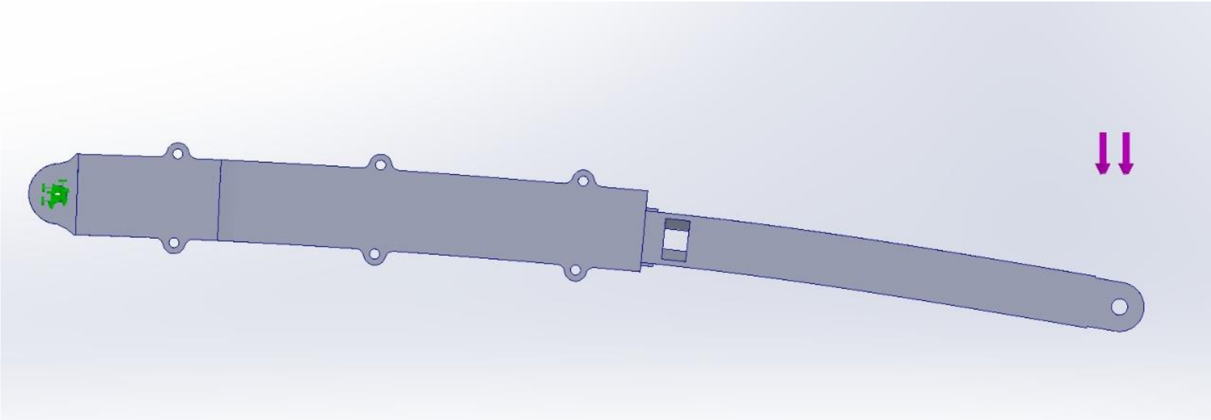
The equivalent strain distribution remained low throughout the structure, concentrated mostly at the transitional regions, confirming uniform stress transfer and good continuity in design. A design safety factor greater than 2.5 can be assumed based on the ratio of PLA yield strength to maximum observed stress. This indicates a conservative and safe design suitable for prototype-level use.

The actuator’s performance under simulated loading confirms the structural viability of using PLA for moderate-load applications, though for heavy-duty or repeated-load scenarios, a stiffer and tougher material may be recommended.

