



ESCUELA TÉCNICA SUPERIOR DE INGENIERÍA (ICAI)
GRADO EN INGENIERÍA ELECTROMECÁNICA
Especialidad Mecánica

UNMANNED HYDROFOIL VEHICLE

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Madrid

Junio, 2018

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UNMANNED HYDROFOIL VEHICLE

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VEHÍCULO HIDRO-ALA NO TRIPULADO

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RESUMEN DEL PROYECTO

Introducción

Este proyecto consiste en el diseño y análisis de un vehículo hidro-ala no tripulado (*The Medi-Gator*) que utiliza el mismo principio de elevación de los aviones, así como un sistema de navegación autónoma. El vehículo está diseñado para el transporte de medicinas a aquellas zonas o islas de difícil acceso para barcos grandes u otros vehículos. El uso de la hidro-ala, que eleva la parte superior del vehículo por encima de la superficie del agua, permite mejoras en la velocidad, el manejo, y en la navegación. Además, podrá participar en las misiones humanitarias de los grandes buques, ayudando en la asistencia de las áreas necesitadas o en peligro.

La gran novedad de este vehículo, comparado con otros vehículos de su tamaño, es su alta eficiencia. Permite alcanzar velocidades elevadas sin perder la estabilidad longitudinal y lateral. Esto es debido a los cambios en las fuerzas de sustentación y resistencia del vehículo. La fuerza de resistencia al movimiento del vehículo será reducida considerablemente, cuando al alcanzar una determinada velocidad la fuerza de sustentación correspondiente permita elevar el casco por encima del agua. La parte del vehículo que quedará sumergida en el agua es pequeña y por tanto la fuerza de resistencia también, permitiendo alcanzar velocidades mayores que cualquier otro barco del mismo tamaño. Por otro lado, la estabilidad del vehículo se mantiene en todo momento gracias a la reducción de la fuerza de resistencia al movimiento de este, pero principalmente a el rápido control de alabeo y cabeceo por parte de los alerones. Cada alerón será controlado de forma continuada, autónoma e independiente para adaptar el cabeceo y alabeo del vehículo a las condiciones de navegación y así garantizar un movimiento estable.

También presenta otra gran ventaja, no necesita combustible. La potencia necesaria para su funcionamiento será suministrada por unas baterías recargables localizadas en el casco y distribuida a cada uno de los elementos a través del cableado.

El vehículo ha sido diseñado para transportar una carga máxima de 18 kg y alcanzar una velocidad máxima de 13.4 m/s. A velocidad de crucero, 10.3m/s, la máxima durabilidad de la carga es de dos horas. De la misma forma que las alas de un avión lo elevan, la hidro-ala elevará el casco con la carga por encima del nivel del agua. Una hidro-ala funciona exactamente igual que un ala, la diferencia es el fluido, agua o aire, y su correspondiente densidad y viscosidad. Como todos los aviones, su diseño tendrá un ala frontal donde se produce la mayor fuerza de sustentación del vehículo y unido, a través del fuselaje, un estabilizador horizontal con los dos alerones.

La navegación podrá ser tanto autónoma, usando el autopiloto *PixHawk* o controlada remotamente. El rumbo del vehículo, su velocidad y elevación se registrarán continuamente con el acelerómetro PixHawk y el sensor externo, de modo que las condiciones de funcionamiento se puedan adaptar a las condiciones del entorno.

Metodología

El primer paso en el desarrollo del diseño completo del vehículo hidro-ala no tripulado (*UHV*) fue la determinación de su misión, así como el estudio de los requisitos funcionales de cada subconjunto del vehículo: el casco, el mástil, el motor, el fuselaje, el ala y el estabilizador horizontal con los alerones. Una vez establecidas las funciones de cada parte se procedió al dimensionamiento de cada una de ellas y a su posterior modelado en 3D usando el programa *Solidworks*.

El vehículo, llamado *The Medi-Gator*, tiene dos modos de operación: *on plane*, cuando se encuentra volando por encima del agua y *off plane*, cuando el vehículo completo navega por el agua. Para conseguir una navegación eficiente en ambos modos de operación se consideró muy importante diseñar el casco del vehículo lo más aerodinámico posible. Para cada subconjunto, el análisis previo de los requisitos funcionales fue crucial para diseñar su tamaño y forma y conseguir resultados positivos. Pero, además de considerar la función de cada parte por separado, fue importante considerar también la conexión e interacción de las mismas. Uno de los factores limitantes del diseño fue la impermeabilización de todo el conjunto.

Una vez que los gráficos estaban hechos y los elementos seleccionados, se procedió a seleccionar los materiales de cada parte de acuerdo con su función. La siguiente figura muestra el diseño final.



Figura 1 Diseño final. The Medi-Gator

A continuación, el siguiente paso fue el análisis de la estructura del vehículo, su estabilidad longitudinal y lateral, la interacción de las variables que afectan su funcionamiento y el balance de fuerzas: resistencia del fluido oponiéndose a la propulsión del motor y sustentación oponiéndose al peso. Todos los cálculos se basaron en los requisitos funcionales establecidos para el conjunto: velocidad máxima, velocidad de crucero y duración de la carga. El objetivo de los cálculos además de comprobar el correcto funcionamiento del vehículo era seleccionar los elementos externos como las baterías, el motor y la caja de cambios, de acuerdo con ellos.

Primero se estudió la localización del centro de gravedad y de flotabilidad para analizar la estabilidad. Luego las fuerzas aerodinámicas, resistencia y sustentación. La fuerza de empuje estaba garantizada gracias a la existencia de la hidro-ala. La fuerza de resistencia fue calculada para determinar la fuerza de empuje necesaria para alcanzar la velocidad deseada.

Por último, el proceso se finalizó con la estimación del coste total, basado en los precios de mercado y los procesos de manufactura.

Resultados

Después del análisis de todas las variables que influyen en el funcionamiento del vehículo, se logró el diseño completo del vehículo. Los cálculos realizados garantizaban flotabilidad, suficiente empuje para contrarrestar la fuerza de resistencia y suficiente fuerza de sustentación para elevar el casco del vehículo a la altura deseada. Además, se comprobó que la estructura de este fuera consistente y estable. Para estudiar la estabilidad, se calcularon el cabeceo y alabeo máximos del vehículo antes de desestabilizarse para establecer los límites de movimiento a la hora de programar su funcionamiento. Después de todo, se comprobó que el diseño era factible.

En resumen, un vehículo eficiente es el resultado de un buen equilibrio de fuerzas. La información recogida por los diferentes sensores externos es actualizada continuamente en el sistema para que se elaboren respuestas rápidas que adapten la fuerza de elevación o el empuje a la situación específica o al modo de operación. Este control se puede conseguir gracias a la acción del *PixHawk*. El vehículo está controlado en las tres direcciones, cabeceo y balanceo por los alerones y la griñada por el timón cuando está en modo *off plane*.

Conclusiones

El diseño realizado del vehículo es competente e innovador, principalmente por sus dos características principales: no tripulado y autónomo. Una gran ventaja que presenta, aparte de las ya mencionadas, es la ubicación de los componentes electrónicos en el casco evitando todo posible contacto con el agua. Sin embargo, es un diseño teórico basado en unas condiciones determinadas, que no contempla todos los posibles factores limitantes, como por ejemplo ráfagas de viento u obstáculos. Es por ello, que el diseño queda abierto a futuras investigaciones para mejorar su funcionamiento y adaptabilidad a distintos escenarios. Una de las mejoras sugeridas es la instalación de un mecanismo de retracción en el mástil para reducir el nivel mínimo de agua para encender el vehículo. Eso aumentaría la adaptabilidad del vehículo a diferentes tipos y profundidades de agua y facilitaría su manipulación y transporte.

Por último, el vehículo, aparte de ser utilizado para el reparto de medicinas, tiene muchas otras aplicaciones. Por ejemplo, para recopilar información utilizando un sonar acuático y así poder estudiar la topografía de las superficies marinas o los arrecifes; o para sustraer muestras de agua y así analizar después en un laboratorio sus propiedades.

UNMANNED HYDROFOIL VEHICLE

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Collaborating Entity: ICAI - Universidad Pontificia Comillas

PROYECT SUMMARY

Introduction

This project discusses the design and analysis of an unmanned surface vehicle, The Medi-Gator, that utilizes a hydrofoil and autonomous waypoint navigation. This vehicle is designed to transport medicines at the proper temperature to remote islands or areas which traditional boats or vehicles are unable to readily access. The use of a hydrofoil will allow to have an improved speed, maneuverability, and a relatively smooth operation, since the hull will be lifted out of the water. Furthermore, it will be deployable from larger humanitarian vessels to provide aid to damaged or underdeveloped areas.

The big innovation that this vehicle brings out and make it competitive in the market is its efficiency compared to any other boat its size. Considerable high speeds can be reached while maintaining good longitudinal and lateral stability. The explanation is based on changes in drag and lift forces. The craft will experience a reduced amount of drag in comparison to any other boat since at soon as it reaches a determined velocity the according lift will let the vehicle fly over the water. Therefore, the only part facing the waves or chop will be the mast. Since the mast is small the drag will be reduced considerably in comparison to a normal boat, which will let the vehicle reach higher speeds. In addition, stability of the vehicle will also be improved since the hull will only be in contact with the air, but even more thanks to the control system of pitch and roll in the horizontal stabilizer with the elevons. The craft will continuously control, autonomously and independently, each elevon to adequate pitch and roll to each movement smoothly. It is thanks to the fast adaptability of the direction and the angle of the vehicle that the stability is well maintained. In addition,

it presents another big advantage, no fuel is needed for the functioning of the vehicle. The whole system is electric, and all the power comes from the rechargeable batteries and distributed to each subsystem through the wiring.

The design is based on a payload of approximately 18kg. The maximum speed it will be design for is 13.4 m/s with a 2 hour of durability of charge at cruising speed 10.3 m/s. The vehicle will be expected to cruise at a specific height above the water level in order to obtain a smoother operation. This will be achieved, as mentioned before, because of the principles of a hydrofoil. Similarly, to how wings lift plains in the air, the hydrofoil is able to lift the payload above the water. Basically, a hydrofoil works exactly the same as an airfoil does, the difference is the fluid, water or air and their corresponding density and viscosity. Like most aircraft, hydrofoils consist of a larger front wing where the majority of lift is generated, a smaller rear wing, and a central, streamlined body onto which the wings are attached called the fuselage.

The autonomous waypoint navigation of the vehicle will be controlled by a PixHawk autopilot and it will also have the capability to be controlled remotely. Course heading, speed and elevation will be continuously recorded by the PixHawk's accelerometer and external sensor, so that the operating conditions can be adapted to the environment.

Methodology

The first step taken in the development of the complete design of the unmanned hydrofoil vehicle (UHV) was the mission statement and the determination of the functional requirements of each subassembly of the vehicle: the hull, the mast, the motor, the fuselage, the front wing and the horizontal stabilizer with the elevons. The next step was the dimensioning of each part followed by the 3D modeling using the program Solidworks.

The Medi-Gator will have two operation modes: *on plane mode*, above the water, and *off plane mode* in the water. For both modes was important to design the shape of the hull as streamlined as possible to achieve maximum efficiency. For each subassembly, the previous consideration of the functional requirements was crucial to design the size and shape of each part and obtain efficient and adequate results. But not only the function of each part itself, but the connection and interaction between

them. One of the limiting factors was the water, the waterproofing of the entire assembly was seriously taken into account during the design, epoxy or rubber O-rings were located in the more problematic areas.

Once the graphics were done and the elements of each assembly selected, the material of each part was chosen accordingly to its function. The figure below shows the final assembly.

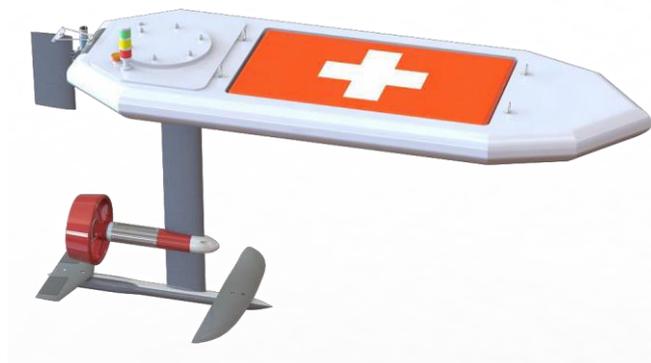


Figure 2 Final design. The Medi-Gator

Furthermore, the next big step was the analysis of the structure of the vehicle, its longitudinal and lateral stability, the interaction of the variables that play a part in its functioning and the forces to which the vehicle is subjected: drag opposing thrust and lift opposing weight. All the calculations were based on the following established overall functional requirements: top speed, cruising speed and endurance. The aim of all the calculations was to ensure a good functioning of the vehicle and to select the “off shell” elements (gear box, motor, batteries...) accordingly to meet the requirements and calculations. The first analysis was the stability based on the center of gravity and buoyancy, the corresponding forces and the floatability. Then the aerodynamic forces, lift and drag. Lift is guaranteed thanks to the presence of foils, the front wing and the elevons. On the other hand, the total drag, parasite and lift-induced drag, was calculated in order to determine the minimum thrust and calculate the corresponding torque on the shaft of the propeller to achieve the necessary velocity.

Once the design was clear and stated, the final cost was estimated, based on the market prices of each piece and the manufacturing processes.

Results

After the analysis of all the variables that influence the functioning of the vehicle, it was accomplished the complete design of the vehicle. The calculations guaranteed floatability, enough motor thrust to counteract the drag and enough lift to lift the hull out of the water to the desired height. Additionally, the structure designed was proved consistent and stable. For the stability, maximum pitch and roll angle were calculated in order to set the limits of movement when programming. The design of the prototype was then concluded feasible.

All in all, an efficient vehicle is the outcome of a good equilibrium of forces. The information collected from different sensors is continuously computerized and transformed into responses to adapt the lift force and thrust to the specific situation or operation mode. This is possible thanks to the PixHawk. The vehicle is controlled in the three directions, pitch and roll by the elevon system and yaw by the rudder when off plane.

Conclusions

The Medi-Gators is predictably considered a very competent and innovative design, mainly because of its two big features: unmanned and autonomous. A big advantage that presents apart from the ones already mentioned is that the electric/electronic components are located in the hull above the water, what reduces even more their risk of damage. However, it is still a theoretical design based on specific conditions, that leaves areas open for improvement and further research. One of the improvements suggested is the installation of a retraction mechanism in the mast so that the minimum level of water at which the vehicle can be turned on is reduced considerably. That would increase the adaptability of the vehicle to different types and depths of water and facilitate the handling and the transport of it.

Lastly, the vehicle could be used, apart from the delivery of medicines, for many other applications. For example, to collect data by installing a sonar and studying the information scanned to analyze the topography of underwater surfaces or the coral reefs; or by subtracting samples for the study of water qualities.



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REPORT

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Chapter 1 INTRODUCTION

This report discusses the design and analysis of an unmanned surface vehicle (The Medi-Gator) that utilizes a hydrofoil and autonomous waypoint navigation. This vehicle is designed to transport medicines at the proper temperature to remote islands or areas which traditional boats or vehicles are unable to readily access. The use of a hydrofoil will allow to have an improved speed, maneuverability, and a relatively smooth operation, since the hull will be lifted out of the water. Furthermore, it will be deployable from larger humanitarian vessels to provide aid to damaged or underdeveloped areas.

The overall design is made up of six sub-assemblies: the hull, the mast, the motor, the fuselage, the front wing, the horizontal stabilizer with the elevons.

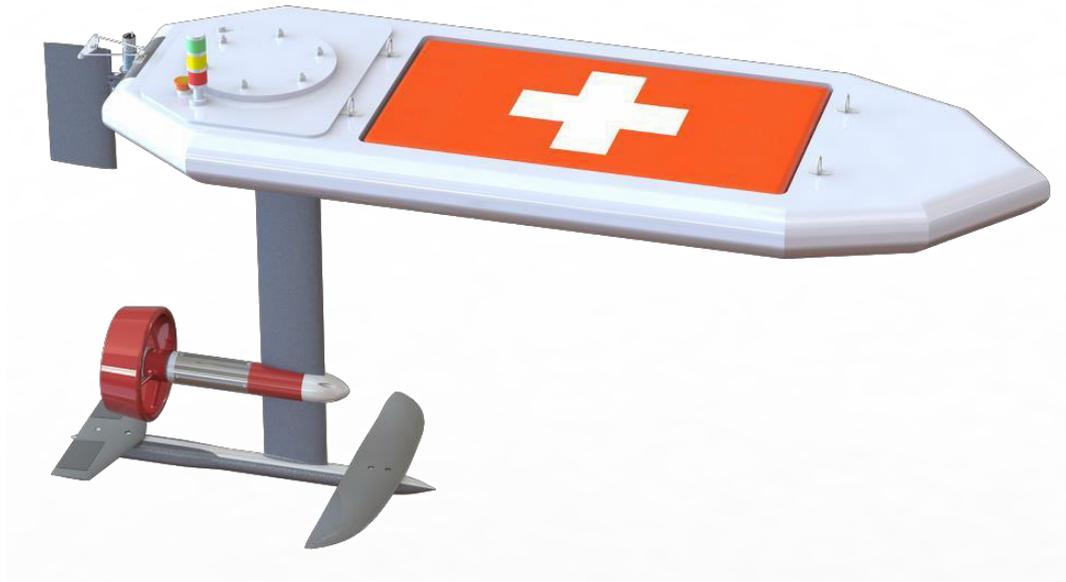


Figure 1 The Medi-Gator



1.1 MOTIVATION

The development of this project is at the same time very challenging and exiting. Firstly, because it requires knowledge of different fields of engineering, some of it known, some other to be discovered and that can be challenging. For instance, the field of aerodynamics since the analysis of drag and lift is crucial for the project. However, getting to know all the different fields, their applications and the linkage between them is very interesting. Additionally, its mission is humanitarian, which motivates me even more. It's great to help others using my skills and my knowledge.

Secondly, the idea of building an innovative real project from scratch considering all the variables that play a part in its design is very exciting. I'm motivated to learn how to develop a project from its initial steps till it's functioning and to relate all the variables correctly to achieve a goal: the correct functioning of the vehicle. There will be many steps in the process: design of each part in accordance to the functional requirements, model of parts in Cad, assembly of parts, selection of materials, analysis of forces and stability, estimation of cost... Through the way I'm sure I will have a lot of uncertainties and struggles, but to overcome them is also part of the process. At the end it would be very rewarding to have developed a useful and real project by bringing together all the techniques and skills learnt during the years of degree. For example, the Project will allow me to bring into practice the skills I acquired attending the Innovation for Engineers course and the Mechanical design one in the University of Florida.

Last but not least, the opportunity to do research in the University of Florida, learning from my teacher, Mr. Ifju, and the work and aptitudes of my colleagues gives me a great motivation to develop the project. This opportunity will enable me to discover a different method of study and work compared to my home university, which will be very enriching.



Chapter 2 MISSION AND PAYLOAD

DESCRIPTION

The mission of the Medi-Gator is to assist in humanitarian missions by providing an effective solution to unmanned medicine delivery over aquatic environments. The Medi-Gator aims to be effective in a variety of aquatic environments to include rivers, lakes, estuaries, tributaries, and even near-shore ocean conditions.

Possible applications of the unmanned surface vehicle include delivery of medicines or antivenoms up rivers to remote villages or delivery of medicines or blood from larger vessels (i.e. one of the U.S. Navy's hospital ships such as the USNS Comfort) to shore in cases of disaster relief. For instance, a possible scenario where its application will be very useful could be the Amazon river. The Amazon river it's 6,992.6 km long, connecting three countries: Brazil, Colombia and Perú. It's considered an essential resource of transport and connection between these countries, where the action of the Medi-Gator could be very useful, even more when considering that many areas of this countries have scarce medical resources. Its function adapts completely to the scenario and due to its high speed, transport of goods (specially medicines) between cities connected by the Amazon river could be improved. Its fast and efficient when the time is limited.

The payload of the Medi-Gator is a temperature-maintaining container having an approximate volume of 28,000 cubic centimeters. Medicine, blood, antivenoms, vaccines, etc. that need to be kept chilled would be placed inside of this container which is secured to the hull of the vessel. The vessel would then be driven, either remotely or autonomously, to its destination where the medical supplies would then be offloaded. Its smooth operation allows to accomplish the mission of the Medi-Gator since the medicines are preserve in good condition and position during the journey to the destination.



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Chapter 3 STATE OF THE ART

The idea of the hydrofoil first emerged in the late nineteenth centuries. The very first prototype to set a speed record was the H-4 designed by Alexander Graham Bell. Since then, designers have tried to build hydrofoil water aircrafts to beat speed records and obtain optimal efficiency. The boats designed through the years had different features based on the mission they wanted to accomplish. Some were used for transportation of passengers, others for military missions (US Navy) and other for sports.

The incorporation of hydrofoils in boat's designs has become very popular for water sports, to improve their efficiency and speed towards the competitions. Prototypes have been designed for sailing, surfing, windsurfing... In 2009, the Hydroptere set the new record in sailcraft speed: 50 knots (26m/s) at a high of 5 meters over the water. After, the launch of flying catamarans took place in the American's cup. Nowadays the New Zealand team is working on their design for the 36th American's cup: the AC75. Its principal innovative feature is the two canting twin T-foils incorporated one on each side of the boat, to allow two different configurations of navigation: one foil lowered or both foils lowered. This last configuration will give more stability to the boat when navigating in difficult sea conditions.



Figure 3 L hydroptere



Figure 2 AC75



Moreover, the hydrofoil has been also implemented in the boards of surfers and windsurfers called foilboards. These prototypes are quite similar to our design in terms of appearance, structure, size, elements...



Figure 5 Foilsurfing



Figure 4 Windfoiling

Additionally, Thébault, the father of the Hydroptere has recently developed a new project: The Seabubbles; an electrical vehicle that is presented as a solution to the environmental and transport problems of large cities. To control the vehicle “on plane” mode a Fly-by-wire system is used. With the information, wirelessly sent to a computer and collected from the vehicle’s sensors, a stable flight can be continuously maintained.



Figure 6 The Seabubble

These are just some of the examples in which hydrofoils have been used. Therefore, the principle of foils is a very up to date implementation and is a focus of interest nowadays in the water crafts industry.



Finally, as what refers to the Medi-Gator design, it will be primarily based on the Efoil lift technology. The Efoil is a hydrofoil surf-board electric-powered which is controlled by its rider wirelessly via Bluetooth connectivity. The power, as in The Medi-Gator design is supplied by rechargeable batteries and the average speed that can be reached is 12 m/s. The Efoil's main parts are: the board, the mast with the built-in motor and the wing. The principal difference between the Efoil design and the Medi-Gator's is its innovative features: autonomous and unmanned. The vehicle is controlled via waypoint navigation and can also be remotely controlled; and in the rear wing the elevon system controls pitch and roll. Thus, a rider is not required and furthermore, its mission will be different: delivery of medicines.



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Chapter 4 DESIGN REQUIREMENTS AND OBJECTIVES

The unmanned surface vehicle will implement a hydrofoil that allows the vehicle to cruise at a specific height above the water level in order to obtain a smoother operation. The big innovation that this vehicle brings out and make it competitive in the market is its efficiency compared to any other boat its size. Considerable high speeds can be reached while maintaining good longitudinal and lateral stability. The explanation is based on changes in drag and lift forces. The craft will experience a reduced amount of drag in comparison to any other boat since at soon as it reaches a determined velocity the according lift will let the vehicle move over the water. Therefore, the only part facing the waves or chop will be the mast. Since the mast is small the drag will be reduced considerably in comparison to a normal boat, which will let the vehicle reach high speeds. In addition, stability of the vehicle will also be improved since the hull will only be in contact with the air, but even more thanks to the control system of pitch and roll with the elevons. The craft will continuously control, autonomously and independently, each elevon to adequate pitch and roll to each movement smoothly. It is thanks to the fast adaptability of the direction and the angle of the vehicle that stability is well maintained. In addition, it presents another big advantage, no fuel is needed for the functioning of the vehicle. The whole system is electric, and all the power comes from the rechargeable batteries and distributed to each subsystem through the wiring.

Moreover, the design is based on a payload of approximately 18 kg. The maximum speed we are going to design it for is 13.4 m/s with a 2 hour of durability of charge. This will be achieved, as mentioned before, because of the principles of a hydrofoil. Similarly, to how wings lift plains in the air, the hydrofoil is able to lift the payload above the water. Basically, a hydrofoil works exactly the same as an airfoil does,



the difference is the fluid, water or air, and their corresponding density and viscosity. Like most aircraft, hydrofoils consist of a larger front wing where the majority of lift is generated, a smaller rear wing, and a central, streamlined body onto which the wings are attached called the fuselage.

The power required for the vehicle's motor, the navigation system and the servos that control the elevons will come from the rechargeable batteries. Lithium-ion ones will be chosen, since they have the maximum power compared to others available in the market. The autonomous waypoint navigation of the vehicle will be controlled by a PixHawk autopilot and it will also have the capability to be controlled remotely. Course heading, speed and elevation will be continuously recorded by the PixHawk's accelerometer and external sensor, so that the operating conditions can be adapted to the environment.

Additionally, there are some other factors to be considered in the design of the vehicle. The Medi-Gator will have two operation modes: *on plane mode* (above the water) and *off plane mode* (in the water). For both modes it is important to design the shape of the hull as streamlined as possible. Besides, the elements that make up the electrical/electronic system must be kept away from the water. For this, special attention must be paid so that no compartment or joint is improperly sealed. Moreover, the chosen materials will have the properties in accordance to their function, for instance lightweight and corrosion resistant.

Furthermore, since the maximum speed the vehicle will be able to reach is approximately 14 m/s it will be assumed that the cavitation phenomenon will not be a limiting factor in the design. The cavitation phenomenon disturbs the lift created by the foils as they move through the water at speed above 30 m/s, bending the lifting foil.

Finally, in terms of production, a production rate of 100 units per month has been estimated.



Chapter 5 FUNCTIONAL REQUIREMENTS AND DESIGN DESCRIPTION

In this part, the process followed for the design based on the functional requirements will be described in detail for each part of each subassembly.

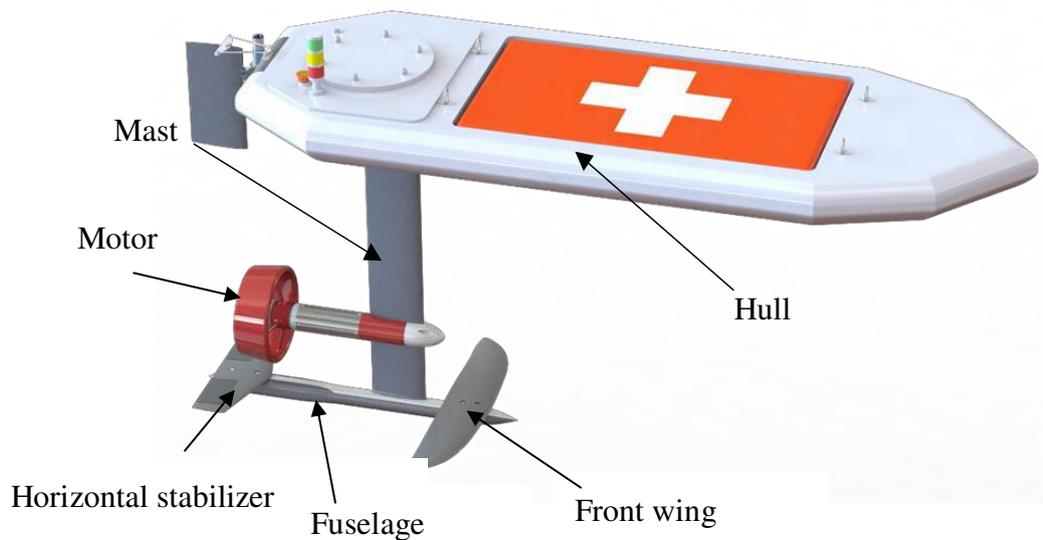


Figure 7The Medi-Gator subassemblies



5.1 HULL ASSEMBLY

The hull subsystem functions generally to act as a buoyant support for the payload, mast, motor, and hydrofoil system and to allow for sealing of electronic and computerized equipment which needs to be housed within the system. The general form of the hull follows a simple planing profile, to allow the hull to move over the water without parting it.

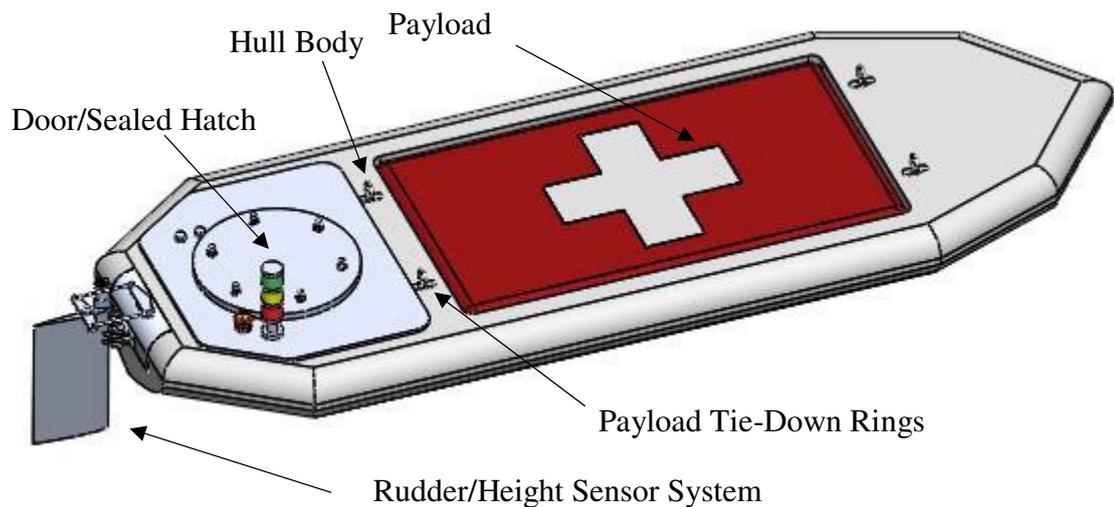


Figure 8 Hull subassemblies

Hull body:

Storage of the payload, electronics and batteries

The cooler payload itself is designed to be placed into an extruded cut hole on the top surface of the hull and to sit flush with the top of the hull itself. Directly adjacent to the payload, towards the stern of the system, is the extruded cut housing the electronic systems powering and controlling the system. The cut is designed to contain five Panasonic 6S9P-90A-NCR18650GA batteries and the Ardupilot Pixhawk autopilot which are secured within the hatch using industrial grade Velcro. This method of securing the batteries and Pixhawk allows for easy removal if

necessary when the system is deployed, while providing enough force to hold the parts in place.

C-MEC 6S9P 90A NCR18650GA Batteries

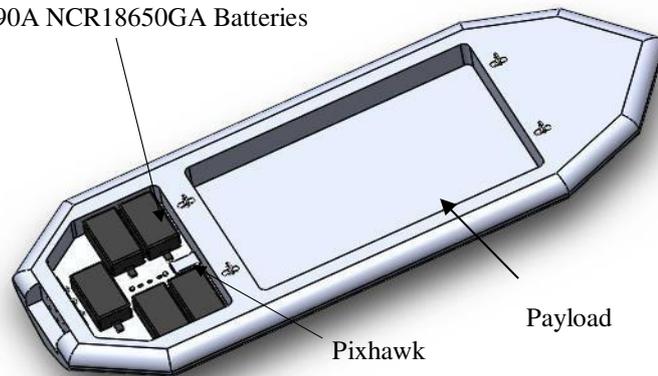


Figure 9 Storage of the hull

Payload secured to the hull

The payload will be secured with two ratchet straps, extending from the front payload tie-down rings to the ones in the rear. These ratchet straps allow for easy accessibility of the payload upon the arrival of the system to its destination

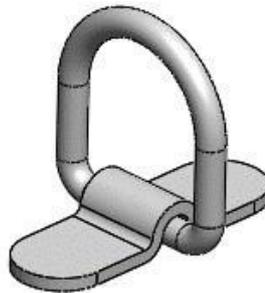


Figure 10 Ratchet straps

Mounting of the depth sensor to the hull

On the stern of the hull, a cut is made to provide space for an aluminum backing plate to provide tapped holes for mounting the ultrasonic depth sensor and the rudder system. This cut also includes six holes which allow for the backing plate to be bolted to the back of the hull.

