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MEC 825 – Mechanical Design
Interim Project Report

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Aerial Manipulation Project

J2TA Engineering

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Introduction

The rise of drone technology has transformed and evolved industries by offering efficient solutions for applications such as surveillance, inspection, and delivery. However, despite their widespread use, drones are predominantly limited to observational tasks lacking physical interaction capabilities. Their limitation restricts their usability in applications requiring precise manipulation or intervention. Integrating a robotic arm in drones provides a significant leap forward with its opportunity to extend its functionality to tasks like object manipulation and interaction in challenging environments where human's wouldn't be able to operate safely [1]. For instance, drones equipped with robotic arms could be used in hazardous environments where human access is not possible such as disaster zones, industrial maintenance, etc. In these scenarios, autonomous or semi-autonomous drone systems capable of detecting, manipulating and transporting objects would offer substantial benefits.

Figure 1: Aerial robot with robotic arm for manipulation applications [1].

Recognizing the limitations of current drone systems, this capstone project aims to design and implement a lightweight robotic arm that can be seamlessly integrated into a drone while maintaining stable flight and delivering precise arm control. By integrating sensors such as ultrasonic distance sensors and cameras for visual recognition, the system aims to achieve semi or fully autonomous operation. The solution has the potential to expand the practical applications of drones in industries where interaction and precision handling are vital.

While the design and control is the primary focus of this project, the UAV itself is external to the project scope. Instead of developing a custom UAV, the robotic arm will be mounted onto a pre-existing drone platform and for this purpose we will be implementing a tricopter. This was selected due to its yaw precision, maneuverability, and power efficiency, making it a suitable choice for aerial manipulation tasks [2]. Unlike quadcopters which rely on differential thrust for yaw control, the tricopter features a servo-controlled rear rotor, allowing for more precise adjustments during arm operation.

Figure 2: Example of a Three-rotor UAV Prototype [3]

With the limited timeframe, this approach allows the project to entirely focus on design, integration, control algorithm, and optimization of the robotic arm ensuring that it can be effectively adapted onto various UAV platforms

The integration of robotic arms into drones presents numerous challenges of ensuring both flight stability and precise control during manipulation. Major problems faced in the design and integration of robotic arms with UAV system include:

1. **Flight Stability:** One of the most significant issues when it comes to this project is the fact that the robotic arm has to be actively working in a dynamic environment which will introduce challenges into flight stability. According to [4], UAVs are inherently underactuated systems meaning they have fewer control inputs than actual degrees of freedom required for stable flight. Adding a robotic arm further implicates this by introducing additional forces and also shifts the Center of Gravity (CoG) leading to instability during flight operation.
2. **Sensor Data Processing Challenges:** In UAV-robotic arm integrated projects, sensor data processing forms the backbone of having reliable sensor data is vital for stable UAV operation and precise manipulation. However, having to implement multiple sensors with a robotic arm introduces potential challenges with data processing due to sensor noise, drift, and limited processing power [5] .
3. **UAV Payload to Arm Weight Ratio:** Robotic arms add significant weight which can affect UAV flight dynamics and reduce the total operational time. The weight-to-payload ratio is a crucial factor in aerial manipulation, requiring lightweight materials to maintain UAV stability [6]. Balancing the arm's weight with the UAVs payload limits is vital to maintain stability and overall performance.

In order to solve the main problems associated with this problem, preliminary solution formulations were developed based on existing studies and taking an engineering approach. They are as follows:

Solving Flight Stability: Decoupled Control Architecture

In terms of keeping the UAV stabilized during operation, implementing a decoupled control system was found to be the most ideal solution where modularity, simplicity, and robustness are key design priorities. This would mean the UAV's flight control and the robotic arm controller arm will be operated independently. This significantly simplifies the stability management as debugging and troubleshooting becomes easier to pinpoint when prototyping and implementing. The UAV's flight controller will be responsible for maintaining flight stability and will treat the manipulator's motion as an external disturbance while the robotic arm controller will focus solely on arm movements without interfering with flight dynamics [7].

Addressing Sensor Data Processing Challenges:

To address sensory processing challenges in our UAV-Robotic Arm system, we will utilize a Raspberry Pi microprocessor for efficient real-time computation. It provides the computational power, connectivity, and flexibility required for projects in this field [8]. Unlike microcontrollers like Arduino, which are limited in processing power and multitasking capabilities, the Raspberry Pi's quad-core ARM Cortex processor enables real-time multi-threaded execution of complex tasks, including sensor data processing, machine vision, and autonomous control [9]. Additionally, to ensure accuracy and stability, we will implement filters to integrate data from multiple sensors in order to reduce noise and compensate for sensor drift.

UAV Payload to Arm Weight Ratio:

Given that our UAV has a maximum payload capacity of 2kg, it is crucial to preserve at least 50% of this weight capacity in safety considerations of the dynamic environments we will test this arm. When the UAV is loaded with near full payload of a robotic arm, it will greatly cause excessive pitching, rolling, or any oscillation leading to flight instability [6]. Moreover, on top of the safety factor considerations, there are ancillary goals which come with this proposed solution including improved flight performance and operating time while decreasing power consumption [4]. This will allow our UAV to maintain a controlled and reliable operation without the arm having any serious influence on flight performance while in operation. Having our payload constraint already stated, our engineering solution for this challenge would also be to strategically distribute the weight by positioning the robotic arm near the UAVs center of gravity to minimize destabilization during flight maneuvers or during arm operations. This would reduce rotational inertia preventing excessive pitch and roll movements which could destabilize flight. This approach ensures that the UAV stays below acceptable payload limitations while improving stability, flying time, and robotic arm precision.

This project proposes a novel solution by integrating a remotely controlled robotic arm designed for optimal weight distribution, energy efficiency, and precise manipulation. The design methodology involves:

- **Conceptual Design:** Detailed Analysis of drone payload limits, power requirement, and arm control mechanisms
- **Component Selection:** Sourcing lightweight yet durable materials for the arm and selecting motors with high enough torque efficiency for smooth and stable movement of the arm
- **Sensor Integration:** Utilizing an ultrasonic sensor to measure distances and a camera for visual recognition to enhance detection accuracy.
- **Automation algorithms:** Developing algorithms for semi-autonomous or fully autonomous object detection and manipulation tasks
- **Prototyping and Testing:** Iteratively testing the system to refine object detection, improve flight stability, and ensure effective automation

Literature Review and Background Research

The integration of robotic arms alongside UAVs have been explored in various research studies, primarily for applications such as object manipulation or grabbing in various environments. These systems play a crucial role in applications where traditional ground-based or human-operated systems face challenges. By integrating UAVs with robotic arms, these aerial systems can perform tasks stemming out into several industries. However, the addition of this arm introduces complex challenges including flight stability, disturbances, weight constraints, precise control mechanisms, etc. This literature review explores the current state of research in UAV-integrated robotic manipulators, focusing on key design considerations such as controller mechanisms, dynamics, stability, automation, and precision. By analyzing existing developments, we can identify gaps and innovations in existing research studies and refine our approach to developing a more efficient aerial manipulation system.