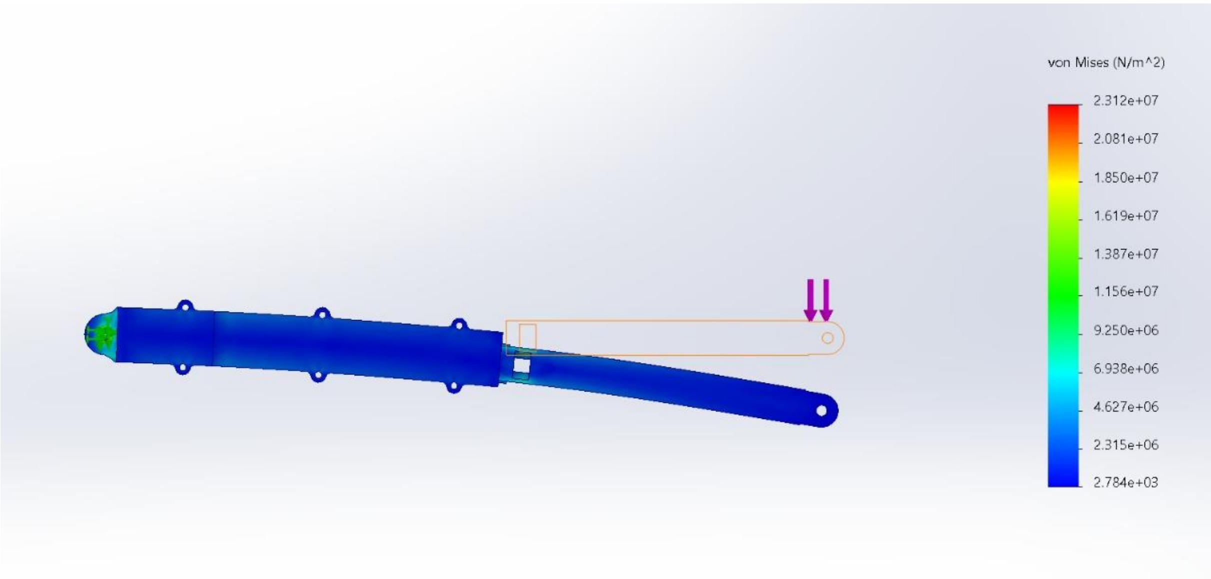
Assembly view of linear actuator



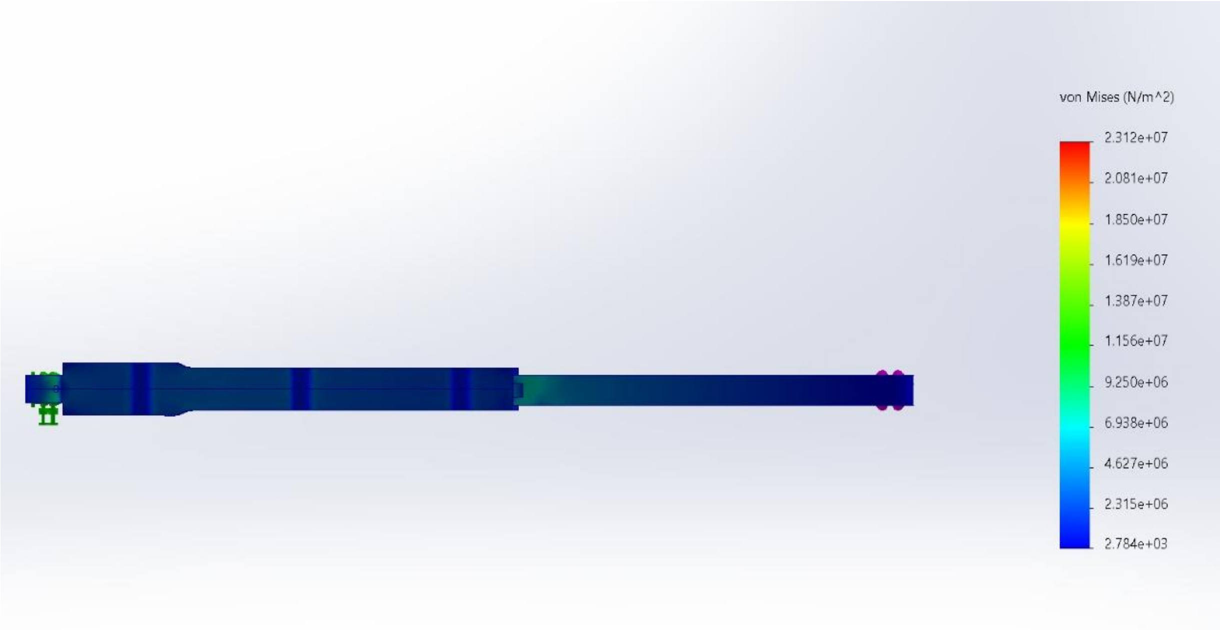
FEA Mesh Generation on actuator arm



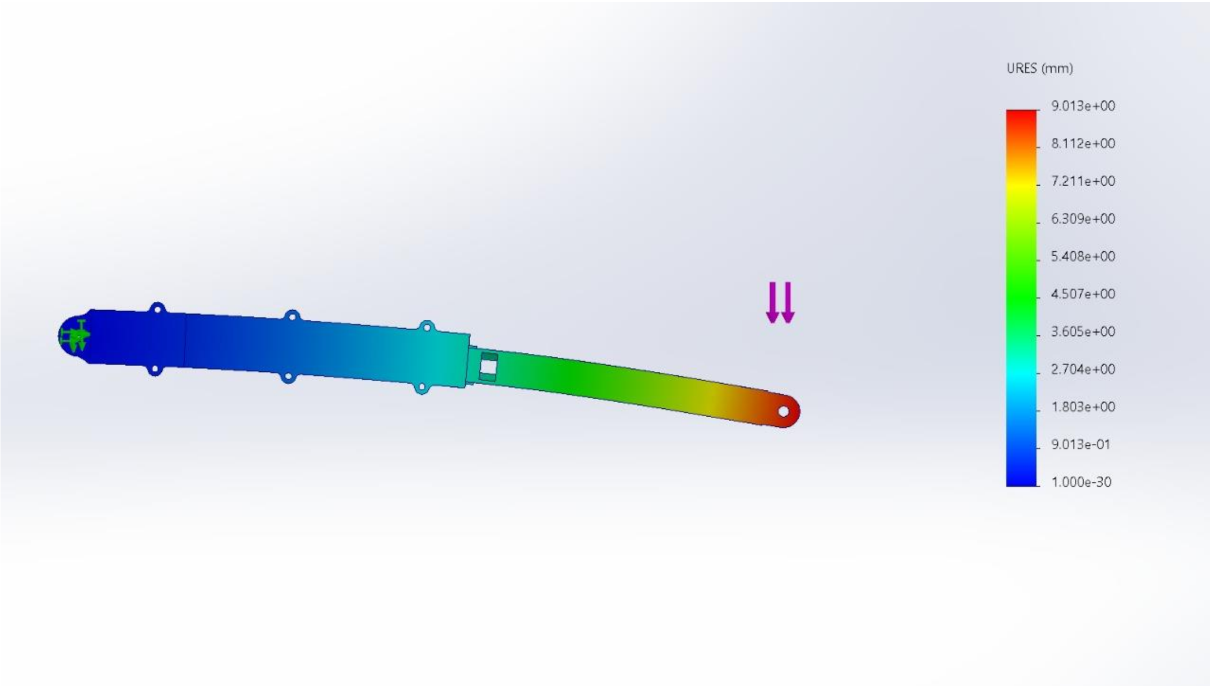
Applied Boundary Conditions and Load Arrows