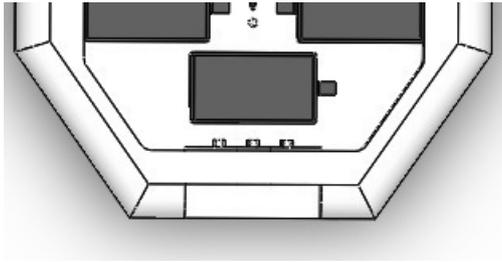


Figure 12 Top view of the mounting of the depth sensor to the hull

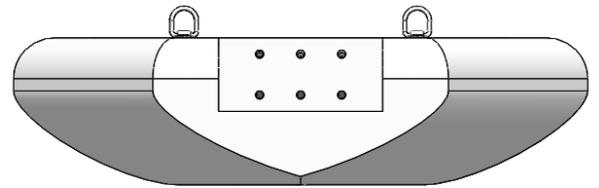


Figure 11 Front view of the mounting of the depth sensor to the hull

Mast connection

On the floor of the extruded space for housing the electronics, there are holes provided for the mast mounting hardware and for wiring to provide power and control to the hydrofoil elevon servos and the thruster.

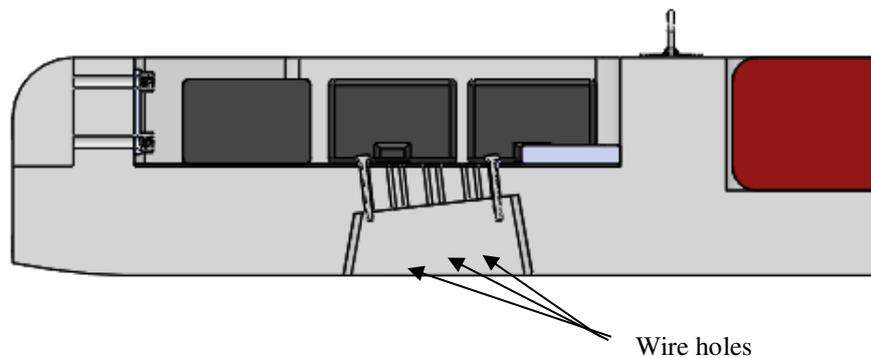


Figure 13 Mast connection to the hull

Minimal drag for modes on plane, off plane

The shape of the hull has been designed in order to have the minimal drag. To prevent the air that passes over the hull from separating in the way the hull will be designed with a parabolic shape (no corners in its profile). The side profile shows a mild rocker in the front to prevent chop in the water from pulling the nose of the hull down. The rocker quickly tapers down to a flat bottom, giving the hull improved pitch and roll stability and allowing it to hydroplane on the water.



Figure 14 Lateral view of the hull

Materials of the hull

The construction of the hull is similar to that of a surfboard, with a foam core to lower the density of the hull and provide a general structure to the hull. The foam center also allows for easy creation of the profile of the hull. The foam center is then covered in fiberglass and epoxy to provide strength and sealing to the hull. However, because the hull core is made of foam, there is no structure to drill threads into or to pin parts directly against. As a result, the hull utilizes multiple nut mounting plates to provide structural support for any fastening needed on the hull system.

Door/Sealed Hatch:

The electronic systems need to be sealed and secured in the electronics compartment in the hull. Accessibility to the electronics is also critical to performing the tasks required by the system. Batteries need to be accessible for recharging and the Pixhawk for controller calibration and tuning. As a result, the system need to be properly sealed with a sealing door that can be removed when needed.

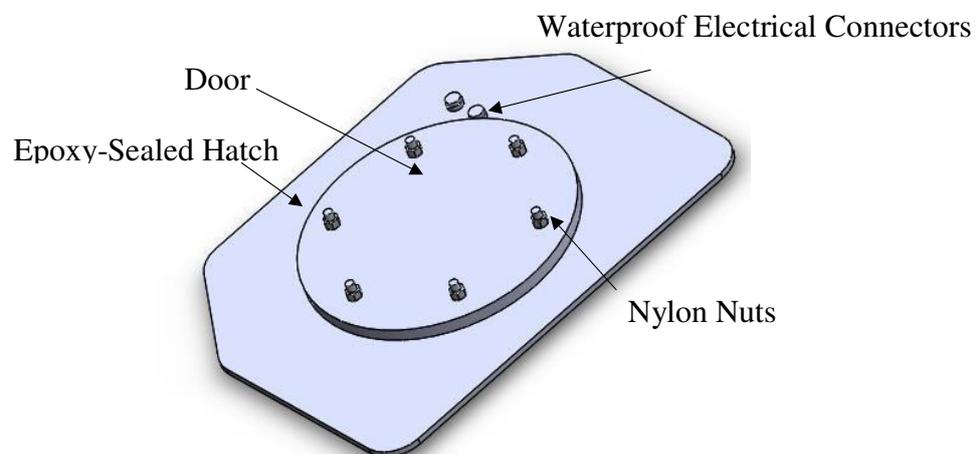


Figure 15 Elements of the door subassembly

The door/sealed hatch system allows for the proper connection to the electronics to the parts needing power and control as well. The door itself is a circular disk with six equally and circularly spaced holes.

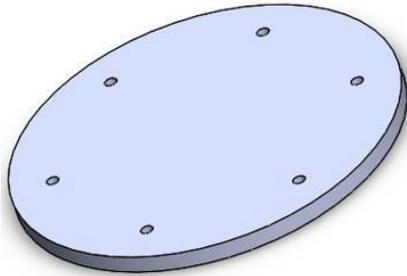


Figure 17 Door

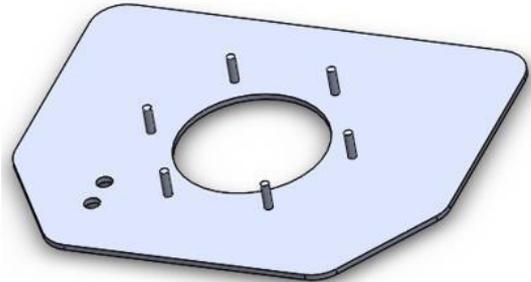


Figure 16 Sealed hatch

The hatch piece is formed primarily from a flat plastic extrusion with an 0.18 m hole cut into its center for access to the parts contained in the electronics hatch.

Sealing of the door

The bottom of the door piece has a sized groove cut into it to allow for a rubber O-ring to be inserted for sealing. The six holes on the door are to allow for threaded pins to pass through for fastening. The hatch piece itself, which is epoxied to the hull to allow for proper sealing of the electronics hatch on the interface between the hatch and the hull. The hole is surrounded by six equally and circularly spaced M10-1.5 pins. These pins provide the door piece with a guide for placement onto the flat surface of the hatch piece. The flat surface allows the O-ring to seal the internal electronics from the wet environment outside of the electronics hatch.

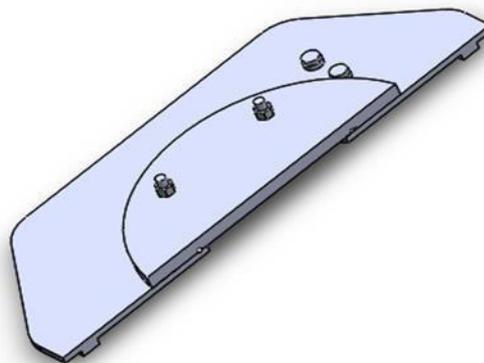


Figure 18 Cut view of the door assembly



Electrical connectors

The sealed hatch also contains two holes for two Seacon VMF-FS waterproof electrical connectors to provide power and control to the servo and sensor mounted on the stern of the system. These connectors are epoxied into place for structural support and sealing purposes.

Rudder:

Given that the hydrofoil system is driven using pitch and roll control while on plane, the elevon system provides no yaw control to the system. As a result, the system needs a mechanism to control the yaw when not on plane. To provide the forces needed for yaw control, a servo driven rudder system was designed for attachment to the rear of the system.

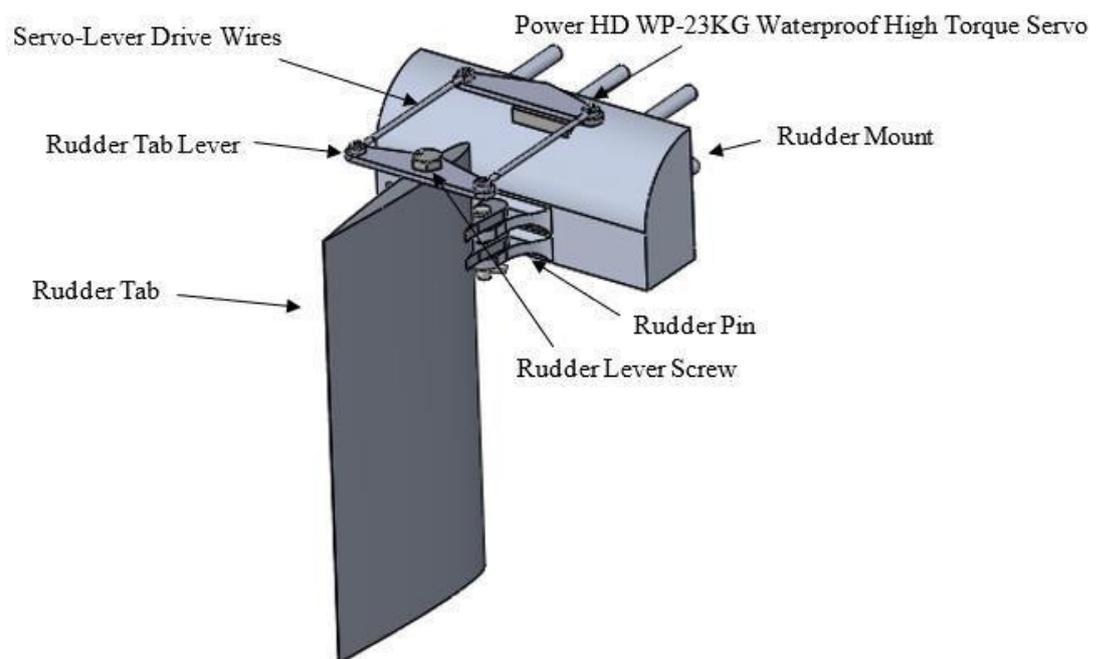


Figure 19 Rudder subassembly elements



Rudder Servo

The rudder system is servo driven, with power supplied from the batteries in the hull through the sealed electrical connectors. The servo ratio is 1:1 (The rudder will rotate the same degrees as the servo).

Rudder Mount

The subsystem is attached by the rudder mount designed for the system. Because the rudder mount secures the hull, rudder servo, rudder tab, and the sensor subassembly, the surface features vary. On the stern facing side of the rudder mount, two extruded flanges extend 0.02 m from the rudder mount surface coincident with the stern of the hull. These flanges have a thru hole to allow for a pin to be placed to hold the rudder and rudder mount together. To the port side of the flanges are two M7-1.0 threaded holes for mounting the height sensor bracket. The extruded cut in the top of the ruder mount provides a space for a Power HD WP-23KG Waterproof High Torque Servo to be epoxied in and secured to the hull. On the bow facing side of the rudder mount six threaded pins serve to fasten it to the hull. Additionally, the rudder mount will be epoxied to the mating surfaces on the hull for sealing purposes. Then on the other side, through the hull, there is a nut mounting plate with nuts to fasten the pins into plates.

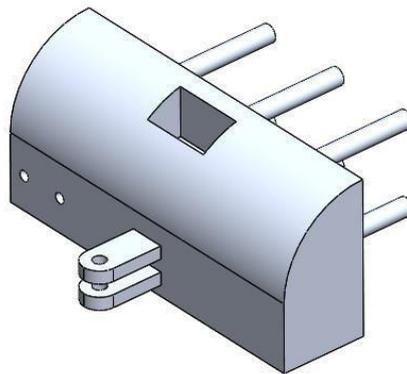


Figure 20 Rudder Mount



Rudder tab

The rudder tab has an airfoil profile, to allow for minimal drag impact while in the system is in motion and providing the proper forces required to swing the rear of the hull to meet yaw change requirement. The rudder tab has an extruded cut keyway in the top to be driven by the rudder top lever. Within the keyway a threaded hole for fastening the rudder top lever to the rudder tab. On the part of the rudder tab facing the bow, there are two extruded flanges to pin together with the flanges on the rudder mount. The rudder top lever is connected to the rudder servo with a crimped drive wire connection.

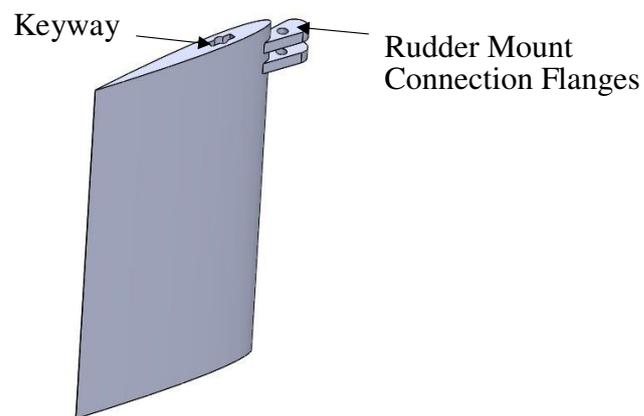


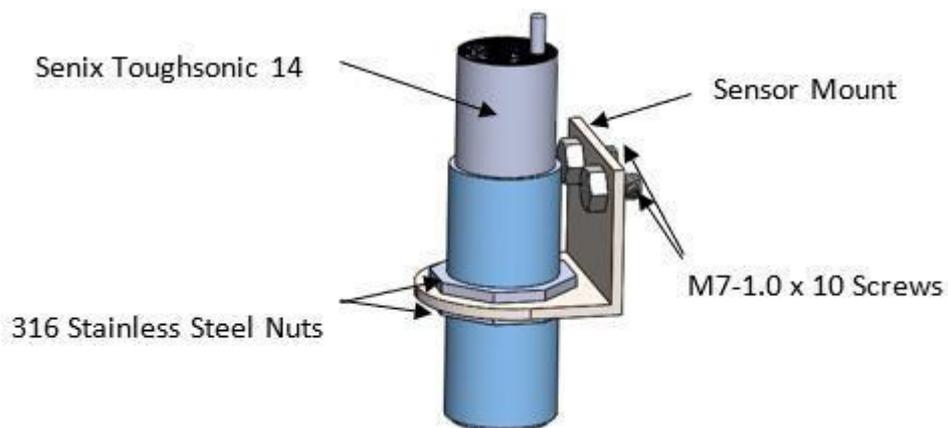
Figure 21 Rudder tab



Height sensor system:

Also attached to the rudder mount is the height sensor system to allow for proper positioning and balance control of the craft. The sensor system is fastened to the rudder mount with two M7-1.0 x 10 screws through the sensor mount.

The sensor used for measuring the distance from the water is the Senix Toughsonic 14, which allowed for ultrasonic distance measurements to be taken and relayed to the Pixhawk autopilot. The sensor itself had a threaded housing which was mounted with two stainless steel nuts on each side of the mounting bracket for securing. The distance sensor would be calibrated with the autopilot system to allow for proper measurement of distance from the water. The height sensor has power and controller cables running to the waterproof electrical connectors on the door/hatch system to interface with the batteries and Pixhawk.





5.2 FOIL ASSEMBLY

5.2.1 MAST

The mast is designed as a NACA 0010 with a chord of roughly 0.15 m and total length of 0.82 m. Long enough to leave the payload above the water and the hydrofoil system under it on plane mode.

The mast has three major connection points with the hull, motor mount, and fuselage. The hull connection point has a cap with three 0.045 m M6 x 1.0 fasteners and a hole for wires to run through.

Fuselage connection

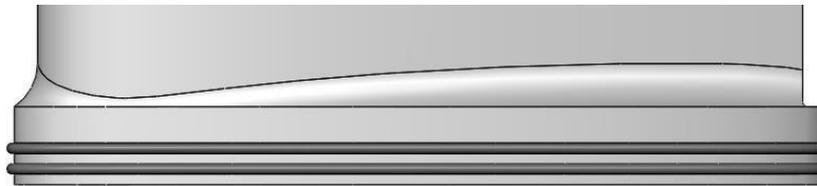


Figure 23 Fuselage connection to the Mast

Like the hull, the fuselage connection has the same fastener connection. Sealing of the fuselage connection is completed by a double O-ring bore seal with channels cut into the oval portion on the mast. The oval portion of the mast is discussed in more detail in the fuselage description.

Wires storage

The mast holds and connects all the electrical wires from the servos and batteries located in the hatch in the hull to the motor and the horizontal stabilizer. The mast has channels that run through it, large and wide enough to house all the wires required.

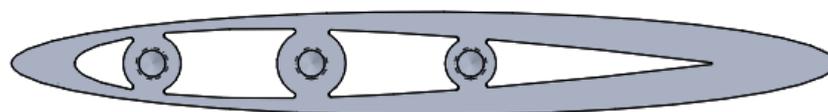


Figure 24 Channels of the mast for the wiring



In addition, the wires of the motor will be transferred from the mast through the hole drilled in its surface at the height of the motor-mast connection.



Distance from hole to fuselage connection= 0.2 m

Distance from hole to right edge of mast= 0.05 m

Hole diameter= 0.02 m

Figure 25 Mast

5.2.2 PROPULSION ASSEMBLY

Thanks to the propeller the thrust required for the navigation of the vehicle can be provided: The rotational motion of the gear box and motor is converted into a linear thrust force. In the propeller there are two edges, the leading and the trailing which have different pressure levels: one positive, one negative. The difference in pressure between the two faces of the propeller cause a thrust force. Moreover, it is because of the negative pressure on the back of the blade, that the phenomenon cavitation can appear. A gas in solution in the water under the pressure will evolve into bubbles that will collapse and will damage the blades.

It is convenient therefore to take into detail consideration the design of the propeller in order to minimize drag and maximizing efficiency to obtain the most thrust at low rpm. That is why the diameter of the propeller central hub must be smaller than the diameter of the outer case of the motor assembly so as to reduce the maximum drag caused by the fluid coming from the motor assembly to the propeller.

Moreover, the weight of the propeller is to be minimized. As in the motors used in boats, the propeller will have three blades.

Another geometry factor is the rake angle of the propeller, in other words, the angle that the propeller blades have with the vertical. Typical values of rake angles are between -5 to 30 degrees. With a high rake angle, water can adhere to the blades better and handle aerated fluids which will contribute to the lift of the hull and consequently a decrease in its drag.

The thruster provides all the thrust to the vehicle to combat the drag and provide a forward velocity. As shown above the thruster is located just above the fuselage on the mast. It is imperative that thruster assembly is sealed from water entering the thruster cavity, as the components on the inside are not waterproof.

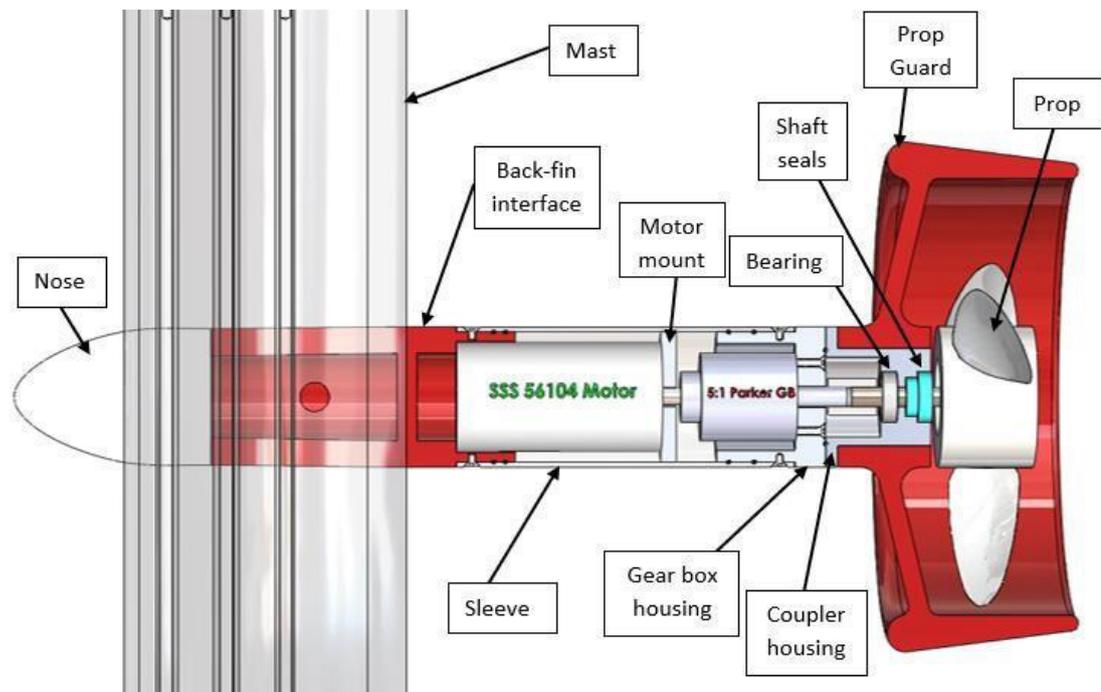


Figure 26 Propulsion assembly elements

The nose and back-fin interface bolt together around the mast about 0.2 m from the bottom of the mast. They are held in place with a combination of grip force provided

by the bolts and adhesive from an epoxy applied between the nose, back fin interface and mast.

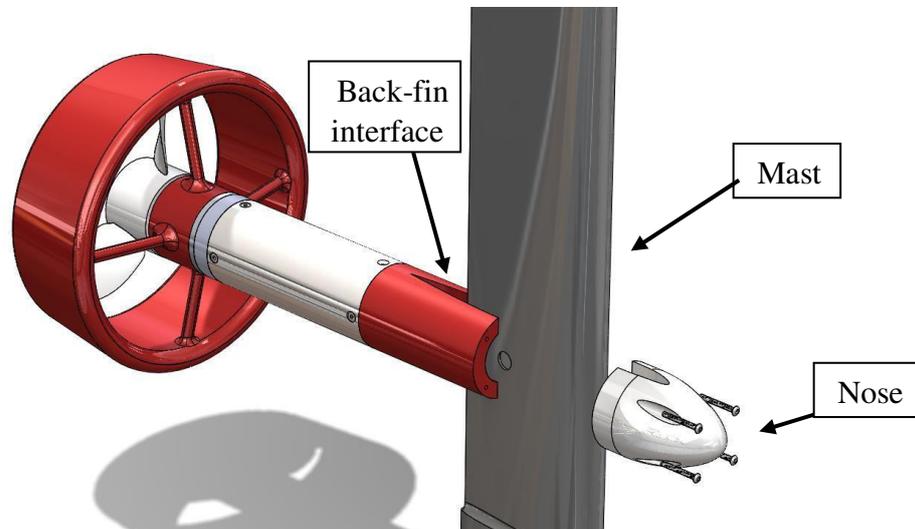


Figure 27 Motor-mast connection

The Sleeve is secured to the back-fin interface as well as the gear box housing with four sized M4 screws. This prevents the sleeve from disconnecting from the back-fin interface and the gearbox housing from disconnecting from the sleeve.

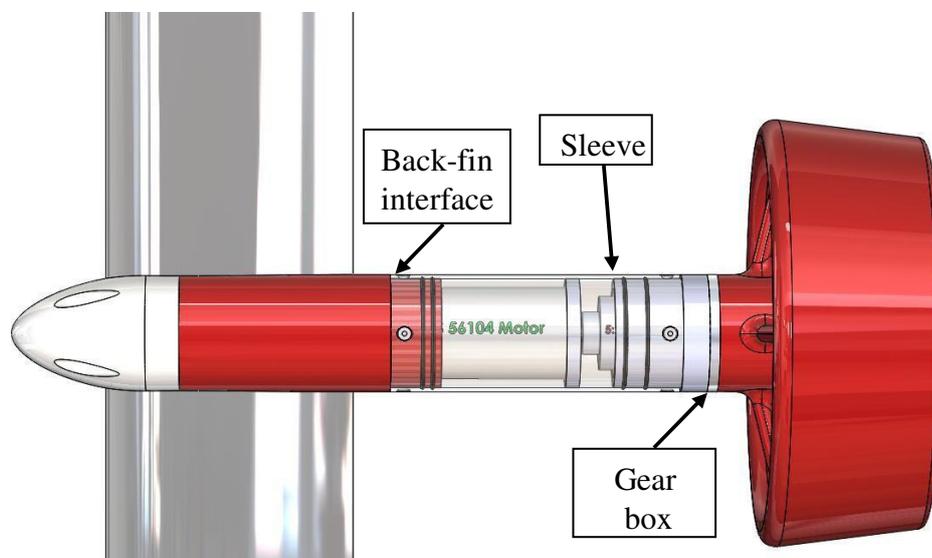


Figure 28 Motor-mast attachment

The motor is secured into the motor mount with four mounting screws that pass through the mount into the stock motor mounting holes.

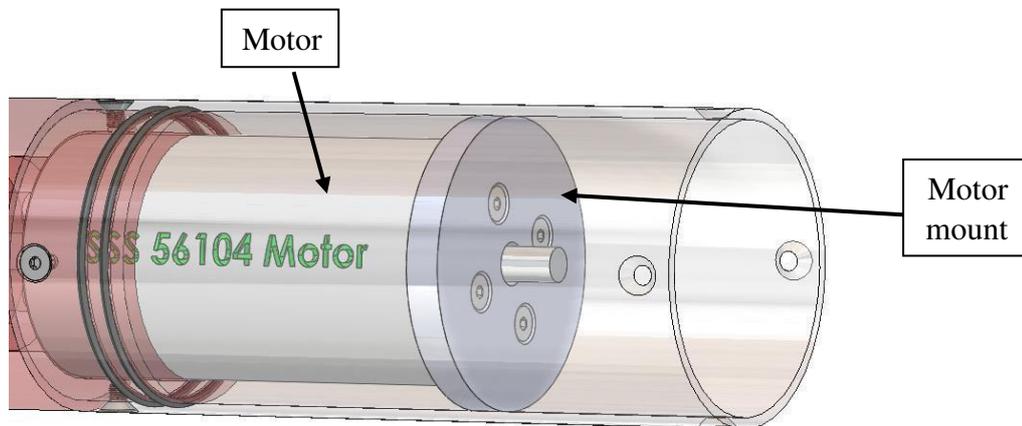


Figure 29 Motor and motor mount attachment

The gear box is secured to the gear box housing with 4 face screws that are treated into pre-tapped holes in the gear box.

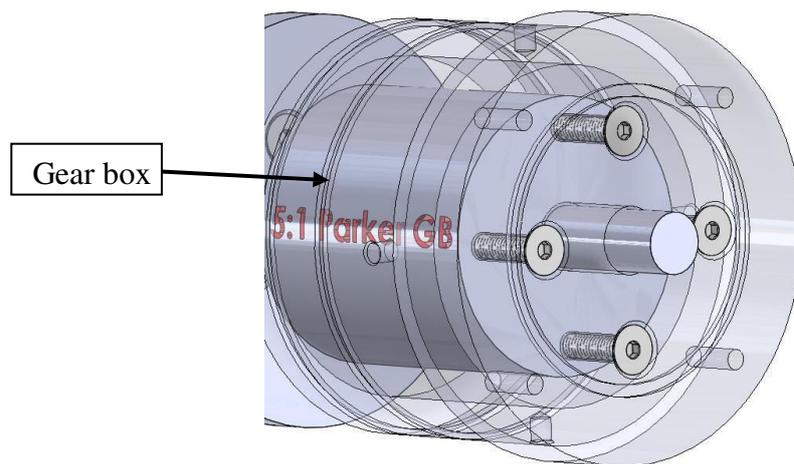


Figure 30 Gearbox

The prop guard has four face screws that pass through the coupler housing and thread into the gearbox housing. This secures the prop guard and coupler housing in place.

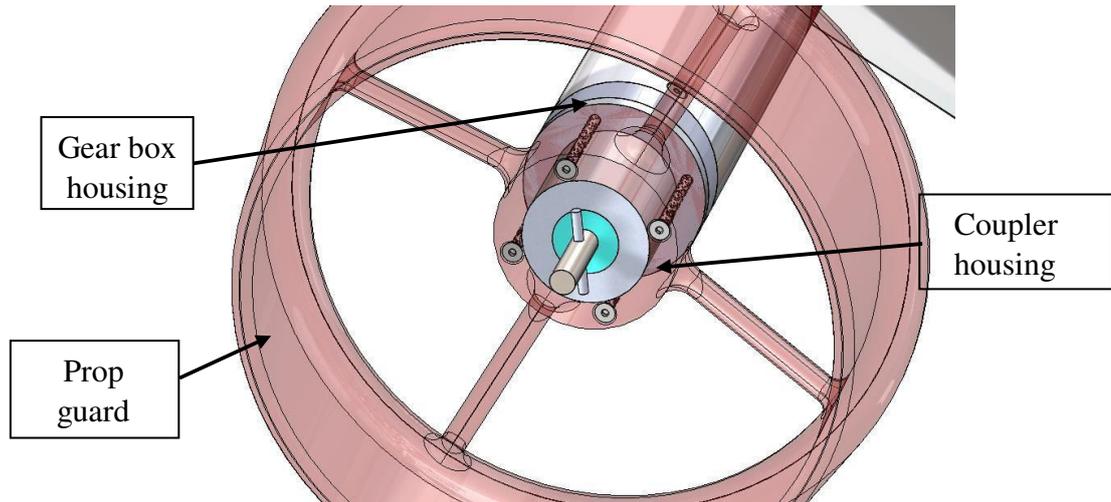


Figure 31 Attachment of the propeller guard

The output shaft has a rod that mates with a slot in the back of the propeller that makes the prop spin with the output shaft.

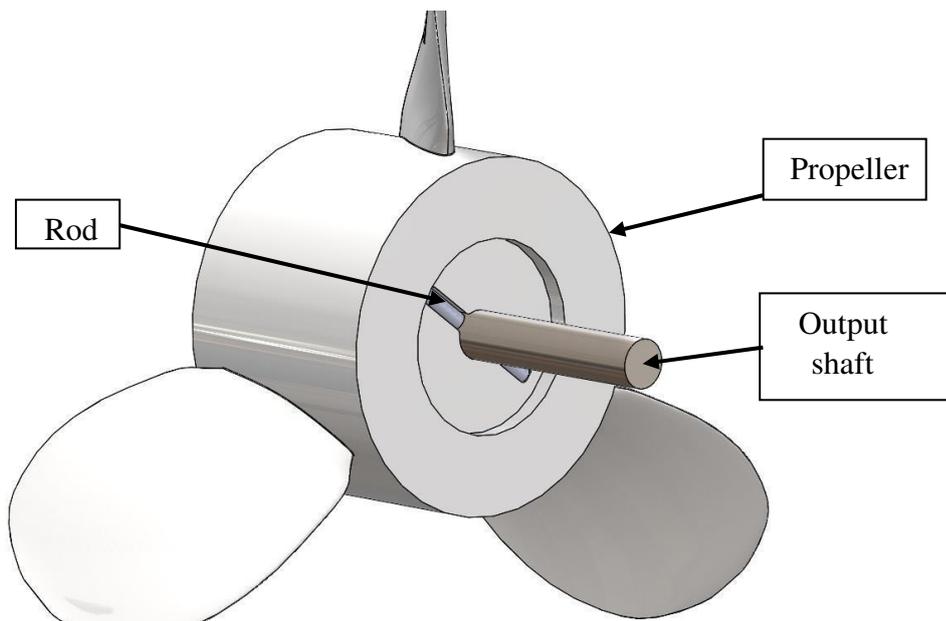


Figure 32 Connection output shaft with propeller

The end of the output shaft has a threaded section that allows the propeller nut to secure the propeller to the shaft.