A survey done in 2019 provides a comprehensive study of aerial manipulators on the market focusing on system design, modelling, control architectures, etc [10]. Although the design and selection of UAV is not the primary focus of this project, it is still important to understand the different types of UAV platforms used for aerial manipulation systems and analyze their advantages and disadvantages. This study compares the tradeoffs between helicopters versus multi-rotor UAVs and when it would be suitable to use each in scenarios. It was found that although helicopters can handle higher payloads, they come with complex aerodynamics, increased vibrations, and difficult control. In contrast, multi-rotor UAVs are mechanically simpler and easier to control, but they have lower payload capacity and higher power consumption, and so most researchers focus on multi-rotor UAVs because of their numerous advantages which outweigh the disadvantages.

Figure 3: Types of UAV platforms for aerial Manipulation [10]

The AEROARMS project [7], demonstrates one of the most advanced developments in aerial robotic manipulation designed for industrial inspection and maintenance tasks. This initiative by the European Union features a multiple degree of freedom robotic arm mounted on the multi-rotor UAV allowing for direct contact operations and manipulation while maintaining flight stability. One of the main advancements in this project is the control strategy in which they explored both unified and decoupled control architectures depending on the tasks. For tasks which required precise force exertion meaning contact-based industrial inspections, the unified approach was used. In other instances where the manipulation was lightweight and low computational, the decoupled system was implemented to ensure safe and stable flight without overcomplicating the control system. As this was a high budget project, autonomy was an essential due to its use cases in industry and so, computer vision algorithms were applied for object detection, real-time tracking and for object pickup and dropoff. Furthermore, the AEROARMS project was able to look into multiple operational modes for this UAV-arm integrated system for different scenarios. These included teleoperation with haptic feedback, semi-autonomous shared control, and fully autonomous visual servoing. This gave a variety of functionalities for this system depending on the task needed to be performed.

Figure 4: Four Operational Modes of AEROARMS Aerial Manipulation System [7]

The Prima Ultra-Lightweight 5 DoF Arm (PUL5AR) is another notable design in the lightweight aerial robotic arm manipulation department designed for VTOL UAVs [6]. Unlike other traditional aerial manipulators which often come across issues with stability, the PUL5AR design minimizes destabilization by keeping the CoG close to the UAVs base. In specific, the first 2 servos are located at the base of the arm to reduce interia of the whole system when in flight which minimizes shifts in CoG [6] (Bellicoso et al., 2015). This methodology is something which can be easily adapted onto new designs and will be something we take into consideration. Furthermore, the robotic arm is designed in such a way that it folds onto itself during takeoff and landing significantly improving the UAVs handling and efficiency. In order to maintain a low weight to payload ratio, the mechanism is built from honeycomb and 3D printed materials ensuring a balance between structural rigidity and flexibility. The PUL5AR robotic arm is designed with five degrees of freedom (5-DoF) which allows precise manipulation tasks making it optimal for most aerial applications. With this multiple degree of freedom arm, the design was intended to fold onto itself for compact storage during takeoff and landing.

It is to be noted that this PUL5AR arm was developed specifically for the ASTEC PELICAN UAV which has a payload capacity of 650g and so the arm is very constrained to be lightweight with a weight of 250g and a maximum payload for the arm of 200g [6](Bellicoso et al., 2015). This explores the modularity and adaptability of designs as it can be seen that for different purposes, drastic changes have to be made in designs to better suit their intended use.

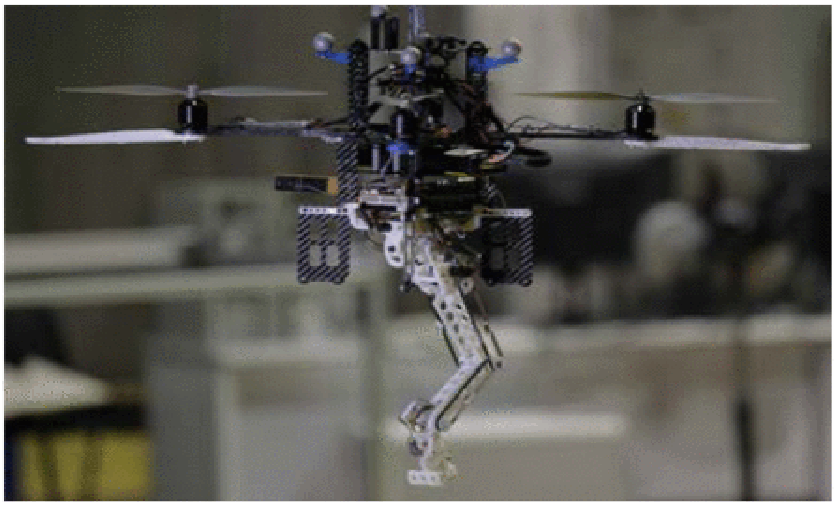


Figure 5: ASCTEC PELICAN equipped with the PUL5AR Arm [6]

As vision based robotic arms are increasingly being implemented in automation applications, they have made their way into agricultural robotics. In particular, one such development is the machine vision robotic arm for vegetable crops in hydroponics which integrates YOLOv8 based vision processing, depth cameras, and ultrasonic sensors to achieve object detection and aerial manipulation [11]. This design varies greatly from previous ones mentioned as the scope has completely changed with payloads in this design ranging from 8-10kg and using materials like aluminum (18-gauge) and mild steel (MS-16) ensuring strength is a priority. The implementation of a depth camera and ultrasonic sensors for both object detection and distance measurement is shown to work well together for object recognition and retrievals as a joint effort. The depth camera is able to determine object positioning within a 0.3m to 3m range while the ultrasonic sensors are placed at the base of the arm to measure object height before grasping [11]. Although this is not an aerial manipulator, this research provides critical insights into structural, control and sensing limitations which must be addressed when designing UAV-arm integrated designs.

Modeling and Control

This system requires dynamic modeling of an air vehicle consisting of a body, arm and gripper. Hovering ability is the most manifest feature of Vertical Take-Off and Landing (VTOL) air vehicles. Their capabilities allow deployment in almost any terrain, while fixed wing aircraft require a prepared area for takeoff and landing. The VTOL air vehicles have simple mechanics and good maneuverability. They can perform long flight operations and they are capable of transporting various sensors in order to be used for search and rescue missions [12]. Mathematical representation of the system is developed based on the Newton-Euler approach in the MATLAB-Simulink environment. Based on different designs of the gripper, and payload grasped, the flight dynamics are heavily affected. Hence, it becomes necessary to model the drone, arm as well as payload for an accurate controller design.

We will be using the decoupled UAM control strategy for this project as both the drone and arm are actuated differently as depicted in the schematic diagram in figure [].

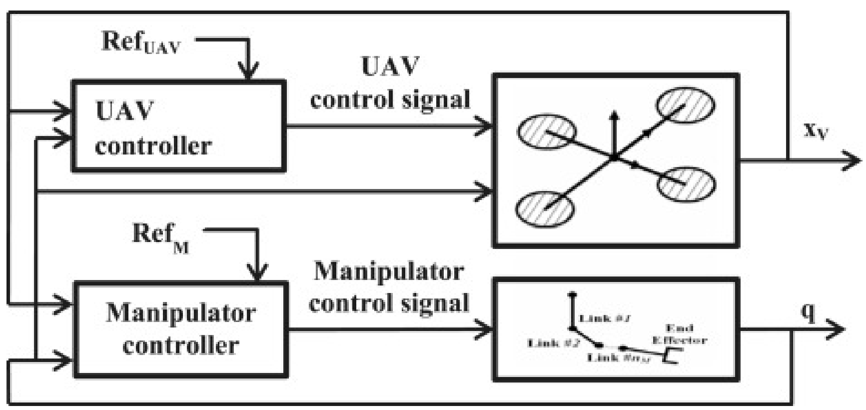


Figure 6 : Schematic diagram of decoupled UAV and manipulator control approach[13]

In recursive Newton-Euler formulation, the drone and manipulator are considered as two distinct subsystems, interacting at the manipulator base frame.
The manipulator control algorithm used for this project would be independent joint control using (PID, PID+gravity compensation. In the simplest implementation, the effects of the manipulator on the UAV are treated as disturbances and therefore are not explicitly taken into account in controller design [13].