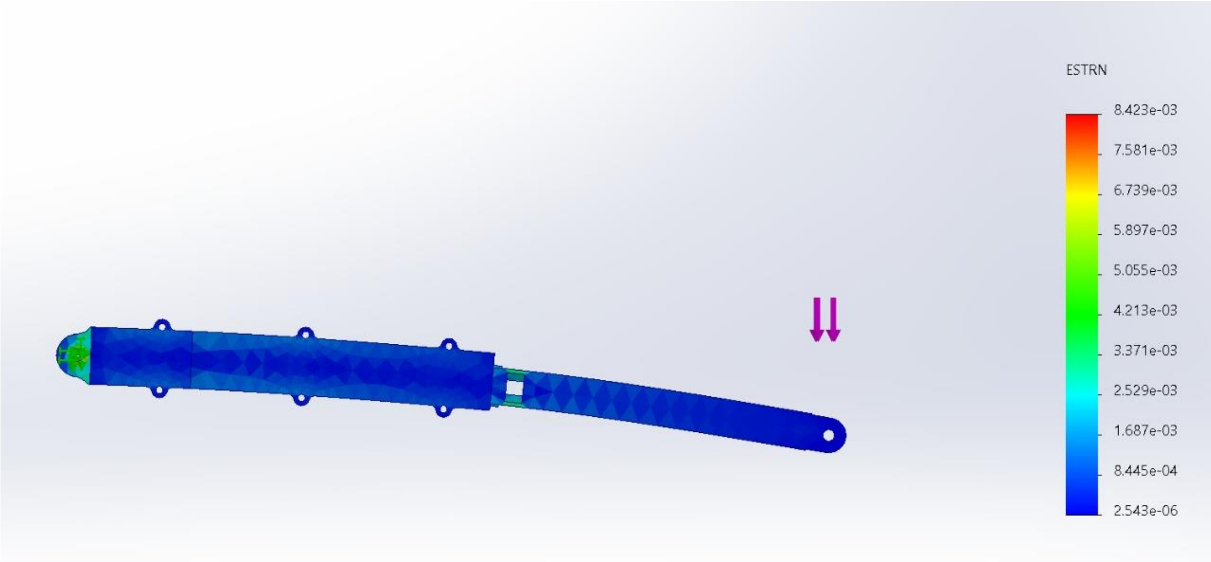
Von Mises Stress Distribution (N/m²)