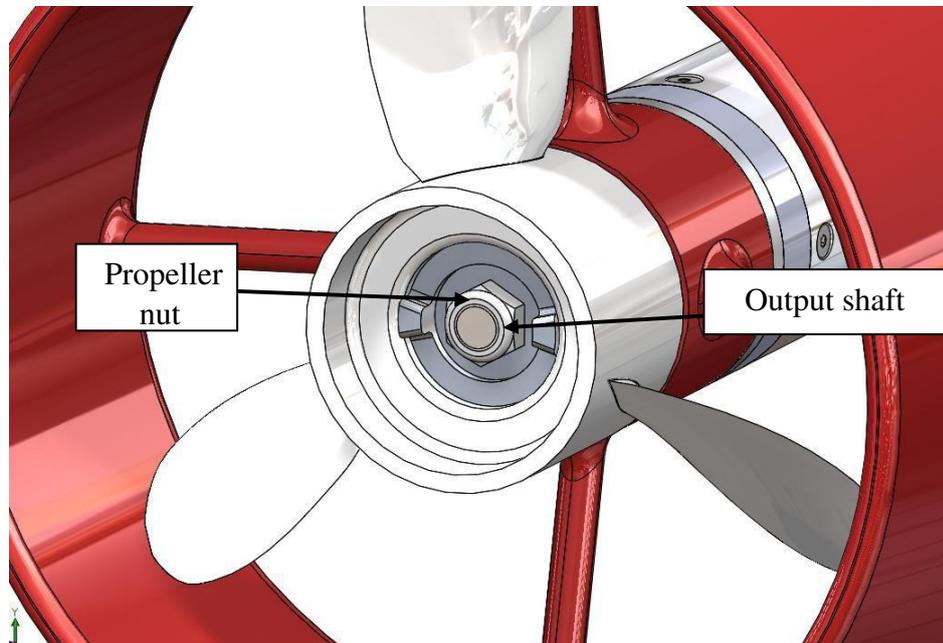


Figure 33 Fastening of the propeller and shaft

Thruster sealing

The output shaft is sealed with 2 shaft seals made by Freudenberg Sealing Technologies pressed into the coupler housing. These allow the shaft to still rotate but prevents water from entering in through the shaft.

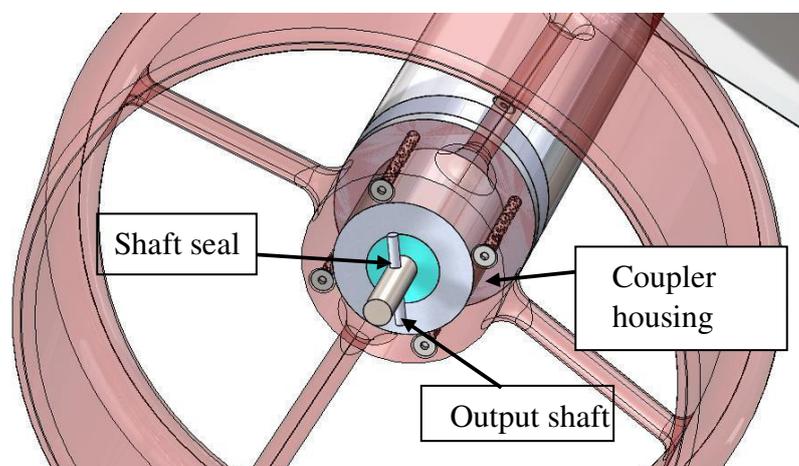


Figure 34 Sealing of the output shaft

Between the interface of the coupler casing and the gear box housing there is an O-ring face seal that would prevent any water from leaking into the interface.

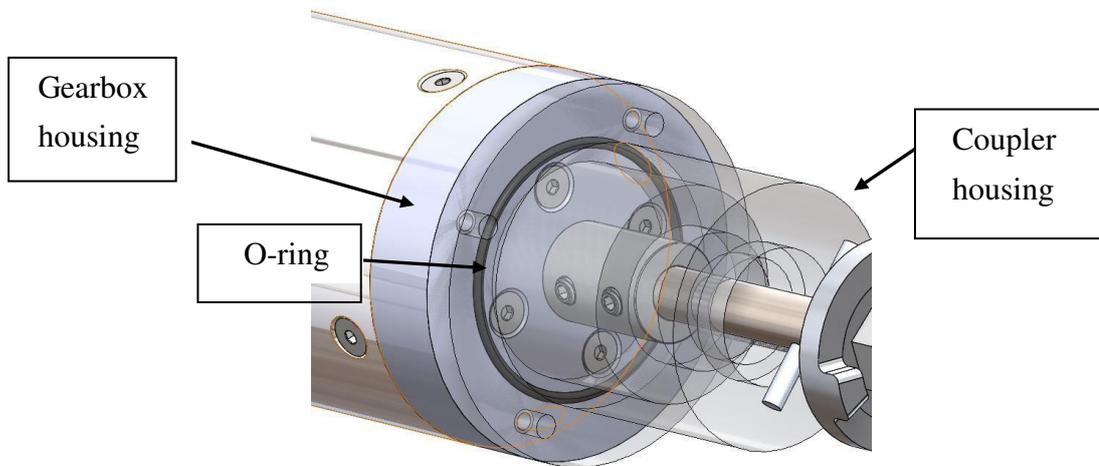


Figure 35 Sealing of the interface coupler casing- gearbox

Where the sleeve interfaces with back-fin interface and the gearbox housing there are double bore O-ring seals. These will prevent any water from entering through these interfaces. Where the mast interfaces with the back-fin interface and the nose it sealed with a combination of adhesive and RTV silicon gasket maker.

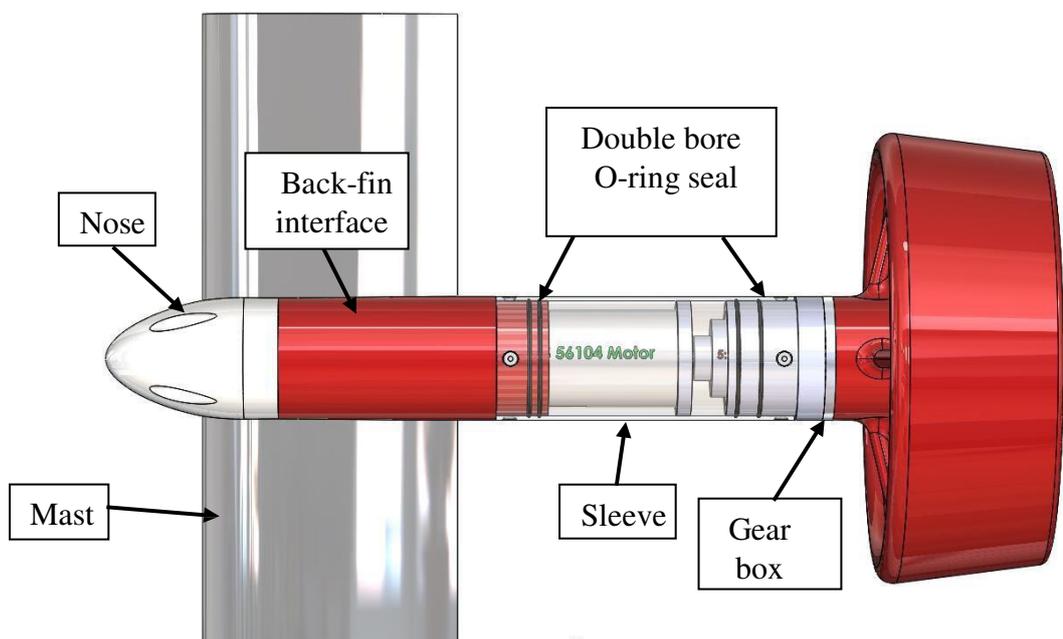


Figure 36 Double bore O-ring sealing

5.2.3 FUSELAGE ASSEMBLY

The fuselage has an overall diameter of 0.05 m and length of just over 0.77 m.

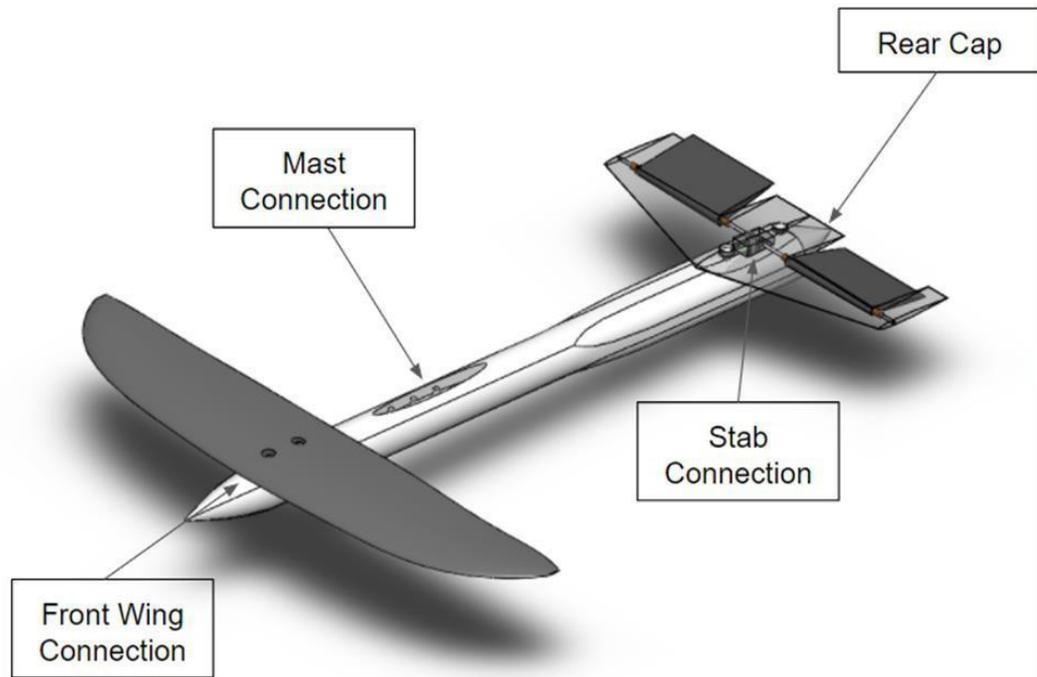


Figure 37 Fuselage assembly elements

Front Wing Connection

The front wing is connected using 0.07m M6 stainless-steel button head cap screws, which provide sufficient bolt force to hold the wing in place under the maximum tensile and shear conditions determined by lift and drag, respectively. Sealing the front wing connection is not necessary since this portion of the fuselage is solid and not exposed to any electronics.

Mast Connection

The cut in the fuselage for the mast connection is capable of being manufactured since the mast has an oval shaped part at the point of connection. The oval shape removes the need for a sharp edge to be cut into the fuselage. The three fasteners used are 0.045m M6 x 1.0 thread to ensure proper loading conditions in maximum tensile strength. It was necessary to seal the mast connection point since wires are

running through the mast to the rear portion of the fuselage. The mast connection is sealed by a double O-ring seal with a channel cut into the oval portion of the mast creating a bore seal.

Horizontal Stabilizer Connection

The horizontal stabilizer uses a 0.012m M6 x 1.0 faster for the front fastener, but since the rear fastener is limited to depth due to the rear cap, the rear fastener has a length of 0.008 m. Sealing the horizontal stabilizer is done by applying RTV silicon prior to attachment and then fastening while the silicon is drying. Once dry and fastened, the horizontal stabilizer will provide a water tight seal with the fuselage.

Fuselage internal section

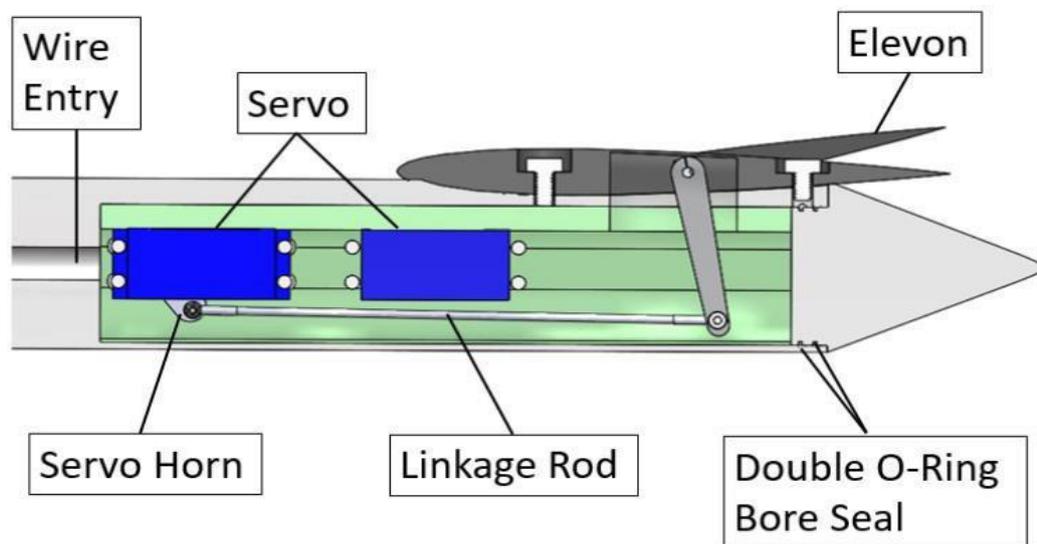


Figure 38 Fuselage intern elements

The internal portion of the fuselage is encapsulated with two servos, one for each elevon, two servos and elevon horns, a two-part mounting bracket, eight servo mounting rods, two linkage arms, and four fastener and bolt connections for connection of the linkage arms to the respective horns.

The design of the control surfaces is actuated by a push-pull system utilizing the rigidity of the linkage rods. The green portion of the figure shows the mounting bracket, which fits snug into the fuselage. This configuration provides an easy

bracket assembly outside of the fuselage to be slid into the fuselage. The bracket is held from translating by fitting against the rear cap.

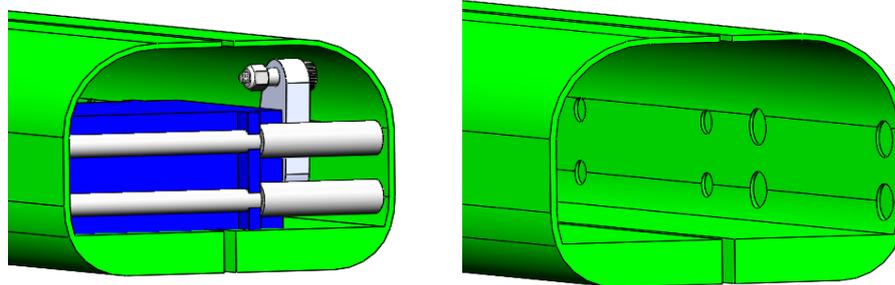


Figure 39 Servo mounting

The internal servo mounting rods have a heightened diameter to prevent the servos from translating side to side in the bracket. The rods and bottom flat portion of the bracket complete the need of securing the servo configurations. The servo horns have a degree of freedom of 45 degrees and corresponding the elevon horns move 21 degrees giving a mechanical advantage in regard to torque generated from the servos.

Fuselage rear cap

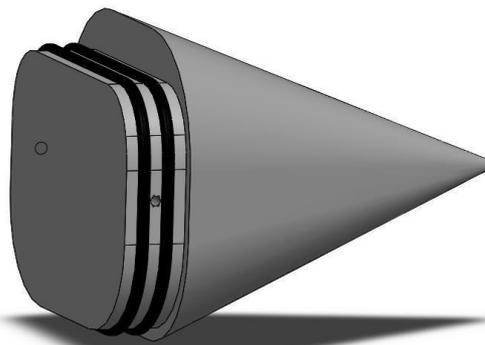


Figure 40 Fuselage rear cap

The rear cap of the fuselage is designed to match the frontal profile of the fuselage. Sealing the fuselage cap is done by turning two channels in the cap for O-rings to snap in. The O-rings ensure a water tight bore seal, but to ensure the cap does not fall off due to a shear force, 0.003m M2 x 1.0 fasteners are threaded to either side of the cap.



5.2.4 HORIZONTAL STABILIZER ASSEMBLY

Pitch and roll control of the craft is performed via two elevons located on the horizontal stabilizer. The elevons can be actuated independently of each other, allowing them to pitch, roll, or pitch and roll the vehicle. The elevons are limited to $\pm 20^\circ$ in their movement. Each elevon is actuated by a rod that is connected to an elevon horn which is connected via a servo rod to a Power HD servo that is capable of outputting 2.25 Nm of torque at the output gear. This torque is effectively doubled since the elevon horn is twice the radius of the servo horn. The elevon horns themselves are machined from 6061 aluminum for strength and corrosion resistance. The actual power transmission from the elevon rod to the elevon is achieved using a stainless steel rectangular key that extends throughout the entire width of the elevon. The elevons are made of a G10 composite material that ensures durability and corrosion even in submerged salt water conditions while keeping weight low.

Like the elevons, the horizontal Stabilizer is machined from a solid block of G10. It is secured to the fuselage by two 316 stainless steel M6 fasteners for strength and corrosion resistance. Sealing between the horizontal stabilizer and the fuselage is achieved by the use of room temperature vulcanization (RTV) silicon. RTV silicon is also used to seal the bolt holes in the horizontal stabilizer. Sealing of the elevon rod transit into the horizontal stabilizer is achieved by a combination of grease and the fitment of the rod inside the vespel bushing.

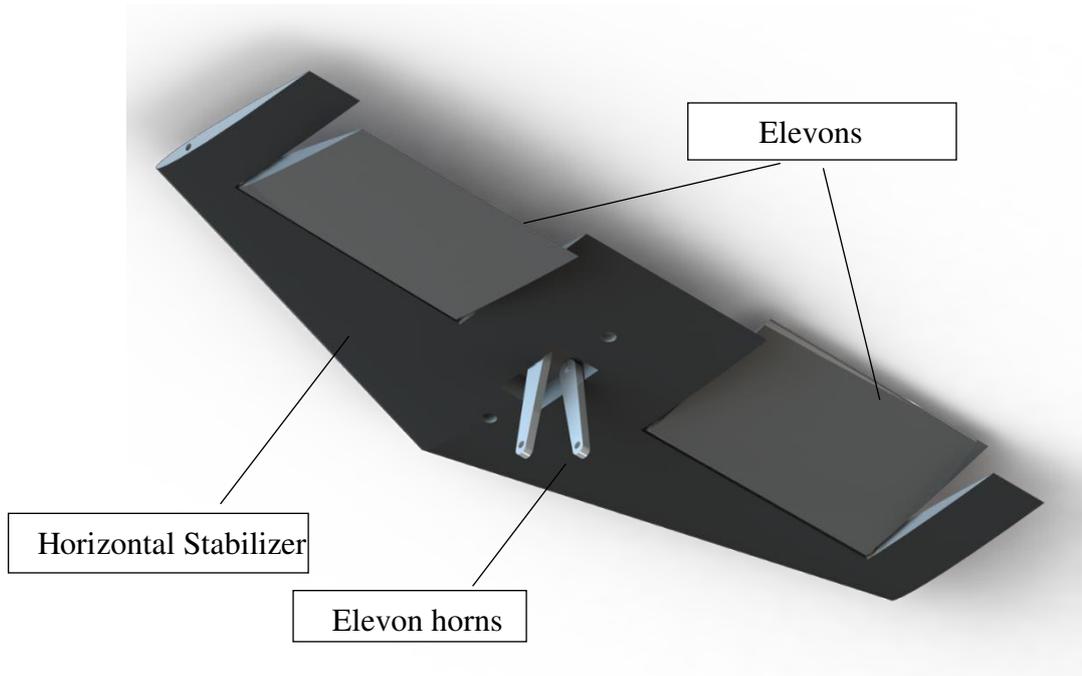


Figure 41 Horizontal stabilizer assembly elements



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Chapter 6 FUSELAGE ASSEMBLY PROCEDURE

Elevon Subassembly Procedure

1. Place horizontal stabilizer on a flat workspace table. Make sure side with box cut out is facing upward and pointed side facing away.

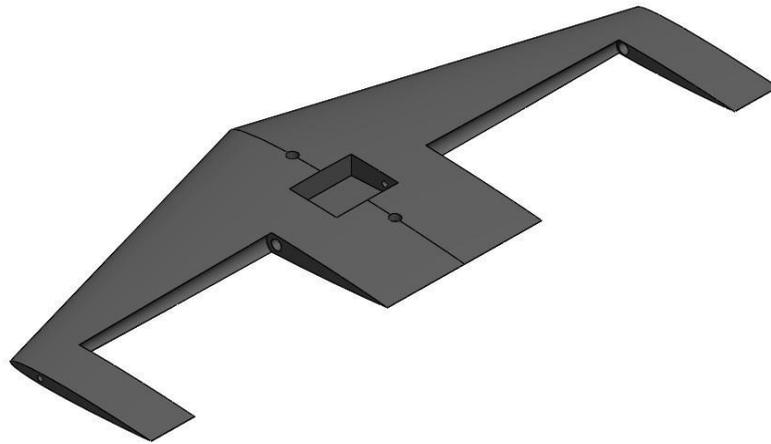


Figure 42 Step 1 on HS assembly procedure

2. Pick up bushing (with other hand). Beginning with the left side of the stabilizer, insert part into appropriate hole located on the inside of the elevon cut out. Repeat with other bushing located on the opposite end of the cut out.

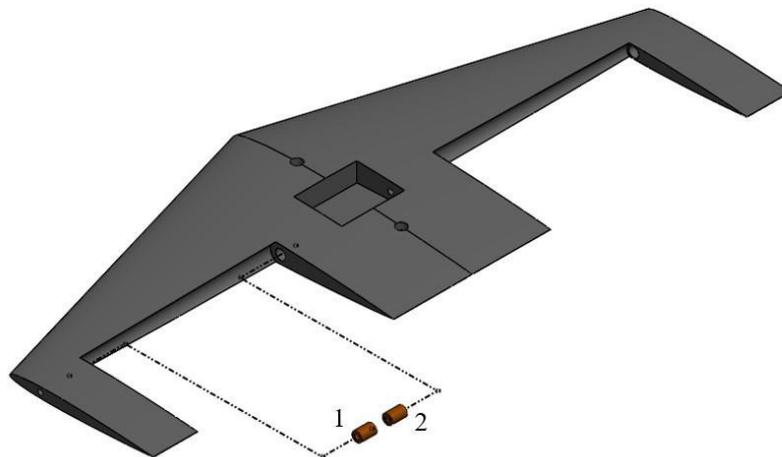


Figure 43 Step 2 on HS assembly procedure



3. Pick up elevon and align with bushings (from previous step) for both ends of the part. Hold in place.

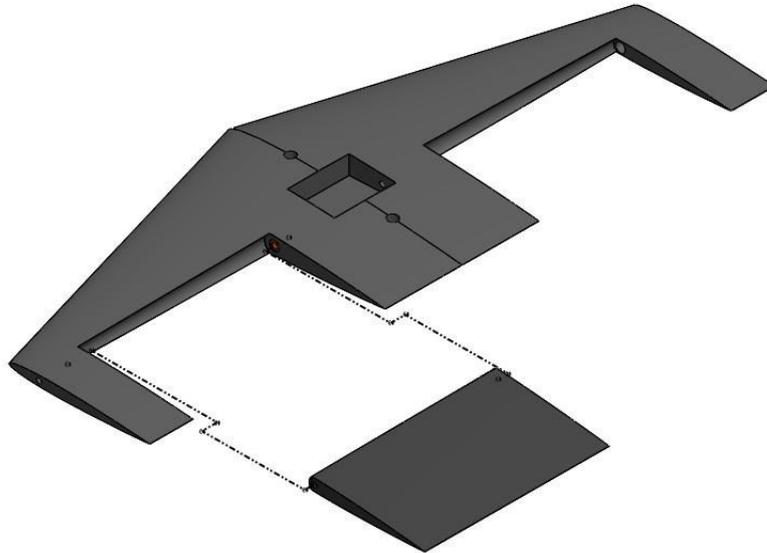


Figure 44 Step 3 on HS assembly procedure

4. Pick up rod and push through hole located on the leftward side of the horizontal stabilizer. Push all the way through the elevon, fully into the rightmost bushing and through into the box cut out in the center of the stabilizer.

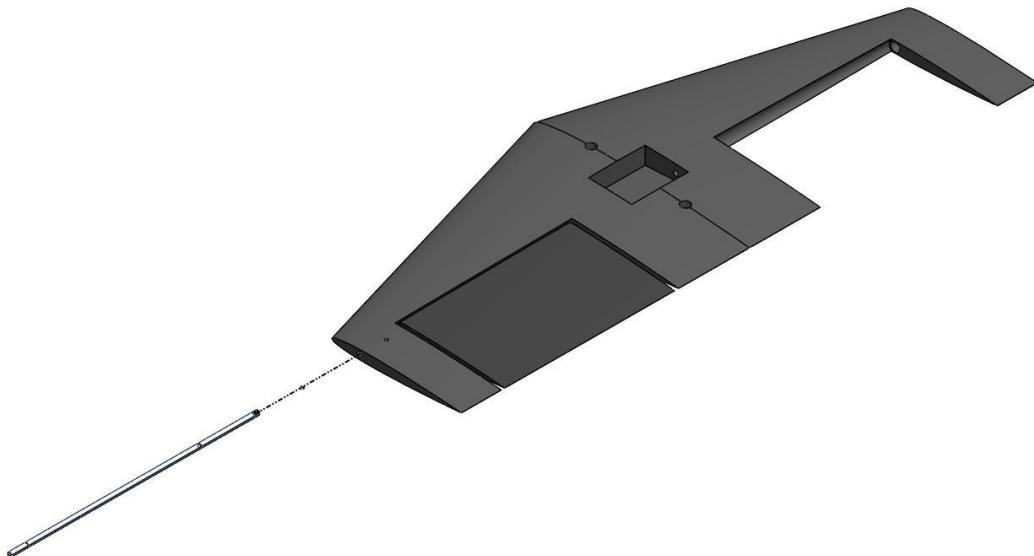


Figure 45 Step 4 on HS assembly procedure

5. Pick up key and push through the same hole located on the side of the stabilizer as in the previous step. The key should be pushed all the way into the elevon until it is fully inside and can hardly be seen.

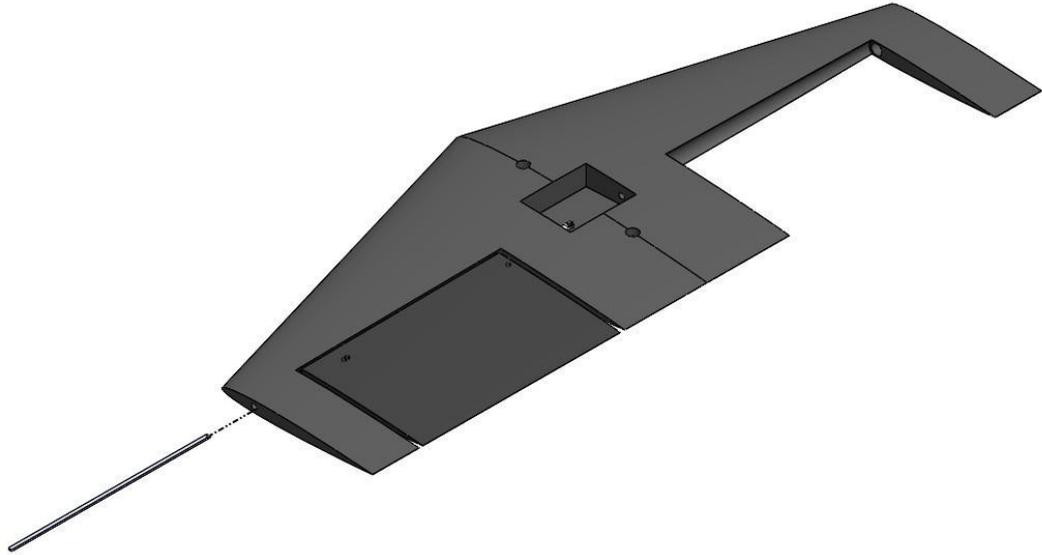


Figure 46 Step 5 on HS assembly procedure

6. Pick up snap ring and align with small indented cut out located on the left side of the elevon. Push (snap) the ring into place over the rod. Repeat for the right side of the elevon.

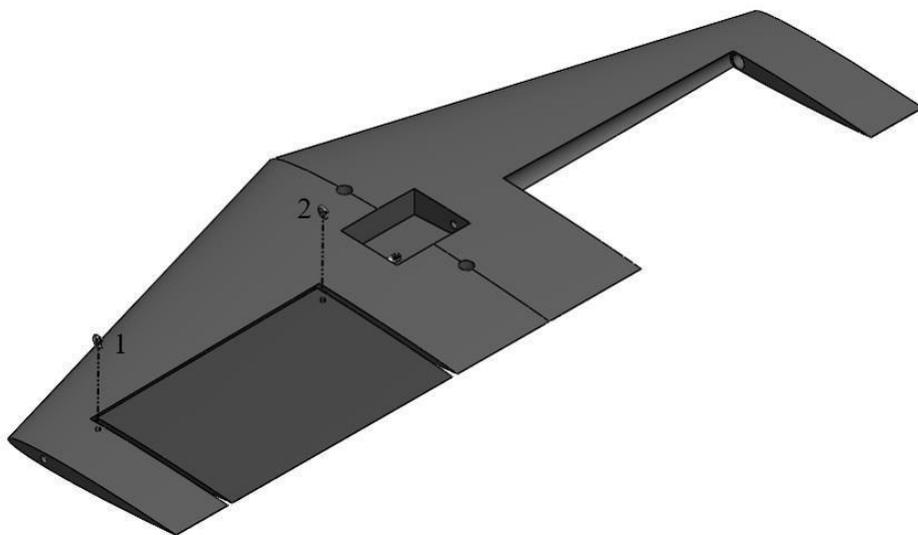


Figure 47 Step 6 on HS assembly procedure

7. Pick up the horn and align the bottom hole (thickest side down) with the right end of the elevon rod, which should be protruding through into the box cut out in the center of the stabilizer. Align properly with the rod end shape to ensure a good fit.

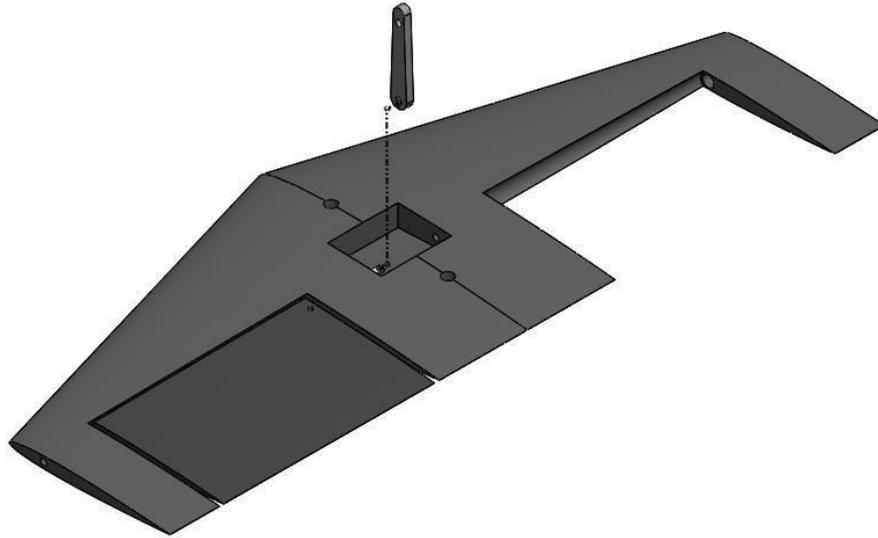


Figure 48 Step 7 on HS assembly procedure

8. Pick up horn fastener and align with screw hole located near the bottom of the horn. Tighten with a socket head screw driver.

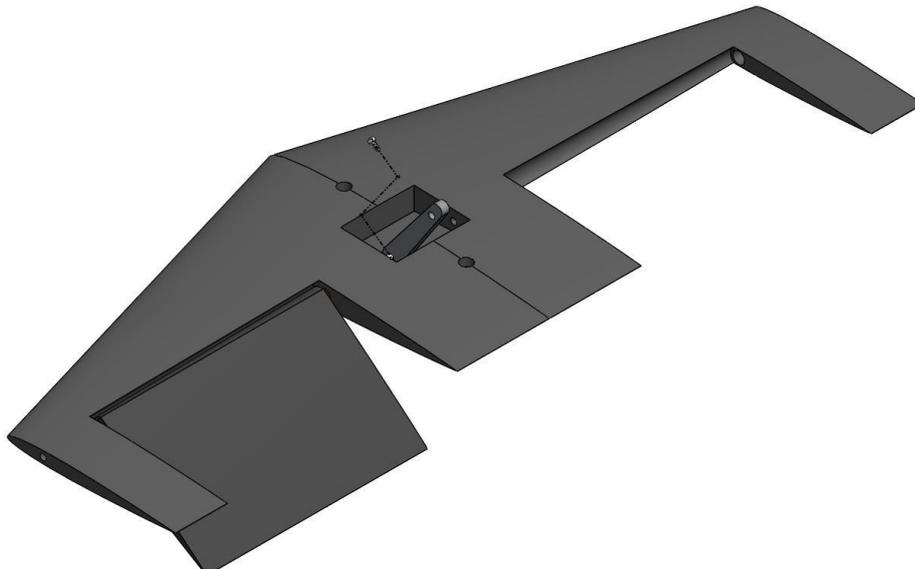


Figure 49 Step 8 on HS assembly procedure

9. Repeat steps 2 through 9 with the right side of the stabilizer to assemble the right elevon.

Chapter 7 CALCULATION/ANALYSES

The craft's center of buoyancy and mass were found using SolidWorks. By changing all the materials to an identical arbitrary selection, the center of "mass" given by SolidWorks became the center of volume. This was used to find the center of buoyancy. The locations of each in vector form are given below.

$$\underline{r}_{CB} = 54.2\underline{j} - \underline{k}$$

$$\underline{r}_{CG} = 54\underline{j} - 6.7\underline{k}$$

The figure below shows the following forces: The weight (W), the buoyancy force (B), the drag force (D), the thrust (T), the force on horizontal stabilizer (H), the wing lift (F).

