Universidade de Aveiro
2024

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Design and Development of a Modular Reconfigurable Aerial Vehicle

Keywords

Design, Development, Reconfiguration, Reconfigurable, Aerial Vehicle, Vehicle, MAV, MRAV, Modular, Module, WBS, Swashplate, Swashplateless,counter rotating, Drone.

Abstract

This study proposes the development of a modular reconfigurable aerial vehicle for enhanced efficiency and logistical management in construction sites. The modular design enables seamless connections and detachments, facilitating versatile payload transportation and improved resource utilization. The proposed vehicle employs co-axial motors with counter-rotating blades for stable and controlled flight, extended flight time, and enhanced maneuverability. The project's scope encompasses performance, reliability, and design requirements, ensuring the drone meets the demands of complex construction tasks. The MRAV's potential extends beyond construction, with applications in search and rescue, disaster relief, and specialized missions in remote or hazardous areas. The development of MRAVs represents a significant advancement in aerial technology, offering transformative capabilities for various industries.

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Chapter 1

Introduction

1.1 Background

In construction sites, efficiency and logistical management are crucial elements for project success. In this context, the introduction of a small aerial vehicle specialized in transporting equipment and materials represents a revolution in how companies address the challenge of cargo movement in construction environments. This drone, designed to meet the demands of the industry, will enhance safety, optimize available resources, transportation and offer cost reductions. But if one is great, multiple will be best. This drone will be able to attach and detach to other drones forming a connected fleet that works synergistically to accomplish complex tasks, such to transport larger payloads, and this versatility allows the drones to be dynamically configured to meet the specifications of each mission.

It is important to mention that this is a non-profitable project, it is to be used as a tool for research and education along the journey.

1.2 Problem Statement

Modular Reconfigurable Aerial Vehicles are comprehended as individual and fully functioning aerial vehicles capable of performing tasks on their own whilst at the same time being able to assemble with other vehicles such as them in order to better perform some of its tasks. Such vehicles have built-in mechanisms that facilitate this assembly.

It is also worth noting that such study might help comprehend how future in-space assemblies might take place, and help accelerate that reality in terms of the technology used.

1.3 Objectives

Every project must have clear objectives set to be fulfilled, and this one is no exception, therefore, some were set for this project to go on by. On this study, the objectives have been divided into two categories, being primary and secondary.

The primary objectives were:

- Development of two independent aerial vehicles capable of reconfiguring in flight.
- Study, comparison and selections of assembly methods for the vehicles.

The secondary Objectives were:

- Demonstration of the scientific principle and applicability.
- Use of co-axial motors with counter rotating blades for propulsion.
- Optimization of the structure of the aerial vehicles.

And one extra goal was to attach a payload to the modules if all the above were successful.

1.4 Significance of study

The development of a modular reconfigurable aerial vehicle (MRAV) holds significant potential to revolutionize the construction industry and beyond. This innovative technology offers several key advantages:

- Adaptability and Versatility.
- Extended Flight Time and Maneuverability.
- Cost-Effectiveness and Scalability.
- Educational and Research Potential.

Potential Applications Beyond Construction: MRAVs hold the potential to transform various industries, including:

Search and Rescue: MRAVs can quickly access remote or hazardous areas, providing search teams with enhanced situational awareness and the ability to transport injured personnel or critical supplies.

Disaster Relief: MRAVs can deliver emergency supplies, assess damage, and support rescue operations in the aftermath of natural disasters or other emergencies.

Specialized Missions: MRAVs can be customized for specific tasks, such as carrying out scientific research, monitoring environmental conditions, or performing surveillance in remote locations.

In conclusion, the development of modular reconfigurable aerial vehicles represents a creative step forward in the field of aerial technology. With its potential to enhance efficiency, adaptability, and versatility, MRAV technology has the power to revolutionize construction operations, streamline logistics, and enable new applications across various industries.

1.5 Scope

In this study there were also requirements set to be fulfilled and to guide the path to the solution, requirements which are also divided into three categories, Performance, Reliability and Design.

Therefore, the requirements set, in order of priority are:

1. Performance:
    - Stable and controlled flight.
    - In-flight reconfiguration.
    - 6 Degrees of freedom.
    - Use of the swashplateless system.
2. Reliability:
    - 10 minutes of flight.
    - Resistant structure.
    - Protected avionics.
    - Reusable.
3. Design:
    - Simple design.
    - Easy to assemble.
    - Easy to maintain.

1.6 Work Breakdown Structure

Figure 1.1: WBS

The project was divided into 6 sections in the first proposed WBS:

1. State-of-the-Art Review and Trade-off Analysis:
   - Where it is intended to understand the study, the problem and objectives, propulsion, swashplateless system and define all the literature review.
2. Module Design:
   - Define the connection between the modules, as well as the architecture and components, it's structural design and make some test guides for the next section for the critical components.
3. Initial Tests:
   - Realize the tests prepared beforehand and analyze their results.
4. Module Development:
   - Acquisition of the rest of the components and build the vehicle, assure its flight and solve any issues that might be encountered.
5. Validation and Testing:
   - Continuation of the tests and maybe a demonstration of it working to recognize its potential and limitations.
6. Documentation:

- Should be done during all stages of the project and it propose should be reporting all the results gotten and all steps made to the project.

For this projects there were some risks identified. Bellow there's a list from the most impactful to least and the respective mitigation strategy to them:

1. Swashplateless failure:
    - Deep research and of different configurations and testing. Contacting the creator of the system to gather information in order to iterate the model until correct.
2. Structure's mass:
    - Realization of tests on the motors to ensure lift is possible.
3. Technical difficulties:
    - Research on the connections between components, the components and it's compatibility.
4. Reconfiguration:
    - Testing of the different mechanisms proposed and the different concepts generated.

Chapter 2

Literature review

2.1 Swashplateless

The swashplateless[3] is a usually lighter version of the swashplate. The swashplate is a device, notably used in helicopters, that allows for the control of cyclic and collective pitch of the aircraft's rotor blades. This cyclic pitch control can alter the pitch and roll of the helicopter. However, mechanical control of blade pitch is complex, as these controls are transmitted from the pilot or actuators on the non-rotating frame to the blades on the rotating frame through the swashplate, typically causing significant drag and high maintenance load.

Swashplateless replaces this mechanical difficulty with an electronic challenge. In other words, swashplateless involves fewer components in the system and between control and response. However, controlling it is challenging on the electronic side. In swashplateless, a cyclic system is used to induce high pitch in the blades as they pass through one part of the rotor and then low pitch as they pass in the opposite position. To achieve this, a sinusoidal component is applied to the motor in phase with it's rotation, exciting a variation in lag angle and, consequently, in pitch with each revolution. Essentially, sinusoidal variations in motor speed and acceleration enable the MAV (Micro Air Vehicle) to move in the indicated direction.

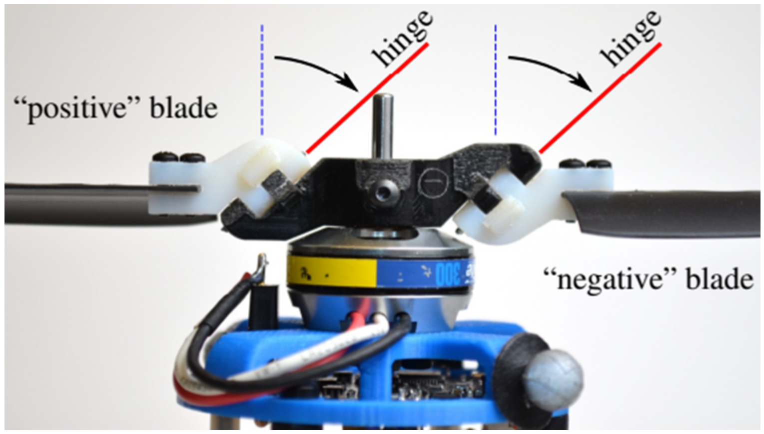


Figure 2.1: Swashplateless

The design of this component is very simple. It consists of one piece connected to the rotor and two additional pieces, each attached to the blades. These two pieces are connected to the first one through hinges. As can be seen in the figure, these hinges are not vertical, and this is what allows the lead-lag movement of the MAV. According to Tom Stanton [4], adding washers and brass inserts to the hinges decreases friction between the material of the system and reduces the amount of wear, because they are swinging back and forth so often during the rotation, the 3d prints would wear out. He also concluded, in terms of the hinge angle, it can be changed and the lower the angle is, the harder it is to tune, because it is more mechanically sensitive therefore the slightest electronic input generates a massive mechanic output, the higher angles are easier to control, however for the motor to speed up and down at those frequencies would heat the motor, nonetheless it was not conclusive on what is the best angle for the hinges.