Stress Distribution (von Mises, N/m²) – Side View



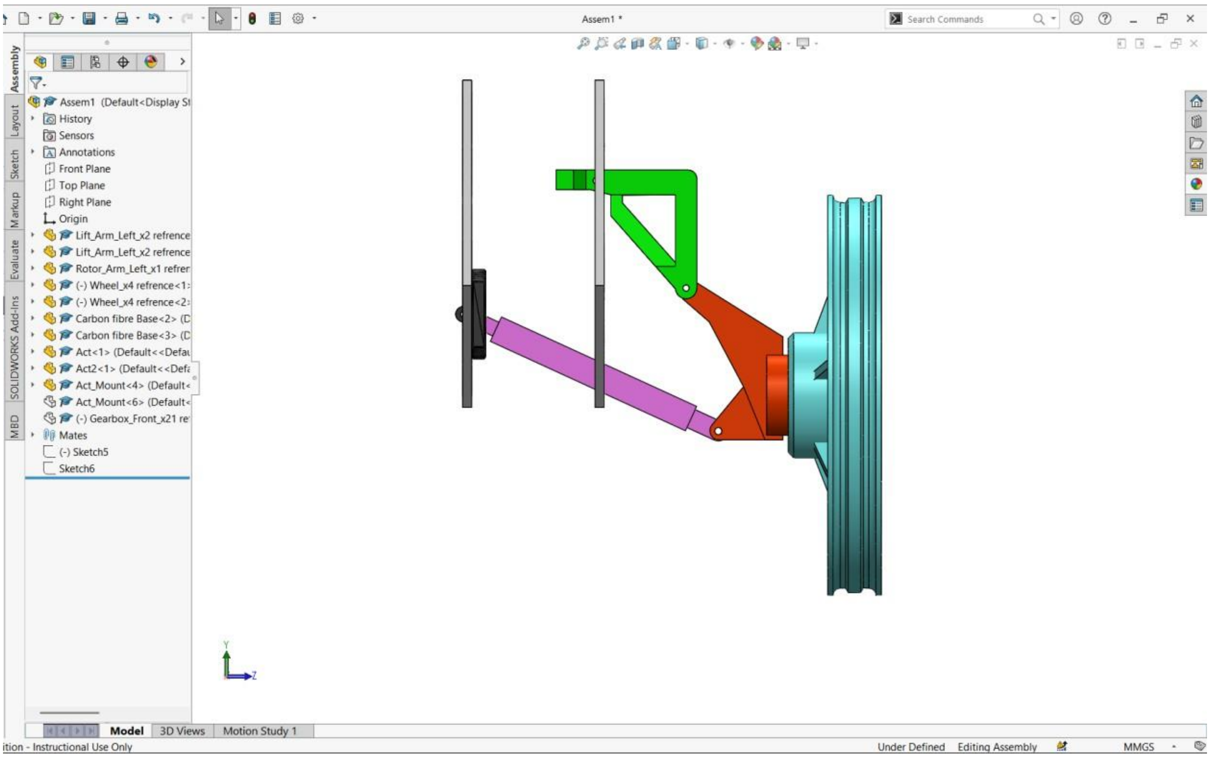
Total Displacement(URES)