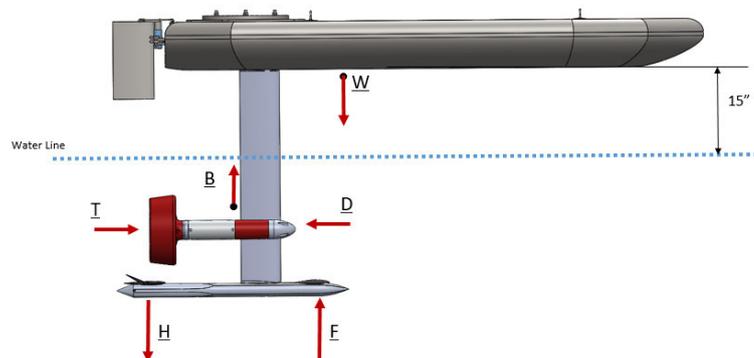


Figure 50 Force diagram

Stability

Center of gravity

The center of lift must be on the middle of the front wing to ensure a good flight. If it were located further ahead there would be too much lift generated. On the contrary, if located further behind the stability of the vehicle would be highly reduced.

Furthermore, depending on the distance between the center of gravity (CG) and the center of lift (CL) different operation outcomes will be obtained. If the CG is



forward the hull noses down, the vehicle is more stable, less efficient and the stall speed is higher because of the greater weight the wings have to support. On the contrary, if the CG is located backward, the vehicle will be more effective, less stable and with an inherent tendency to enter a stall.

All in all, as the center of gravity is moved rearward, the vehicle will reach higher cruise speed and therefore greater efficiency but lower stability due to the decrease of the downforce in the tail. Moreover, the stall speed decreases and the recovery from stall becomes more unlikely because of the difficulty to make the hull to nose down and recover the equilibrium.

Thereupon, we will try to achieve a good balance between efficiency and stability in the design. That is why it has been chosen the more conservative design: to locate the center of gravity ahead of the center of lift to guarantee stability.

Pitch angle

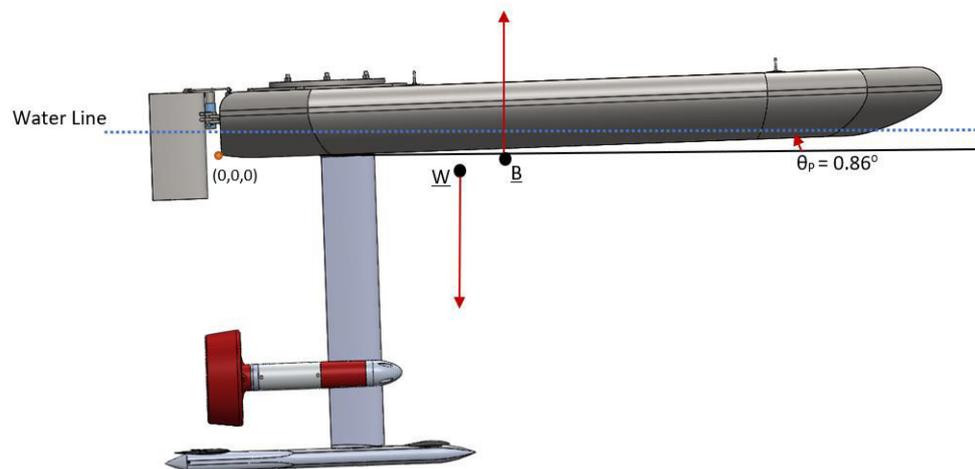


Figure 51 Buoyancy force vs Weight in terms of pitch angle

To do the analysis two forces were considered: the buoyancy force, weight of the displaced water and the weight of the fully loaded vehicle. The pitch angle (θ_p) was determined by dividing the height difference between the two vectors by the overall length of the hull. This yielded an angle of $+0.86^\circ$ (counterclockwise) when the vehicle is at resting position. This will ensure that the craft will not nose down forward into the water at low speeds.

Roll angle

The roll angle (θ_R) for the craft was determined using SolidWorks as well. Using trial and error, different angles were evaluated for a restoring moment from the weight and buoyancy. At an angle of 35° there failed to be a moment needed to induce restabilization. This determined that the vehicle would be stable for all roll angles of 35° or less in the static position.

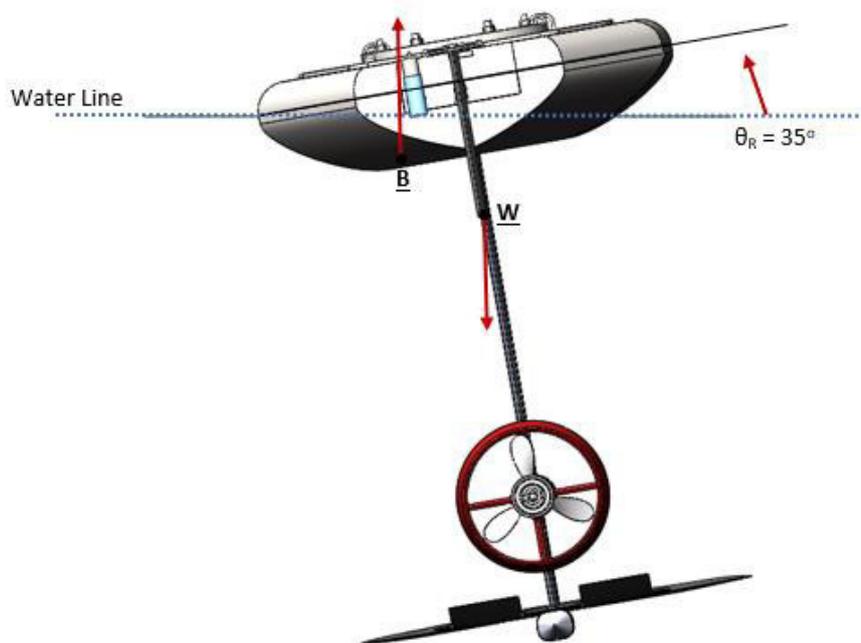


Figure 52 Buoyancy force vs Weight in terms of roll angle

When the vehicle is being propelled through the water, there are two main forces that appear on scene and go hand by hand: drag, opposed to the movement of the vehicle and lift, opposed to the weight. The aerodynamic force is the composition of both.

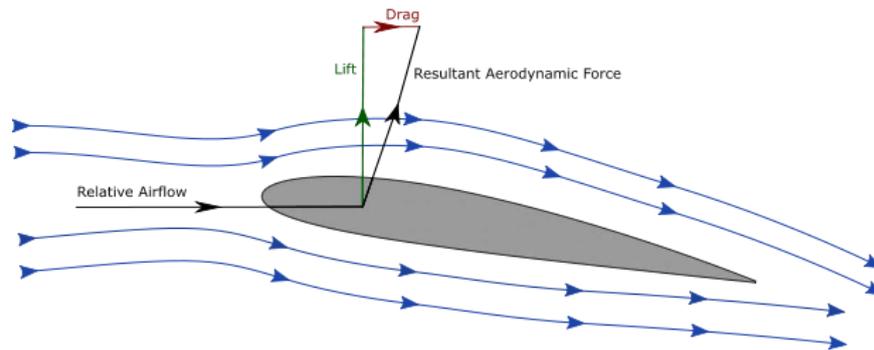


Figure 53 Aerodynamic force, resultant of lift and drag forces

Lift

The lift force raises the hull above the water when a certain velocity is achieved. But velocity isn't the only parameter, the angle of attack is another crucial parameter to consider when analyzing the lift. The increase in the angle of attack will increase the lift (it will also increase the lift-induced drag). The lift coefficient increases as the angle of attack increases up to a limit: stall point. At this point, part of the air going through the wing stays stocked there and disrupts the lift. The equation (1) of the lift force is the following:

$$L = 0.5C_L\rho V^2A \quad (1)$$

The vehicle's control surfaces, the elevons; will move up and down according to the performance needed at each moment. When they go up the angle of attack is reduced, and therefore the lift created is reduced. On the other hand, when they go down the lift is increased because the angle of attack increased. The angle of the elevons will be modified to create the lift required for a concrete maneuver. To change the roll angle, the two elevons will move differently whereas equally to change the pitch.

The desired riding point is slightly above the midpoint of the mast which brings the bottom of the hull out of the water to a height of 0.4m. The riding point is established by the weight of the craft counteracted by the buoyant force and lift from the horizontal stabilizer and front wing. The buoyant force reduces significantly as the hull rises out of the water due to a reduction in volume of water



being displaced. The reduction in buoyant force is accompanied by the lift from the horizontal stabilizer and front wing.

Cruise speed

When analyzing the lift of the vehicle there are three interdependent variables to consider: the lift of the front wing, the downforce of the elevons and the weight. There are two main scenarios of study: The first one, when the vehicle picks up speed; there will be more down force on the horizontal stabilizer, in other words, the elevons will be raised. In this scenario it can be observed how the hydrofoil's nose up. This downforce in the elevons is required to obtain the stability since the center of gravity is ahead of the center of lift, otherwise the hydrofoil would nose down due to the moment created by the two forces. The second one, when the speed is lowered, for instance because a high-water current, there will be less downforce on the elevons and the nose of the hull will dive and return to the stable speed. The advantage of having a downforce in the elevons is that it can be more controllable according to each situation and the stability is assured.

Firstly, the front wing was designed to have a zero angle of attack. For a NACA 63-412 as shown in the Figure 54 this produces a CL of 0.35. At cruise speed of 10.3 m/s, equation (1) shows there is approximately 1400 N of lift. This much lift will cause the motor to rise out of the water. That is why the elevons must be raised to reduce the lift force reducing the angle of attack.

The lift force required on the front wing to reach the desired cruising altitude is 625N. Then the CL needs to be reduced from 0.35 to 0.16 and consequently the Figure 54 shows that the angle of attack will drop to $\alpha = -2^\circ$. To contrast this the elevons will be raised. However, to optimize efficiency, the angle of attack for the front wing was determined by the required angle to provide enough lift to rise the hull out of the water at our cruising speed of 10.3 m/s without any pitch change from the horizontal stabilizer elevons. In this way, the power necessary at cruise speed will be reduced. Using Fig. (1), the angle of attack needed for the NACA 63-412 for a CL value of 0.16 is $\alpha = -2^\circ$.



Now it is desired to analyze the dynamics with the elevons at an angle up to determine a lower speed accompanying the same water level cruising position. The same lift force of 625 N is required to raise the craft to the desired height. The lift force of the front wing is reduced by changing the cruising speed to 5.6 m/s. In order to counteract the decrease in lift force to remain constant, a higher value of C_L is desired. The horizontal stabilizer provides a pitch to the entire craft by deflecting the elevons, which increases the angle of attack of the front wing related to the value of C_L . Determining the elevon angle with the entire craft pitch angle was done by setting the moments, with respect to the center of mass, of the elevon downforce and front wing lift equal to zero.

Once the necessary force on the elevons was determined, the lift equation could be reverse engineered to determine the elevon angle to provide the necessary downforce at 12.5 mph (Fig. 12). Solving the lift equation for the necessary lift coefficient of the front wing and correlating the respective $C_L = 0.55$ to the overall angle of attack needed on the front wing gives us an angle of attack on the front wing of 2.5° (Fig. 11). Since the angle of attack on the front wing is mounted at -2° the craft must be pitched up 4.5° . The needed pitch is accomplished by raising the elevons.

The lift coefficient (C_L) changes depending on the type of wing and the angle of attack as shown in the graphics below. The Figure 54 shows the relationship of the angle of attack to coefficient of lift for the NACA 63-412 front wing. The blue and orange vertical lines represent the necessary angle of attack to lift the vessel with the elevons in a neutral position and deflected, respectively. The angle of attack from blue to orange is changed by pitching the overall vessel.

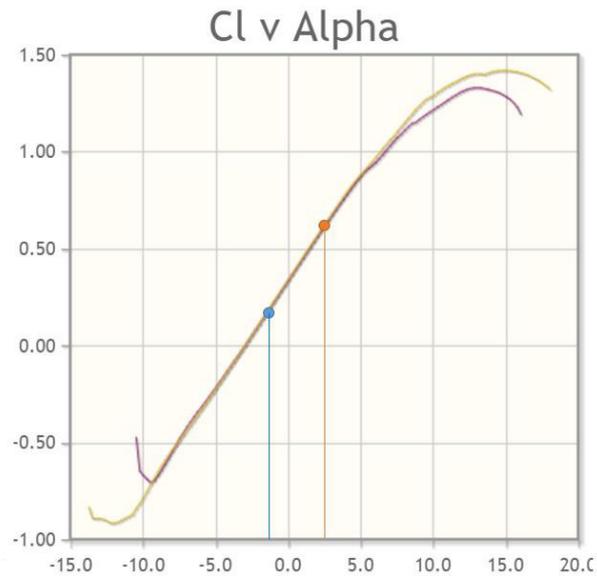


Figure 54 Relationship of the angle of attack to coefficient of lift for the NACA 63-412 front wing.

The Figure 55 shows the relationship of the angle of attack to coefficient of lift for the NACA 0012 elevons.

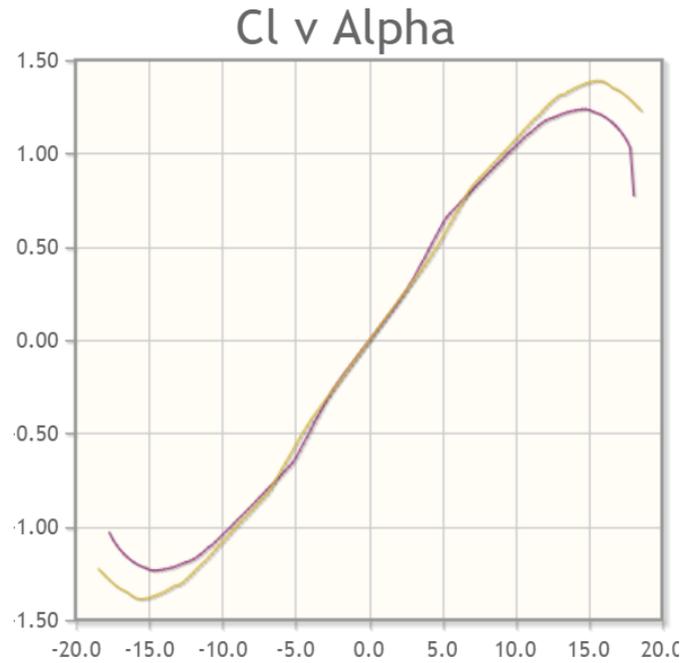


Figure 55 Relationship of the angle of attack to coefficient of lift for the NACA 0012 elevons.



Structure

The mast is the main structural part of the vehicle which receives forces, pressures and torques. The Finite Element Analysis method is applied to study the maximum roll angle that can be reached so that the mast will not present any fracture. While doing the analysis the first consideration is that the wing, the fuselage and the horizontal stabilizer assembly connected at the bottom of the mast is going to be considered fixed (the movement in the x and y axis is restricted)

The outcome of the iterative analysis of the bending forces based on the roll angle and the weight of the hull assembly using the simulation tool of Solidworks is that the allowable angle for the mast to bend is 30°.

The figures below show the free body diagram of forces, the stress and the deformation results.



Figure 56 Free body diagram

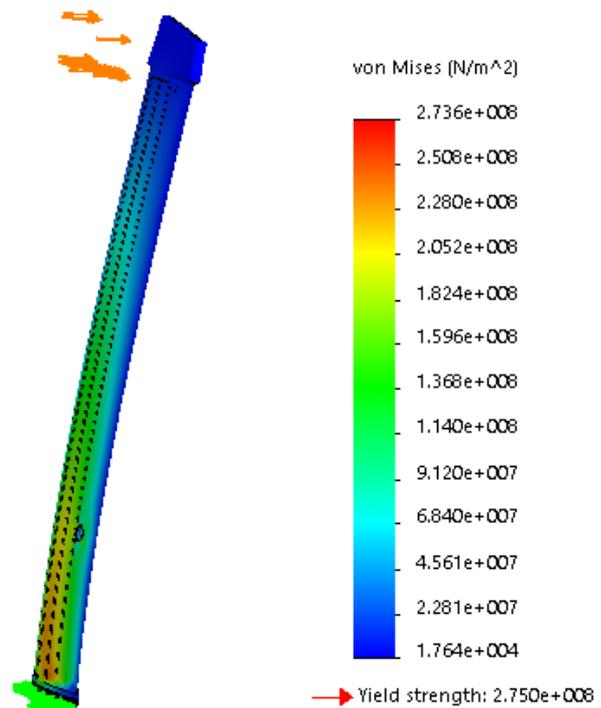


Figure 57 Stresses

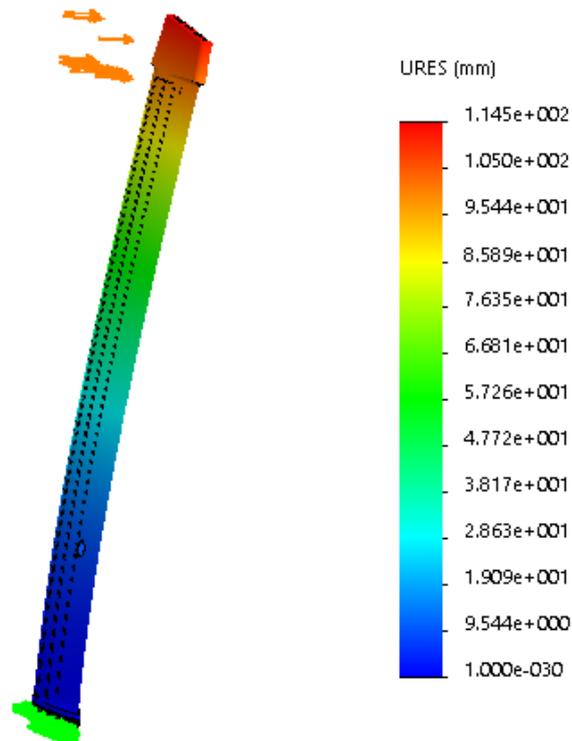


Figure 58 Displacement



Drag

Lift and drag are dependent one of each other, that's why the outcome, when lifting an entire boat introducing a large angle of attack, will not be assured to accomplish a good efficiency because there will be also a large amount of drag. In other words, the fact that the vehicle is flying above the water doesn't mean it will go faster.

As the vehicle increases the speed, drag becomes a bigger issue to take care of. Thanks to the hydrofoil the hull will be above the water and drag will be reduced, but not completely. Moreover, not only drag but also the structural risks will be reduced, since when the vehicle is in the "off plane" mode the hull has to crash its way into the waves and the structure can be considerably affected.

There are two main drags: parasite and lift-induced drag. The parasite drag is the one caused by a moving body passing through a fluid, it increases when friction is increased because of an increased speed. However, the lift-induced drag is a result of the lift and will vary depending on the speed. In order to maintain lift, at low speed a high angle of attack is required and therefore the induced drag increases. On the contrary, at high speeds a small angle of attack is required to maintain lift and the induced drag is reduced.

Drag forces for all the components were calculated using the formulas below (See Appendix A for nomenclature)

$$D = 0.5\rho V^2 S_{ref} C_D \quad (2)$$

$$C_D = C_{D0} + \frac{C_L^2}{\pi A R_e} \quad (3)$$

$$C_{D0} = C_f * FF * IF * \frac{S_{wet}}{S_{ref}} \quad (4)$$

$$S_{ref} = span * chord \quad (5)$$

$$C_f = \frac{0.058}{Re^{0.5}} \quad (6)$$



$$Re = \frac{\rho V l}{\mu} = \frac{V l}{\nu} \quad (7)$$

$$FF_{Streamline} = 1 + \frac{1.5}{\frac{l}{d}} + \frac{7}{\frac{l^3}{d^3}} \quad (8)$$

$$FF_{Hoerner} = 1 + 2\frac{t}{c} + 60\frac{t^4}{c^4} \quad (9)$$

The density of water (998.2kg/m³) was used and areas of flow contact were taken individually from each components 3D model. The reference area used was of the front wing. All drag coefficients (except for the hull) were calculated using a spreadsheet, see appendix B.

The drag force and coefficients for the hull were found using the same methods as for the horizontal stabilizer calculations. The drag induced by air was found to be negligible compared to the drag of water. The drag induced by the portion of the hull underwater is the sum of viscous and wave drag. This is shown below.

$$D_{Total} = R_v + R_w \quad (10)$$

$$R_v = 0.5\rho V^2 A C_v \quad (11)$$

$$C_v = \frac{0.075}{(\log_{10}(\frac{VL}{\nu} - 2))^2} \quad (12)$$

$$R_w = 0.5\rho V^2 A C_w \quad (13)$$

$$C_w = 0.0022e^{\frac{\frac{V}{\sqrt{gL}} - 0.33}{0.057}} \quad (14)$$

The individual viscous and wave drags obtained were $2.26V^2$ and $34.4V^2$. The calculations were left in terms of velocity (in SI units) to be able to evaluate drag at different speeds.



$$D_{Hull} = 36.66V^2 \quad (15)$$

$$D_{Stabilizer} = 0.12 V^2 \quad (16)$$

$$D_{Fuselage} = 0.06 V^2 \quad (17)$$

$$D_{Mast} = 0.24 V^2 \quad (18)$$

$$D_{Motor} = 0.13 V^2 \quad (19)$$

The following graph shows the drag as function of speed.

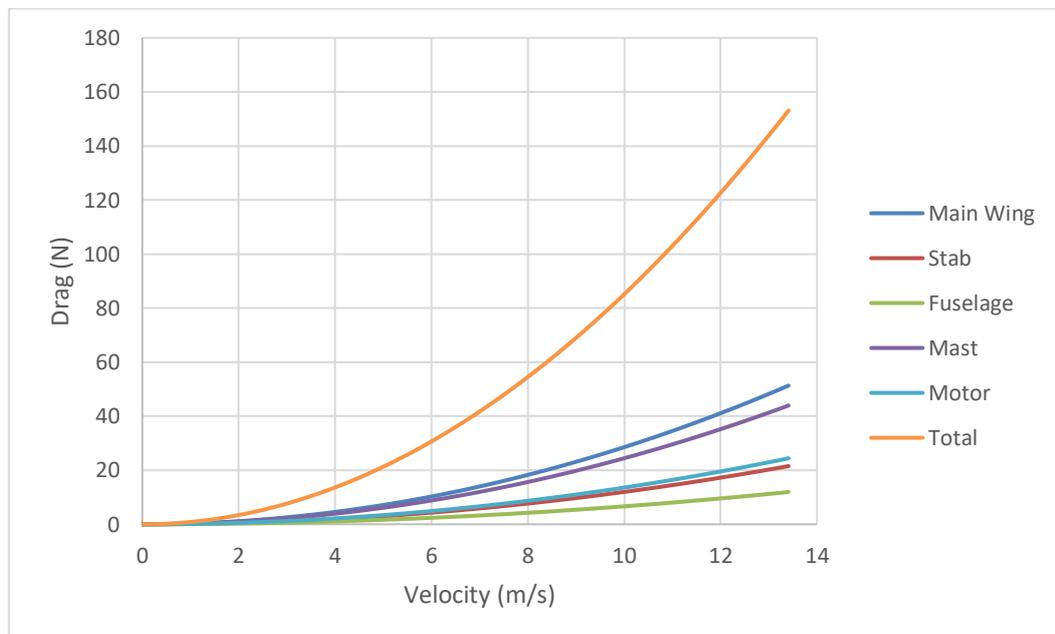


Figure 59 Drag vs Velocity

At a cruising speed of 10.28m/s, drag is 90N. At nearly max speed of 13.41m/s, the drag is 153.132N. Additionally, note that the drag is changing over the time, increasing its value as speed increases. However, the graphic is an approximation and there are some details not considered. First when the hull is running in the water at very low speed, the drag coefficients are much larger than the ones shown in the graphic. Once the hull reaches a specific velocity and starts to be lifted out of the water, the drag is reduced significantly and there is a change in the curve. After, as



the vehicle speeds up from this point the hydro drag is converted to aero drag and once the speed is enough to make the aero drag significant for the hull's operation there is a change in the curve and the drag starts to increase again.

The velocity at which the hull begins to fly is calculated using equation (1). After plugging in the lift, the weight of the hydrofoil (625N); the density of water; the wing area; and the coefficient of lift (Assumed to be 1) a velocity of 4m/s was obtained.

Floatability

Following Arquimedes's principle: "*Any body plunged inside a fluid experiences an ascending force called push, equivalent to the weight of the fluid removed by the body*". The floatability of an object depends on how the ascending force is compared to the weight of the object and consequently compare to its density. If the density of the object in contact with the water is lower than the water density, it will float. The volume of the hull is 0.1811m^3 and its mass is 120kg, then its density $662.61\text{kg}/\text{m}^3$. Since its smaller than the water density, $998\text{ kg}/\text{m}^3$, the hull will float in the water. Precisely, half of the hull will be out of the water since 0.1811m^3 takes up 180kg of water.

Thrust

The thruster provides the force that combats the drag and provides a forward velocity. Being that drag is the only force opposing thrust, the thrust must equal drag to get to a desired constant velocity. Drag at the desired max speed of 13.41m/s (30mph) was found to be 153 newtons. Therefore, our thruster must output at least 153 newtons. Additionally, another design objective is to produce the more thrust possible with the minimum torque on the propeller shaft (Q) since the propeller torque is loaded on the gearbox and the motor shaft.



Propeller

The design process followed was first to design the propeller in accordance with the design requirements (peak conditions) and afterwards based on the results, design the motor and the batteries. To find an optimal shape of the propeller a software program called OpenProp was used. Given the inputs shown in table 1 the program outputted an optimized propeller shape along with the propeller parameters.

Table 1 OpenProp Inputs

N° of blades	3
Rotor diameter	D=0.23m
Hub diameter	d=0.04m
Fluid density	$\rho=1000\text{kg/m}^3$
Peak ship speed	$V_s=13.4\text{m/s}$
Rotational speed of propeller	n=1800rpm
Thrust	T=153N

The figure 60 shows the results obtained after the simulation. The program outputted the value for the following parameters, at the introduced peak conditions: Advance coefficient (J), thrust coefficient (K_T), torque coefficient (K_Q), efficiency (EFFY), thrust coefficient based on V_s (C_T), torque coefficient based on V_s (C_Q) and propeller torque (Q) and the performance curves of K_Q and K_T .

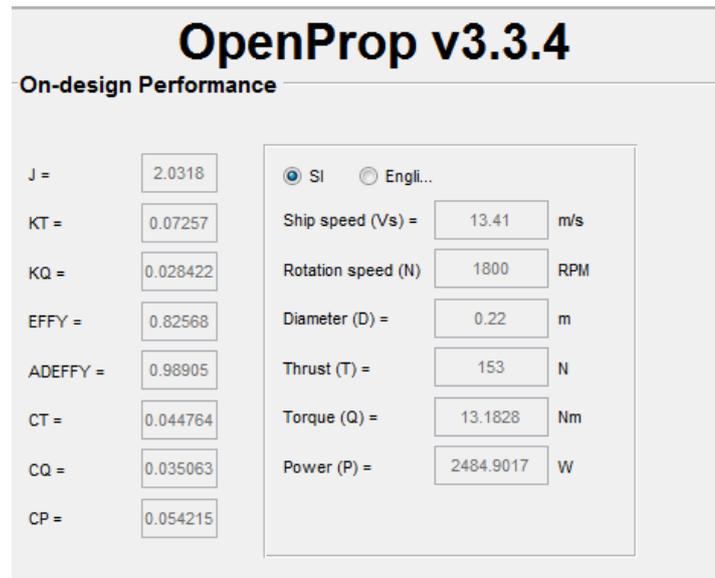


Figure 60 Propeller parameters



Figure 61 Propeller 3D model

Once the peak conditions have been studied it is important to study the other design requirement: the vehicle must be able to operate for 2 hours at the continuous conditions shown in the table below.

Table 2 Continuous conditions

Continuos ship speed	Vs=10.3m/s
----------------------	------------



Thrust	90N
--------	-----

Using the data obtained from OpenProp at peak conditions, the torque and rotational speed of the propeller can be calculated for the continuous conditions. Once the calculations of both peak and continuous conditions are done, the adequate motor, gearbox and batteries will be studied. The following equations were used in the process (See Appendix A for nomenclature).

Advance ratio of the propeller through the water (rotation to translation)

$$J_s = \frac{Vs}{nD} \quad (20)$$

Thrust coefficient of the propeller

$$K_T = \frac{T}{\rho n^2 D^4} \quad (21)$$

Torque coefficient of the propeller

$$K_Q = \frac{Q}{\rho n^2 D^5} \quad (22)$$

Propeller efficiency:

$$\eta = \frac{TVs}{Qw} = \frac{TVs}{Qn2\pi} = \frac{K_T J_s}{2\pi K_Q} \quad (23)$$

Solving for “n” in equation (20) and substituting in equation (21),

$$K_T - \frac{TJ^2}{\rho Vs^2 D^2} = 0 \quad (24)$$

Then, from the K_T graphic a linear approximation is obtained,

$$K_T = 0.60 - 0.279 J \quad (25)$$

Now, combining equation (25) and (24) and substituting the speed, Vs, the thrust, T, the rotor diameter, D and density for peak and continuous conditions the value of J is obtained. After, since the advance coefficient is known (J), the rotational speed can be calculated using equation (20). Lastly to calculate the torque of the



propeller for the cruising speed, equation (22) is solved for Q substituting the values of n and J obtained.

Table 3 Propeller parameters for both conditions

Peak conditions	Continuous conditions
$J=2.09$	$J=2.11$
$n=1721\text{rpm}$	$n=1273\text{rpm}$
$Q=13.18\text{ Nm}$	$Q=6\text{ Nm}$

With regards to the results obtained at the peak conditions, they are very similar to the ones calculated using OpenProp.

Motor and battery selection

The previous calculations provide a rpm and torque that the motor and gear box combination would have to produce to the output shaft. Knowing that brushless dc motors typically have a max speed of 9000 a 5 to 1 gear reduction was chosen. This meant that the motor would also need to produce about 2.6 newton meters of torque at peak conditions. This allowed us to select a SSS 56104 Brushless Motor which has a max RPM of 9000 and max torque of 3 newton meters. Due to optimization of the propeller at 9000 rpm the craft will move at about 31.4 mph.



Figure 62 Parker PV40TN-005 In-Line Planetary Gearhead



Figure 63 SSS 56104 Brushless Motor 500KV

The following graphics show the difference in torque and rpms between the motor and the propeller, due to the action of the gear box, that reduces the higher engine speed increasing the torque in the process. That's why at the same velocity, the motor will have more rpms but less torque than the propeller.