2.2 Coaxial counter rotating blades

Counter-rotating blades are a type of propeller configuration where two or more propellers spin in opposite directions along a common axis. This configuration is commonly used in coaxial motors, which are rotary airscrews or turbines mounted one above the other on concentric shafts. The top motor rotates in one direction and the rear one rotates in the other. The torque created by one of the propellers will be canceled by the one created by the other.[5]

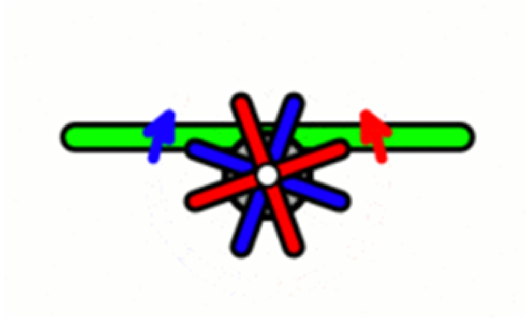


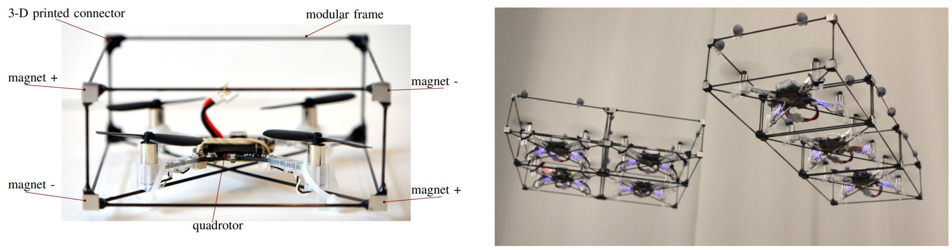
Figure 2.2: Coaxial Counter Rotating blades

There are some advantages and disadvantages to this system. It improves the efficiency due to cancelling the torque, allowing for better power transfer, it also increases stability of the aircraft, especially in hover mode. However, it is more complex, leading to higher cost and can be very noisy.[6] One other test, with the aim of finding the best coaxial layout for drones, and it was concluded that at higher speeds (>1750 RPM), the separation distance between propellers has little to no observable impact on rear propeller efficiency and increasing rear propeller size (diameter) may exacerbate the relative decrease in rear propeller thrust generation as front propeller speed is increased and increasing front propeller speed may cause lower thrust and torque generation in the rear propeller. So these are things that we need to take in consideration when choosing the blades and position of the rotors.[7]

2.3 Reconfiguration

One of the main objectives of this project is to demonstrate the concept of having two drones assemble and "join forces" in flight. For this purpose, a thorough study of this application was needed, where it was possible to learn about all the approaches used in the past to achieve the same objective. One of the main difficulties this presents include the mechanism used to assemble the modules, given the fact that our goal is to do so in flight.

A few studies have been made where this goal has been achieved using quadcopters, and their assembly is done in flight, the same as we pretend, where in that study, autonomous drones are used and to them are enclosed and attached a frame made with carbon fibre rods that contains magnets on the vertices to achieve the reconfiguration, where the modules connect to each other by the magnets [8].



(a) A Flying Modular Robot. (b) Flying modular structures.

Figure 2.3: Flying Modular Robots.

Studies have also been made using single rotor drones with fixed-pitched propellers which by itself cannot fly, and each module can move on the ground until it docks with another and only afterwards, they could achieve flight [9].

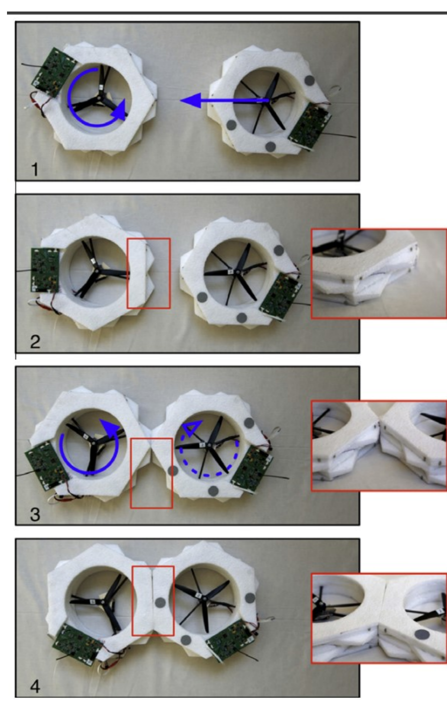


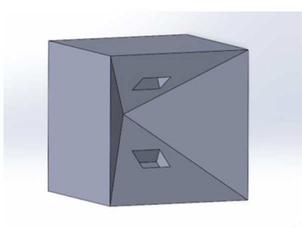
Figure 2.4: DFA concept.

Chapter 3

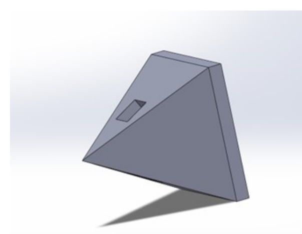
Design and Development

3.1 Reconfiguration

For this project, the goal is to use a concept with similarities to both studies presented, which would include a mechanical and magnetic assembly mechanism. For that reason, three concepts were prepared, each of them using the same principle, which consists of two components (one male and one female) where the *male* part connects to the *female* part.



(a) Female



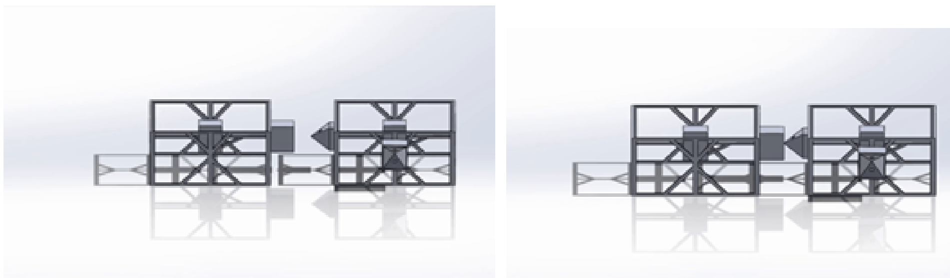
(b) Male

Figure 3.1: Reconfiguration parts.

In this concept, it is expected that the male part can more easily connect to the female given its proposed shape, where it would allow more freedom and the modules would not need to be 100% aligned for them to join, the pyramid shape would allow for the vertices of the male to always tend towards the female. This proposal also includes a slot for magnets to be placed inside, which would help assure the modules have a stronger connection in flight and would transit the forces from one to another.

The three proposals, as mentioned before, use this same concept, being:

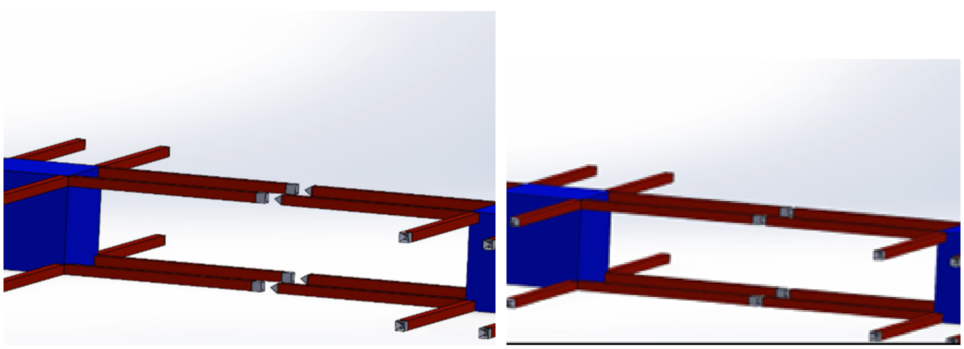
1. **Concept 1:** The connection between modules is on a single and point. This proposal would allow an easier connection, although in counterpart it would make the module heavier and more unstable.



(a) 1 (b) 2

Figure 3.2: Illustration of the first concept.

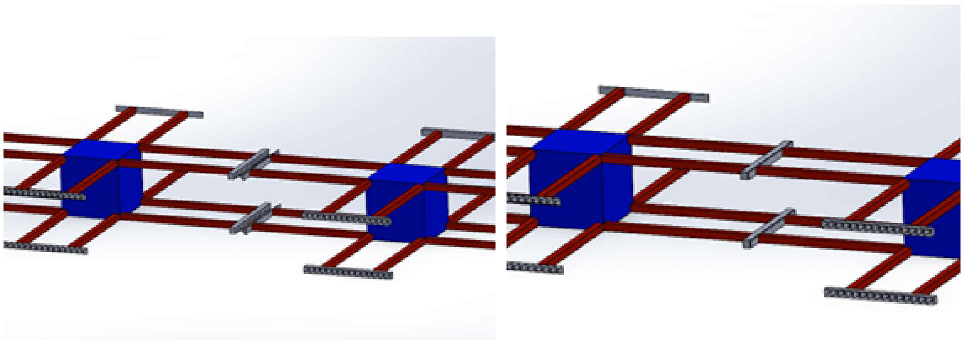
2. **Concept 2:** In this proposal, the connection is made in four, smaller points. This indicates that the stability in flight would be greater, and the weight of the aircraft would decrease significantly, but they would need to be more aligned for the connection to happen.



(a) 1 (b) 2

Figure 3.3: Illustration of the second concept.

3. **Concept 3:** On this last proposal, the connection is intended to be made in two arrays of points (number to be determined), where it is thought to offer more stability than the other two proposals, while having less weight than the first proposal and being easier to connect than the second.



(a) 1

(b) 2

Figure 3.4: Illustration of the third concept.