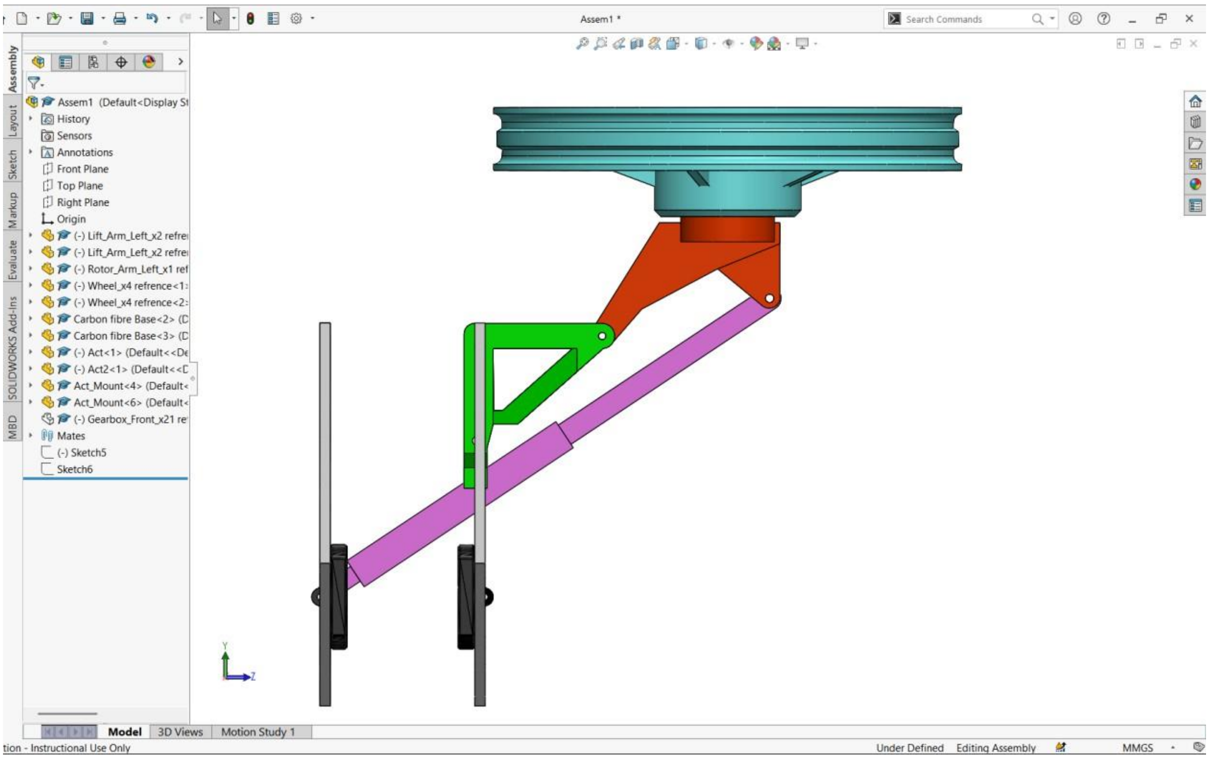


Equivalent Elastic Strain(ESTRN)

CHAPTER 5
SIMULATIONS

“Transformation Mechanism (Showing the Transition Between UGV and UAV Modes)”





The described assembly functions as a **four-bar linkage** mechanism (with one link being telescoping) that connects the vehicle frame to the movable hub. In a classic four-bar linkage, four rigid bars are connected in a loop by pin joints, allowing a range of planar motion. Here we have:

1. the **base frame** (the chassis and support brackets, which contain two fixed hinge points – one for the green arm's servo pivot and one for the base of the pink actuator),
2. the **input crank (green lift arm)** which is hinged to the base and driven by the servo,
3. the **output link (orange rotor arm)** which carries the cyan hub and is connected via joints to the green arm and to the pink actuator, and
4. the **floating link** provided by the pink linear actuator, which connects the orange arm back to the base at the lower hinge.

When the pink actuator is locked at a given length, these four links form a movable quadrilateral. The green arm and pink link attach at two points on the base (forming the "ground" side of the four-bar), and meet at the orange rotor arm which carries the wheel. This configuration is what allows the wheel to move in a prescribed path as the mechanism operates. In essence, the system is a **planar four-bar linkage with an actuated link** (the linear actuator alters the effective length of one side).

Notably, the mechanism may be arranged in a **parallelogram configuration** or similar, meaning the links could be arranged so that the wheel maintains a near-constant orientation during motion. For example, if the green lift arm and the pink actuator were kept roughly parallel through the motion (and the brackets on the base are parallel), the orange rotor arm would also stay nearly parallel to the base – this would keep the wheel (cyan) upright as it moves. Designs for transformable drones have indeed used a parallelogram four-bar linkage for stability: in one implementation, a four-bar linkage (with the linear actuator as one bar) was used to pivot wheels and propeller guards, keeping them properly oriented through the transition. By using a similar four-bar approach here, the mechanism ensures that the heavy rotor hub moves in a controlled arc or straight-line lift (depending on geometry) rather than flopping around.

Because one of the "bars" of this four-bar is a linear actuator, the mechanism's geometry is variable. This effectively gives the system two degrees of freedom (one from the servo-driven rotary joint, one from the extending actuator). The combination of a rotary joint and a prismatic joint in one closed chain is sometimes called a hybrid linkage or can be thought of as a type of **six-bar linkage** if we consider the actuator's two sliding segments as separate links. However, conceptually it operates as a four-bar linkage whose shape can change on command. Many transformable vehicle concepts use exactly this kind of linkage: a robust lever-arm system to handle structure, coupled with a linear actuator for powerful extension

Transformation Sequence: UAV Mode to UGV Mode:

Switching between UAV (flight) mode and UGV (ground) mode is achieved through a two-step actuation sequence involving the linear actuator and the servo-driven lift arm. The process can be described step-by-step for both directions of transformation.