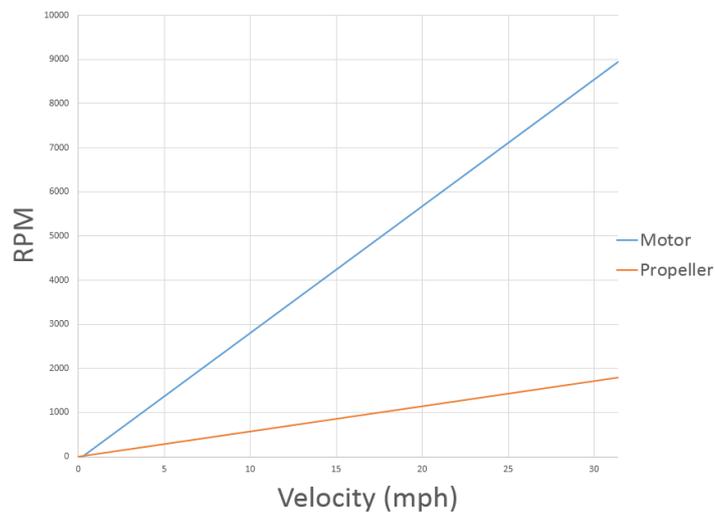


Figure 64 Graph showing Velocity verse required RPM

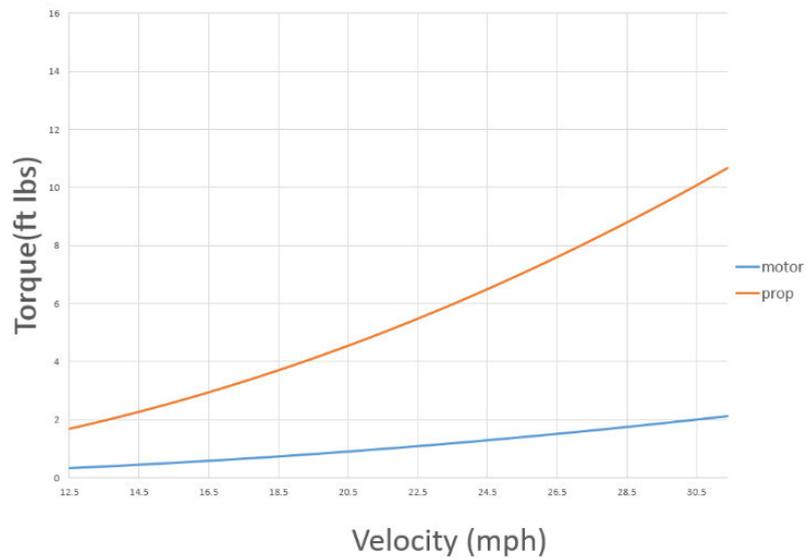


Figure 65 Graph showing velocity vs torque required

Now that the motor is chosen, and its specifications known, the required current and voltage for a certain torque and rotational speed are calculated introducing different gear ratios for both peak and continuous conditions. The equations (26), (27) and (28) are used to calculate the current, the voltage and the power respectively.

Table 4 Motor specifications

Kv (rpm/V)	R (Ω)	Ke (V/rpm)	Ke (V/rad/s)	Kt (N m/A)	Io (A)	IMax (A)
500	0.0221	0.002	0.0191	0.0191	1.2	88

$$I = \frac{Q}{K_T} \tag{26}$$

$$V = IR + K_E n \tag{27}$$

$$P = \frac{Qn2\pi}{60} \tag{28}$$



Table 5 Results for the Motor at continuous conditions for different gear ratios

Gear ratio	Torque (Nm)	n (rpm)	Current(A)	Power(W)	Voltage(V)
1	6.70	1300	350.79	912.11	10.35
2	3.35	2600	175.39	912.11	9.08
3	2.23	3900	116.93	912.11	10.38
4	1.68	5200	87.70	912.11	12.34
5	1.34	6500	70.16	912.11	14.55

Table 6 Results for the Motor at peak conditions for different gear ratios

Gear ratio	Torque (Nm)	n (rpm)	Current(A)	Power(W)	Voltage(V)
1	13.17	1800	689.42	2481.90	18.84
2	6.58	3600	344.71	2481.90	14.82
3	4.39	5400	229.81	2481.90	15.88
4	3.29	7200	172.35	2481.90	18.21
5	2.63	9000	137.88	2481.90	21.05

As shown in the table 5 and 6 the peak condition set the needed voltage, 70.16V while the continuous sets the current, 21.05A.

Battery power

One of the objectives of the design is to minimize the current in the engine during the 2 hours of operation of the vehicle. Mainly due to safety, the less current, the fewer amperes circulating on each cable and the lower the probability of overheating.

Now that the thruster assembly has been set it was possible to size the batteries. It was found that at max speed the voltage required was roughly 22 volts. To account for motor efficiency 6 cell batteries were needed since each lithium battery cell comes with 3.7V. In this way, the peak point is covered. To meet the 2-hour minimum ride time at 10.3m/s it was found that we would need at least 162 amp hours. From this it was decided to use five CMEC 6S9P NCR 18650GA Batteries



that had 38.5 amp hours each. Thus, providing the craft with enough power to run at 13.4 m/s for 2 hours and 22 minutes.

Table 7 Batterie´s specifications

Battery Specs	Value
Voltage	22.2 V
Capacity (each)	38.5 Amp hours
Total capacity	192.5 Amp hours



Figure 66 CMEC 6S9P NCR 18650GA

Cooling system

The cooling of the motor won't be necessary since the water is constantly cooling the upper case of the motor, and this cooling is transmitted, thanks to the aluminum material, to the inside. On the other hand, in the hull's hatch that houses the Piwhack and the batteries, a small fan will be installed so that the heat released by them does not stay in the hatch causing an overwarming. Moreover, instead of having one battery, which will cause a big problem due to overheating because of the high current circulating through the wires, 6 different batteries will supply the total power. In this way the heating problem is reduced: the total voltage will be divided in the different batteries and consequently the current through each wire will be reduced.



General Fastener Analysis

All fasteners used are of high grade stainless steel. As such, detailed analysis of the structural mechanics of each connection point were not performed. For example, the highest load experienced by any fastener was located at the connection between the front wing and the horizontal stabilizer, which has a factor of safety of over 10 even at the maximum speed of the vessel.

Elevon Rod Minimum Diameter

The following calculations were used to find the minimum elevon rod diameter, given the hydrostatic force acting on the piece.

$$\sigma = \frac{F}{A} = \frac{27 N}{\frac{\pi D^2}{4}} \quad (29)$$

$$\text{Factor of Safety} = \frac{\sigma_{ult}}{\sigma} = \frac{579.849 \text{ MPa}}{\sigma} \quad (30)$$

Setting the equations equal and solving for D using a factor of safety of 1 yields a minimum rod diameter of 241.3 μm . To achieve a more nominal sized rod, the factor of safety was upped to approximately 13 and a 0.0032m rod was selected. The material was chosen to be 316 Steel.

Servo Rod Minimum Diameter

The rod was analyzed for buckling and the following equations were used:

$$F = \frac{n\pi^2 EI}{L^2} \Rightarrow 20 \text{ lbs} = \frac{1 * \pi^2 * 193 \text{ GPa} * I}{0.4572 \text{ m}}$$

$$I = \frac{\pi D^2}{64}$$

where $n = 1$ because of the condition that the rod is being pivoted at both ends. Solving for I in the first equations and substituting that result into the second equation allows D to be solved for. A diameter of 0.0036 meters was calculated. 316 Steel was selected as the material.



Servo and Elevon Gear Ratios

The following equations were used to solve for the elevon horn arm length and rotation range. The servo parameters were taken directly from the specifications of the selected model. Torque of the elevon was estimated to be 11 Nm.

$$l_e \tau_s = l_s \tau_e$$
$$l_e \sin \theta_e = l_s \sin \theta_s$$

The calculations yielded a elevon horn length of 0.01 meters and a rotation range of 20°.



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Chapter 8 OPERATING INSTRUCTIONS

Note: The vessel can either be placed in the water prior to or after loading the payload.

1. The user places the medical supplies inside of the cooler and closes the lid.
2. The user places the cooler inside of the payload compartment of the hull and secures it with the ratchet straps using the integrated tiedown points.
3. The user then energizes the vessel by turning the on/kill switch, releasing it into the on position.
4. The user can then deliver the payload either autonomously using the Pixhawk autopilot or via human remote control.
5. Once the payload has been delivered to the target destination, the ratchet straps are removed by the receiving party and the cooler's payload can be accessed.



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Chapter 9 SAFETY

The status indicator will allow the user to know if the vehicle is completely autonomous (green light), if it is being remote controlled (yellow light), or if it is completely off (red light).

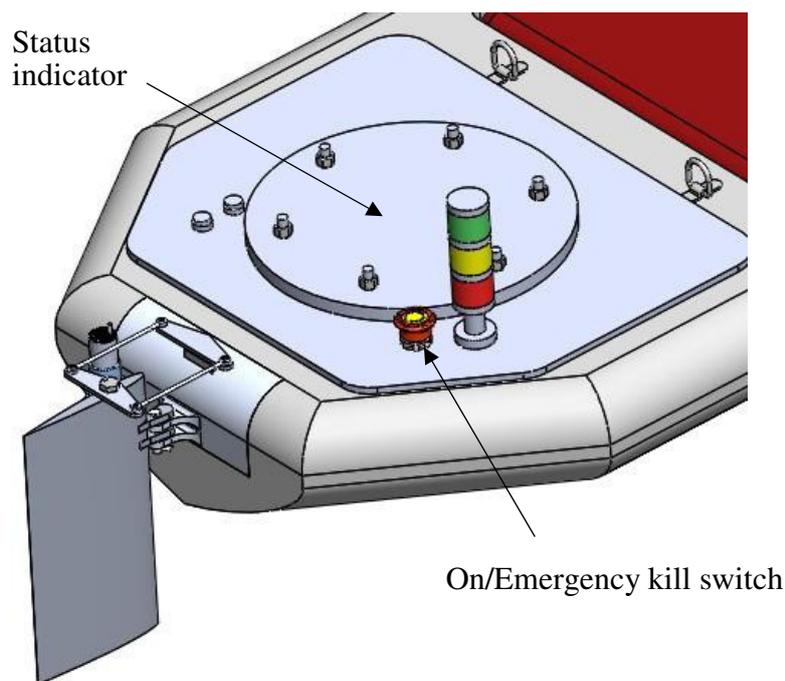


Figure 67 On/Emergency kill switch location on the hull

In order to start the vessel, manual tactile action must be taken by the user, meaning that the user must physically rotate the on switch before the craft will receive any power. This on switch doubles as a kill switch, so if the craft goes haywire while a user is near it the user can simply slam down the kill switch and the vessel will cease all function immediately.



Additionally, the motor and electronic speed controller (ESC) are protected from current spikes by a 150A fuse and are protected from voltage spikes by a transient voltage suppression diode. As such, any malfunction causing a power overload will blow one of those components and the craft will cease thrust. Additionally, this means that a power overload will only destroy small, cheap components rather than the relatively expensive motor or ESC. Additionally, the Pixhawk autopilot system is protected from power overloads by a 10A fuse for the same reasons as above. Moreover, the recessed propeller and propeller guard prevent injury to the user while handling the craft in regard to the sharp and potentially moving propeller.

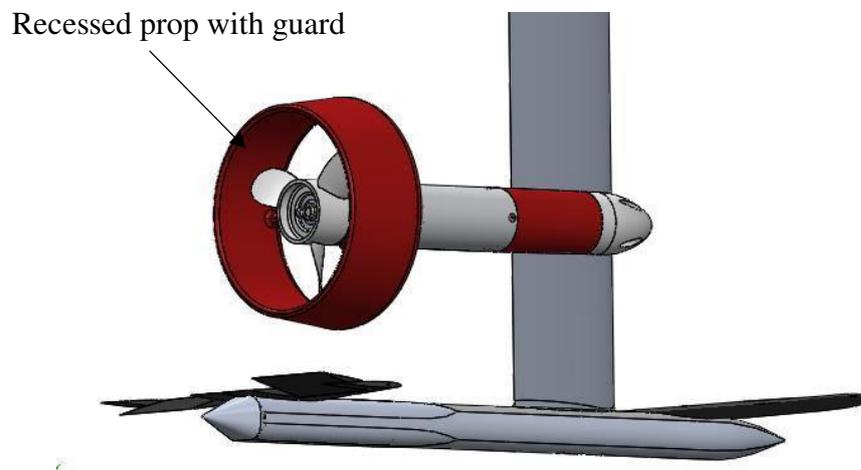
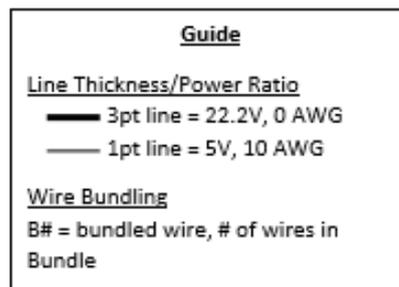
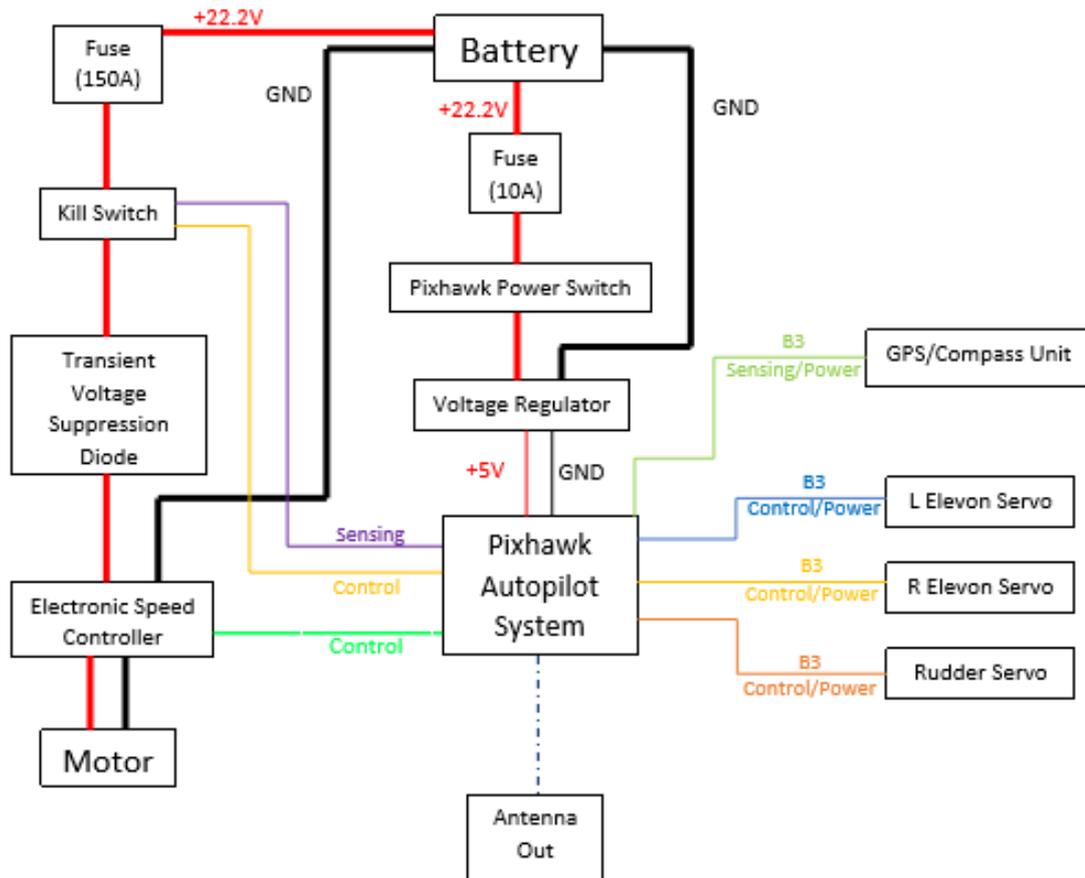


Figure 68 Recessed propeller with guard



Chapter 10 ELECTRICAL DIAGRAM





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Chapter 11 BILL OF MATERIALS

Part Number	Part Name	Quantity
10-01	Hull	1
10-02	Payload Cooler	1
10-03	Tie Down Ring	4
10-04	PixHawk Autopilot	1
10-05	CMEC 6s9p NCR 18650 GA Batteries	5
10-06	M6x1-50 Tuttle Box Screw	2
10-07	M6 Washer	2
20-01	Hull Cap	1
20-02	Hull Cap Porthole	1
20-03	Rubber O-Ring	1
20-04	Nylon 6-6 HEX NUT	6
20-05	Waterproof Electrical Connector	2
20-06	Indicator light/Antenna	1
20-07	Power/Kill Switch	1
30-01	Rudder	1
30-02	Rudder Top Lever	1
30-03	Rudder Mount	1
30-04	Rudder Pin	1
30-05	Rudder Plate	1
30-06	PowerHD Servo	1
30-07	Rudder Servo Rod	2
30-08	M2x0.4 Shoulder Screw for Horns	4
30-09	M2x0.4 Nylock nut	4
30-10	M10x1.25-45	1
40-01	Senix ToughSonic 14 Ultrasonic Depth Sensor	1
40-02	Sensor Bracket	1
40-03	30mm Hex Nut	2
40-04	M7.0x1.0-10	2
50-01	Fuselage	1
50-02	Fuselage Cap	1
50-03	M2x0.4-5 Fuselage Cap Screw	2
50-04	Fuselage Cap Buna-N O-Ring, 48mm x 2mm Diameter	2
50-05	M6x1-25 Front Wing Fastener	2
50-06	M6x1-8 Horizontal Stabilizer Fastener	2



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50-07	Front Wing	1
60-01	Servo Mounting Rod	8
60-02	Servo Bracket	1
60-03	PowerHD Servo	2
60-04	Servo Horn	2
60-05	M2 - 0.4 - 8mm 316 Stainless Steel Shoulder Screw	4
60-06	M2 - 0.4 - 18-8 Stainless Steel Nylock Nut	4
60-07	Servo Rod, Long	1
60-08	Servo Rod, Short	1
70-01	Elevon	2
70-02	Elevon Rod	2
70-03	Elevon Horn	2
70-04	Elevon Rod Key	2
70-05	Retaining Ring, 1/8" ID Spring Grip Side Mount	4
70-06	M1.6x0.35-4 Elevon Horn Screw	2
70-07	Horizontal Stabilizer	1
70-08	Vespel Sleeve Bearing, 1/8" Diameter 3/8" Length	4
80-01	Mast	1
80-02	Motor Back Fin Interface	1
80-03	Motor Metal Sleeve	1
80-04	Motor Nosecone	1
80-05	SSS 56104 Motor	1
80-06	Gear Reducer	1
80-07	Set Screw Shaft Coupling	1
80-08	Motor Back	1
80-09	Coupler Housing	1
80-10	Propeller Shaft	1
80-11	Propeller Shaft Rod	1
80-12	Propeller Guard	1
80-13	20 x 10 x 6 Shaft Sealer	1
80-14	20 x 10 x 7 Shaft Sealer	1
80-15	Double shielded ball bearing 10 mm ID	1
80-16	M4-0.5 316 Stainless Steel Hex-Drive Flat-Head Screw	8
80-17	M4x0.7 Stainless Steel Button Head Hex Drive Screw	4
80-18	M4x0.7 Corrosion Resistant Stainless-Steel Hex Nut	4
80-19	M4x0.7 mm Hex Drive Round Headed Screw	4
80-20	M4x0.7-12 316SS Fastener	4
80-21	M4x0.7-60 316SS Fastener	4
80-22	67mm x 2mm diameter O-ring	4
80-23	48mm x 2mm diameter O-ring	1



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80-24	Motor Mount	1
80-25	Propeller	1
80-26	Propeller Nut Assembly	1
80-27	318mm 1mm diameter Buna-n O-ring	4



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Chapter 12 COST OF ANALYSIS

Product	Cost	Quantity	Total
SSS 56104 Brushless Motor	\$150.00	1	\$150.00
Parker PV40TN-005 In-Line Planetary Gearhead	\$452.76	1	\$452.76
Set Screw Shaft Coupling	\$10.38	1	\$10.38
Double shielded ball bearing for 10mm shaft	\$6.89	1	\$6.89
Freudenberg Sealing Technologies Simrit 72 NBR 902 Seal, 20x10x6	\$6.25	1	\$6.25
Freudenberg Sealing Technologies Simrit 72 NBR 902 Seal, 26x10x7	\$6.51	1	\$6.51
M4 -0.7 20mm 316 Stainless Steel Hex Drive Rounded Head screw	\$0.08	4	\$0.32
M4-0.7 35mm 18-8 Stainless Steel Hex Drive Rounded Head Screw	\$0.21	4	\$0.84
M4-0.7 316 Stainless Steel Hex Nut	\$0.07	4	\$0.28
M4-0.5 316 Stainless Steel Hex-Drive Flat-Head Screw	\$0.06	8	\$0.48
144 Oil-Resistant Buna-N O-Ring	\$0.18	4	\$0.72
M6-1 25mm 316 Stainless Steel Hex Head Screw	\$0.31	5	\$1.55
M6-1 100mm 316 Stainless Steel Hex Head Screw	\$3.37	2	\$6.74
M6-1 316 Stainless Steel Hex Nut	\$0.19	2	\$0.38
M1.6-.35 4mm 316 Stainless Steel Socket Head Screw	\$0.21	2	\$0.42
Sleeve Bearing, 1/8" Diameter 3/8"	\$42.64	4	\$170.56
Retaining Ring, 1/8" OD Spring Grip Side Mount	\$0.07	4	\$0.28
86mm ID 2mm Oil Resistant Buna-N O-Ring	\$0.75	1	\$0.75
4 mm ID 1mm Oil Resistant Buna-N O-Ring	\$0.06	4	\$0.24
M2-.4 8mm 316 Stainless Steel Shoulder Screw	\$6.27	2	\$12.54
M2-.4 18-8 Stainless Steel Nylon Insert Locknut	\$0.71	2	\$1.42
Digital Servo, High Torque Metal Gear 23KG 6V	\$43.99	3	\$131.97
M10-1.5 Nylon Hex Nut	\$0.20	12	\$2.40
M6-1 50mm 316 Stainless Steel Hex Head Screw	\$0.56	2	\$1.12
M7-1 10mm 316 Stainless Steel Hex Head Screw	\$0.18	2	\$0.36
M10-1.25 45mm 316 Stainless Steel Hex Head Screw	\$0.83	1	\$0.83
Pivoting Bolt on Tie down Ring 1.5" ring, Zinc Plated Steel	\$2.19	4	\$8.76
SEACON VMF-FS Rubber Molded Connectors	\$30.00	2	\$60
Senix Toughsonic 14 remote water level sensor	\$495.00	1	\$495

Total Commercial Off-The-Shelf price: \$1530.75



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Fuselage	Machined Die Cast Aluminum	\$167	\$7 for aluminum stock and 2 hours of machining
Rudder	Die Cast Aluminum	\$3	Cost of raw material
Horizontal Stabilizer	Machined G-10	\$121	\$1 Cost of raw material and 1.5 hours of machining
Elevon (2)	Machined G-10	\$161	\$1 of raw material and 1 hour of machining per elevon
Elevon Rod Key (2)	Machined 316 Stainless Steel	\$40	\$0.01 of material cost and 0.25hr of machining per each
Elevon Rod (2)	Machined 316 Stainless Steel	\$80	\$0.04 of material cost and 0.5hr of machining per each
Mast/Front Wing	Purchased from Neilpryde, mast slightly machined	\$750	Cost of machining mast assumed to be offset by bulk pricing of hydrofoil. Using retail price of hydrofoil
Payload Cooler	Custom-made cooler	\$200	Estimated based on similar sized coolers on the market
Hull Cap	Injection Molded ABS Plastic	\$6	Price based solely on raw material cost
Hull Cap Porthole	Injection Molded ABS Plastic	\$5	Price based solely on raw material cost
Motor Nosecone	Machined Die Cast Aluminum	\$22	\$2 raw material cost plus 0.25hr of machining
Motor Back Fin Interface	Machined Die Cast Aluminum	\$42	\$2 raw material cost plus 0.5hr of machining
Motor Metal Sleeve	Machined Extruded Aluminum	\$21	\$1 raw material cost plus 0.25hr of machining
Motor Mount	Machined Aluminum	\$21	\$1 raw material plus 0.25hr of machining
Motor Back	Machined Aluminum	\$81	\$1 raw material plus 1hr of machining
Propeller Shaft	Machined 316 Stainless Steel	\$41	\$1 raw material plus 0.5hr of machining
Gearbox Mount	Machined Aluminum	\$81	\$1 raw material plus 1hr of machining
Propeller	Machined Aluminum	\$121	\$1 raw material plus 1.5hr of machining
Propeller Guard	Injection Molded ABS Plastic	\$4	Price based solely on raw material cost
Propeller Nut Housing	Die Cast Aluminum	\$1	Price based solely on raw material cost
Hull Servo Mount	Machined Die Cast Aluminum	\$45	\$5 raw material plus 0.5hr of machining



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Servo Linkage Rods (2)	Machined 316 Stainless Steel	\$61	\$1 raw material plus 0.75hr of machining
Servo Mounting Bracket	Machined Extruded Aluminum	\$81	\$1 raw material plus 1hr of machining
Servo Bracket Rod (8)	Machined Aluminum	\$41	\$1 raw material plus 0.5hr of Machining
Elevon Horn (2)	Machined Aluminum	\$41	\$1 raw material plus 0.5hr of machining
Fuselage Servo Horn (2)	Machined Aluminum	\$61	\$1 raw material plus 0.75hr of machining

Total Custom Part Manufacturing price: \$2798.00

Notes:

1. All prices are rounded up to the nearest dollar
2. All machining times are rounded up to the nearest quarter hour
3. Die cast parts are priced based on the material price. Die pricing was not accounted for because pricing per part varies greatly based on the number of parts made over the life of the die and the complexity of the die itself.
4. Machining costs were estimated based on an assumption of \$80/hour to machine the part. This is in addition to the price of the material itself
5. All aluminum in the above table is of the 6061 alloy family
6. Aluminum pricing was assumed to be \$2240 per metric ton
7. Stainless steel pricing was assumed to be \$3400 per metric ton
8. G10 pricing was assumed to be \$2400 per metric ton
9. ABS plastic pricing was assumed to be \$3300 per metric ton
10. This is a rough costing estimate, and in all probability will have a much higher price than the actual cost to machine all of these parts.

Total overall cost: \$4328.75



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Chapter 13 CONCLUSIONS AND FUTURE

IMPROVEMENTS

Based on everything said, the unmanned hydrofoil vehicle is predicted to be feasible and with competent features to be successful in the market. However, there are still some fields open for improvement, even more after testing the prototype.

Firstly, a change in the sensors attached in the vehicle will be favorable. Their function is to gather information of the direction and elevation of the vehicle to ensure a good operation. Instead of the sensor Senix Toughsonic 14, based on ultrasonic distance measurements attached in the rear part of the hull, two sensors will be installed in the fuselage. One, a static pressure sensor, will measure the depth of water and the other one, a pitot pressure sensor will measure the velocity of the water. These new sensors are less expensive and improve the accuracy of the results obtained (mm accuracy/resolution) and thus the efficiency.

Secondly, the vehicle tests showed that the control system had to be improved. Firstly, the weather conditions weren't accurately considered in the design and when testing the vehicle, it was discovered that the vehicle was very susceptible to the wind, questioning considerably its stability. To solve this, the hull size should be reduced, and the mast shortened. Apart from being more stable with a smaller hull and mast the weight of the vehicle will decrease, facilitating its transportation. Furthermore, during the testing it was also clear that a change in the control surfaces must be done since they couldn't provide enough authority. The solution for this is to enlarge the horizontal stabilizer and the control surfaces; this will allow the elevons, for instance, to be more effective with a tiny change in angle.

In addition, it has been considered for the design that during the journey the cooler will maintain the medicines at the right temperature with the help of ice inside it but it would be a great improvement to take advantage of the kinetic energy of the



vehicle to generate energy and maintain the cooler at a specific temperature without the need of ice. Also, a future improvement could be to take advantage of the solar radiation and install solar panels on the hull. In this way, the batteries life wouldn't be a major concern.

Lastly, it has always been considered for the design described through this report that the user holds the vehicle till the necessary depth of water is reached: the height of the vehicle (1m) and then release it. The vehicle will be on duty as long as the depth of water is greater than 1 meter, if not it will stop navigating. However, it will be much more convenient and more competitive to install a retraction mechanism in the mast. In this way, the minimum depth of the water required for the vehicle to be on duty will be greatly reduced, practically the height of the hull, 0.2 meters. This will enable the user to deploy the vehicle almost in the shore and the installed mechanism will push down the mast accordingly with the depth of the water measured by the static pressure sensor. Thanks to this new feature, the vehicle is much more versatile and easier to transport.

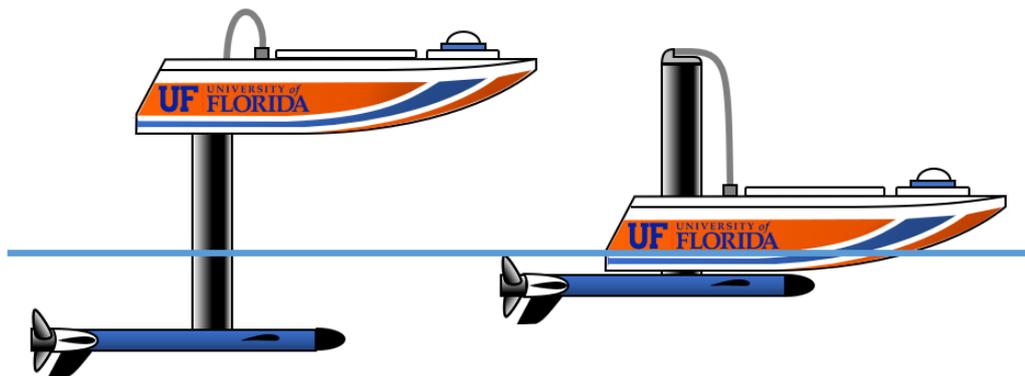


Figure 69 Improved design. Source: Peter Ifju



13.1 OTHER APPLICATIONS

The Medi-Gator is a vehicle that has been designed for a specific mission: to facilitate the delivery of medicines to remote places where the access for bigger boats is arduous. Nevertheless, the principle of hydrofoils could be applied in similar vehicles to the Medi-Gator for other missions. In that case, the design will be adapted accordingly to each mission and consequently some elements will be changed or subtracted compared to the Medi-Gator's design, or new ones will be added.

One of the possible applications is to collect data. There are different ways; for example, by installing a sonar, which sends waves that reflect in the surfaces back to the receiver, data about the bottom profile of the area of study can be recorded by a computer. Studying this information scanned it is possible to detect which animals live in a specific area, to analyze the topography of underwater surfaces or to analyze the coral reefs... Another way to collect data is by subtracting samples, of water in this case, during the vehicle's navigation to be analyzed afterwards or to collect data using the water quality sensors. The data will allow the user to analyze the characteristics of the different ecosystems and the water qualities: temperature, pressure, pH, salinity, conductivity, the substances in it and their concentration... All in all, the collection of data is the first necessary step before any study related can be carried out.

In addition, another useful application is to take pictures or record water sport's competitions; the vehicle results very convenient for this since it can navigate close to the objective and capture every moment with high quality. Furthermore, it could be used to help the environment. Everyday lots of trash is lost into the see, fouling the water and altering the ecosystem. Using the recorded data by the vehicle we could optimize time, save fuel and money and go to pick it up to the places where we know is located.



Lastly, it could be used for a delivery mission. Instead of the payload being a cooler to transport the medicines, it could be a simple box with the items to be delivered inside. For instance, delivery of food, tools or fuel from shore to the boats.

All in all, there are lots of different applications the vehicle can be useful for, but practically all of them are based on the collection of data for later studies. Using the vehicle for it, results a big advantage given the fact that there is no fuel consumption, time is saved since it's unmanned and its maintenance is easier than a vessel. Also, it brings out a big advantage for the sensors collecting the information since the hull is above the water preventing them from touching the water.