Adaptive control is also another relevant position control that allows to systematically deal with time-varying parameters of the system, such as center of mass and moment of inertia. Disturbances due to the manipulator and its possible payload can be effectively handled by an appropriate adaptation law in the outer position control loop of a quadcopter. Specifically, it was shown that decoupled PID control of the manipulator joints, PD control of the inner attitude control loop, and adaptive control of the outer position control loop can successfully achieve precise hovering flight and trajectory tracking [14].

Electronics

The integration of electronics components into our arm-drone design project is fundamental for its functionality in terms of autonomy and efficiency. These electronics are able to enable precise control, data acquisition, communication, and automation.

To serve the purpose of the microcontroller, an Arduino UNO R3 was chosen as the initial platform due to its simplicity. These boards are able to significantly help progress in the early stages as they have direct servo control to test, low power consumption, and real-time execution with minimal overhead. It served as an excellent entry point for this project, but came with many limitations to further progress which includes limited computational power, multitasking, and sensor processing. To address these concerns, a switch to Raspberry Pi was made to be our long term solution.

As the project evolved into a more controls oriented perspective, more advanced features are required, including camera-based control, ultrasonic sensor integration, and real-time processing. Unlike Arduino which operates in 8-bit microcontroller, Raspberry Pi 5 features a Quad-Core ARM Cortex processor, capable of running multiple processes simultaneously. This allows us to process real-time sensor data (ultrasonic, IMU, camera) while controlling the robotic arm. Furthermore, Raspberry Pi has full operating system support as it runs Linux based OSs while allowing running Python, OpenCV, ROS, and AI frameworks. Additionally, the enhanced communication interface allows for more leeway into how we want to shape our project as Raspberry pi is able to support Wi-Fi & Bluetooth, USB & Internet, and multiple GPIO pins allowing an ample amount of choices for communication [16].

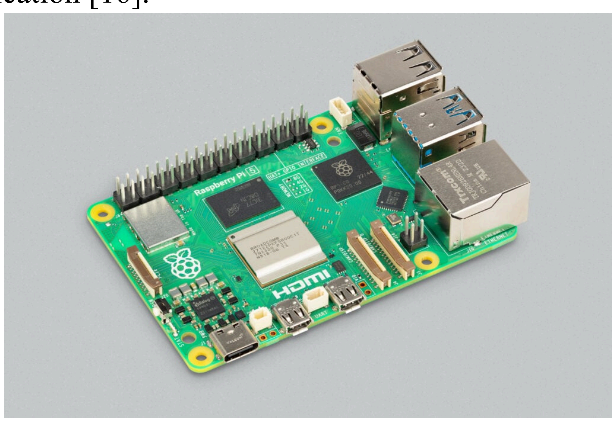


Figure 7: Raspberry Pi 5 [9]

However, the main concern we are able to address with Raspberry Pi is the ability to have high-resolution camera support integrated. Raspberry Pi is equipped with a Camera Serial Interface (CSI) and USB ports which allow for seamless integration of high-performance camera sensors which play a critical role in improving the robotic arms autonomy and decision-making [16].

Through the use of Arduino UNO R3, some testing was done as a form of research with servo motors in order to prepare for when we test with the Raspberry Pi 5. The following schematic illustrates the wiring diagram of how the manual controls for the 3 servos from base on the robotic arm were tested with their position limits. This gave thorough insights as to how we can incorporate manual control with multiple servos and the use of push buttons or joysticks. The following schematics illustrate multiple iterations with different sensors such as potentiometer and ultrasonic sensors to simulate before implementing on hardware.

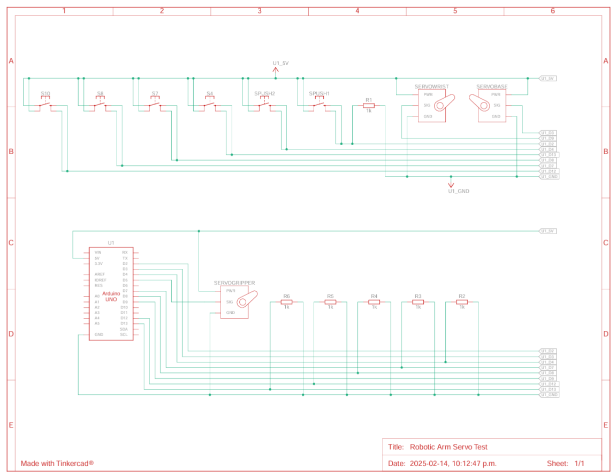


Figure 8: Schematic of Servo Tested with Pushbuttons

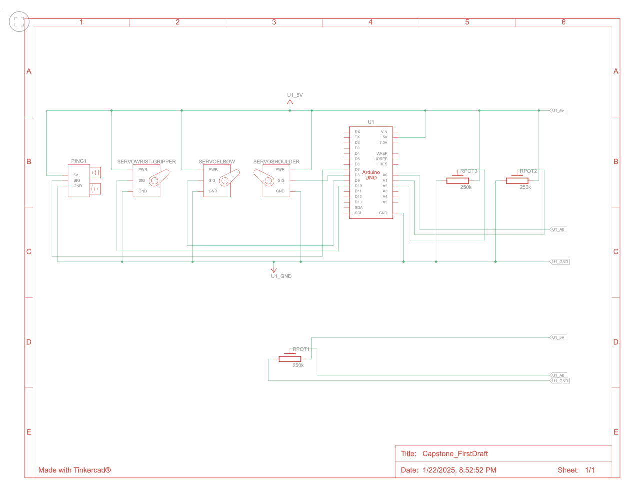


Figure 9: Advanced Schematic with Potentiometer and Ultrasonic Sensors

As our system will involve multiple servos and many sensors, the Raspberry Pi pins will be populated very quickly and an effective alternative to diverge this would be the implementation of the PCA9685 servo driver. This servo driver would be able to control up to 16 servos using I2C communication, making it a practical solution for managing multiple actuators [17].

Key Takeaways for Best Practices:

The integration of robotic arms with UAVs has been explored deeply in research studies particularly for object manipulation across various industries. These systems are able to provide substantial advantages in environments where traditional ground-based solutions are not feasible.

Existing research highlighted their best practices and challenges came across when designing such similar projects. Through these papers, we aim to tackle these challenges while still following these key practices to ensure proper engineering etiquette.

In terms of UAV selection, it was clear that multi-rotor UAVs offer superior control and maneuverability compared to other machines like helicopters. Despite the lower payload capacity, the advantages far outweigh the drawbacks with simpler control mechanisms and easier implementation.