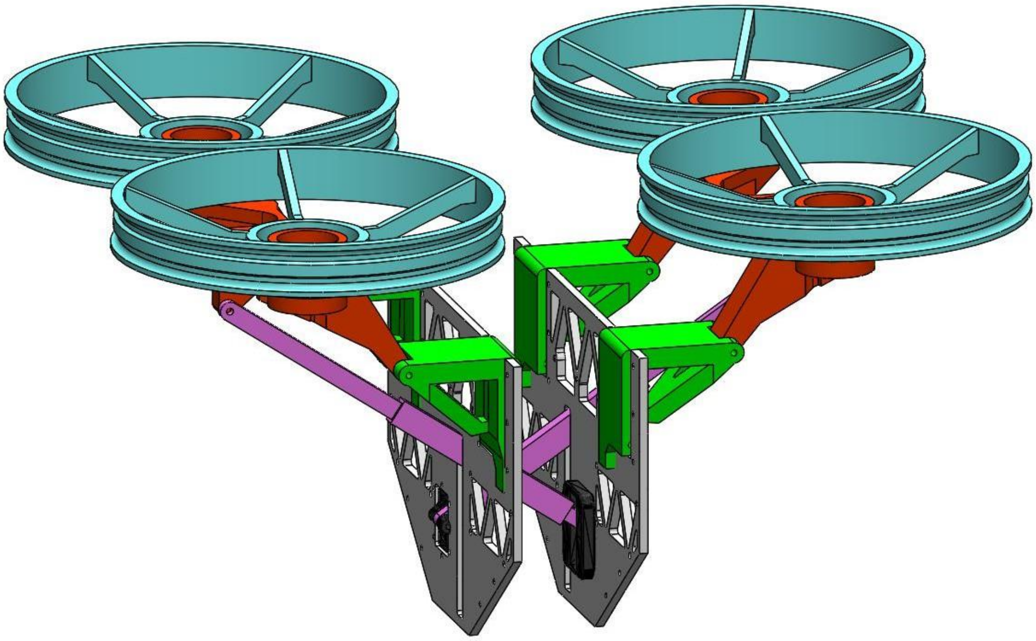
1. **Lowering (Retracting) the Rotor Assembly:** In the UAV configuration, the cyan wheel is in the raised position (ready for flight). To begin the conversion to ground mode, the pink linear actuator **retracts**, shortening its length. As the actuator contracts, it pulls on the orange rotor arm. This causes the orange arm (and the attached wheel) to swing downward and inward toward the chassis. Essentially, the linear actuator is drawing the rotor assembly down from its high flying position. The guide rails ensure that this motion happens in the correct plane – the wheel moves along a roughly vertical or arced path without twisting. During this step, the green lift arm (initially upright) is held in place, acting as a guiding hinge. The retraction continues until wheel nears the desired lower position. At this stage, the vehicle's centre of gravity is lowered, and the rotor is no longer extended above the vehicle.

2. **Rotating the Lift Arm to Ground Mode Position:** Once the actuator has retracted and brought the rotor assembly to a lower position, the **green lift arm rotates 180°** to finalize the UGV mode configuration. The servo motor drives this rotation. The green arm, which was upright, now swings downwards (inverting its orientation). As it rotates, it carries the attached end of the orange rotor arm with it, effectively folding the linkage into a compact form optimized for ground travel. At the end of this rotation, the green arm might be pointing downward or backward, and it may serve to **lock the mechanism** in the ground position. In this default UGV mode, the cyan wheel is now repositioned – likely lowered and tucked near the vehicle's body. The rotor would be stowed safely, oriented differently to avoid ground contact or damage. At the same time, any wheels or ground mobility systems on the UGV can fully engage. The servo effectively **switches the system into UGV mode** by this 180° arm rotation, as was intended in the design description. The transformation to ground vehicle mode is complete, and the mechanism remains stable in this configuration while the robot drives.