Chapter 14 REFERENCES

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Part II. Appendix



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APPENDIX A NOMENCLATURE

Lift and drag calculations

L-lift

C_L -coefficient of lift

ρ -density of the fluid

V-velocity of the vehicle

A-wing area

D-drag

S_{ref} - front wing area

C_D -coefficient of drag

C_{D0} -parasit drag coefficient

AR-aspect ratio

e-efficiency factor

C_f -skin friction

FF-form factor

IF-interference drag

Swet-wet surface

Re-Reynolds number

l-chord length

μ -dynamic viscosity

ν -kinetic viscosity

l-length

d-diameter

t-thickness

c-chord



Rv- viscous drag

Cv-coefficient of viscous drag

Rw-wave drag

Cw-coefficient of wave drag

g-gravity

Motor calculations

Vs-vehicle's speed

n-propeller shaft rotation rate

D-propeller outer rotor diameter

T-vehicle's thrust

Q-torque exerted by the propeller

Kv-RC Motors Constant

K_E-voltage constant

K_T-torque constant

R-motor resistance

I_o-no load current

I_{max}-maximum allowable current

I-current

V-voltage

Elevon and Servo calculations

F-force

A-area

σ-stress



APPENDIX B ELEVON SUBASSEMBLY TIME

Step	#(RP)	Tool (TA)	Alpha	Beta	Sum	Handling Code	Handling Time (TH)	Insertion Code	Insertion Time (TI)	Total Time (s)
Horizontal Stabilizer	1		360	360	720	33	2.91			2.91
Bushing	4		180	0	180	01	1.43	30	2	13.72
Elevon	2		180	360	540	20	1.8	06	5.5	14.6
Rod	2		180	360	540	23	2.36	30	2	8.72
Key	2		180	180	360	13	2.06	30	2	8.12
Snap Ring	4		360	0	360	14	2.55	30	2	18.2
Horn	2		180	360	540	02	1.88	16	8	19.76
Horn Fastener	2	3	180	0	180	01	1.5	48	8.5	23
									Total	109.03



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APPENDIX C DRAG COEFFICIENTS

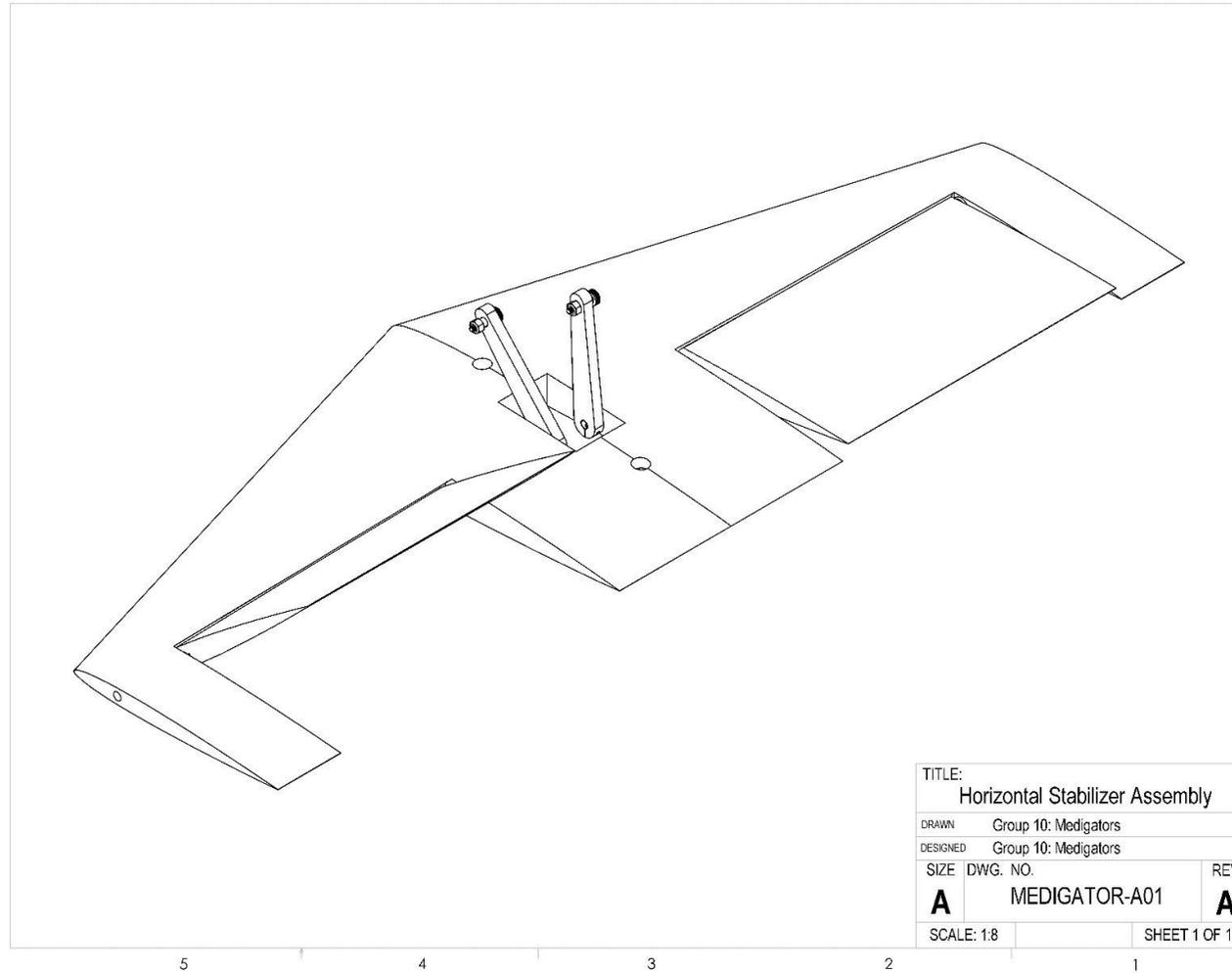
Vinf (m/s)	S_ref (m ²)										
13.4112	0.0993										
Density (kg/m ³)	Dynamic Viscosity Pa*s										
998.2	0.001002										
Component Name	S_wet (m²)	L_ref (m)	t/c or l/d	FF	FF Eqn Type	Re	Cf	IF	C_D	% Total	
MainWing (NACA 63-412)	0.1239	0.0889	0.12	1.252	Hoerner	1187734.151	0.0035	1.04	0.00575	34%	
HorizontalStabilizer (NACA 0012)	0.0481	0.0603	0.12	1.252	Hoerner	805094.0379	0.0038	1.04	0.00241	14%	
Mast (NACA 0010)	0.1215	0.1461	0.10	1.208	Hoerner	1951277.535	0.0032	1.04	0.00492	29%	
Motor	0.0921	0.4665	6.48	1.117	Hoerner Streamlined Body	6232598.219	0.0025	1.04	0.00273	16%	
Fuselage	0.0553	0.7990	24.97	1.012	Hoerner Streamlined Body	10674910.99	0.0023	1.04	0.00134	8%	
									0.01715	100%	



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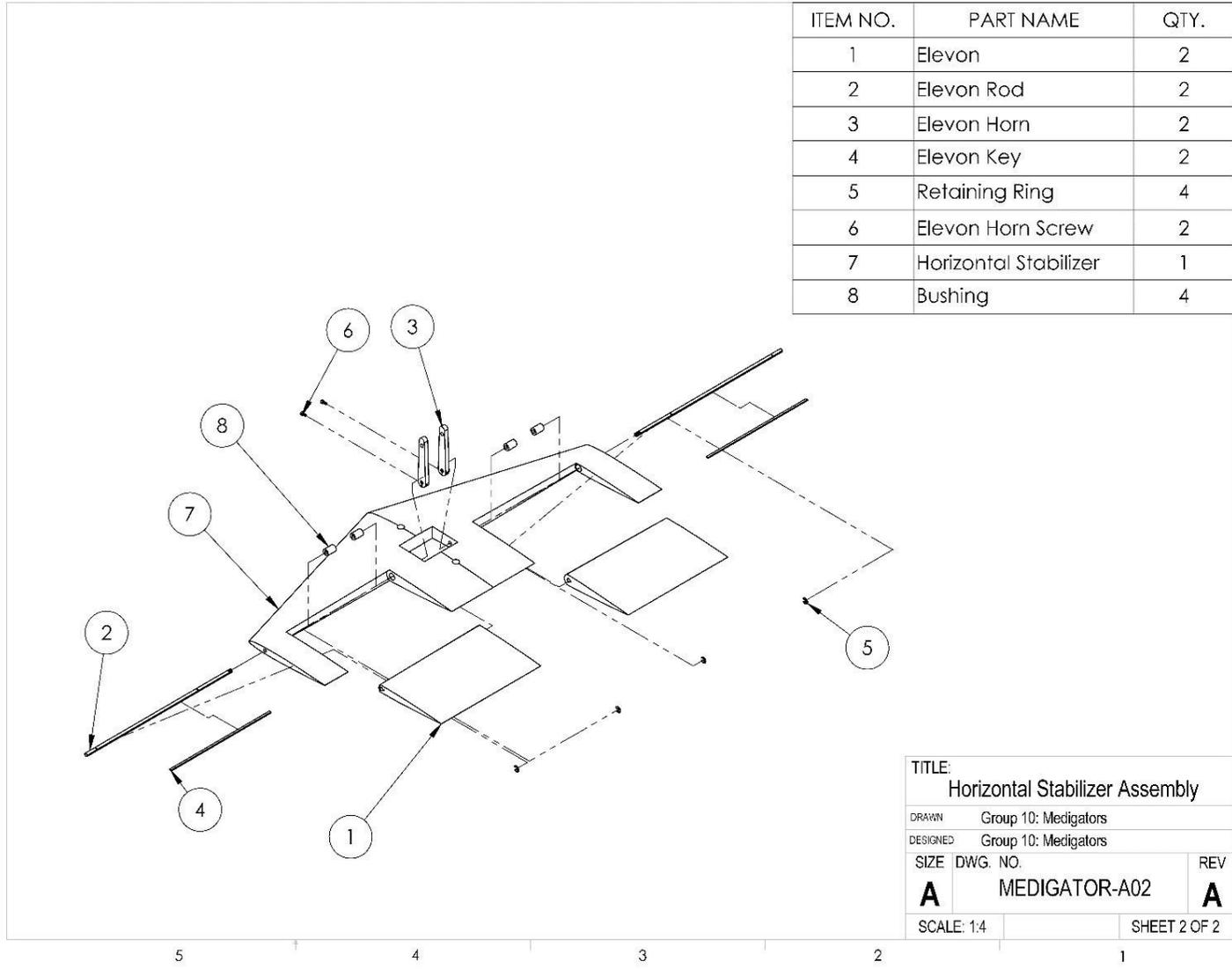


APPENDIX D HORIZONTAL STABILIZER ASSEMBLY





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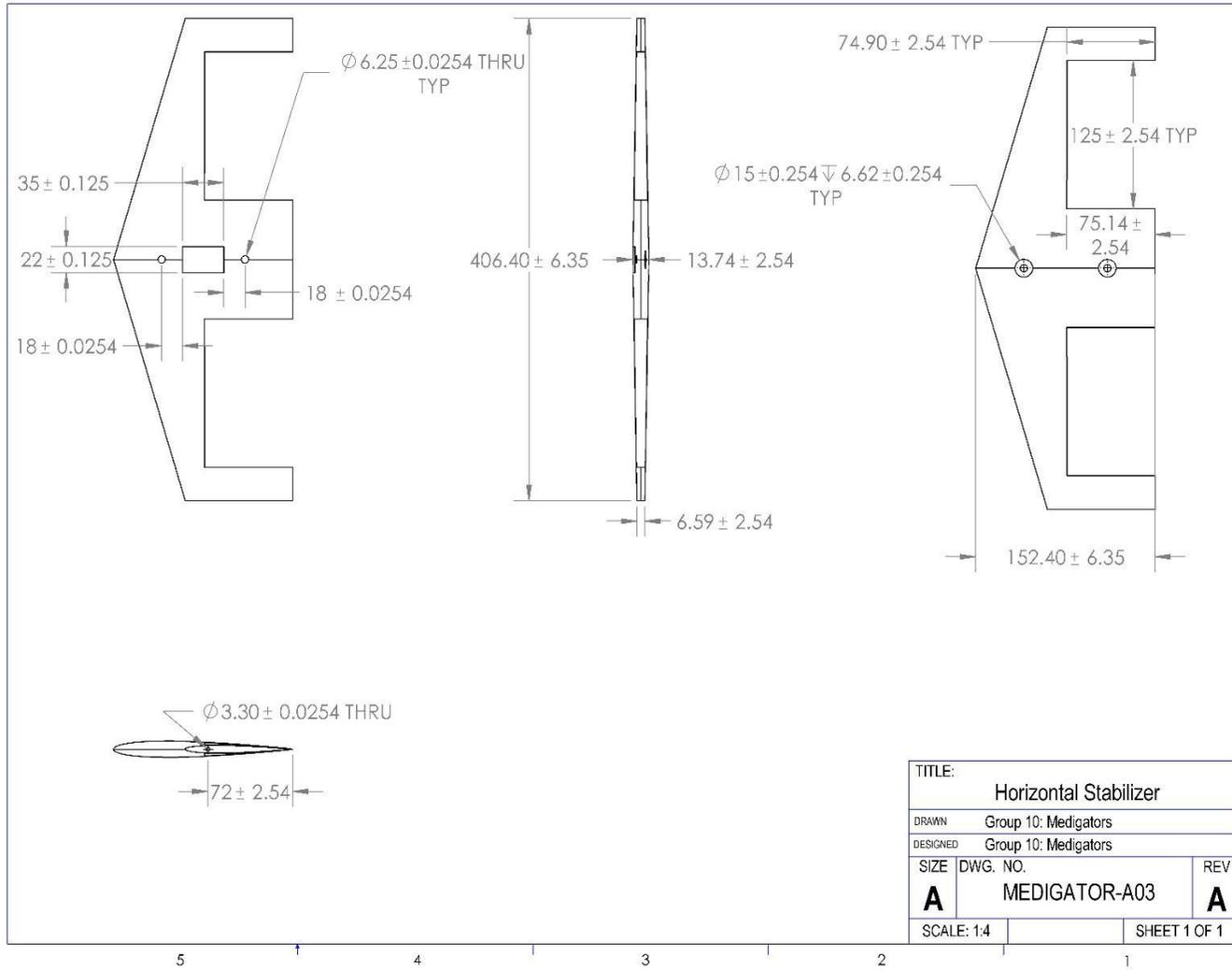


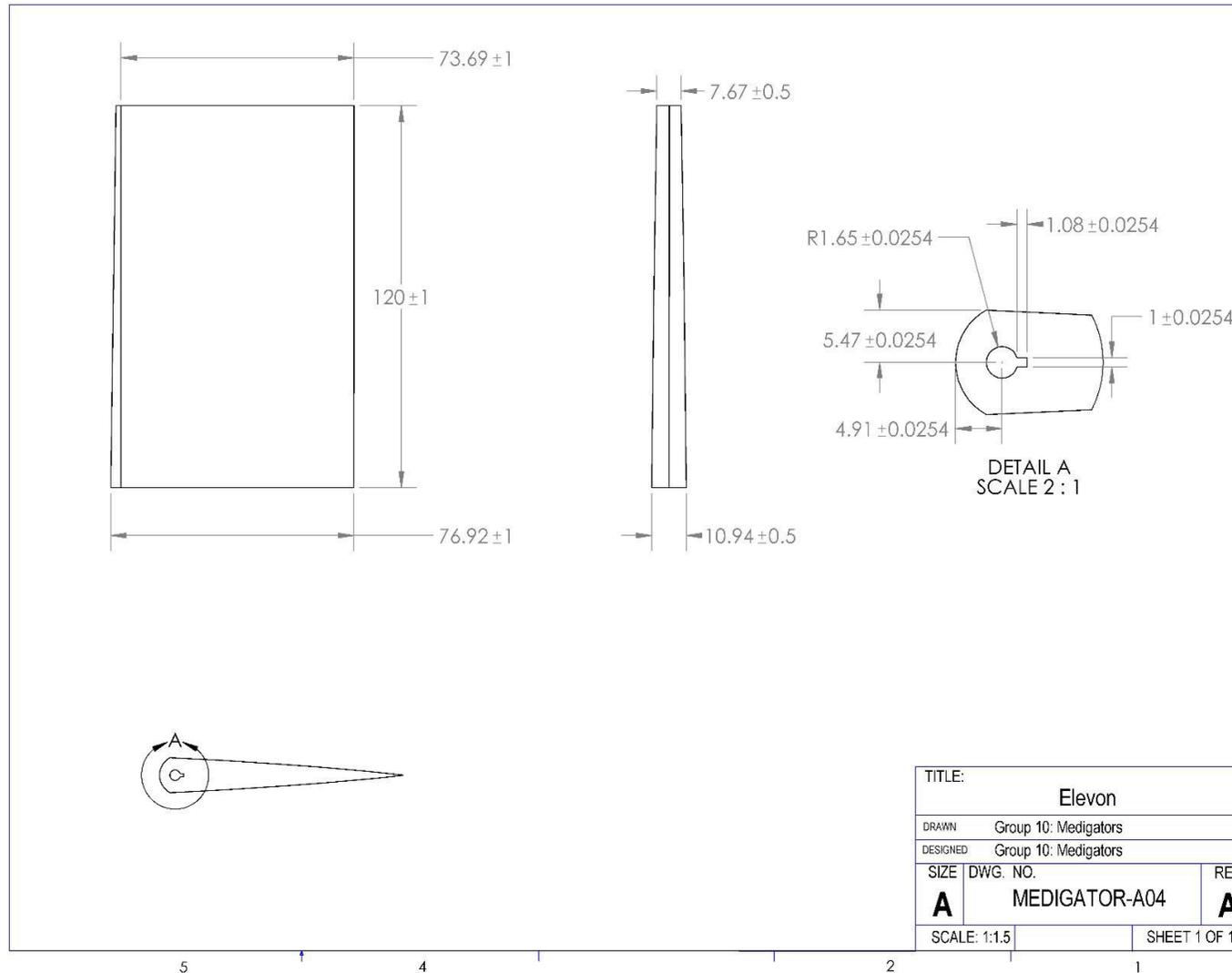
ITEM NO.	PART NAME	QTY.
1	Elevon	2
2	Elevon Rod	2
3	Elevon Horn	2
4	Elevon Key	2
5	Retaining Ring	4
6	Elevon Horn Screw	2
7	Horizontal Stabilizer	1
8	Bushing	4

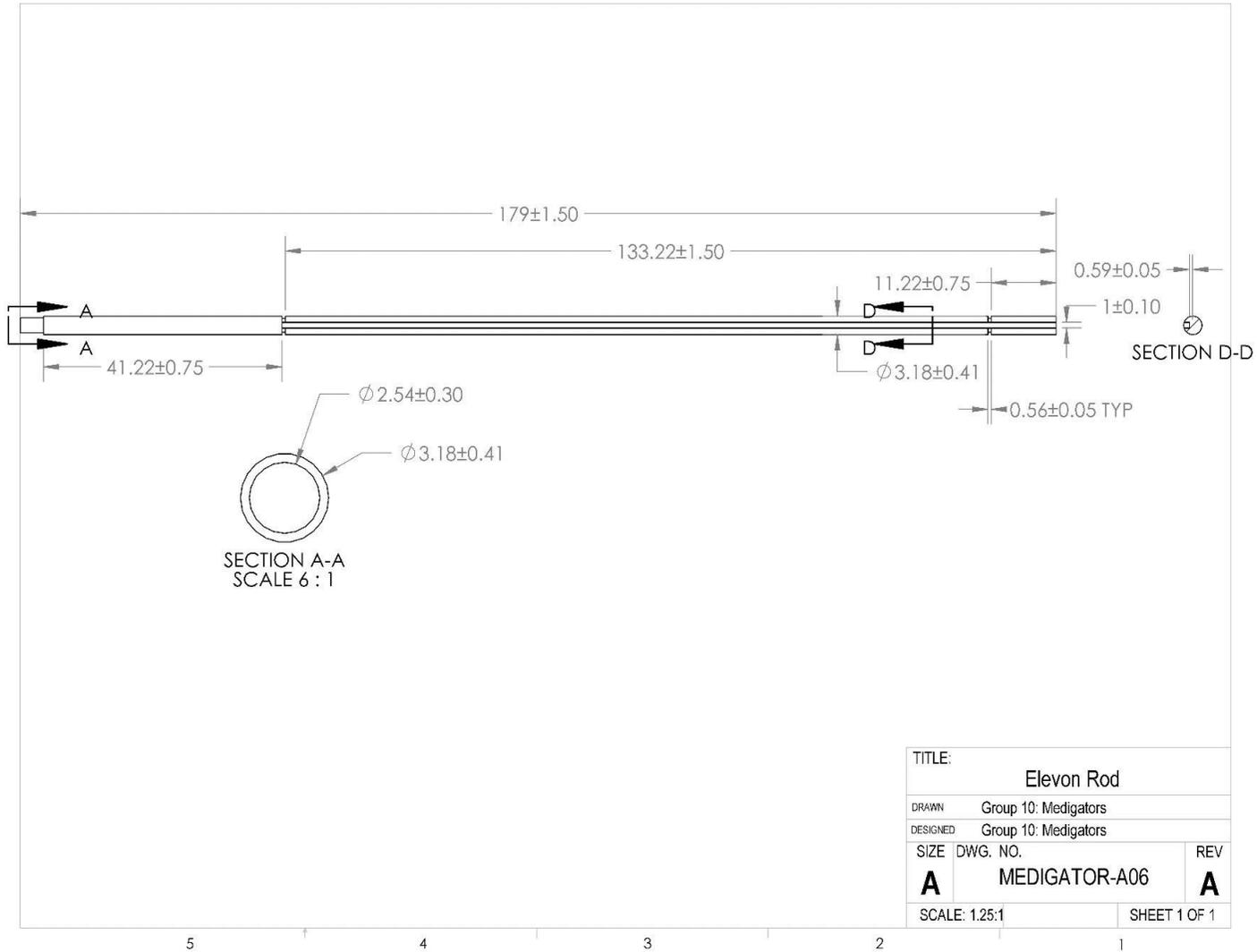
TITLE: Horizontal Stabilizer Assembly		
DRAWN	Group 10: Medigators	
DESIGNED	Group 10: Medigators	
SIZE	DWG. NO.	REV
A	MEDIGATOR-A02	A
SCALE: 1:4	SHEET 2 OF 2	

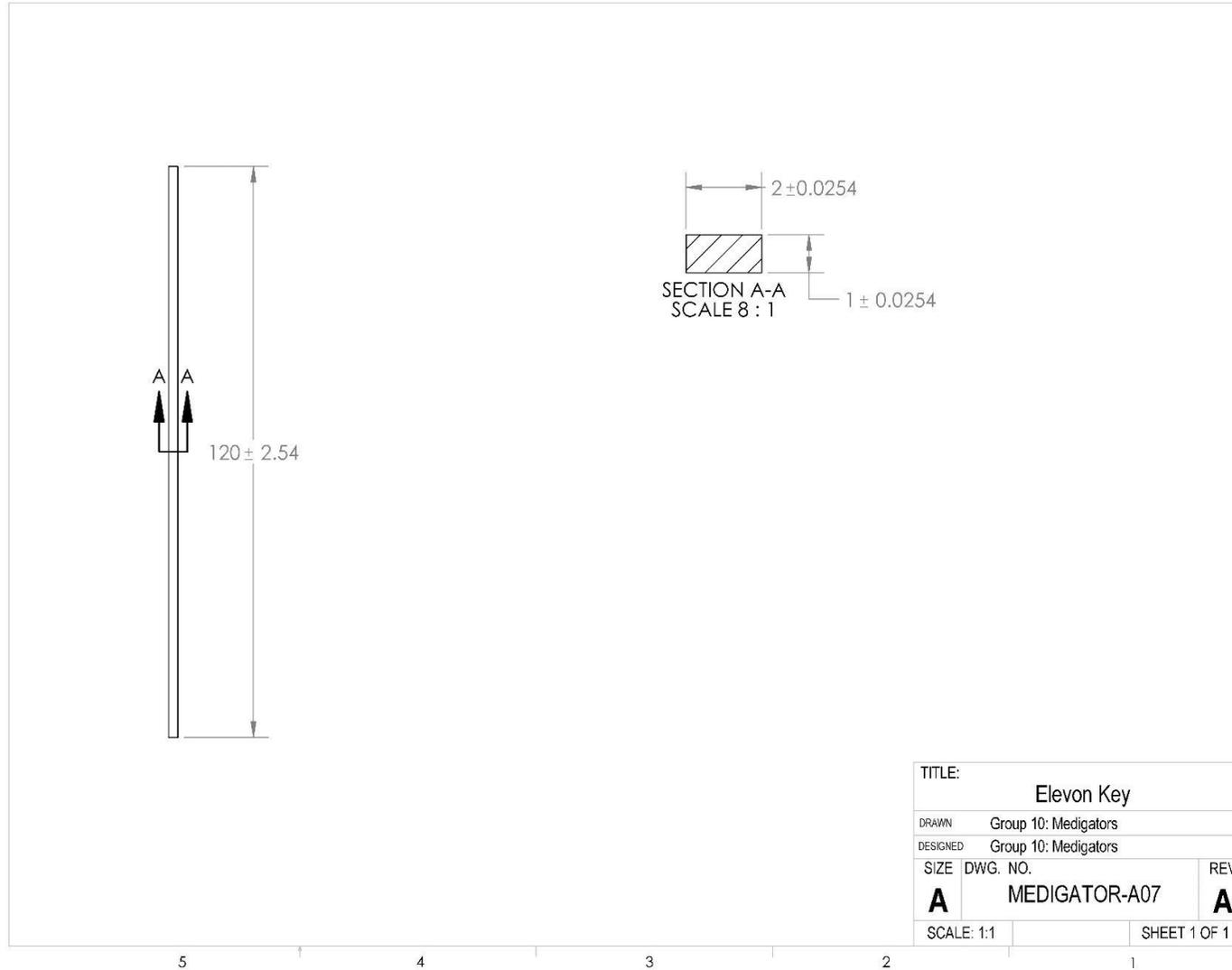


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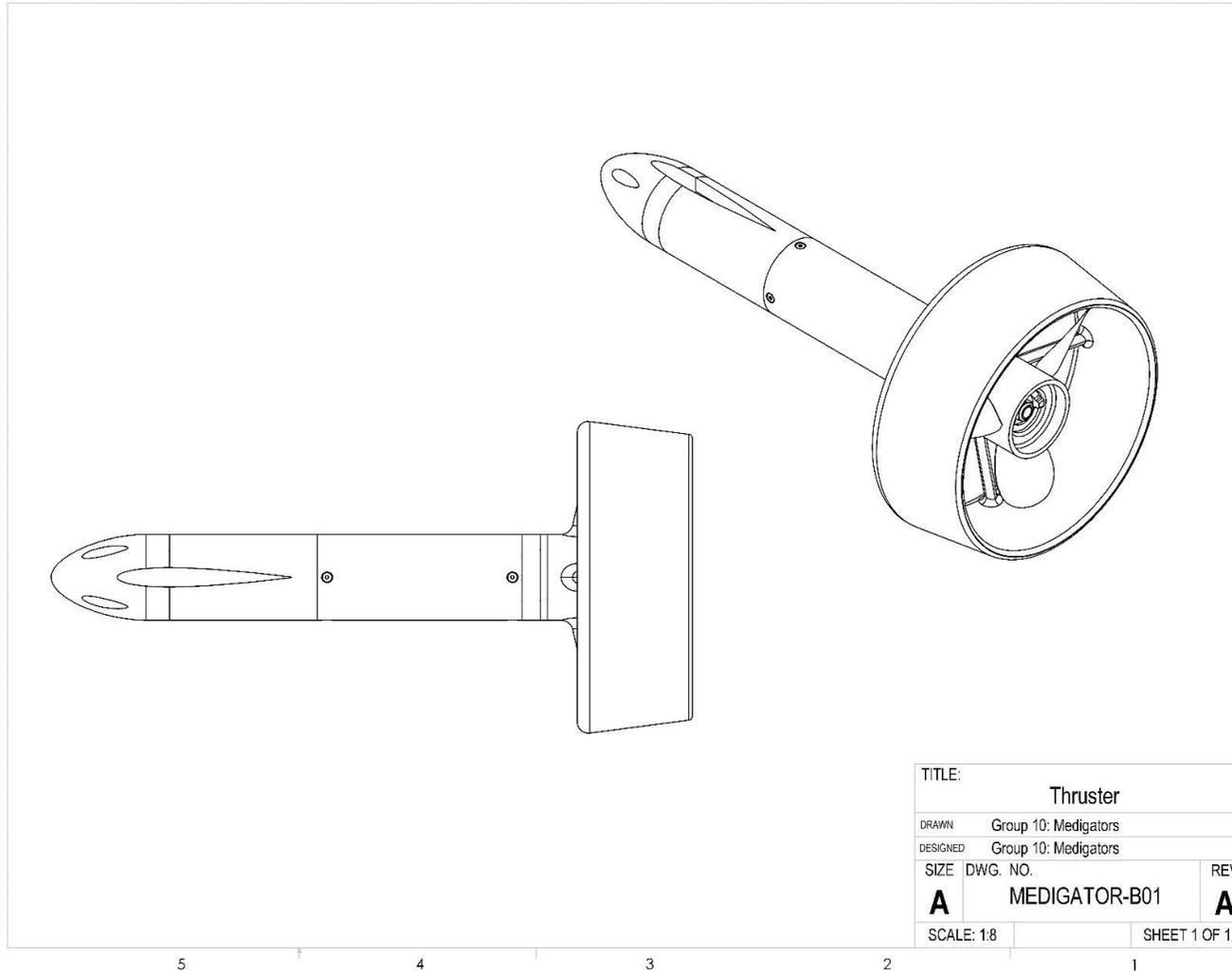




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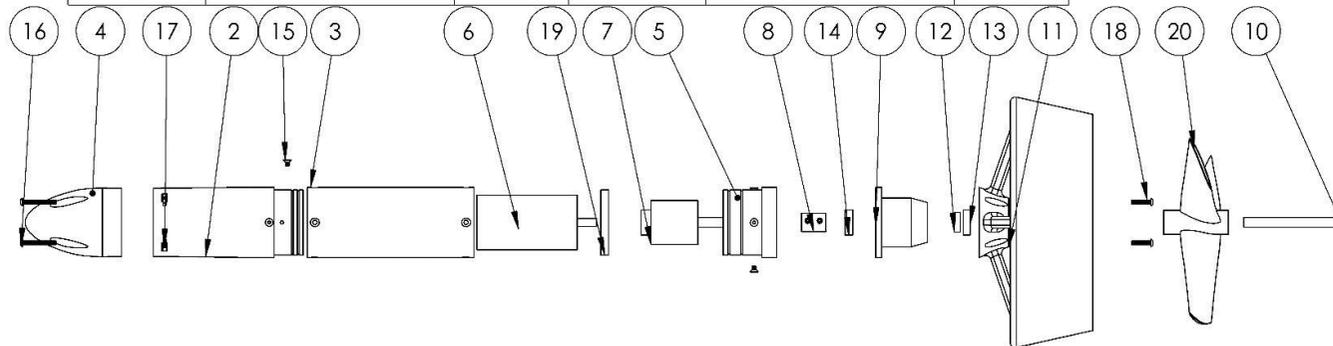
APPENDIX E THRUSTER ASSEMBLY





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ITEM NO.	PART NAME	QTY.	ITEM NO.	PART NAME	QTY.
1	foil mast	1	11	prop guard	1
2	part b v2	1	12	20x10x6	1
3	metal sleeve	1	13	26 x 10 x7	1
4	part a	1	14	5972K322	1
5	part d v2	1	15	94326A221	8
6	sss 56104 motor	1	16	92095A199	4
7	gear reducer	1	17	94150A335	4
8	5395T311	1	18	94500A283	4
9	back	1	19	motor mount	1
10	shaft	1	20	prop	1



TITLE: THRUSTER ASSEM Assem4		
DRAWN Group 10: Medigators		
DESIGNED Group 10: Medigators		
SIZE	DWG. NO.	REV
A	MEDIGATOR-B02	A
SCALE: 2:11		SHEET 1 OF 1