All three proposals were intended to be tested, in order to better determine which of them is better suited to fulfil our objectives. This was not possible, due to restrictions on knowing how much weight the drone would be able to lift, therefore the model concept was 3D Printed using PLA and motor magnets to demonstrate the concept.
The end result, as shown, proved this to be a good concept on which all three proposals could be applied with the right dimensions, given that the only restriction was the size of the Magnets available.

Figure 3.5: Male and Female printed parts.

3.2 Structure

The vehicle's structure was not developed in this project, although it was pondered the use foam or 3D printing materials due to them having lightweight and protective qualities, given that it would need to hold all the hardware.

However, some of the early thoughts of structure involved using similar structures to [8], involving using lightweight rods, in this case with FDA printing, with the filament yet to be chosen. The other structural principal would be an adaptation of [9], possibly using polypropylene foam as well. This means that the structure would need to be adapted in order for the air to flow in the center of it, allowing the vehicle to be able to lift off the ground. Lastly, the structure would need to include a built-in landing gear, considering that the vehicles will be using coaxial blades, in order to protect the propellers and motor in the bottom of the module, this would require great effort in design to be implemented, given the current restrictions imposed by having a coupling model and swashplateless direction control.

3.3 Components

For this project, it was expected to use the least amount of components possible in order to complete the requirement of having a simple design. Bellow there is a list of the main components of a singular module for the project, noting that there may be additional components in the future.

LiPo Battery:

Figure 3.6: Battery

A 5200mAh 50C LiPo battery with an XT60 connector is a popular choice for radio-controlled (RC) vehicles due to it's combination of high capacity, high discharge rate, and compact size.

Brushless motor Racerstar BA2216 1250KV 2-4S

Figure 3.7: Rotor

The Racerstar BA2216 1250KV 2-4S brushless motor is a popular choice for fixed-wing RC planes and FPV racing drones. It is a high-power and high-efficiency motor that can deliver excellent performance in a variety of applications.[10]

Eletronic Speed Controller(ESC): Flycolor 50A ESC 2-4S Electric Speed Controller 5v 3A BEC with XT60 & 3.5mm Bullet Plugs.

Figure 3.8: ESC

The Flycolor 50A 2-4S Electric Speed Controller (ESC) is a popular choice for RC vehicles due to its combination of high current output (50A), efficiency, and compact size.[11][12]

Computer and flight controller: Teensy 4.1

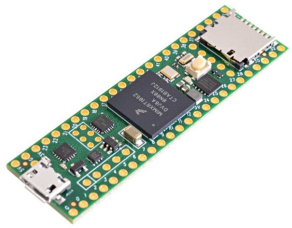


Figure 3.9: Teensy 4.1

The Teensy 4.1 microcontroller is a powerful and versatile device that can be used as a computer and flight controller for a variety of applications having a 32-bit ARM Cortex-M7 processor that can operate at up to 600 MHz, multiple Analog and Digital I/O pins, real time operating system amongst other features.[13]

Propellers: helicopter 19 cm blades

Figure 3.10: Helicopter Blades

Propellers are a good choice for many applications because they are lightweight, powerful, durable and efficient, all of which are important factors for this implementation instead of regular drone blades, considering that one of the goals is to implement a swashplateless system.

Transmitter: FS-I6X

Figure 3.11: Transmitter

The FrSky FS-i6X is a popular 2.4GHz transmitter that is known for its ease of use, durability, and compatibility with a wide range of RC vehicles. It is a great choice for both beginner and experienced pilots. [14] [15]

Receiver : FS-IA6B Receiver

Figure 3.12: Receiver

The FrSky FS-IA6B is a popular 2.4GHz receiver that is known for its reliability, compatibility, and affordability. It is also a great choice for both beginner and experienced pilots, and it is usually used with the FrSky FS-i6X transmitter, ensuring more reliability.[16][17]

Sensor: AS5048B

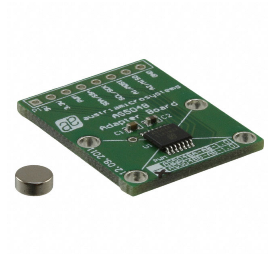


Figure 3.13: AS5048B

The AS5048B is a high-precision absolute encoder with a built-in 14-bit magnetic sensor. It is capable of measuring rotation angles with a resolution of 0.05 degrees, making it ideal for applications where precise angular position is required, as such is this case, in order to measure the absolute angle of the motors for the swashplateless system to be implemented. [18][19]

For the project, the sensor will give the motor shaft angle, and with that the computer will run PID control so the vehicle goes to where the user wants using the transmitter.

1 Module			
Component	Qty.	Mass(g) p/unit	Power(W)
Rotor	2	68	400
ESC	2	82	15
Teensy 4.1	1	12	0.5
Batery	1	475	
Receiver	1	15	0.125
Sensor	1	5	0.25
Cables	N/A	15	
Propellers	4	11	
Swashplateless	1	10	
Total		876	415.875

Figure 3.14: Components per module and power consumption.

The chosen motor, when equipped with 8060 propellers, can produce thrust equivalent to 1170g at maximum power (14.8V and 27.2A). On this project, helicopter propellers, significantly bigger, will be used, therefore it is expected that it will not be necessary to use so much power and there will still be available of mass for the structure. At the estimated power of this module(P=415,875W), the battery would last about 11.1 minutes, which would be enough to ensure that the reliability requirement is fulfilled.

Presented bellow is a possible architecture of the MRAVs for this project:

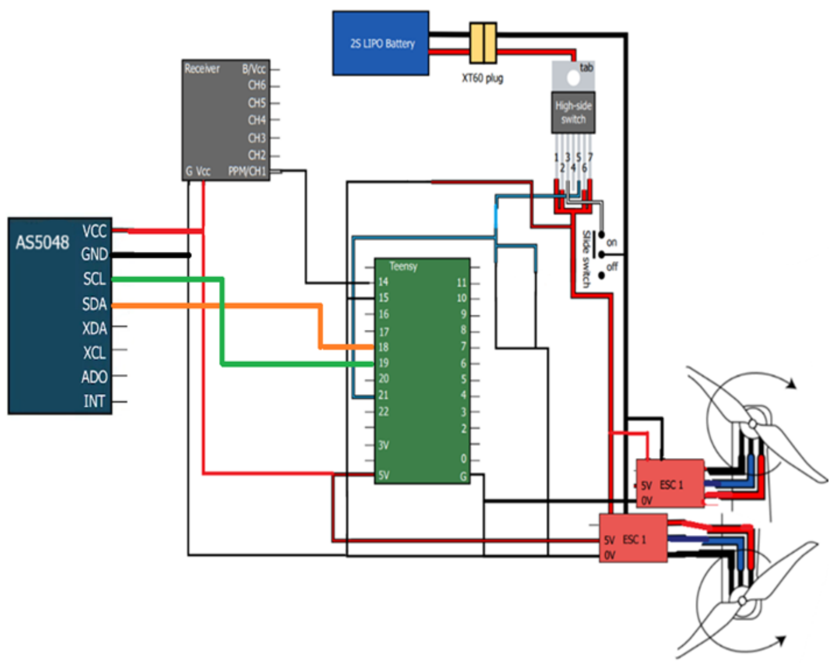


Figure 3.15: Possible Architecture

It is not a final architecture, given that it was not possible to build the MRAVs but it gives an idea of what it could be.

3.4 Swashplateless

There were a few models of the swashplateless made accordingly to the literature review and the components. One of them is this system, in the figure bellow. It is a 65º angle hinge with the horizontal and matches all of the criteria of the components, the motor shaft and the blades fitting.

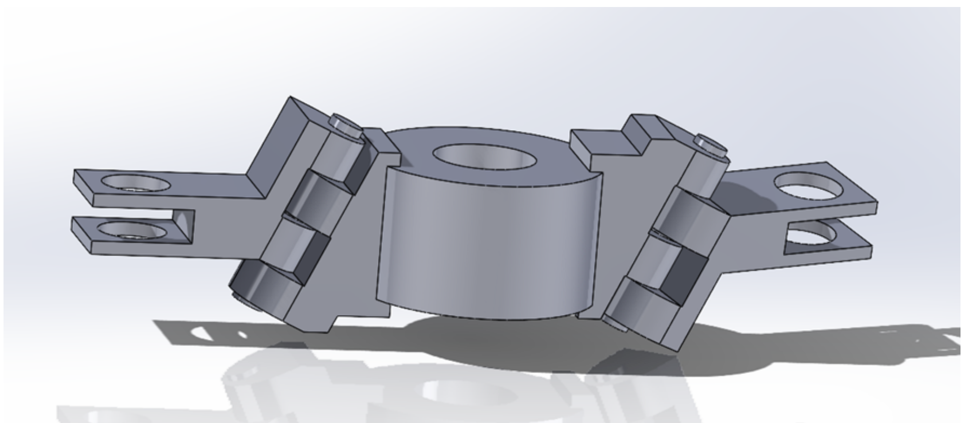


Figure 3.16: Swashplateless Model - CAD

This was the first concept made for this project, and there were further iterations, since it needed to be tested for reliability, motor and propeller fitting and high & low pitch.

It was on the next stage, during the first attempts to 3D print the parts that it was clear that changes needed to be made to the design in order to ensure more precise parts and reduce the difficulties of printing these parts. There was also an unsuccessful attempt to contact James Paulos, the inventor of this amazing piece.
However, that did not stop the progress, and after iterations of printing and fitting, there was a final design that proved durable and fitting the motor perfectly, using 50% infill and PLA, the technichal designs can be found in the attachments.