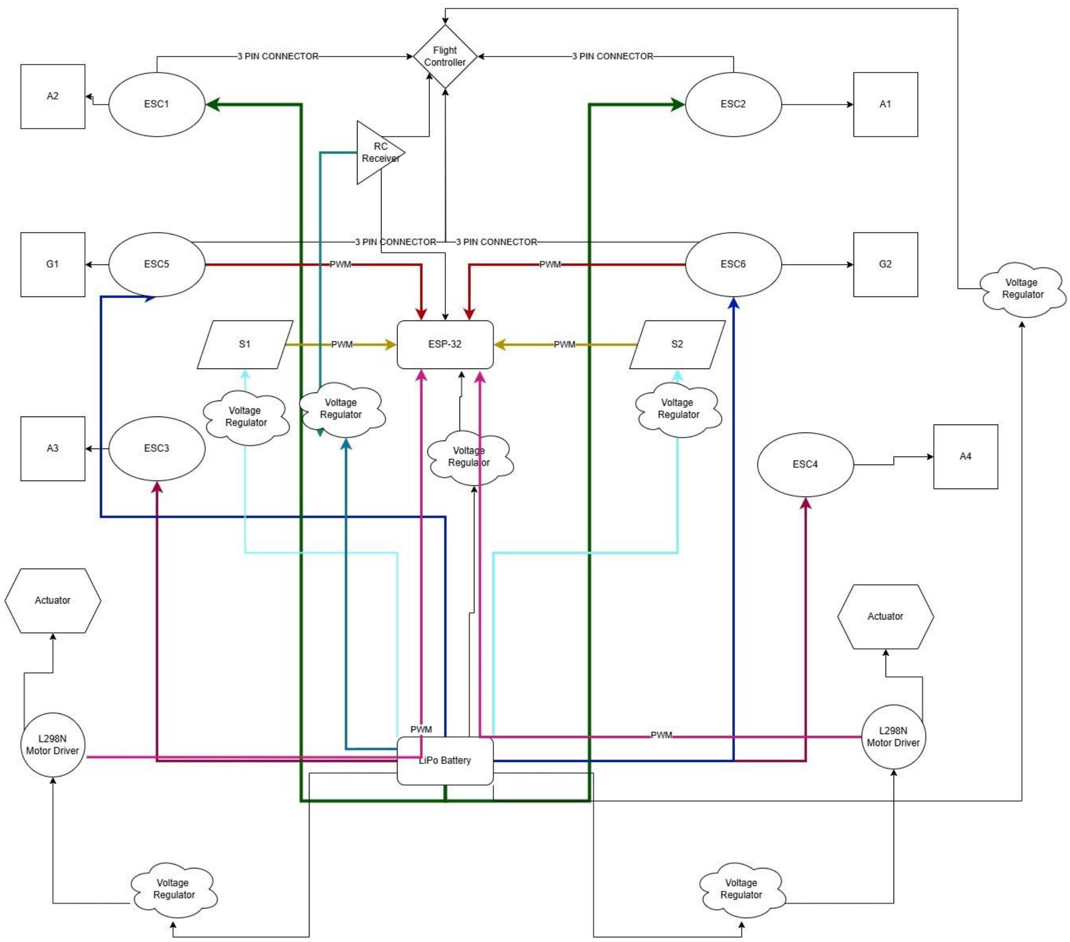
Transformation Sequence: UGV Mode to UAV Mode:

1. **Deploying (Rotating) the Lift Arm for Take-off:** Starting from the UGV configuration (green arm rotated down, mechanism folded, wheel low), the servo actuates the green lift arm in the reverse direction. The green arm is rotated back (another 180° swing, or the reverse motion of step 2 above) to begin unfolding the linkage. This motion raises the joint between the green and orange links, preparing the mechanism to lift the wheel. This step effectively **raises the vehicle's body** or moves components to increase ground clearance for take-off. For example, in a related design, a servo was used to lift the body off the ground in preparation for flight. In our case, rotating the green arm back to its upright position aligns the linkage for extension. It might initially tilt the rotor hub slightly upward and ensure that when the linear actuator extends, it will push the hub mostly vertically. The servo-driven arm motion essentially **unlocks and elevates** the stowed assembly, positioning the orange rotor arm at an angle where the linear actuator can do the most work in the next step. Once the green arm reaches its flight-mode orientation (likely vertical or forward), the system is ready for the main lifting stroke.