When integrating the arm with the UAV, keeping the CoG near the UAV base improves flight stability, with a foldable arm design being an advanced design to enhance efficiency in design for takeoff and landing.

Control mechanisms through various papers have shown decoupled or decentralized systems are favoured in projects of this caliber as they improve stability and allow for the two systems to be treated as two separate subsystems. This allows for the UAV to focus solely on flight while the arm focuses independently without affecting UAV dynamics. This makes it easier to design controllers to ensure UAV remains stable even when the arm is moving around during flight.

When it comes to object detection and sensing, a depth camera was found to be commonly used while ultrasonic sensors come as an additional safety feature to ensure proper grasp. Incorporating both sensors will allow for safe use in industrial operations and in recreational as two sensors will always be better than one.

By incorporating these best practices, we can develop a UAV-integrated robotic arm that prioritizes stability, control, and precision while maintaining modularity for various applications. With these fundamental insights presented, we can now outline our design approach detailing how we implement these principles to create an optimized aerial manipulation system.

Design Approach

The design approach for this project focuses on the integration of a 5 DoF robotic arm with a tricopter with a semi-autonomous control system for aerial manipulation. Given the limited timeline, we have chosen to take a more practical and efficient approach to ensure the system is both functional and adaptable within the constraints of this project.

We are outsourcing the drone from a third party. It's a VTOL with three rotors and two servos as seen in the figure.

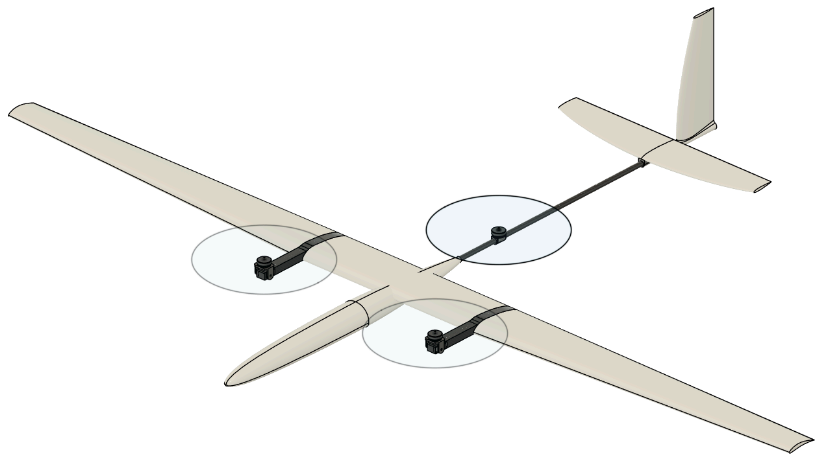


Figure 10: CAD Representation of VTOL Drone

The prebuilt arm was assembled and tested using an Arduino UNO R3 board. This arm was then calibrated to get servo positions and movement parameters for manual control. Once the arm was assembled, tested and calibrated, our team was able to confirm its robustness and reliability. We chose to use the Arduino UNO R3 board due to its simplistic design and robust prototype methods using C++ in Arduino IDE. The next step is to set up the arm sub-system with a Raspberry Pi 5 with 8GB RAM and be able to control it remotely using an Real Time Operating System (RTOS); preferably using Ubuntu. A Graphical User Interface (GUI) will be built to interact with the arm sub-system over the wifi network which gives us the ability to control the arm, get live telemetry of its positioning as well a live point of view of the Raspberry Pi camera placed at the claw of the arm. The system will be uncoupled and each drone and arm subsystems will be piloted separately. The control system of this UAV robotic arm is designed for semi-autonomous operation by integrating manual control alongside sensor-assisted automation with the goal being to ensure precise manipulation while maintaining flight stability. The control system consists of three main components:

1. Processing & Decision Making: Raspberry Pi 5
2. Motion Control: Servo Motors & Robotic Arm
3. Perception & Feedback: AI Camera & Ultrasonic Sensor

The Raspberry Pi 5 will be the central processing unit for this system and will handle processing real time video from the AI camera, running object detection algorithms, interpreting data from ultrasonic sensors and sending movement commands to servo motors accordingly. Instead of using a simple microcontroller, the Raspberry Pi 5 was selected to be used in our design approach due to its high computational power which allows it to simultaneously handle multiple tasks without lag.

The robotic arm has 5 degrees of freedom each controlled by servo motors. Each servo moves a specific joint, allowing the arm to reach and grasp objects. They mechanism of each servo is as follows:

1. Base Rotation Servo: Turns Arm Left or Right
2. Base Arm Servo: Moves Arm Up and Down
3. Arm Servo: Extends or Retracts the Arm
4. Wrist Servo: Adjusts the wrist angle for precision
5. Gripper: Opens and closes arm

The Raspberry Pi 5 controls the servos by sending pulse-width modulation signals, telling each motor how to move. This allows the operator to seamlessly control the arm manually while in operation while letting the system automate the final grasping mechanism.

To ensure accurate grasping, our system will combine both AI Camera with Ultrasonic sensor so the arm can locate and grasp objects with minimal manual effort. The AI Camera will be mounted on the UAV while streaming a real-time video feed to the operator. This will assist the operator to correctly position the arm and wrist so the gripper has no slip ups or miscalculations when grasping the object. It will also process object detection algorithms to help identify the target object visible to the operator in order to position the arm in reachable distance. The ultrasonic sensor will be attached to the gripper itself to directly measure the distance from the gripper to the object in real-time. When the object comes within range of the gripper, the sensor will trigger the gripper to close automatically ensuring a secure grasp.

This system will balance both manual control and automation allowing for efficient and precise object handling. The Raspberry Pi 5 processes all data from the sensors, controlling servos to move the robotic arm, and collecting real-time feedback to ensure reliable grasping.

Drone-Arm Interface and Support Electronic Mounting Design Intent

The design intent for the aerial manipulator project is to design a system that integrates a robotic arm into a drone that can be used for object manipulation. The system in question would include a robotic arm, and its interface with the drone. The drone is excluded from the system as the goal of this project is to have an arm & drone mounting system that can be assembled with any type of drone; hence having the project scope include the drone would make the general-use-case of the arm system redundant. For this project, the choice was made to buy an off-the shelf arm and design a control system along with a mounting system, as the mounting and especially the controls system can be modified to accommodate other arm designs. The robotic arm that was chosen for this project was a 6DOF mechanical arm and gripper set from Amazon [18].

Figure 11: Amazon Arm [18]

This particular arm design has various advantages that are beneficial to the project, especially in the prototype phase. The major advantage of this arm compared to other off-the shelf arms is the low cost for a 6 DOF arm. Other arms with similar DOFs are priced at a higher point due to having better aesthetics, and higher performance; however that extra performance is not justifiable for the price. The secondary major advantage of the arm that was chosen was its design and construction. The arm is composed of numerous sheet metal components that are connected to servo motors. This provides major benefits as the sheet metal construction provides for an extremely lightweight assembly; which is critical for any aerial vehicle as it can affect the drone's range, and the maximum mass of the object that the arm can manipulate. The sheet metal build of the arm also allows for easy parts replacements and modularity. Replacement parts can be made using very fast and cheap methods such as 3D printing or at worst sheet metal forming using custom molds that can be 3D printed [19]. The third major advantage of the sheet metal and servo design is its modularity and as a byproduct of that, design flexibility. Since the arm is made of numerous identical parts with no complex mechanisms, it can be modified by assembling the parts in a different order. For example, the 6 DOF arm can be modified into a 5 DOF or a 4 DOF arm just by removing different links. This opens the door to prototype a controls and electronics system on a simpler arm with a lower DOF and then scale up into potentially a full 6DOF controls scheme. This is in addition to being able to rearrange the links to be able to achieve different overall arm geometries; which has come in especially useful in mounting the arm to the drone's baseplate.