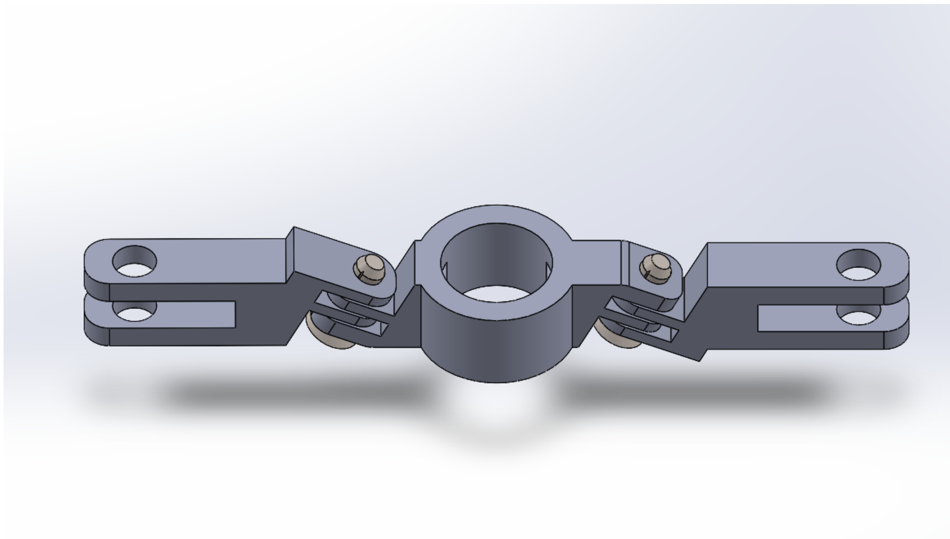


Figure 3.17: Final Swashplateless Model - CAD

Figure 3.18: Final Swashplateless Model with motor and propellers.

Chapter 4

Discussion

The development of a modular reconfigurable aerial vehicle (MRAV) presents a compelling solution for enhancing efficiency and logistical management in construction sites. By enabling multiple drones to seamlessly connect and disconnect, MRAVs offer a versatile platform for transporting equipment, materials, and even specialized payloads. This adaptability translates into improved efficiency, reduced costs, and optimized resource utilization.

The project aimed to design and implement two independent modules capable of reconfiguring in flight. This capability, along with the utilization of co-axial motors with counter-rotating blades, promises stable and controlled flight, extended flight time, and enhanced maneuverability. The modular design, with its emphasis on simplicity, ease of assembly, and maintainability, further enhances the practicality and scalability of the system.

For this to be possible, through careful benchmarking of other projects of similar kind and involving aspects worth consideration, much was learned in order to properly implement the desired outcome, therefore, a new WBS was proposed and components have been carefully chosen.

In this process, an adequate architecture has been selected, which is divided into three parts, being User Input, Flight control and Power-train, each of them involving the listed components. It's worth mentioning that this architecture of the vehicles was taken from [1].

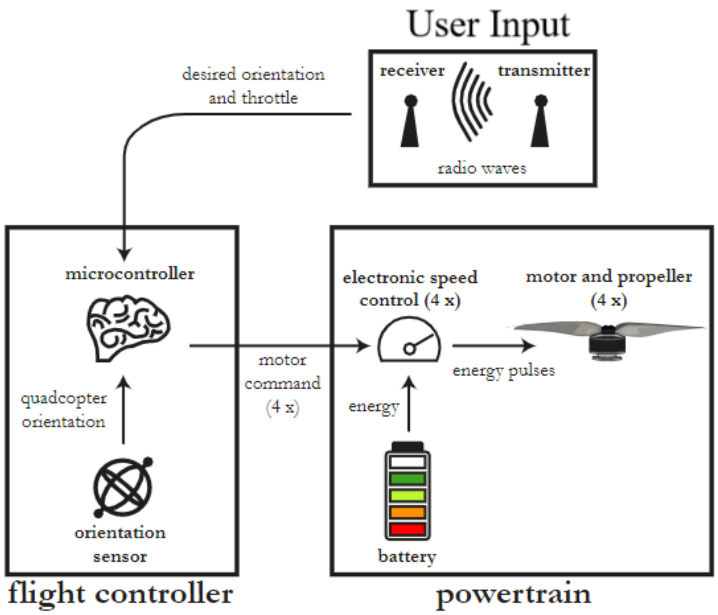


Figure 4.1: Architecture from [1]

Following this architecture would allow there to be guidance in regards to the basics of the project and therefore it would give more room to work on the swashplateless system, the reconfiguration of the vehicles, structure and tests of critical components.

In addition to the architecture, much time was given to focus to the mechanism for the reconfiguration of the vehicles. This was done after reviewing past concepts in [9] and [8]. The proposed mechanism consists on a electromechanical interconnection between the modules, and it is expected to be enough to ensure that the modules stay connected in normal flight conditions. Furthermore, tests were proposed in order to properly validate and choose one of the three proposed concepts, which were not possible to implement for all three concepts(Chapter 5).

Moreover, the structure design of these vehicles was not developed, nonetheless, there were two concepts considered. The first one includes the use of rods as seen in [8], using FDM manufacturing, with the filament yet to be decided. The second concept is similar to the modules in [9] having a more robust structure with the material being a polypropylene foam as well, ensuring all the requirements could be fulfilled.

During this project implementation, it was clear that for the validation of these concepts, in all of the categories, testing would be extremely necessary and pivotal in order to achieve success, which meant the risk of not being able to conclude in the given time-frame was greatly increased.

The project holds immense potential to revolutionize the way construction sites operate. By leveraging the advantages of modularity and reconfigurability, MRAVs can improve logistics, enhance productivity, and reduce costs. As the project progressed, it was crucial to carefully evaluate the performance, reliability, and design of the MRAV systems, ensuring it meets the demands of real-world applications. The project's educational and research components will also contribute to the advancement of MRAV technology, paving the way for broader adoption across various industries.

The potential benefits of MRAVs extend beyond construction applications. Their ability to adapt to various payload configurations and environments makes them well-suited for a wide range of tasks, including search and rescue, disaster relief, and specialized missions in remote or hazardous areas.

Chapter 5

Testing

5.1 Propulsion

Initially, it was proposed to make a simple thrust stand in L shape. The principle of this test is that the thrust produced by the motors and the blades is the same felt by the scale. Both should be positioned at the same distance to the fix point. In that way the torque produce by the rotor will be the same in the point of the scale, as they are away from the same distance the force will be the same.[20]

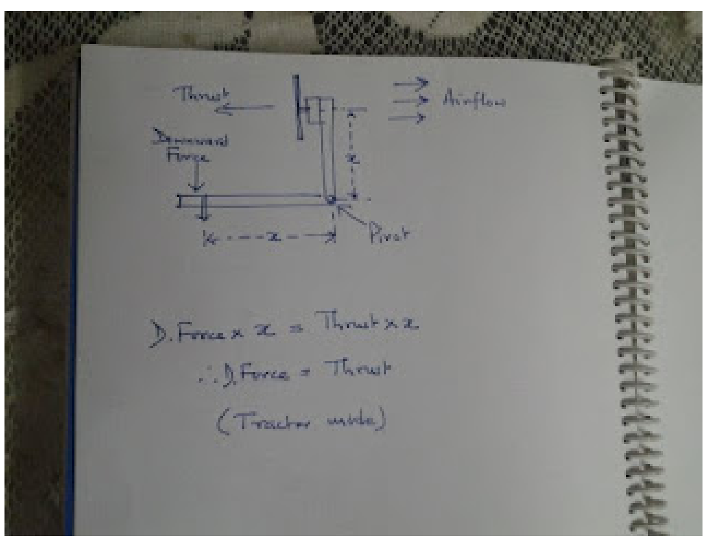


Figure 5.1: Principle

What we need for this test is a scale, two pieces of wood(similar size), some type of mount to fix them, a watt-meter with a built in PWM generator which means that a transmitter+receiver are not required to run the tests, an ESC, a RPM-meter , a led light for the RPM-meter, the battery, a scale and the motor.[21]

Finally it would look like this:

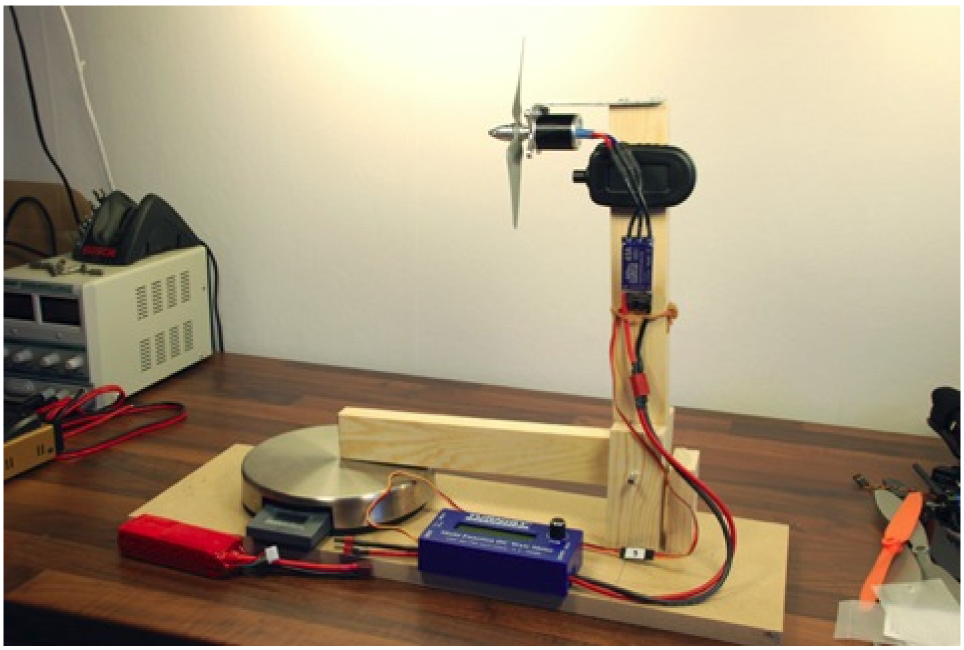


Figure 5.2: Mounted Thrust Stand

As the PWM is moved, different values of current, voltage, RPM and thrust will be obtained. Then it is possible to determine the maximum value of thrust and the best efficiency in terms of thrust/power of the system.