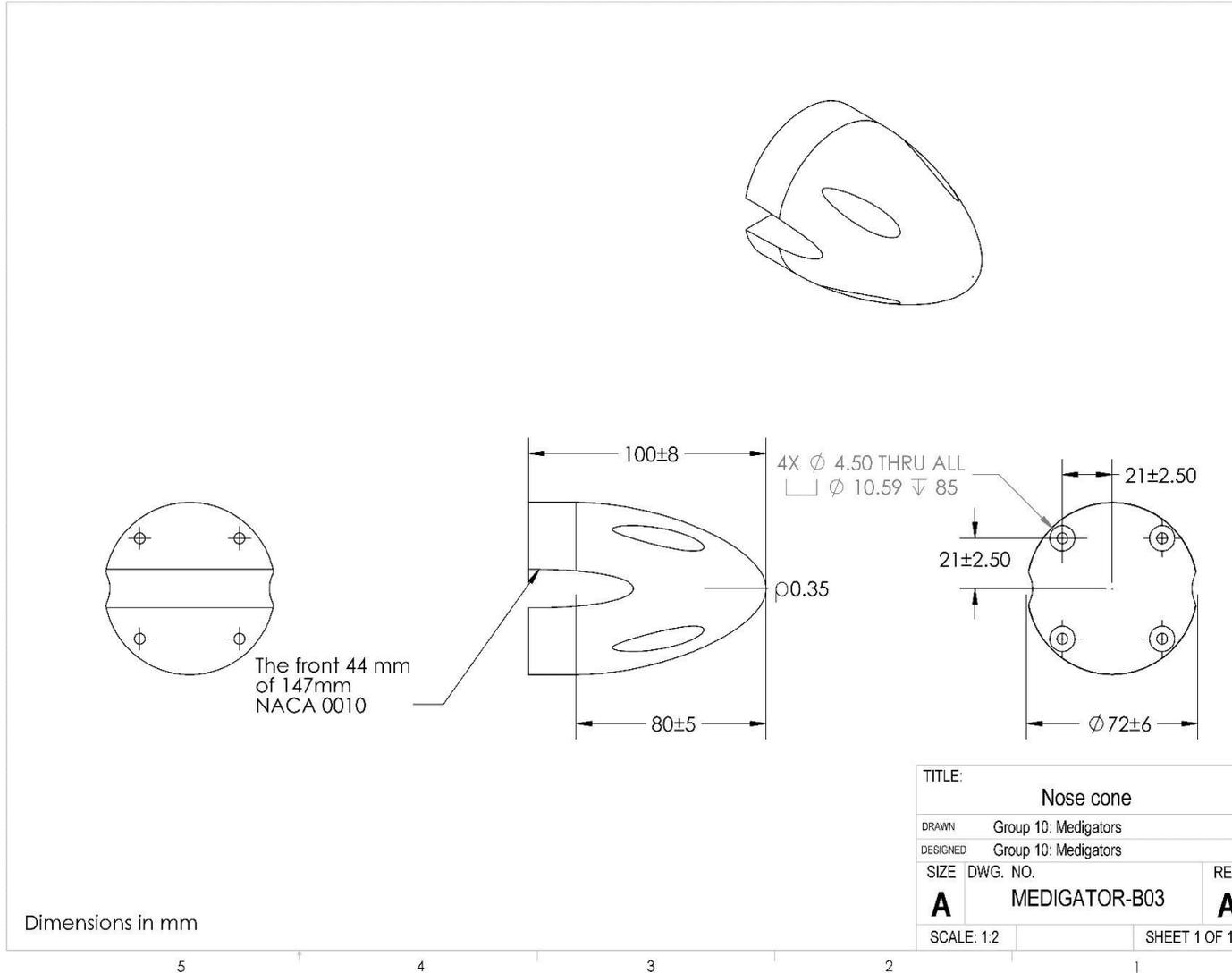
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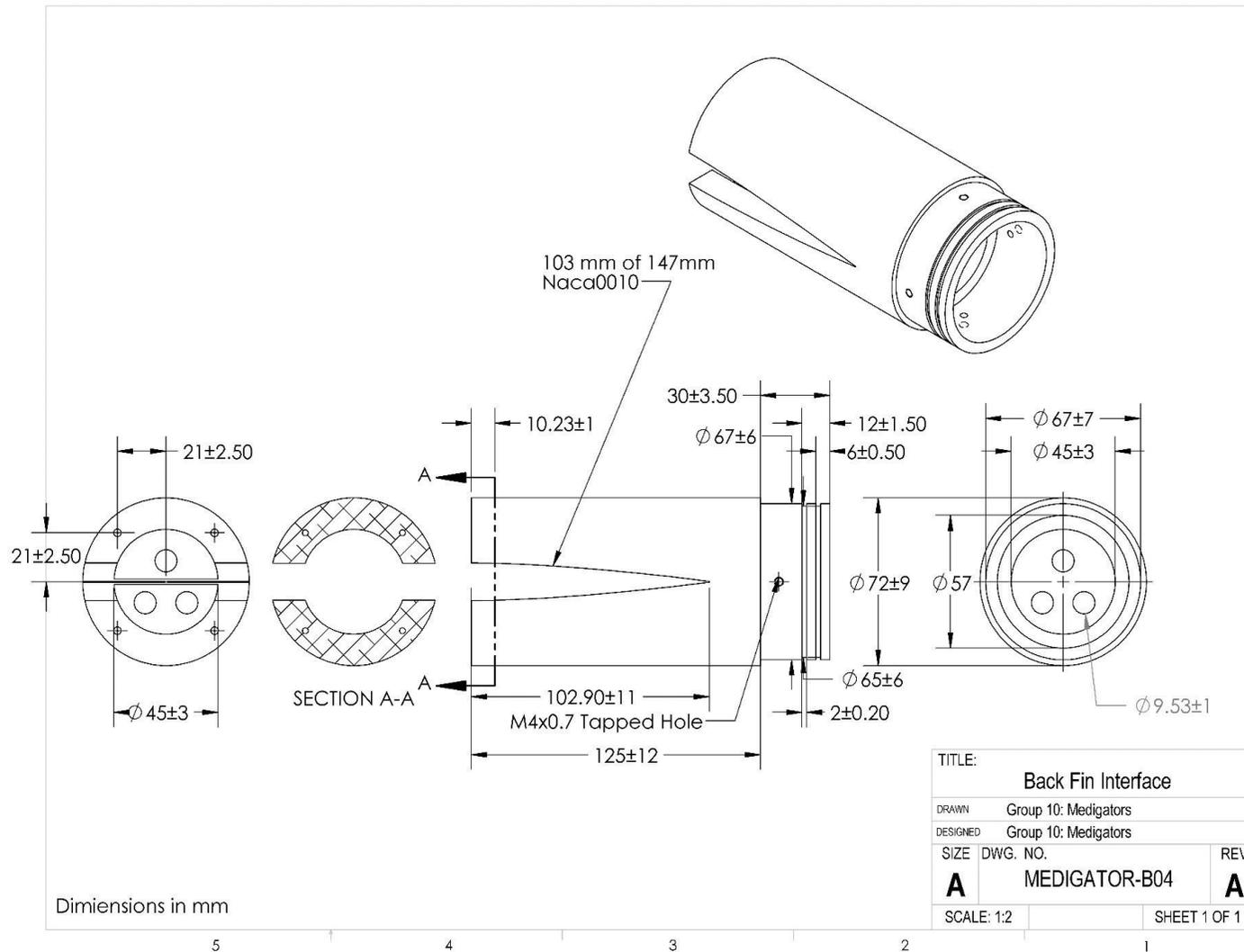
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1



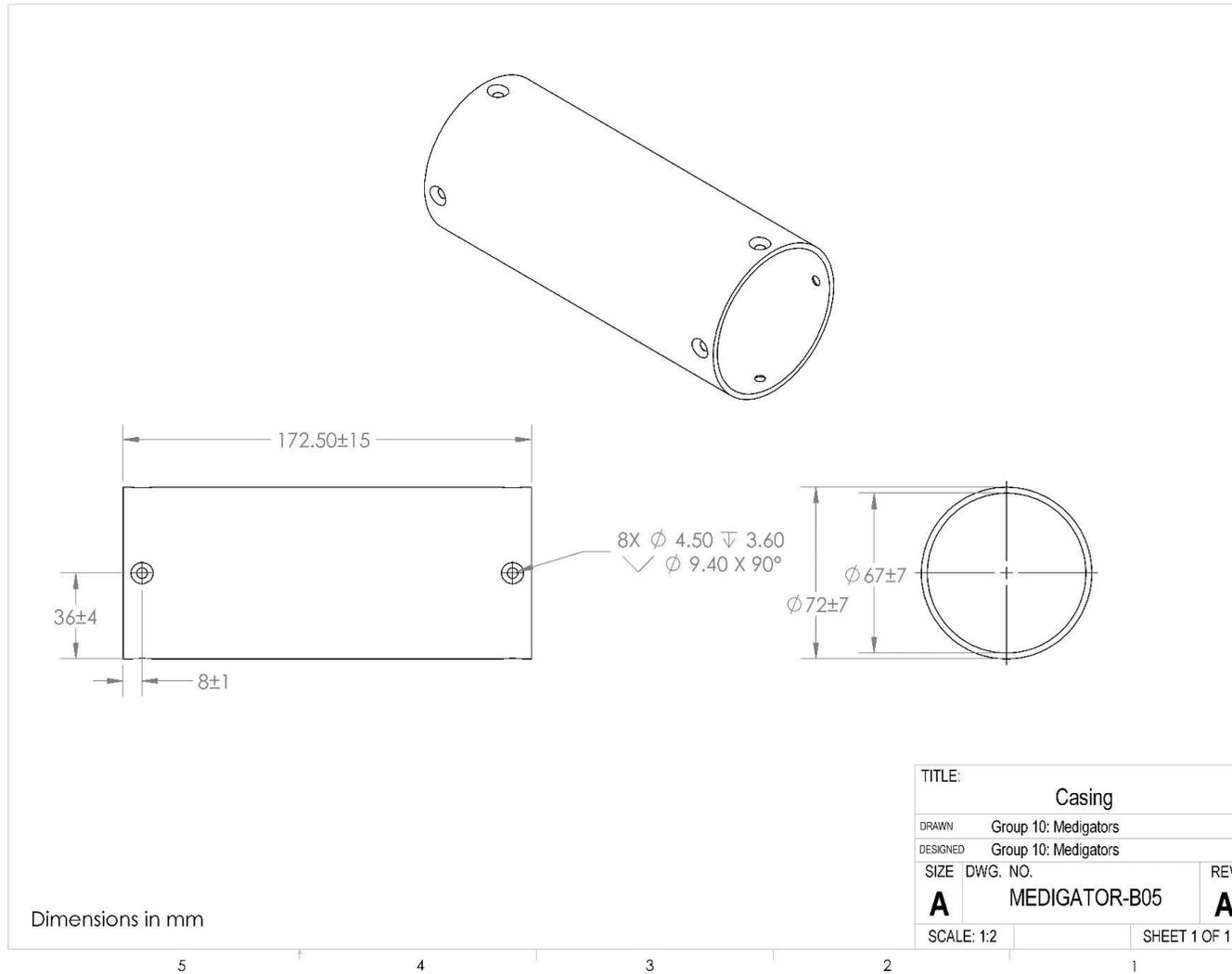


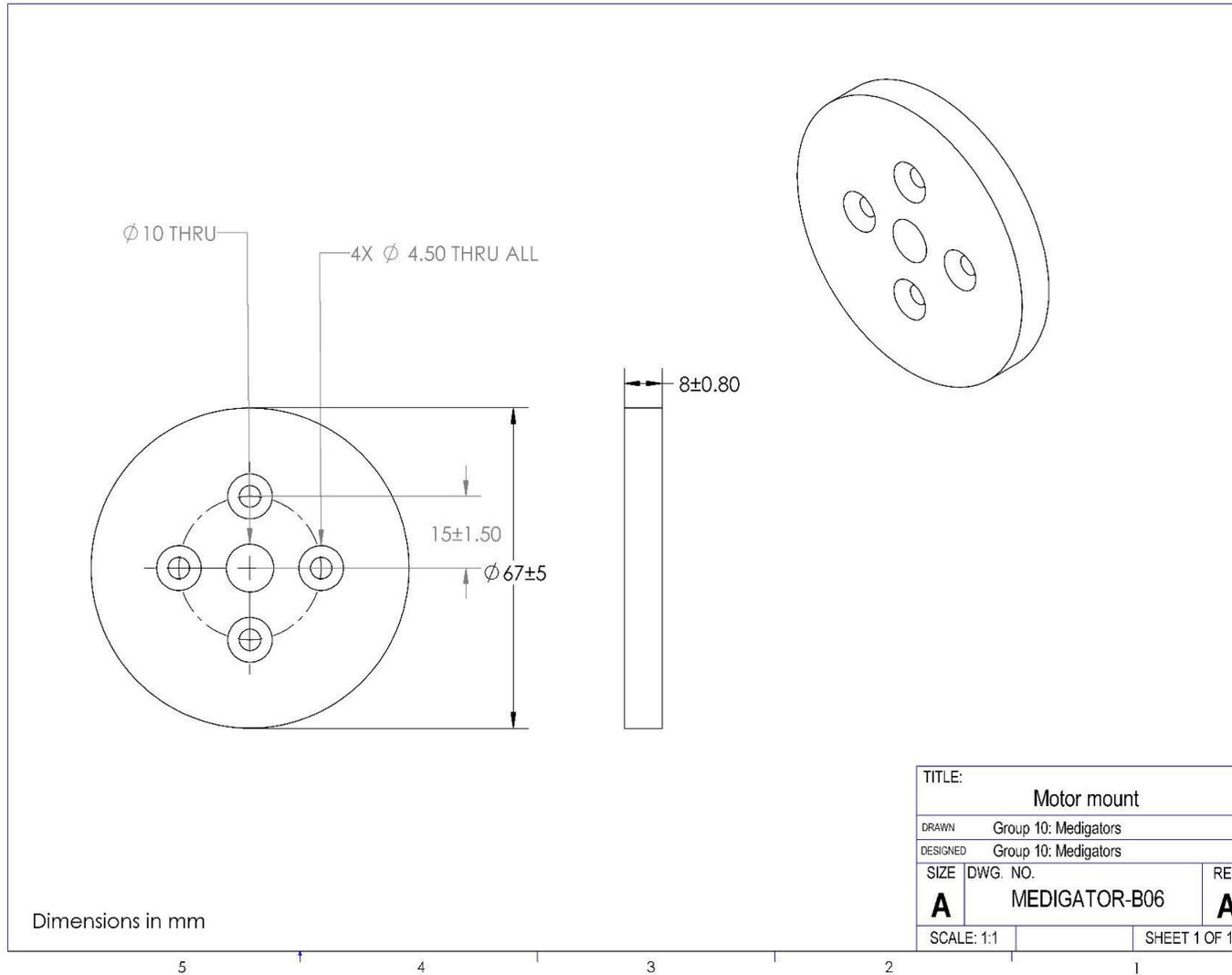
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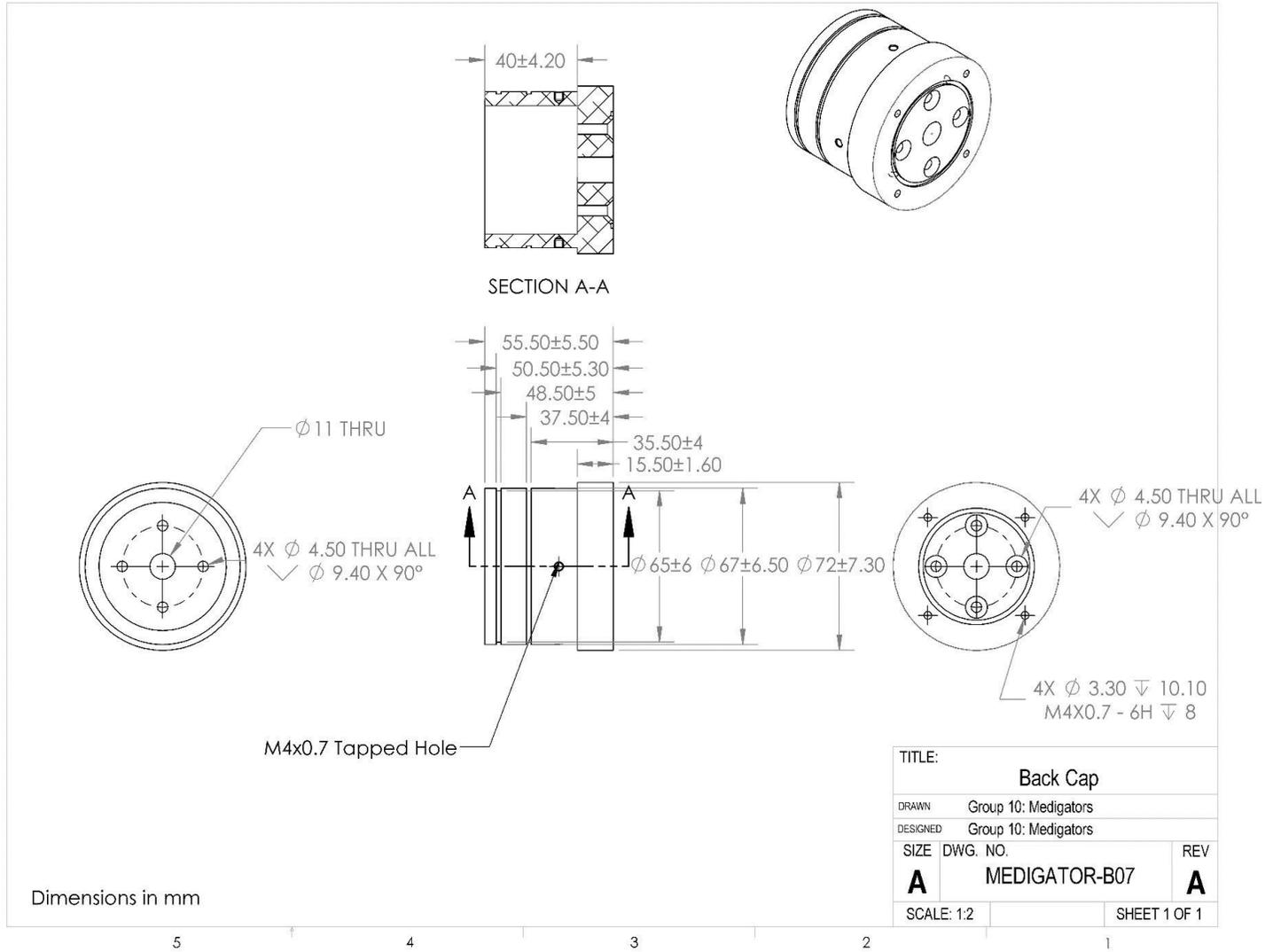


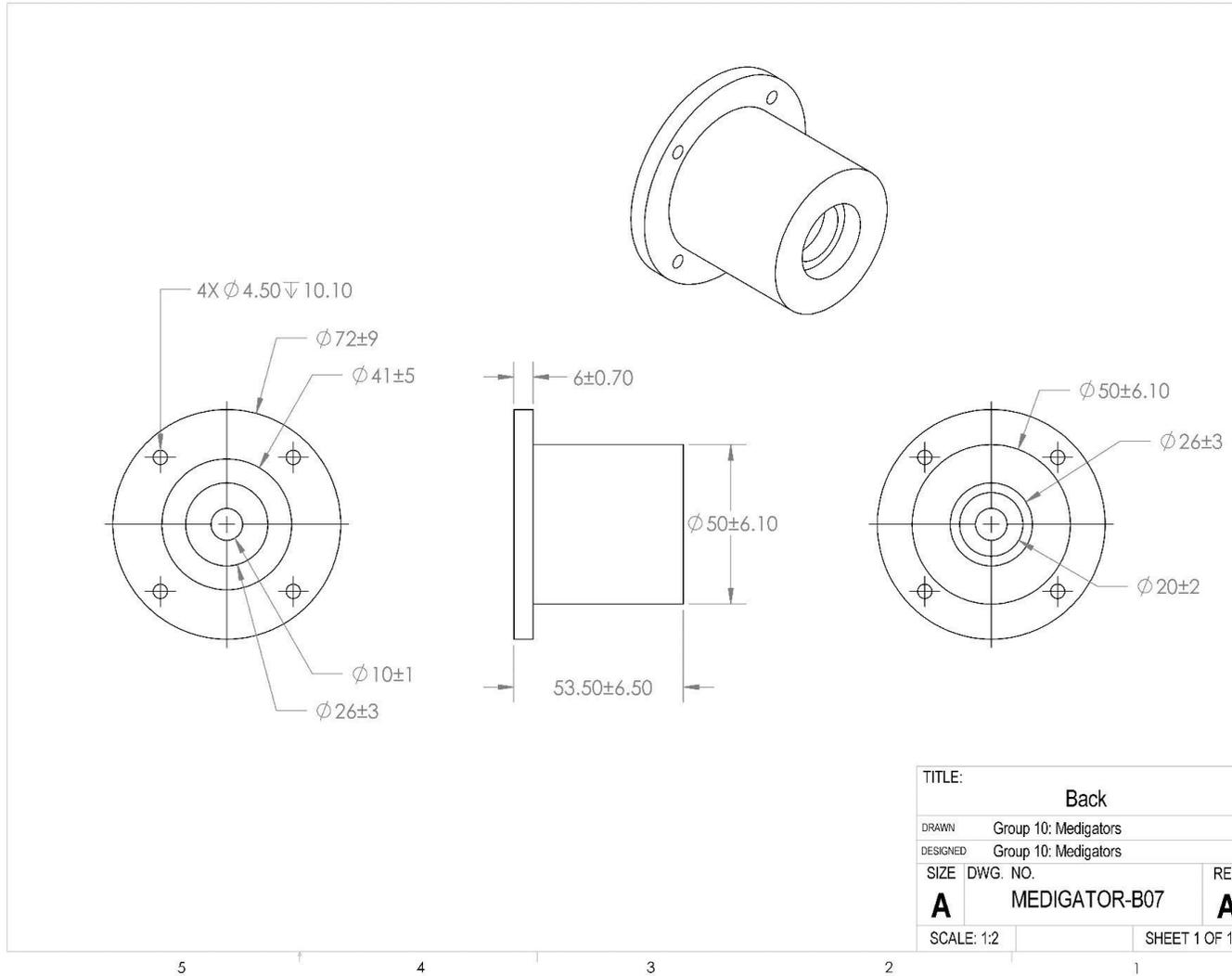


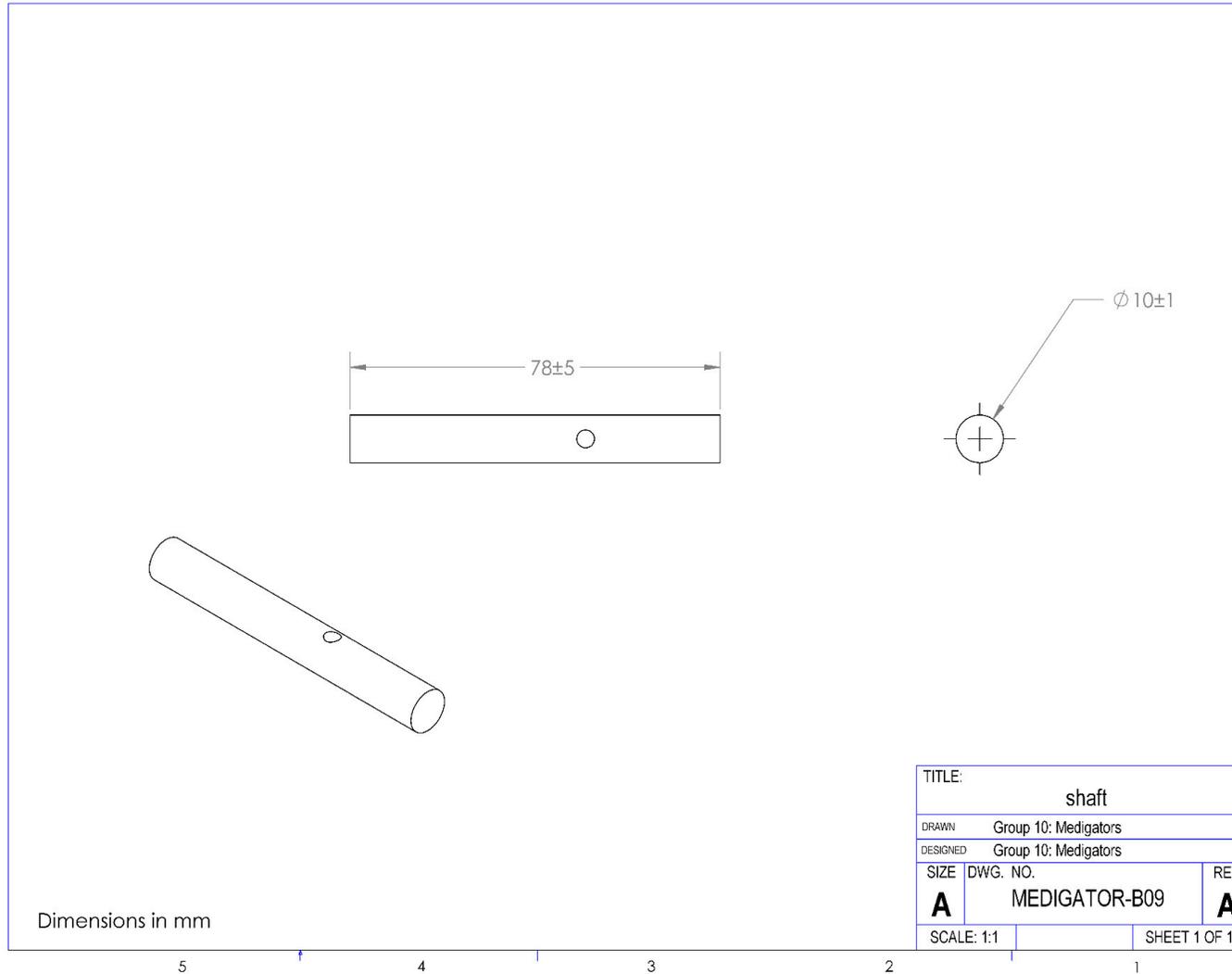
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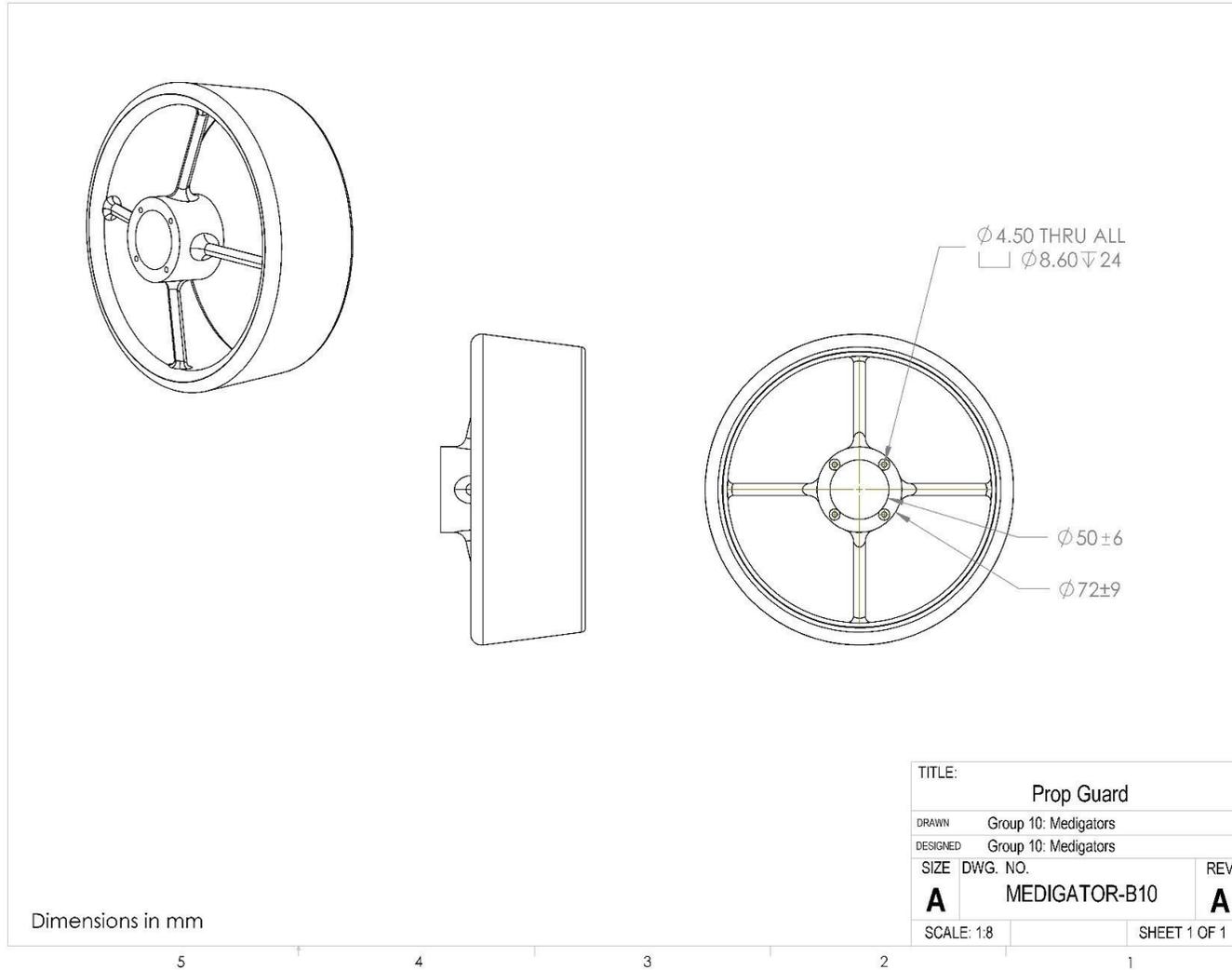