Figure 12: Sheet Metal Components and Servos of Amazon Arm [18]

The servo motors provide an advantage in the prototyping stage as they are a simple part that can be replaced or upgraded easily at minimal cost. This is in contrast with other arm linkage designs such as belt systems, gear systems with complexities such as bearings or geartrains. Although these more advanced systems can be more robust since they can potentially pick up greater loads or provide more accurate, faster positioning, the repair, replacement and upgrade pathways would be more expensive and complex to implement. As an added bonus, the simplistic parts also decrease the time it takes to create representative CAD for visualization and design purposes. A replica of the modified arm was created in Fusion 360 from scratch in order to be able to accurately build mounts and to validate any design modifications. Fusion 360 was chosen as the CAD platform as it is fairly similar to SolidWorks, but more importantly since it is cloud based and can greatly improve collaboration among multiple team members.

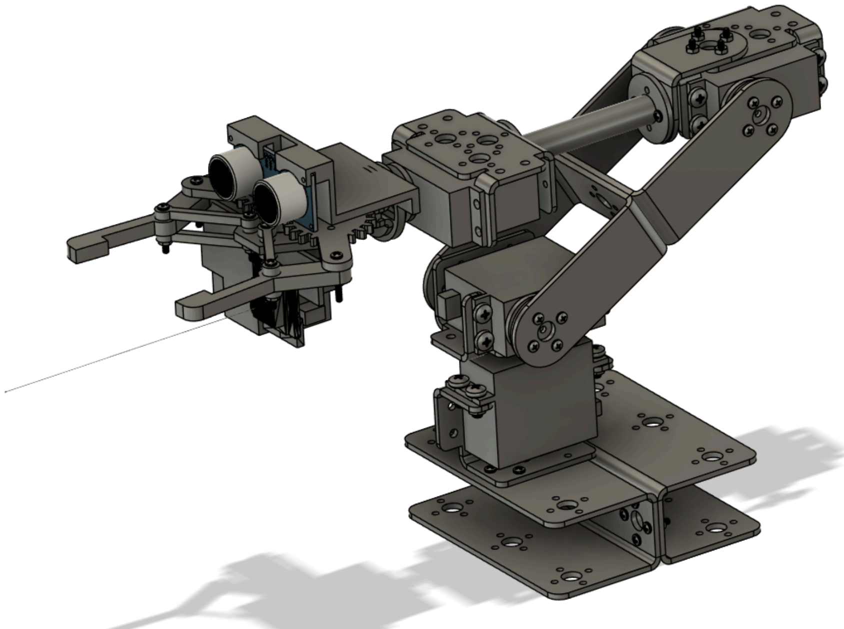


Figure 13: CAD Representation of Amazon Arm Created from Scratch in Fusion 360

The mounting system for the arm is to create a design that is able to mount the arm to the drone's base plate as well as some essential electronics. The electronic components that are essential to the function of the arm are a battery, Raspberry PI 5 and a Raspberry Pi AI camera for image processing.

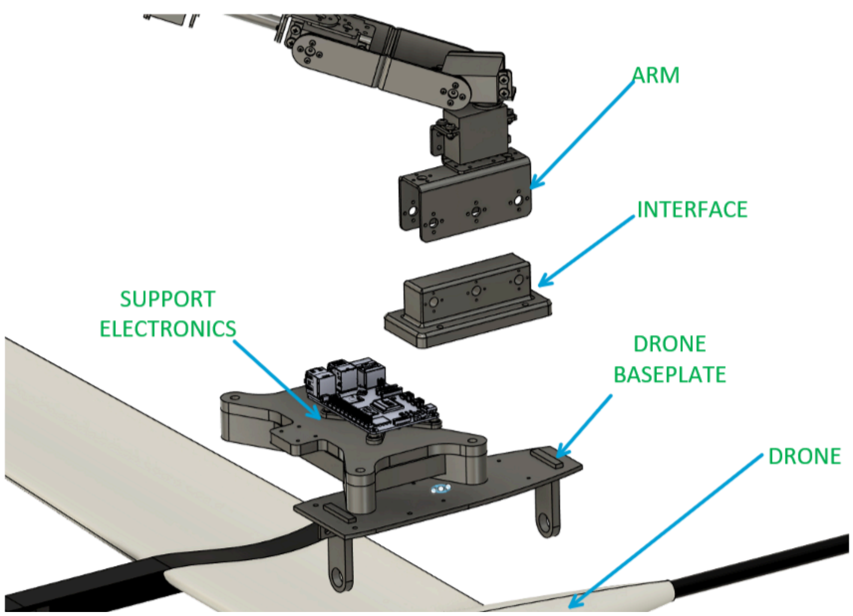


Figure 14: Exploded View of Drone-Arm Interface

The goal of the mounting system is to be able to mount all the components and the arm in the smallest space possible as well as being as lightweight as possible. The strength to

weight ratio is an incredibly important factor of this mounting system as the components need to be strong enough to be able to hold all the components firmly, and transfer the forces from the arm to the drone without failure. It also needs to be lightweight since the heavier the components, the less mass the end effector can manipulate.
In addition to all this, the part has to be cheap and fast to manufacture as this helps in iterating numerous times cheaply in order to converge to an optimal solution. For these reasons,the components are to be 3D printed using plastics instead of using metals. Although metals generally have higher strength compared to plastics, the raw material can be relatively expensive to purchase but more importantly, the machines and machine time needed to manufacture them is expensive with longer lead times. 3D printing was chosen as it avoids the expense and lead times related to machining processes involving CNC machines, while also significantly reducing the lead time cost for the tooling and machines related to processes such as injection molding. The first iterations of prototypes are to be 3D printed using PETG as this material is relatively cheap, widely available, easy and fast to print compared to materials such as ABS or nylon, has a higher Young's Modulus and yield strength compared to other filaments such as TPU, can be 3D printed from a variety of printers unlike as carbon-fiber embedded filaments and is easier to modify using taps, drills as it is not as brittle as other materials such as ABS or PLA [20].