However this concept was changed to one using a load cell, because it is more precise than the balance and the values of mass can be read in the Teensy 4.1. The load cell used was SEN-HX711 [22] which is a 10kg max load.

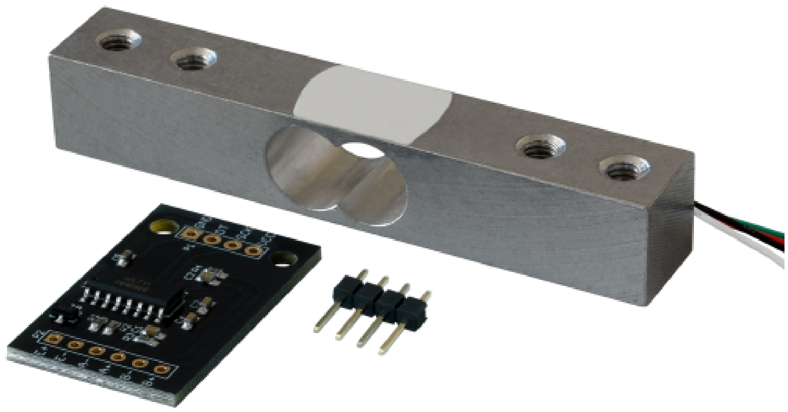


Figure 5.3: Load Cell SEN-HX711

The 10kg straight bar load cell with HX711 amplifier is a strain gauge-based sensor that can translate up to 10kg of pressure (force) into an electrical signal. Here are the key details:

- Measurement Principle: The load cell operates based on strain gauges. When pressure or force is applied to the bar, the electrical resistance of the strain gauges changes proportionally.
- HX711 Amplifier: The HX711 amplifier is a breakout board that interfaces with the load cell. It communicates with a micro-controller using a two-wire interface (Clock and Data).
- Voltage Range: 2.6V to 5.5V
- Temperature Range: -20°C to +85°C
- Typical Operating Current: $<$1.7mA
- Shutdown Current: $<1\mu A$

This load cell is commonly used for building scales, weight measurement, and other applications where accurate force sensing is required.

The test bench was idealized to make it look like a balance as shown in the image below:

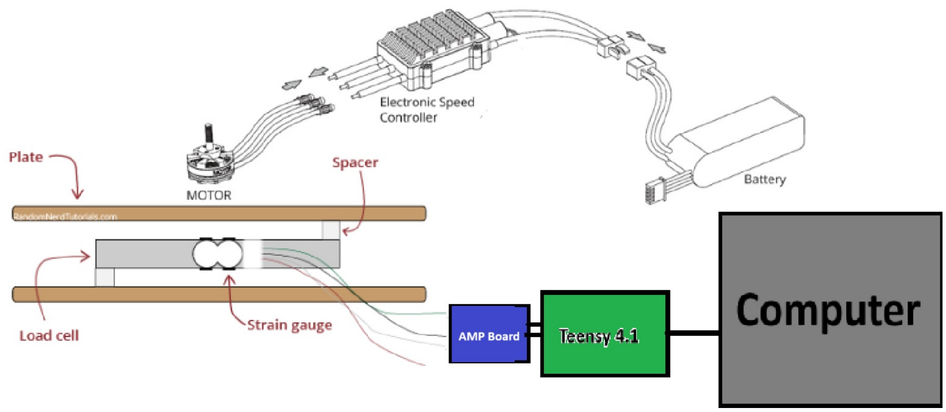


Figure 5.4: Use of the load cell like a weight scale.

The end result of the test bench for propulsion is in the following image:

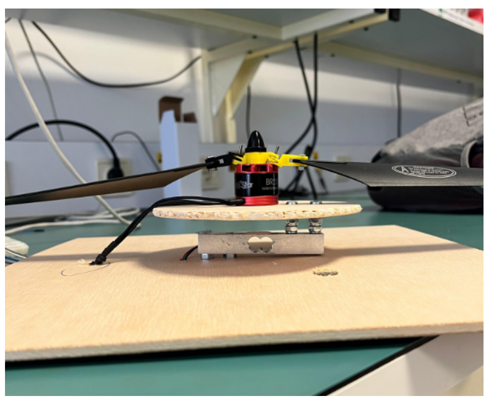


Figure 5.5: Bench test for propulsion with the motor on top.

Initially, the top wooden plate had the same area as the bottom base, but it was noticed that the blades of the rotor would touch the base and the wind produced would affect the measurements read. So it was sawed to make a circle where the motor could be attached. There are some holes in the bottom base so the wires could pass by, so they would not interfere with the rotation of the blades.

It is also notable that calibration was needed for the load cell. For it, it was adapted a code founded in the load cell´s data sheet [22], and we used it. Basically it tares down the weight measured already and asks to put a known weight and it gives back to you the ratio between the tension and the tension measured and the weight of the mass. We then use that ratio for the next tests so we can get the thrust produced by the motor.

```
#include "HX711.h"
// HX711 circuit wiring
const int LOADCELL_DOUT_PIN = 24;
const int LOADCELL_SCK_PIN = 13;
const int Calibration_Weight = 490;
HX711 scale;
void setup() {
 Serial.begin(57600);
 scale.begin(LOADCELL_DOUT_PIN, LOADCELL_SCK_PIN);
 scale.set_scale();
 scale.tare();
 Serial.println("Calibration");
 Serial.println("Put a known weight on the scale");
 delay(5000);
 float x = scale.get_units(10);
 Serial.println(x);
 x = x / Calibration_Weight;
 scale.set_scale(x);
 Serial.println("Calibration finished...");
 delay(3000);
 }
void loop() {
 if (scale.is_ready()) {
 float reading = scale.get_units(10);
 Serial.print("HX711 reading: ");
 Serial.println(reading);
 } else {
 Serial.println("HX711 not found.");
 }
 delay(1000);
}
```

Figure 5.6: Calibration code for the load cell

For the propulsion test it is needed that the motor rotates and for it we need to control it using the ESC, so we need to calibrate the ESC. In the instruction sheet of the ESC it indicates that to calibrate we need to send the maximum throttle to ESC through the Teensy 4.1, wait few seconds and then send the minimum throttle. In this case the maximum throttle corresponds to 255 and minimum throttle to 127 as we are using a *analogwriteresolution* of 8 bits. The code to calibrate the ESC using the teensy 4.1 is below.

```
void setup() {
  // Set the PWM frequency for pin 10 to 500 Hz
  analogWriteFrequency(2, 500);
  // Set the PWM resolution to 8 bits (values between 0-255)
  analogWriteResolution(8);

  // Begin calibration sequence
  // Output a PWM signal with a duty cycle close to 100% (full throttle)
  analogWrite(2,255);
  // Wait for the ESC to recognize the full throttle signal
  delay(4000);
  // Output a PWM signal with a duty cycle close to 0% (zero throttle)
  analogWrite(2,127);
  // Wait for the ESC to recognize the zero throttle signal and complete calibration
  delay(2000);

  // Calibration is now complete
}

void loop() {
  // Your main code here, to run repeatedly after calibration
}
```

Figure 5.7: ESC calibration code

It is needed that the teensy measures various thrust for various speeds of the motor so we have a graphic that gives the estimated thrust per speed of the rotor. To get that we need to control the motor incrementing different speed and the thrust overtime after the speed of the rotor has changed. To be able to this a code was created that would command the Teensy to send the desired speed to the motor and then it would give the thrust measured at that speed. The code is presented in the attachments. The console would give the thrust measurements and respective speeds, and plotting them using Microsoft Excel, made it possible to analyze the results.

It was tested two different combination blades: blades AA and blades BB to find which configuration is best for our micro aerial vehicle. Both of the blades look alike, but they are the mirror of one another.