2. **Lifting the Rotor Hub to Flight Position:** With the linkage geometry now primed, the **pink linear actuator extends** to elevate the cyan rotor wheel to its full UAV mode height. The actuator's extension drives the orange rotor arm outward and upward. As the pink link elongates, it pushes the joint at the orange arm, causing the orange arm (and attached wheel) to swing up. The green lift arm, now upright, guides this motion by constraining the path of the orange arm (they remain connected at the pivot). The guide rails again ensure a straight, controlled lift without lateral deviation. During extension, the rotor wheel rises and also levels out to a vertical orientation if it wasn't already. By the end of this stroke, the cyan wheel is positioned at the top of the mechanism, elevated above the main body, with its rotor clear of any obstructions. This is the default **UAV mode**: the motor can now spin freely to generate lift, and the vehicle is configured as a quadcopter or similar aircraft. At full extension, the linear actuator may lock in place, thus securing the wheel in the flight position. The servo-driven green arm at this point is back in its original orientation, contributing to holding the geometry rigid for flight. The transformation to aerial mode is now complete – the vehicle can take off and fly.



"Complete UGV-UAV Transformer Model"



"Circuit Diagram Representation (Showing the Electrical and Control System Integration)"

CONCLUSIONS

The development of the UGV-UAV Transformer marks a critical step forward in the realization of intelligent, adaptive, and mission-flexible robotic platforms. This project successfully demonstrates the conceptualization, mechanical design, integration, and partial fabrication of a dual-mode robotic system that can seamlessly transition between ground and aerial locomotion. The design incorporates a four-bar linkage-based transformation mechanism actuated through a combination of high-torque servo motors and linear actuators, enabling real-time structural reconfiguration without the need for manual intervention. The successful completion of CAD modeling, actuator simulation, structural stress analysis, and component-level integration confirms both the **engineering soundness** and **functional feasibility** of the proposed system.

The uniqueness of this system lies in its ability to combine the endurance, stability, and payload benefits of ground mobility with the speed, accessibility, and vertical maneuverability of aerial systems. Where most robots are specialized for one domain, our transformer robot offers **multimodal versatility**, capable of navigating rugged terrains as a UGV and then deploying vertically as a UAV to overcome physical barriers, reach elevated areas, or respond rapidly in emergencies.

The envisioned system is poised for significant real-world applications. In **search and rescue operations**, particularly post-disaster scenarios, it can traverse collapsed structures or debris fields on the ground, then transition to flight to reach isolated zones or relay crucial information back to rescue teams. In **agriculture**, it can perform field scouting from the air and ground-based diagnostics like soil analysis or pest detection with enhanced granularity. In **defense and surveillance**, it offers stealth, adaptability, and redundancy, enabling both covert reconnaissance and rapid aerial deployment. In **infrastructure inspection**, such as for power lines, bridges, or pipelines, the system can drive along accessible surfaces and then take flight to inspect hard-to-reach or hazardous sections. Even in **logistics**, the transformer could offer efficient solutions for last-mile delivery, especially in mixed indoor-outdoor or urban environments where fixed-wing UAVs or wheeled robots face limitations.

Looking ahead, the system opens rich opportunities for **future enhancements and research**:

- **Full Autonomy**: Integration of real-time sensor fusion, computer vision, and machine learning-based terrain classification can allow the robot to autonomously select the optimal mode based on environmental context.
- **Advanced Power Management**: Battery optimization through dynamic load balancing, energy-efficient hardware, and potentially hybrid power sources (like solar integration) can greatly extend mission durations.
- **Miniaturization and Weight Optimization**: Replacing prototyped PLA and acrylic with aerospace-grade carbon composites or magnesium alloys can reduce weight and increase flight efficiency without compromising structural strength.
- **Robust Control Architectures**: Tighter coupling between UGV and UAV control loops via unified flight and drive controllers can improve stability, especially during dynamic transformations or in uneven terrains.
- **Modular Payload Systems**: Attachable mission-specific modules — cameras, sensors, robotic arms, sprayers — can make the platform reconfigurable on the fly for multiple tasks.

- **Collaborative Robotics**: Future iterations may operate in swarms, enabling cooperative behaviors such as distributed mapping, coverage optimization, and convoy-based logistics in challenging environments.
- **Extreme Terrain and Planetary Exploration**: With ruggedization, the same design principles could be adapted for autonomous exploration in environments like caves, mountains, or even extraterrestrial terrains (e.g., lunar or Martian surfaces), where transitioning between rolling and flying is particularly valuable.

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