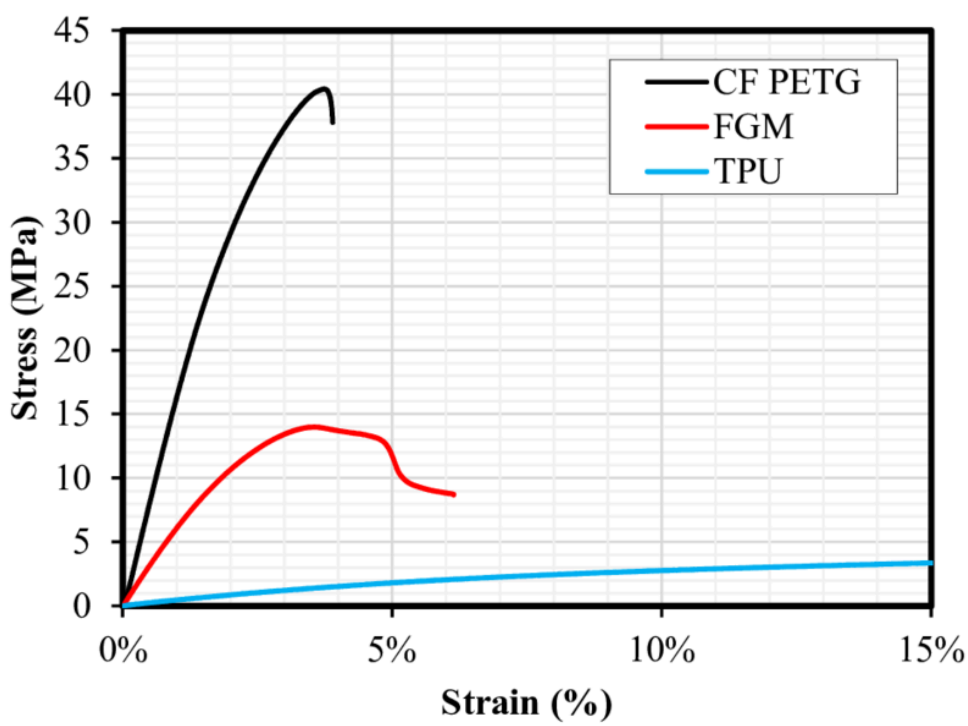


Figure 15: Stress Strain Diagram of TPU vs CF PETG [21]

For later iterations, the components are to be 3D printed using a carbon-fiber embedded PETG to further improve the yield strength to weight ratio [21].

Special consideration must be taken when designing the arm to drone interface. For the prototype, the interface must be able to mount to already existing features in the arm, as this means that modifications to the pre-fabricated sheet metal components is not necessary. In addition, the distance from the drone's baseplate and the arm's base must be carefully investigated as this affects the stability of the drone. Figure 12 shows a simplified drone, arm and interface system where the drone is the black box labelled "DRONE", the circles at the end of the rods are simplified point mass representations of the arm and the "rods" represent the distance from the drone's baseplate and the base of the arm. The different colors of the rod and point mass represent different rod lengths. Two scenarios need to be considered: one where the arm doesn't interact with the environment (ignoring air resistance) and a disturbance occurs to the pose of the drone and the other where the arm's interaction with its environment affects the pose of the drone.

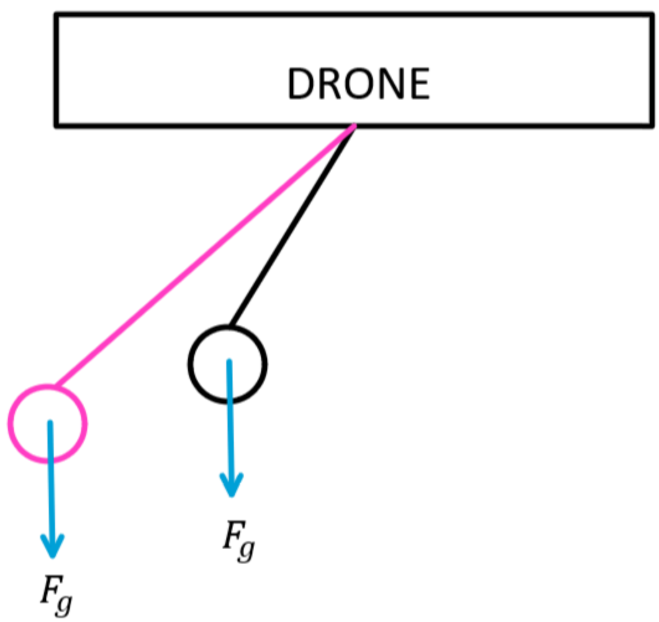


Figure 16: Simplified Drawing of Drone, Drone-Arm Interface and Point Mass Representations of Arm

In the first scenario, since the point mass is at a further distance from the baseplate of the drone, the force of gravity will apply a larger moment that will correct any pitch or rolling disturbances the drone may encounter. This improves the stability of the drone. On the other hand, the larger the moment arm between the arm and the drone's base, the larger the moment applied to the drone from the object/environment the arm's end effector interacts with. This would negatively impact the drone's pitch and roll stability. These two considerations need to be balanced when choosing how far the base of the arm is to the drone's baseplate, hence determining the thickness of the interface component.

The main considerations for the design of the battery housing, Raspberry Pi and camera mount were to have it integrated into a single mounting system. This is to keep all the supporting electronics as compact as possible as well as to have none of the electronics be mounted on the arm itself. An advantage to this design is that it ensures that the support electronics do not need a new mounting strategy even if the arm design changes. Another advantage is that the electronics can be kept close to each other, reducing the amount of wire needed to connect everything to each other which prevents signal degradation and reduces the chance the wires would get tangled with moving components of the arm. The design that was created is a "sandwich" of the battery, the raspberry PI and the raspberry Pi camera, with the battery being the closest to the drone's baseplate.

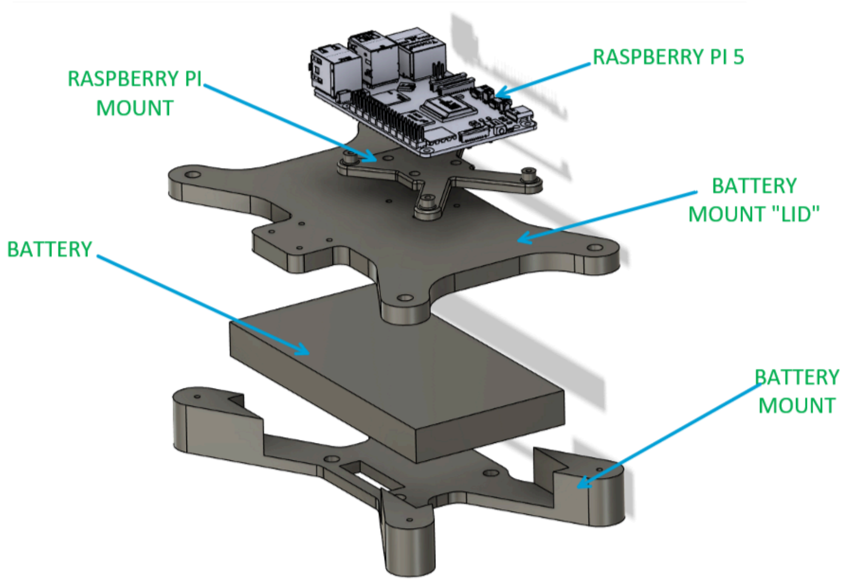
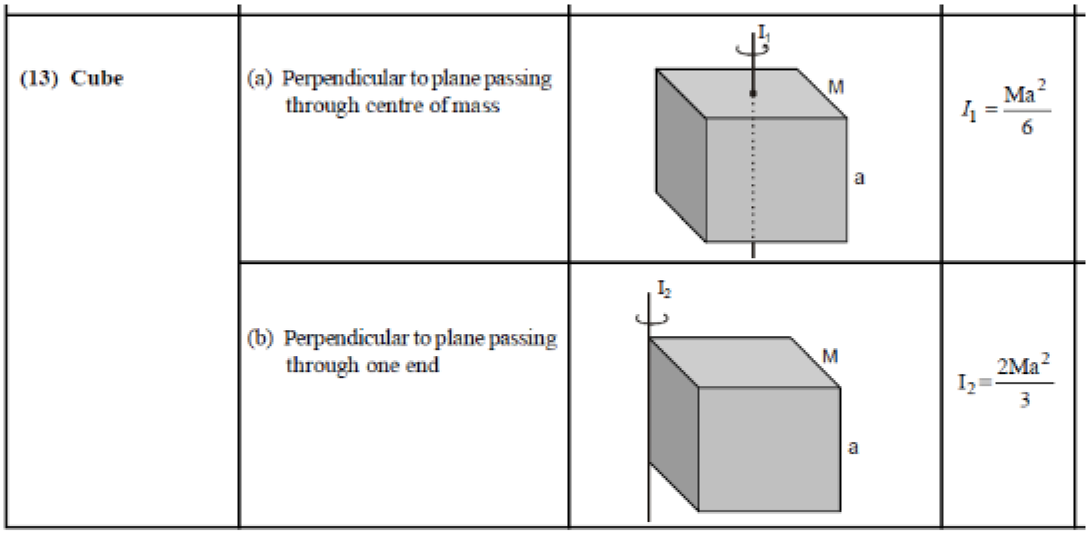