The results we got from both of the blades are:

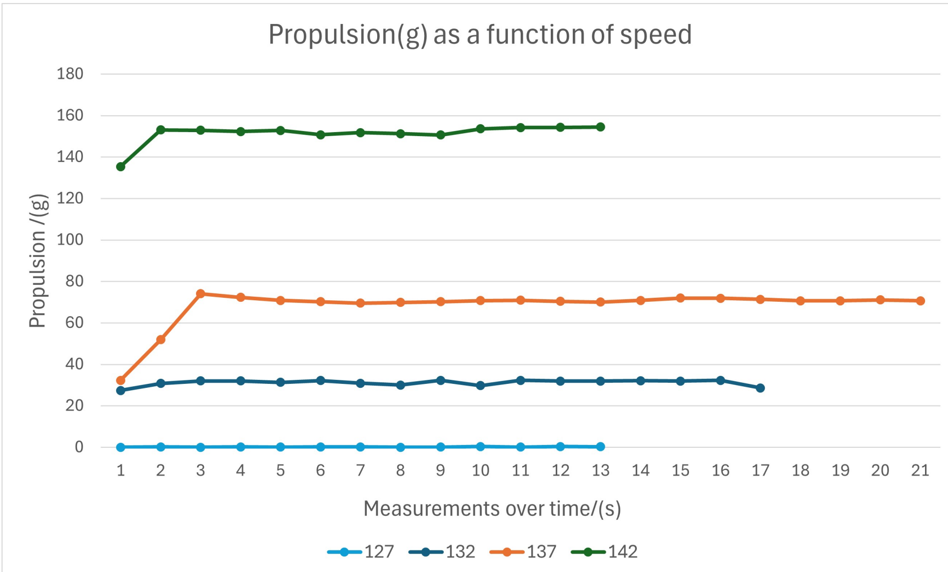


Figure 5.8: Thrust as a function of speed for AA blades configuration

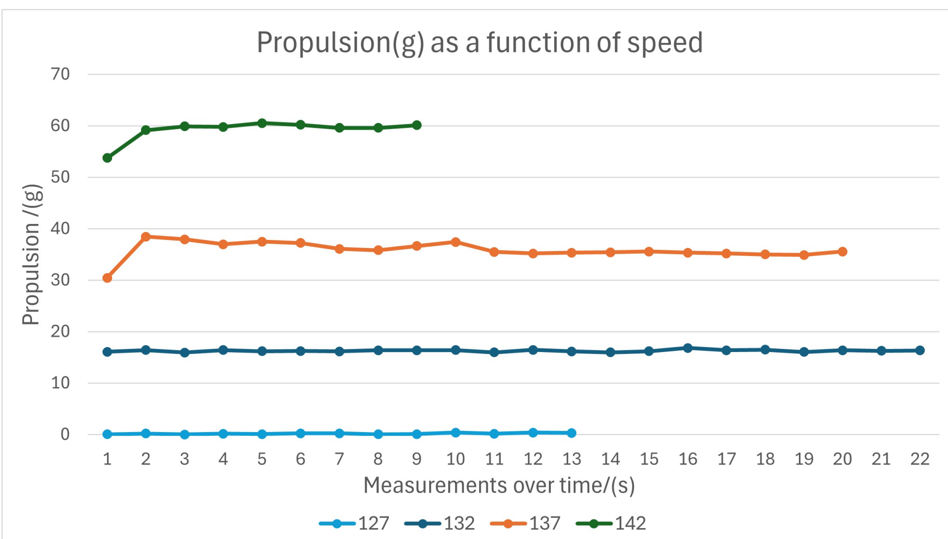


Figure 5.9: Thrust as a function of speed for BB blades configuration

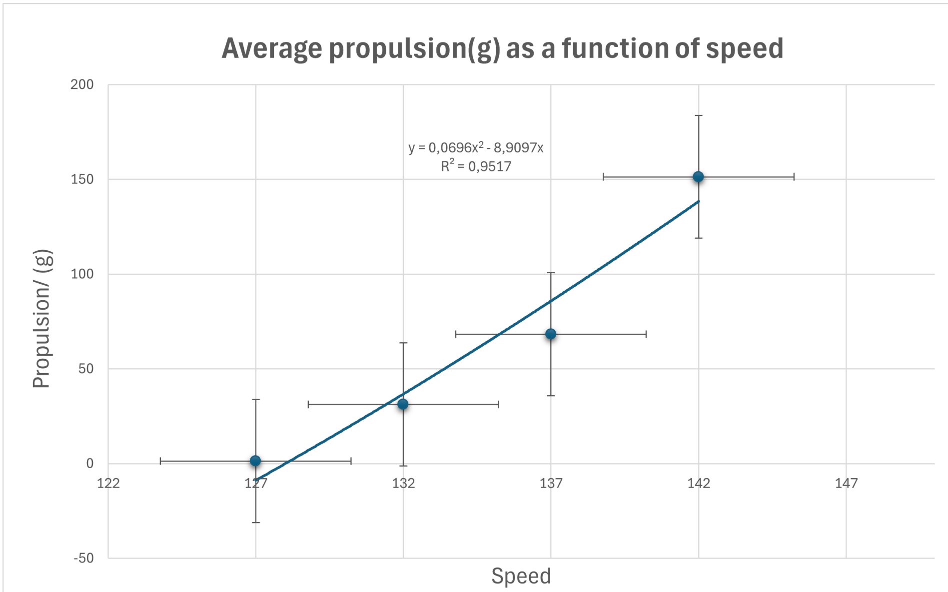


Figure 5.10: Evolution of thrust per speed for AA blades configuration

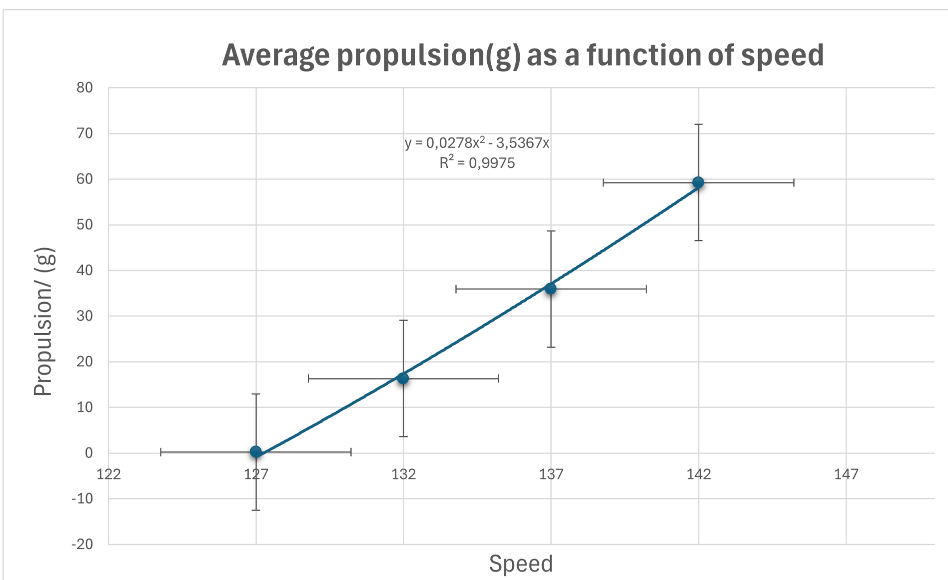


Figure 5.11: Evolution of thrust per speed for BB blades configuration

As it can be seen the AA blades produce more thrust than the BB blades for the speeds that we measured. So for final drone it would be chosen the first configuration.

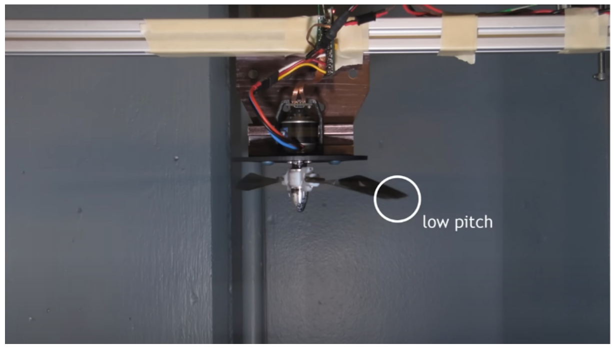
As we can see from these graphics, there are few speeds tested, as the structure of the test bench would resonate and vibrate a lot. To not risk the entirety of the it was chosen that would not be passed that speed and would do a estimated value of thrust for the rest of the speeds. The thrust to speed ratio is not linear so we fitted the trend line with a ratio of 0,75 in excel as shown in the forum Thrust Curve Compensation through $THR_M DL_F AC$. [23]

5.2 Reconfiguration

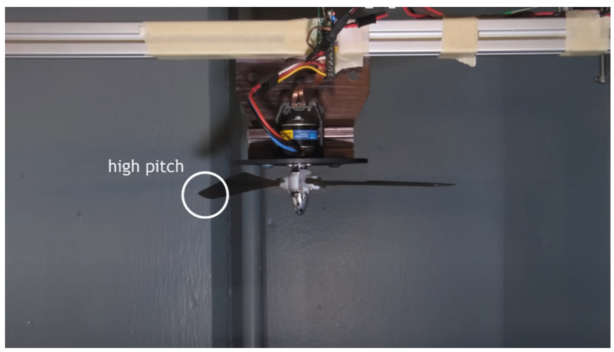
As it was a primary objective in the project, reconfiguration tests were proposed, in order to choose the best association. This test would involve verifying the stability and the endurance of the connection. These tests were intended to determine how the stress in one module propagates to the other, it will also help to determine how efficient this mechanism is compared to others previously attempted by others.These were not implemented because of the delays concerning the general implementation of the MRAVs, however the initial thoughts after the first demonstrative parts were made (as shown in Chapter 3), is that the mechanism works as intended and it is a viable option for the reconfiguration of the vehicles.
However, the force of the connection, which would ensure that the vehicles do not disconnect unintentionally, depends on the attraction force of the magnets, and one possible way to ensure more force distribution between modules is to add more slots for the magnets and ensure that they are as powerful as possible.