Figure 17: Exploded View of Support Electronics

The battery needed to be the component that is closest to the drone as it is the heaviest of the support electronics, and would thus generate the highest moment on the drone's baseplate if placed further away. Since the battery to be used is an off-the shelf portable power bank, little consideration was needed for the shock and puncture protection of the battery since that is already engineered into the battery's case.
Since the battery is the shape of a cuboid, the way it is mounted is of concern. This is due to the mass moment of inertia of the block changing depending on where the mounting point is. The mass moment of inertia of the block (assuming all sides or equal for simplicity) would increase by 275% when held onto a side compared to when held in its center [22].



(13) Cube	(a) Perpendicular to plane passing through centre of mass		$I_1 = \frac{Ma^2}{6}$
	(b) Perpendicular to plane passing through one end		$I_2 = \frac{2Ma^2}{3}$

Figure 18: Mass Moment of Inertia of a Cube [22]

Since the battery can't be supported from its true center, the design makes as much effort to support it as close to its center of gravity as possible; which results in the battery being mounted onto its flat side compared to its skinnier side. The battery is then secured in place with a "lid" onto which are features to be able to mount the Raspberry PI and the Raspberry Pi AI camera.

The design for the Raspberry Pi mount was simple and straightforward. The design is to use the Raspberry PI's existing mounting holes and to elevate the PCB off the mounting surface. This is mainly to create clearance for the various pins and the AI camera's connector that protrudes on the other side of the board. The design is to not have a cover in the early prototype phases as this provides easy and quick access to the GPIO pins and other connections located on top of the board. The AI camera is mounted onto features located on the battery's "lid", and the only requirement was to have it mounted flat on the mounting surface in order to eliminate distortions in the image.

FEM Analysis

All the mounts have currently been designed off of intuition, certain hand calculations and experience. To further refine the design in the latter parts of the project, analysis of various kinds need to be done. One of the main analyses that needs to be conducted is structural validation of the various mounts using FEM. ANSYS Static structure is planned to be used as this provides the most seamless workflow from pre-processing to post processing. In addition, a topology optimization study is planned to be completed to further optimize the various parts for their strength to mass ratio. It is also planned to not analyze components of the arm itself, as they are assumed to be engineered to a sufficient degree; as they are off the shelf parts; and also because characterizing the force response, stiffness, damping and backlash of the individual servos would be highly time consuming and would in the end not produce very insightful data.

There are numerous considerations that need to be kept in mind when performing analysis on 3D Printed parts. The first is to accurately represent boundary conditions. This mainly revolves around simplifying the environment that the mounts interact with. For example, how does one model the arm mounted onto the interface? One can import the entire structure and model all the connecting bolts and nuts explicitly, but that would be time intensive, and would need a large number of elements which would be greater than the student lisence's mesh limit. In addition, the chance for accidental errors in defining various contacts and connections increases. One could try to create a remote point and try to use MPCs (Multi-Point Constraints) to couple them to the interface, but that may not give accurate stress results as the load path may not get represented accurately. The second major issue; which is twofold; would be material definition. Since the components are 3D printed, they are hollow components with a certain infill density printed using a certain infill pattern. This creates problems with geometry representation in the FEA software for pre-processing. In addition, since the part is created using numerous layers, the tensile strength of the part will vary dramatically depending on if the load is in-line with the layer lines [23][24][25]. The failure mode may also vary as instead of material yielding, the part could fail due to delamination of the layers [26].

Trying to explicitly model every phenomenon such as infill pattern, layer separation, etc will amount to a very complex and most probably non-linear analysis that would be out of the scope of the team's current skillset. In order to try and run analysis while trying to avoid these issues, future research on simplification of the problem is needed. If a suitable simplification cannot be made due to the team's lack of skill set, an alternative method of running the analysis assuming 100% infill is to be done.

Revised Timeline

As we have progressed into the design phase, we have made key adjustments to our initial approach based on a better understanding of the project scope. Initially, our assumption was that we would be responsible for designing the robotic arm, focusing on manual control with autonomy being something we delve into if the time permitted. However, after further clarification, it was made clear that this is a control problem with some level of autonomy being a requirement and designing the arm is not the main focus.

As a result, our team collectively decided to purchase the robotic arm and borrow our UAV from a third party and have shifted our efforts toward integration of these components and developing a semi autonomous control system.

Progress so Far:

- **Components Acquisition:** We have acquired all necessary hardware components including drone, robotic arm, servos, sensors, and control boards.
- **Final Control Setup:** We have finalized our project scope and design approach, deciding to implement a semi-autonomous system instead of fully autonomy due to the complexity of controlling all servos in the 5 DoF arm. This approach involves making four out of the five degrees of freedom arm manual control, while only the gripper will be autonomous using an ultrasonic sensor to detect and grasp objects.
- **Preliminary Integrations:** We have begun hardware and software integration, testing communication between components and exploring potential control algorithms.
- **Initial Software Setup:** Using OpenCV and other other softwares, we have been able to get a demo object detection program running as a start
- **Manual Control:** We have already started working on fully manual control using pushbuttons and joysticks to control each servo for precise movement as it made sense to get the basics covered before stepping foot in automation

Tasks Ahead of Schedule:

- **Hardware Acquisition & Assembly:** Initially, we were expecting delays in acquiring necessary hardware parts, but we were able to source and assemble our components ahead of time giving us a better start on integration
- **Automation Planning:** Although automation was considered an end goal, as a team we have collectively begun exploring automation options. This includes research and conceptual designs for integration of different sensors which can be used which include ultrasonic sensors and cameras to enable a semi-autonomous or fully autonomous arm mechanism to detect and manipulate objects.

Tasks Behind Schedule:

- **Software Integration & Testing:** Although we have successfully set up the Raspberry Pi 5 and some other hardware components, full integration with the robotic arm and UAV is taking longer than expected
- **AI Camera Processing & Object Detection:** The AI Camera's built in models require additional fine tuning in order to get accurate real-time object detection and we are still working on optimizing this

Reasons for Delays:

Major Scope Shift: Initially, our team was under the assumption that we needed to design and build a robotic arm, focusing primarily on manual control. After realizing the actual scope, this fundamental change resulted in major change in our initial planning, research and early-stage work which had to be restructured again, setting us back on software development.