5.3 Swashpleteless system

This test was very important in order to realize one of the main objectives of this project, and due to delays in the implementation of the project, it was not possible to test this very important concept. However, it was possible to set important foundations for future testing outside the scope of this project.



(a) 1



(b) 2

Figure 5.12: Low and High pitch of the blades

For this testing to be implemented, the thrust stand would be used initially, and using the AS5048B magnetic encoder to measure the motor shaft angle and the Teensy 4.1 as a flight controller it would be possible to use a PID control so the propellers would perform high and low pitch and turn as intended per user input, either through a computer initially or later, if possible with a transmitter and receiver. Initial steps were taken to implement the system, the code for the measurement was tested, although not enough to make significant conclusions about it's results, however initial thought is that the code, taken from [2] and merged with the previously created code for the motor, shows potential to perform this operation:

```
#include <ams_as5048b.h>
#include <Wire.h>
//unit consts
#define U_RAW 1
#define U_TRN 2
#define U_DEG 3
#define U_RAD 4
#define U_GRAD 5
#define U_MOA 6
#define U_SOA 7
#define U_MILNATO 8
#define U_MILSE 9
#define U_MILRU 10

AMS_AS5048B mysensor;
// Motor variables
int motorSpeed = 127;
const int motorPin = 2; // Adjust this to your motor's pin
unsigned long lastTime;

void setup() {
  //Start serial
  Serial.begin(57600);
  while (!Serial) ; //wait until Serial ready
  // Set the I2C SDA and SCL pins for Wire2
  //Start Wire object. Unneeded here as this is done (optionally) by the AMS_AS5048B object
  Wire.begin();
  //init AMS_AS5048B object
  mysensor.begin();
  //consider the current position as zero
  mysensor.setZeroReg();

//Motor
  analogWriteFrequency(motorPin, 500);
  analogWriteResolution(8);
  analogWrite(motorPin, motorSpeed);
}

```

```
void loop() {
lastTime=millis();
  //print to serial the raw angle and degree angle every 2 seconds
  //print 2 times the exact same angle - only one measurement
  //Serial.print("Angle sensor raw : ");
//  Serial.println(mysensor.angleR(U_RAW, true), DEC);
  if (Serial.available()) {
    String input = Serial.readStringUntil('\n');
    //Serial.println(input[0]);
    processMotorInput(input[0]);
  }

  mysensor.angleR(U_RAW, true);
  //Serial.println(mysensor.getDiagReg());
  Serial.print("Angle degree : ");
  Serial.println(mysensor.angleR(U_DEG, false), DEC);

  while(millis()-lastTime<500);
}
void processMotorInput(char input) {
  switch (input) {
    case 'm':
      motorSpeed = min(motorSpeed + 5, 255);
      analogWrite(motorPin, motorSpeed);
      break;
    case 'n':
      motorSpeed = max(motorSpeed - 5, 127);
      analogWrite(motorPin, motorSpeed);
      break;
    case 's':
      motorSpeed = 127;
      analogWrite(motorPin, motorSpeed);
      break;
    default:
      Serial.println("Invalid input");
      break;
  }
}
```

Figure 5.13: Encoder and Motor code

Despite not being able to test this implementation and iterate in order to perfect it, it was possible to have readings, up to a frequency of 20Hz, despite not being tested on the accuracy of them. This indicates that progress was surely being made on this field.

Chapter 6

Conclusion

The culmination of this drone development project would mark a significant milestone in our journey to explore the boundless potential of unmanned aerial vehicles. This endeavor has been an intricate tapestry of challenges and triumphs, each thread woven into the fabric of our collective learning and growth.

Although it was not possible to complete the project, throughout the process, we have delved into the intricacies of drone technology, demystifying the intricate interplay of mechanics, electronics, software, materials and forms of attachments between vehicles. We gained insights into the principles of propulsion, working together and unusual ways to create a drone, gaining knowledge on this matter, and understanding how everything works by working hands-on on every single aspect of the project, from Research and development to manufacture, assembly and testing.

We concluded this project to be very interesting and challenging, and believe that this work sets stones for future implementations outside the current scope, and that it deserves further appreciation on how to best take this project further.

It is also worth mentioning that this was an excellent way to understand how projects work and develop important skills, having to manage deadlines and work as a team in order to achieve the best possible result, and these are lessons to take for both the academic and professional life.

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Attachments

```
#include "HX711.h"

const int LOADCELL_DOUT_PIN = 24;
const int LOADCELL_SCK_PIN = 13;
const int Calibration_Weight = 490; // Adjust this to your known weight

HX711 scale;

// Motor variables
int motorSpeed = 127;
const int motorPin = 2; // Adjust this to your motor's pin
unsigned long lastTime;


void setup() {
  Serial.begin(57600);
  scale.begin(LOADCELL_DOUT_PIN, LOADCELL_SCK_PIN);

  scale.tare();
  // Load the previously stored calibration factor (if available)
  scale.set_scale(-100.76);

  analogWriteFrequency(motorPin, 500);
  analogWriteResolution(8);
  analogWrite(motorPin, motorSpeed);
}

void loop() {
  lastTime = millis();
  if (scale.is_ready()) {
    float reading = scale.get_units(10);
    Serial.print(motorSpeed);
    Serial.print("|");
```

```
    Serial.print(reading);
    Serial.println(" g");
  } else {
    Serial.println("HX711 not found.");
  }
  if (Serial.available()) {
    String input = Serial.readStringUntil('\n');
    //Serial.println(input[0]);
    processMotorInput(input[0]);
  }
  while(millis()-lastTime < 1000);
}

void processMotorInput(char input) {
  switch (input) {
    case 'm':
      motorSpeed = min(motorSpeed + 5, 255);
      analogWrite(motorPin, motorSpeed);
      break;
    case 'n':
      motorSpeed = max(motorSpeed - 5, 127);
      analogWrite(motorPin, motorSpeed);
      break;
    case 's':
      motorSpeed = 127;
      analogWrite(motorPin, motorSpeed);
      break;
    default:
      Serial.println("Invalid input");
      break;
  }
}
```

Figure 6.1: Code to measure the thrust in different speeds

```
#include <ams_as5048b.h>
#include <Wire.h>
//unit consts
#define U_RAW 1
#define U_TRN 2
#define U_DEG 3
#define U_RAD 4
#define U_GRAD 5
#define U_MOA 6
#define U_SOA 7
#define U_MILNATO 8
#define U_MILSE 9
#define U_MILRU 10

AMS_AS5048B mysensor;
void setup() {
  //Start serial
  Serial.begin(9600);
  while (!Serial) ; //wait until Serial ready
  // Set the I2C SDA and SCL pins for Wire2
  //Start Wire object. Unneeded here as this is done (optionally) by the AMS_AS5048B object (see lib code - #define USE_WIREBEGIN_ENABLED)
  Wire.begin();
  //init AMS_AS5048B object
  mysensor.begin();
  //consider the current position as zero
  mysensor.setZeroReg();
}

void loop() {
  //print to serial the raw angle and degree angle every 2 seconds
  //print 2 times the exact same angle - only one measurement
  Serial.print("Angle sensor raw : ");
  Serial.println(mysensor.angleR(U_RAW, true), DEC);
  //Serial.println(mysensor.getDiagReg());
  Serial.print("Angle degree : ");
  Serial.println(mysensor.angleR(U_DEG, false), DEC);
  delay(2000);
}
```

Figure 6.2: Encoder code from [2]

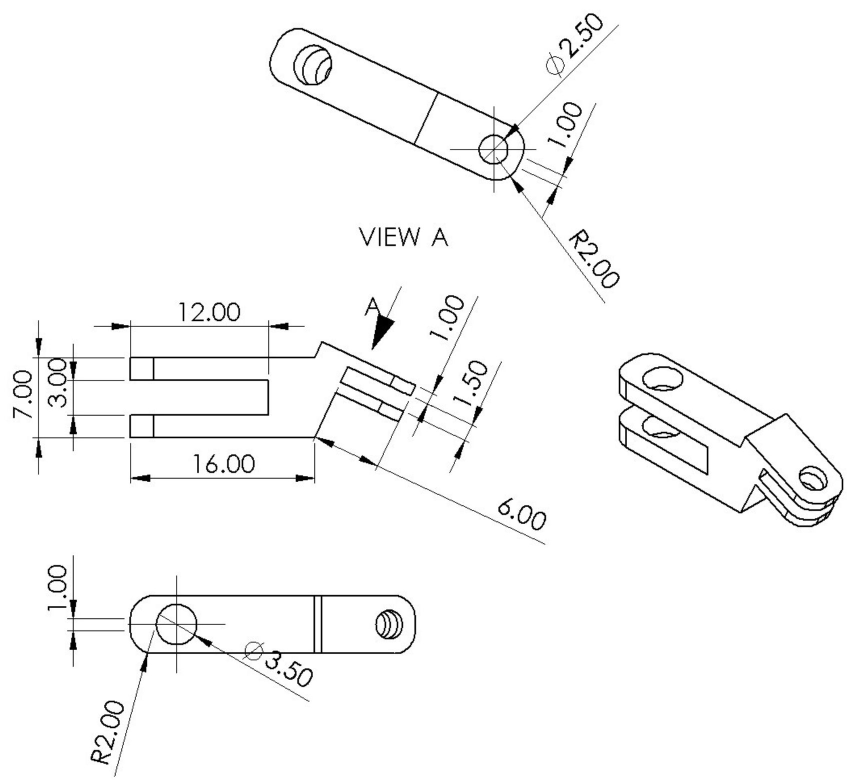


Figure 6.3: Technical drawing of side Swashplateless part.

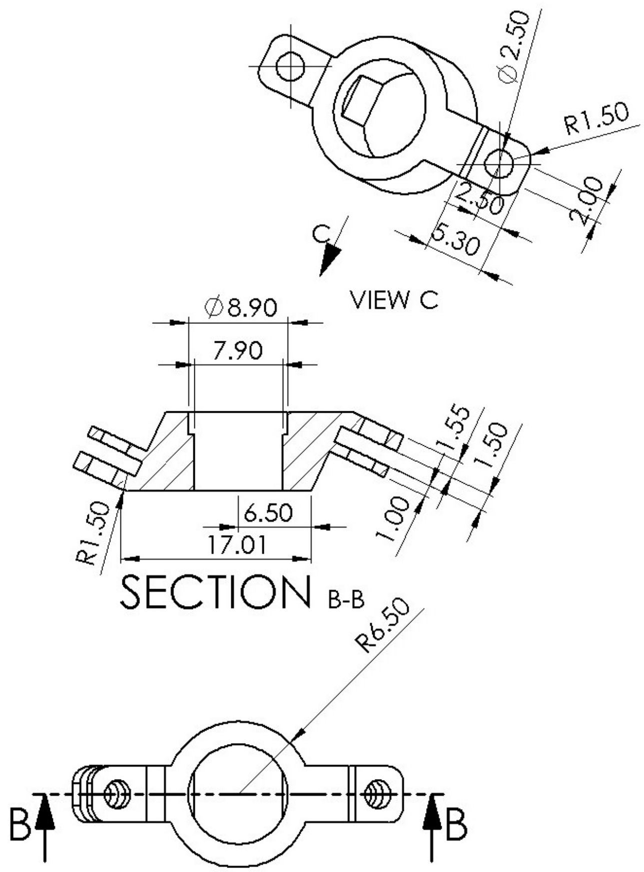


Figure 6.4: Technical drawing of middle Swashplateless part.

Figure 6.5: Swashplateless assembly without motor.

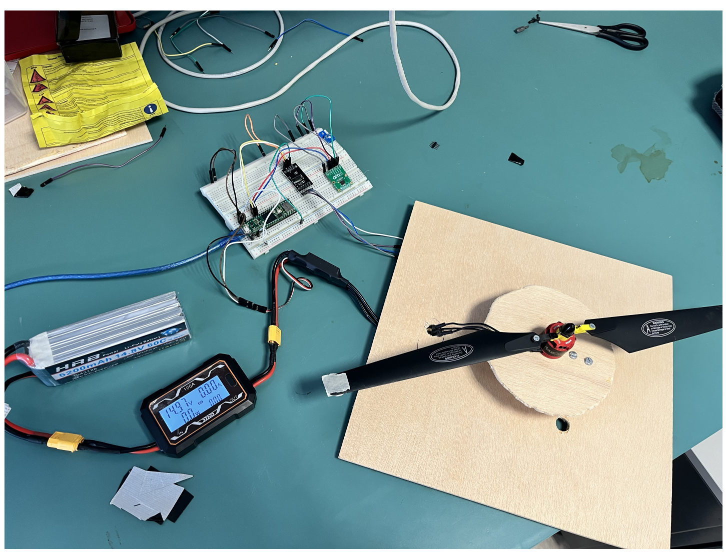
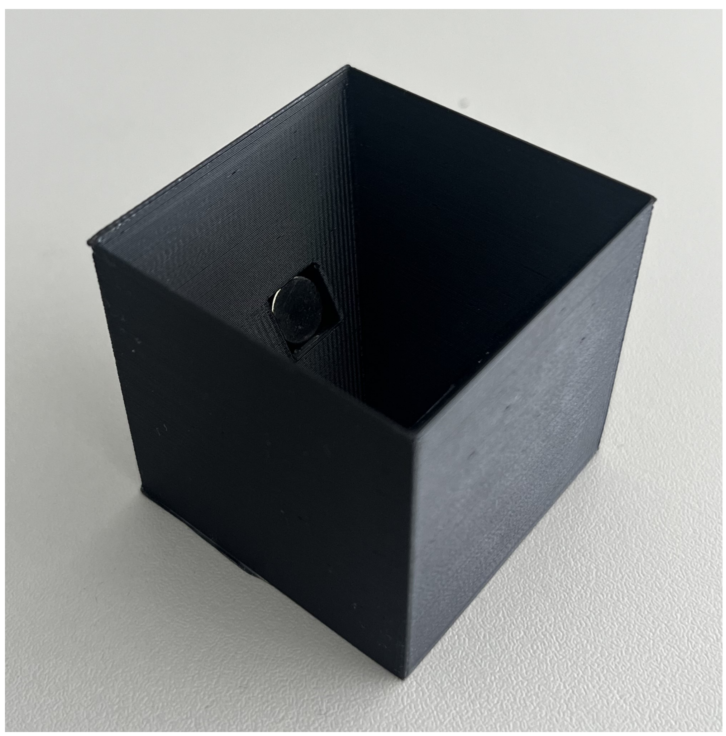


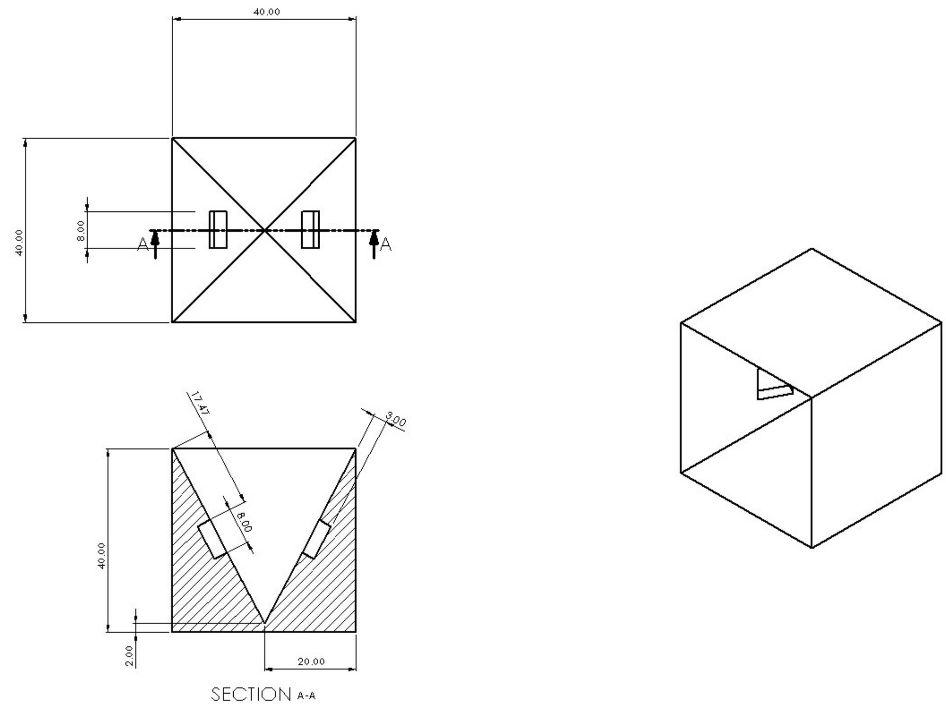
Figure 6.6: Thrust stand fully assembled.

(a) Male

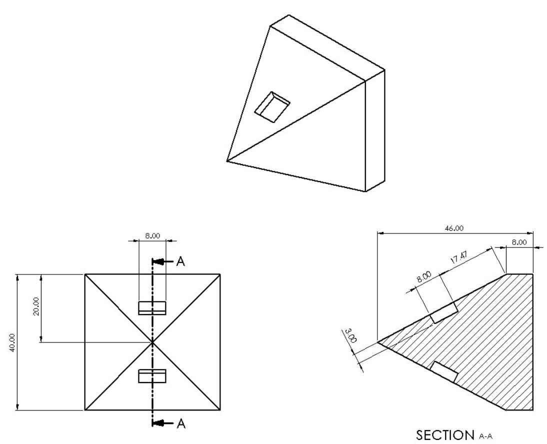


(b) Female

Figure 6.7: Reconfiguration parts



(a)



(b)

Figure 6.8: Technical drawing of Reconfiguration Female(a) and Male(b) parts.