AI Camera & Object Detection: One of the major technical challenges has been optimizing the AI Camera for real-time object detection and tracking. Although the AI Camera has built in models, tuning them for real-time object detection with as small latency as possible has taken much longer than expected.

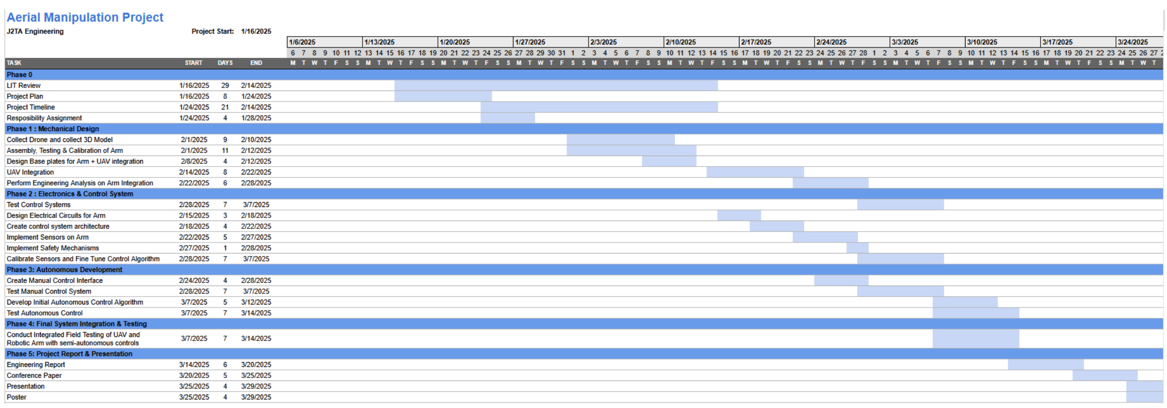


Figure 19: Updated Gantt Chart which is also found in team drive shared with supervisor

Conclusions & Recommendations

This report details the progress of the Aerial Manipulation Project, which aims to enhance the VTOL capabilities by integrating a lightweight 5-DOF robotic arm for object manipulation. This report discusses the current limitations of drones, primarily their lack of interaction with the environment which can be fixed by integration of an arm for precise control. Instead of buying an off the shelf drone, our team opted to get a custom made drone from a third party which enables us to work closely with the drone architecture and make modifications. This strategic decision allows the project to concentrate on the core challenges of the manipulator design, and real time controls.

Key challenges include weight and payload optimization, stabilization during flight, and overall precision and maneuverability. Ensuring precise object detection and manipulation and the integration of sensors to make this happen remains a crucial area of focus in this project. Initial testing has provided valuable insights into these challenges further guiding our interactive design improvements. The selection of hardware components is crucial to get a functional and working UAV arm system. Through literature review and background research, it was found that the Raspberry Pi 5 was the best candidate with its numerous features and adaptability with sensors such as ultrasonic and depth cameras. As software development and AI camera processing still remain key challenges going forwards, ongoing refinements and testing will help optimize real-time object detection and improve overall system performance. Moving forward, the team's focus will be fine tuning and further integration automation features to ensure a fully functional and efficient UAV based robotic manipulation system.

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Appendix

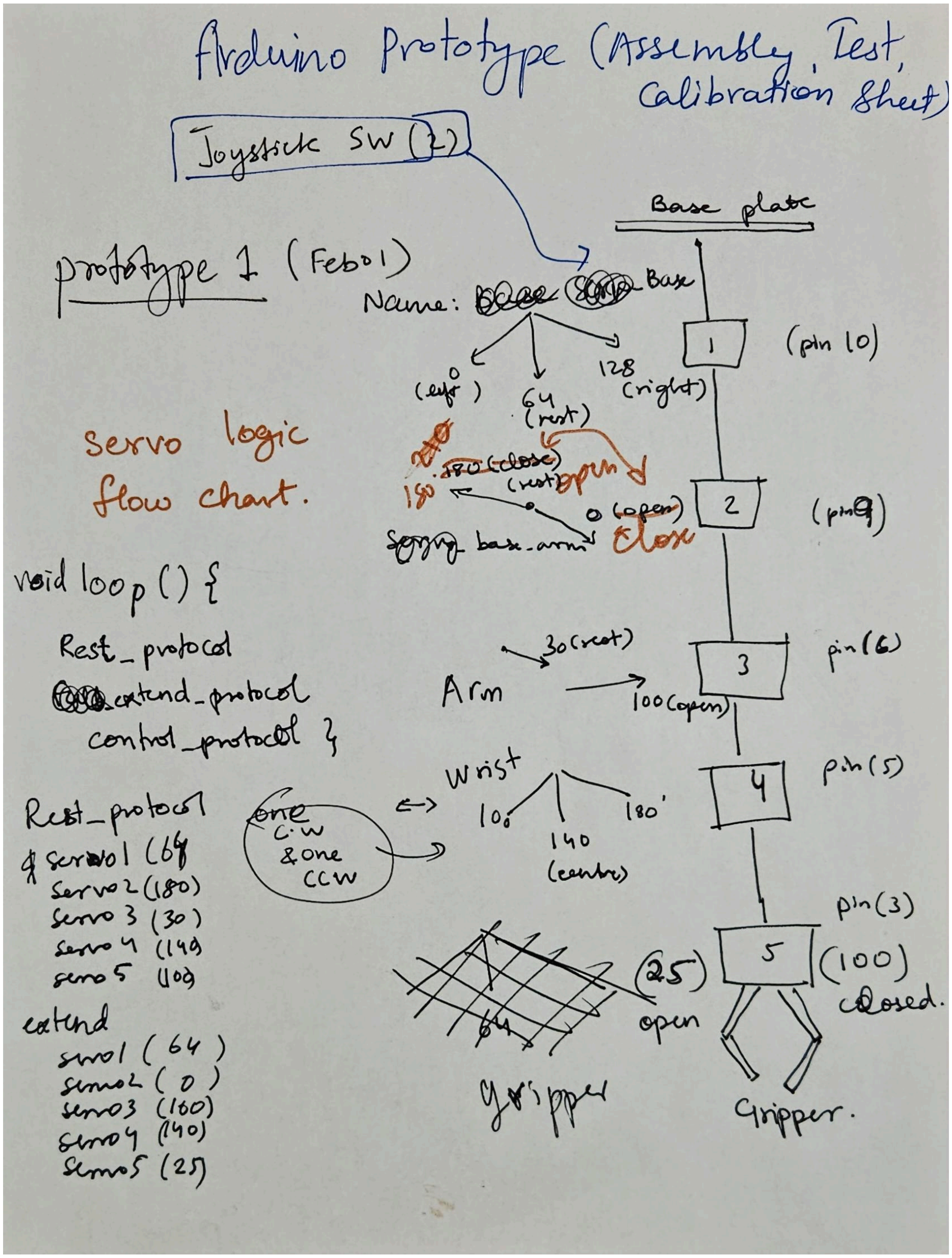

Figure 20: Prototype for assembly and code testing of the arm