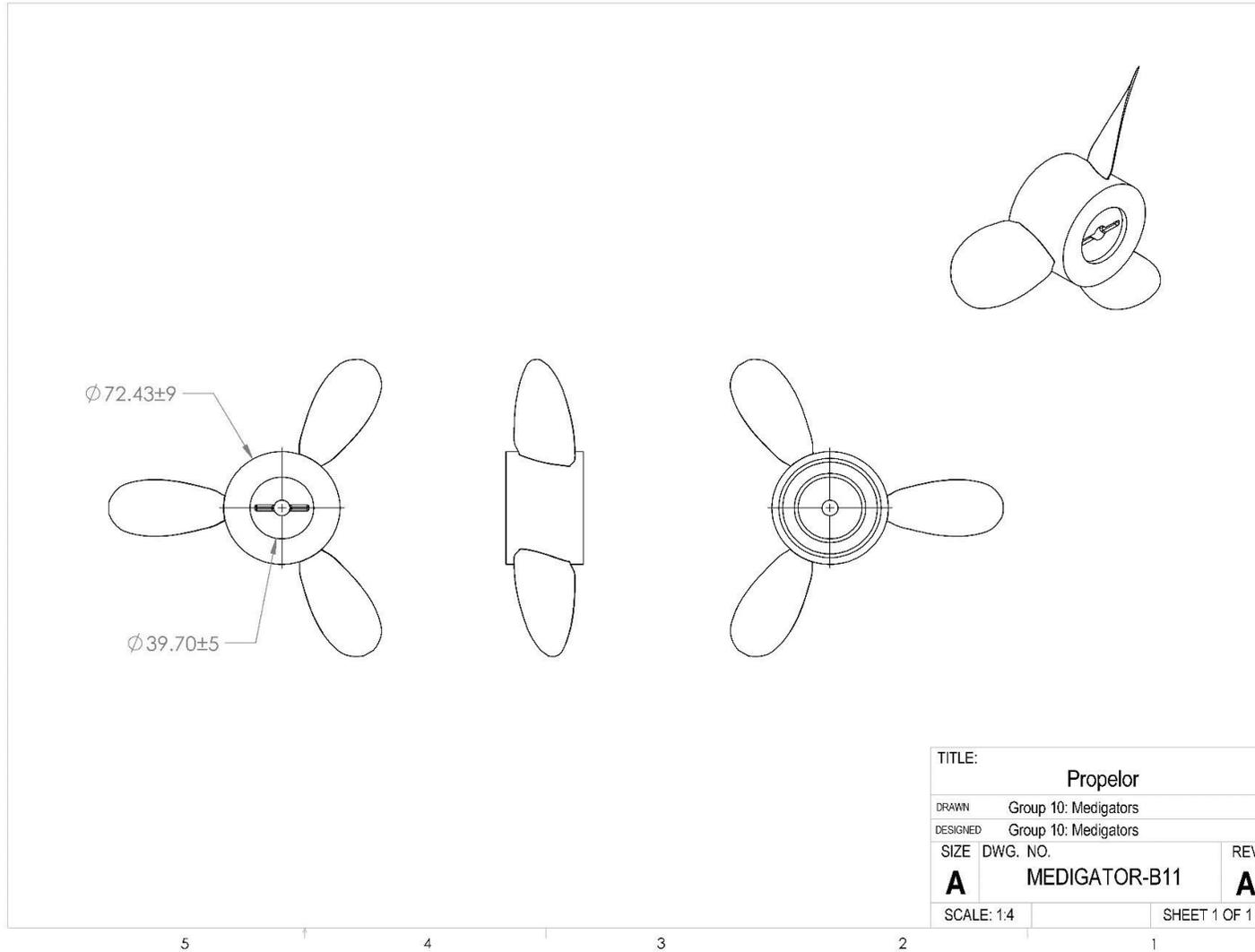










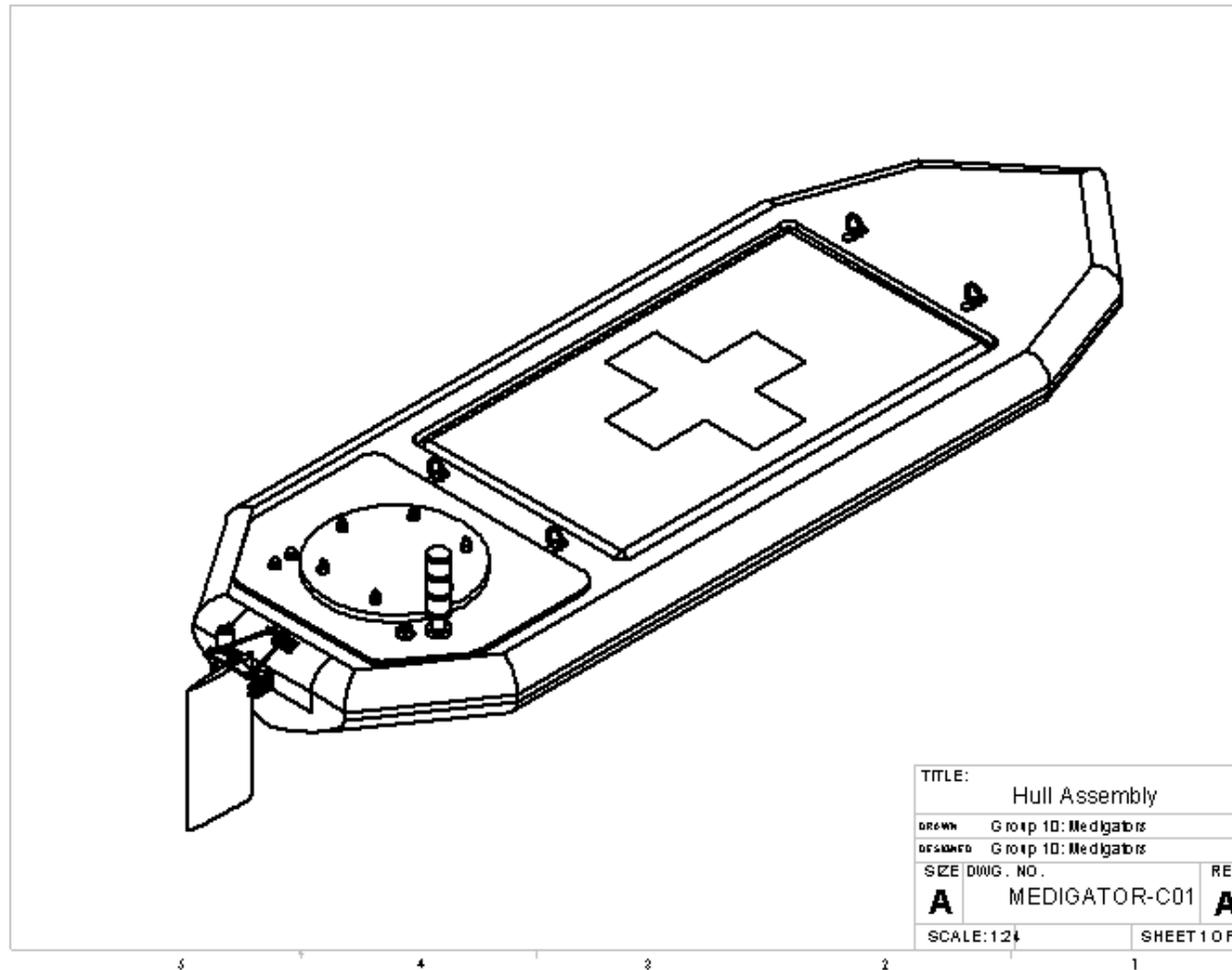


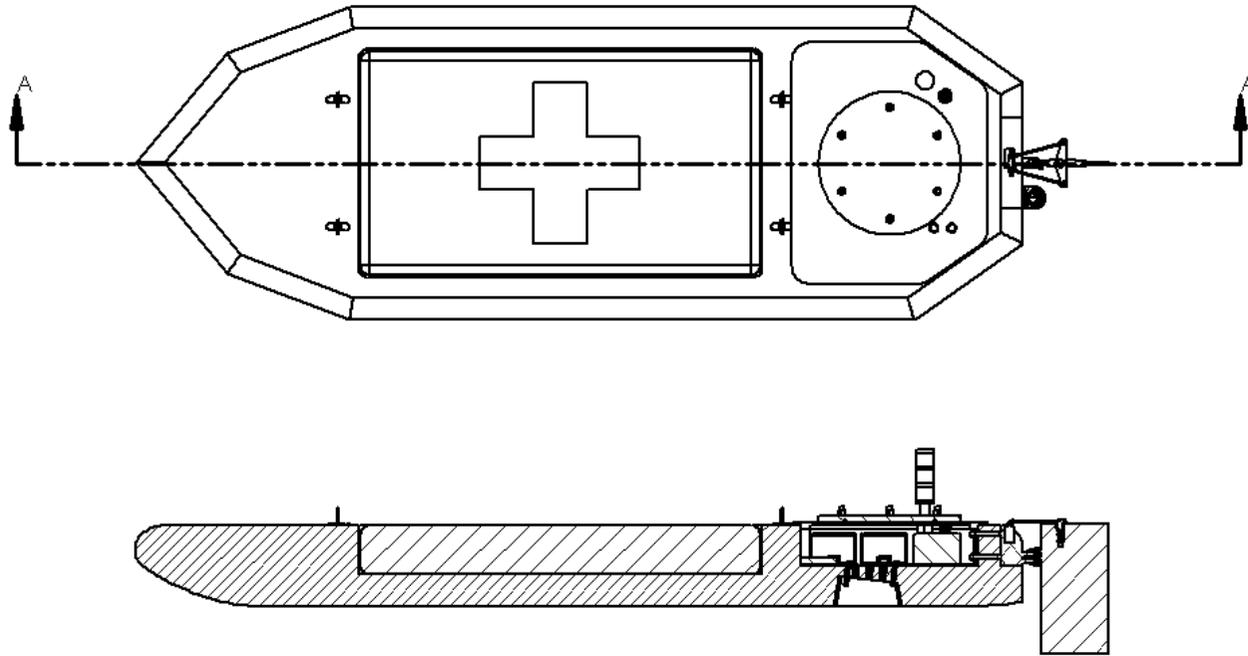


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APPENDIX F HULL ASSEMBLY





SECTION A-A
SCALE 1 : 12

TITLE:	
Hull Section	
DRAWN	Group 10: Medigators
DESIGNED	Group 10: Medigators
SIZE DWG. NO.	REV
A	MEDIGATOR-C02 A
SCALE: 1:24	SHEET 1 OF 1

5

4

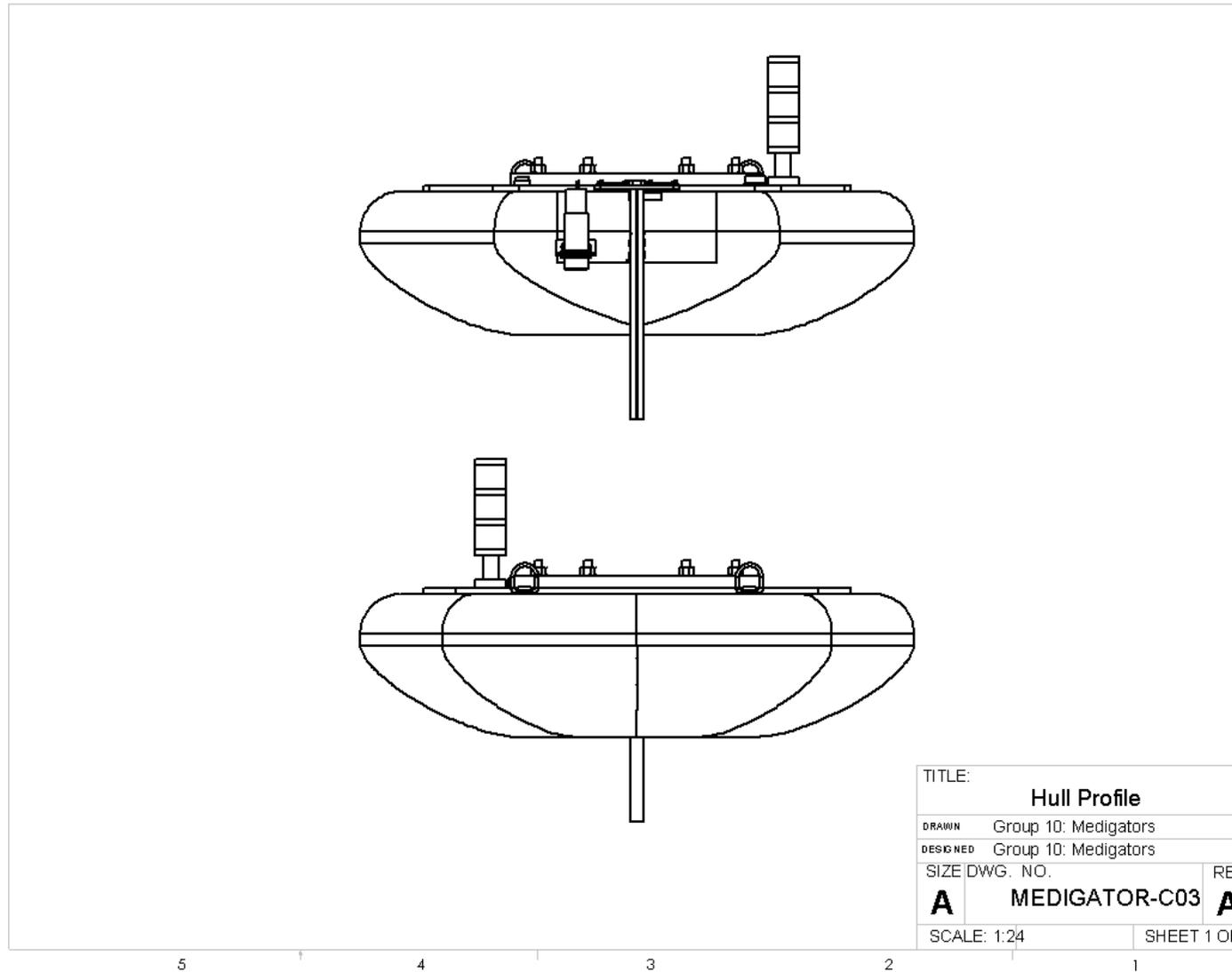
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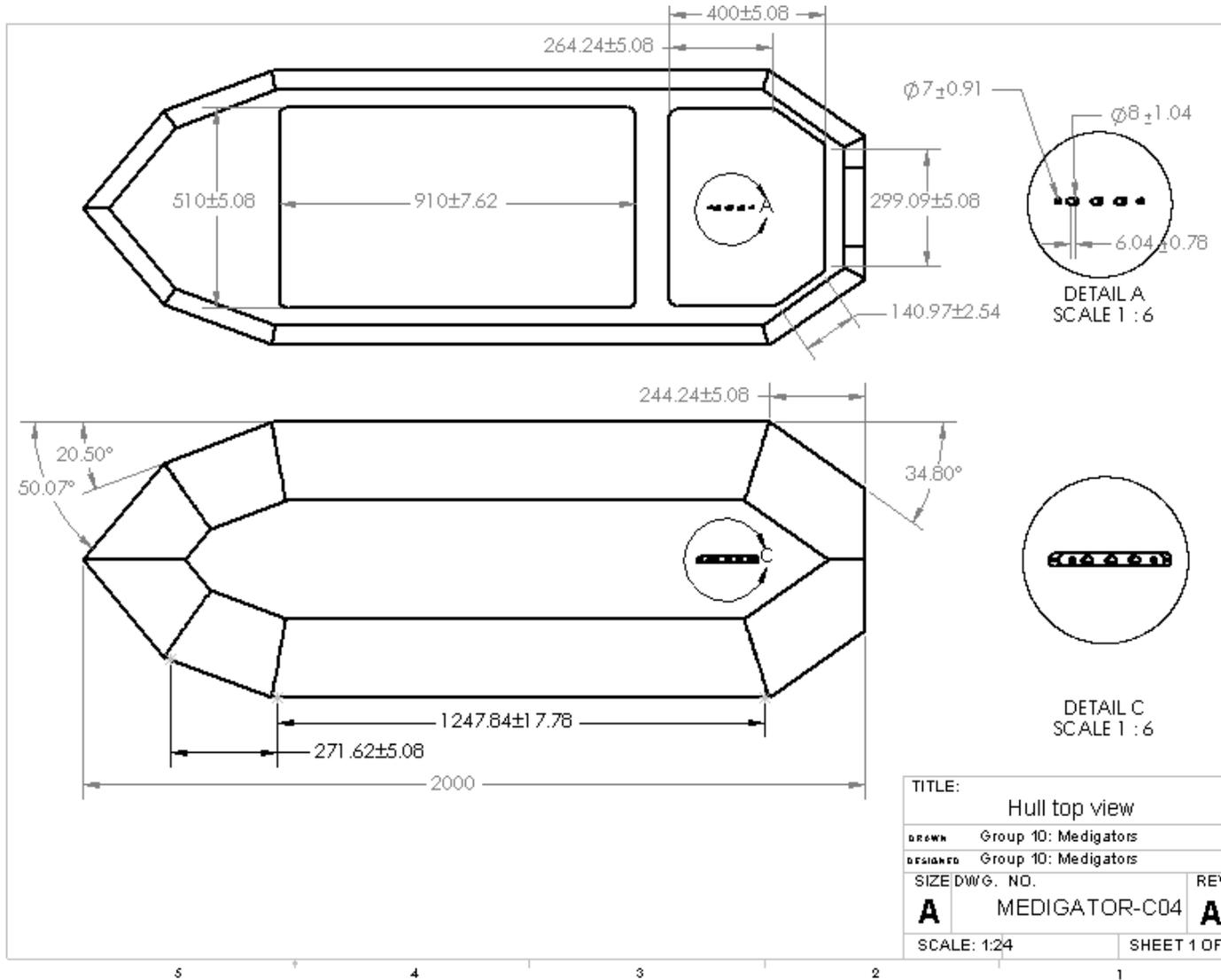


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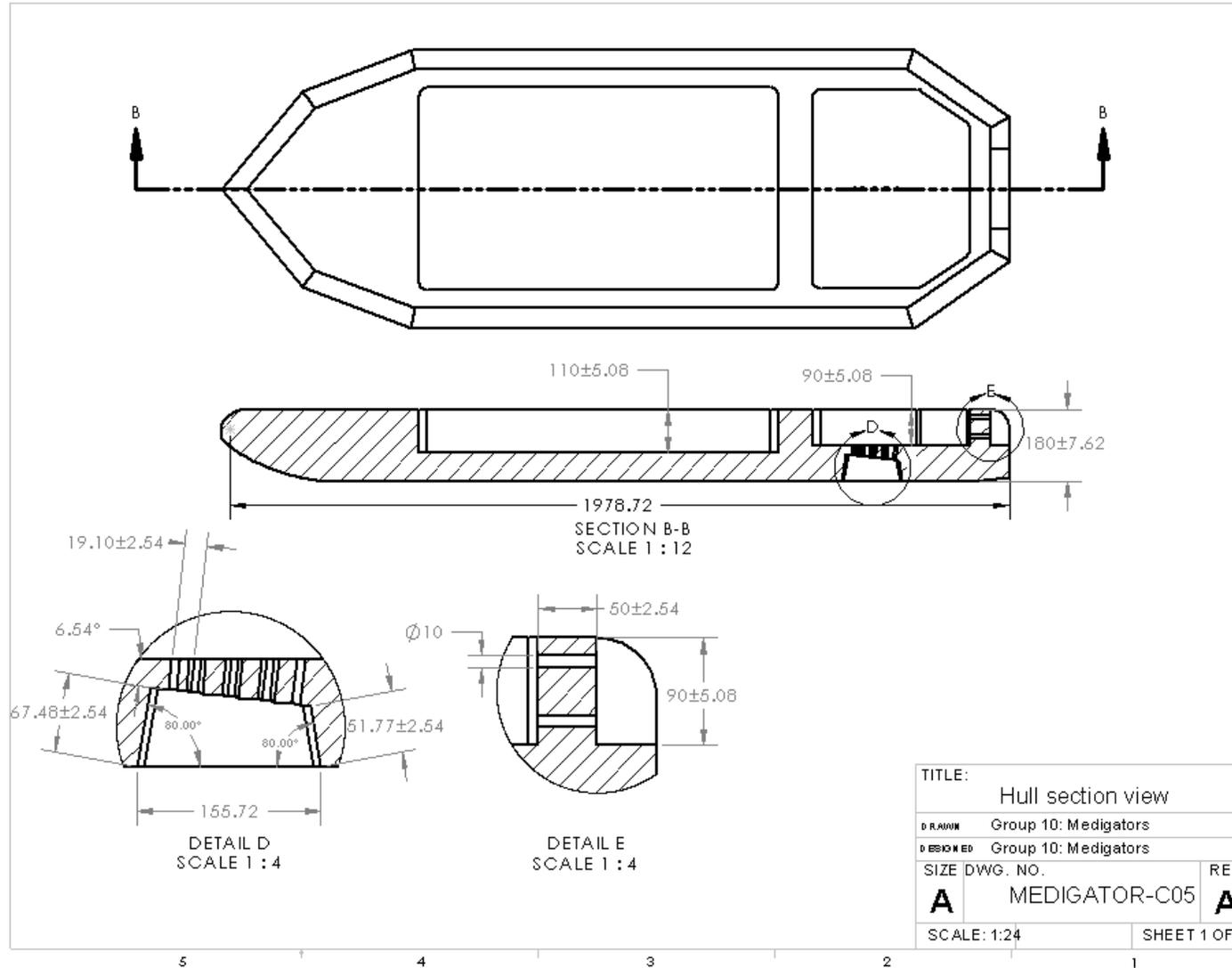


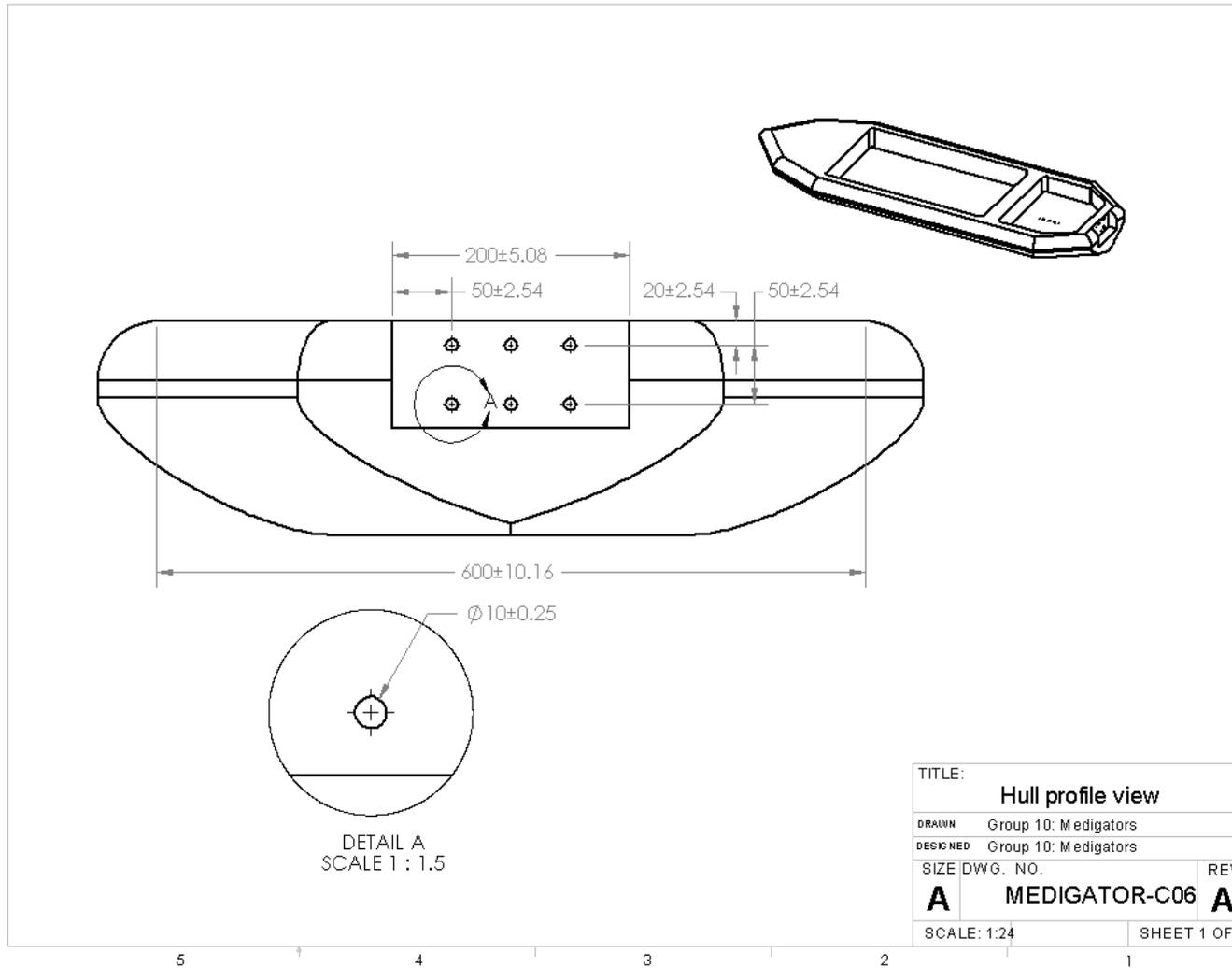
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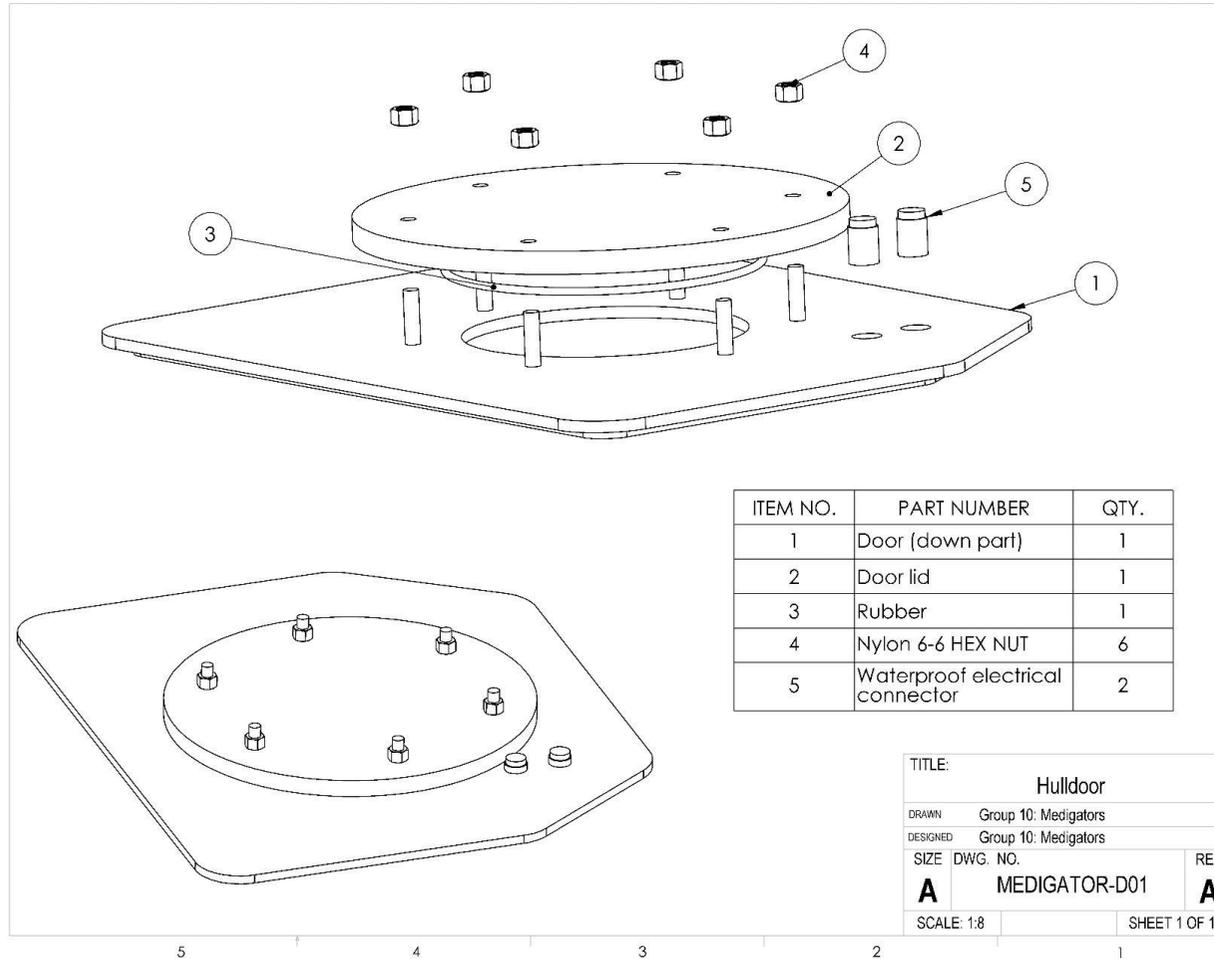
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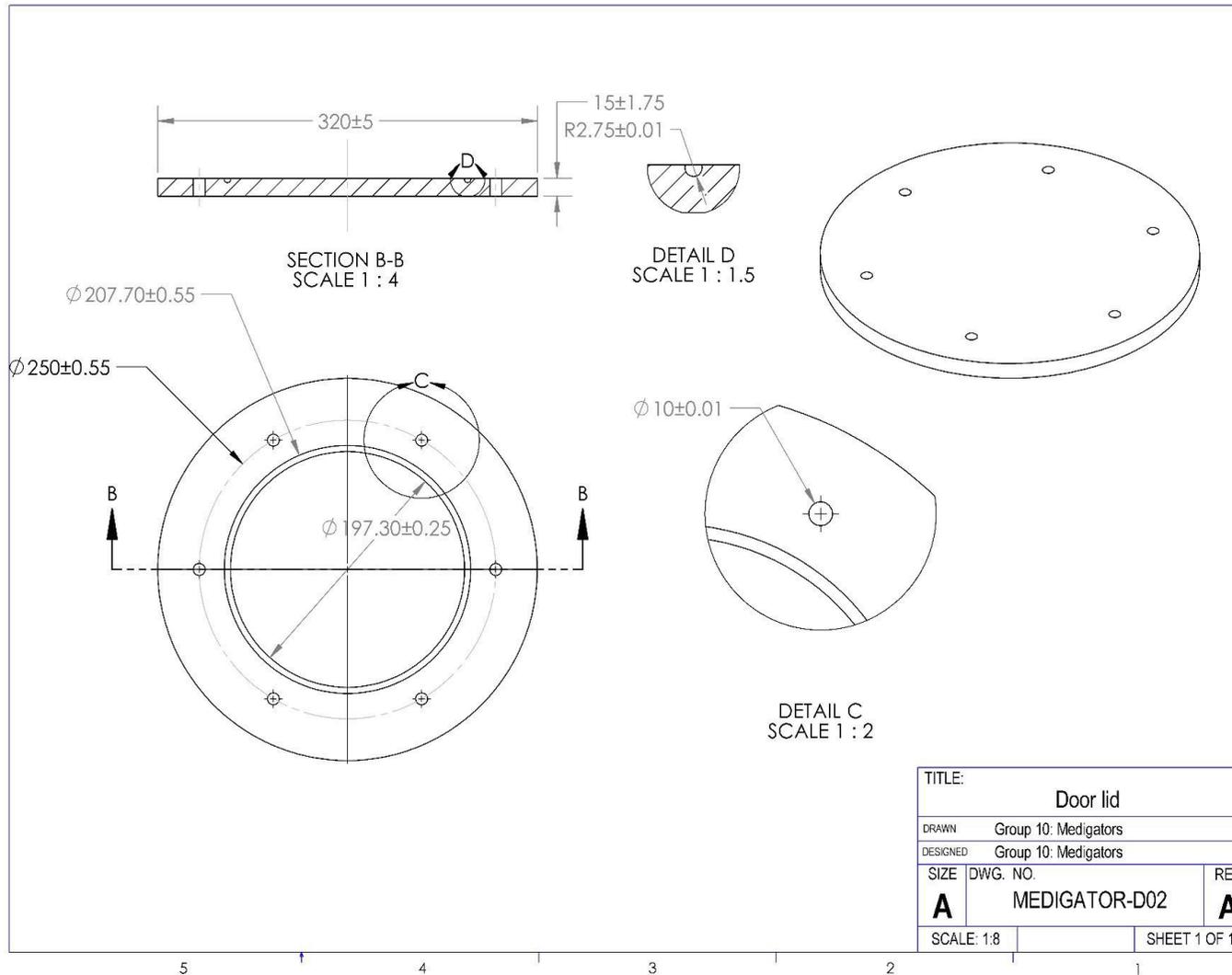






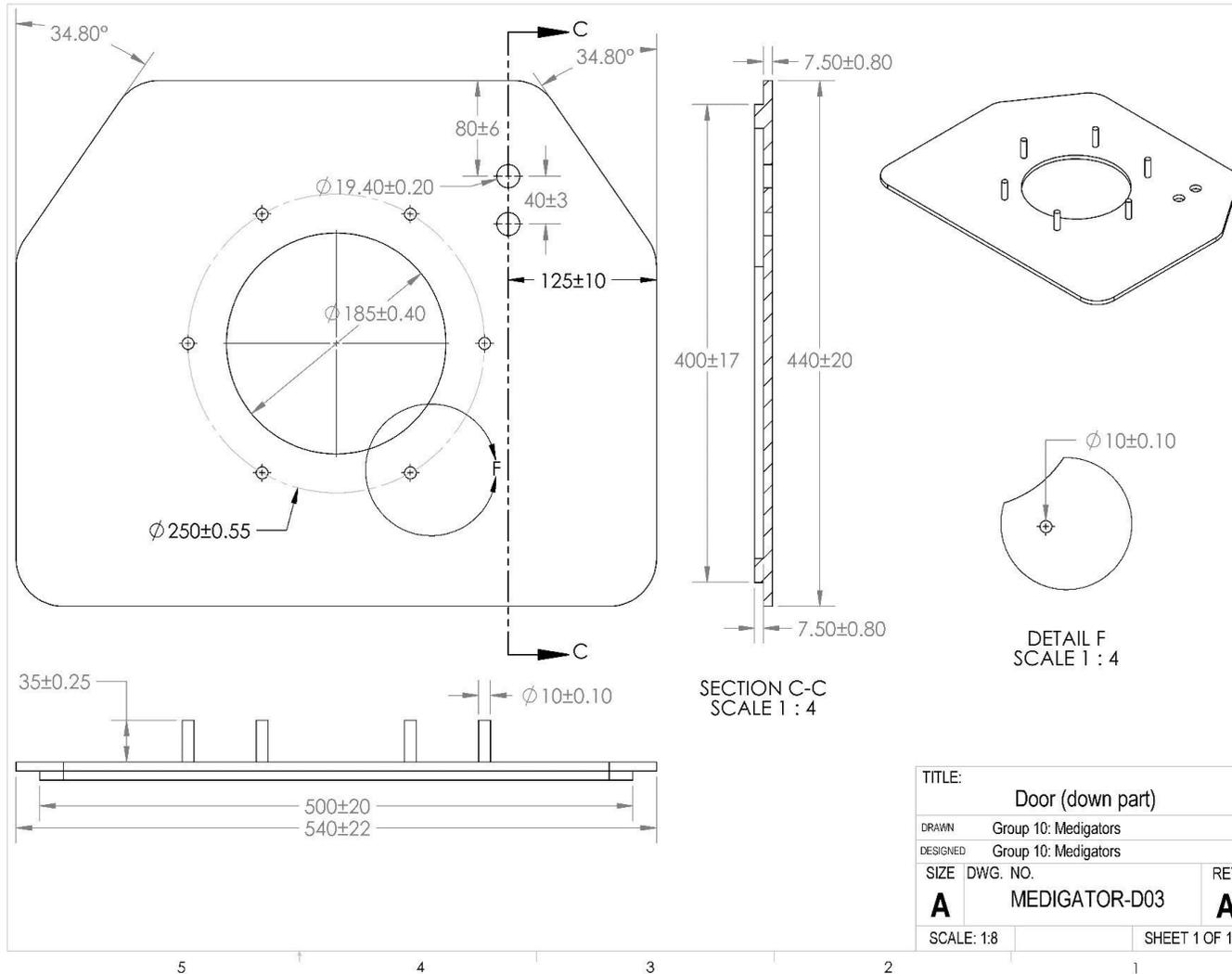
APPENDIX G DOOR ASSEMBLY

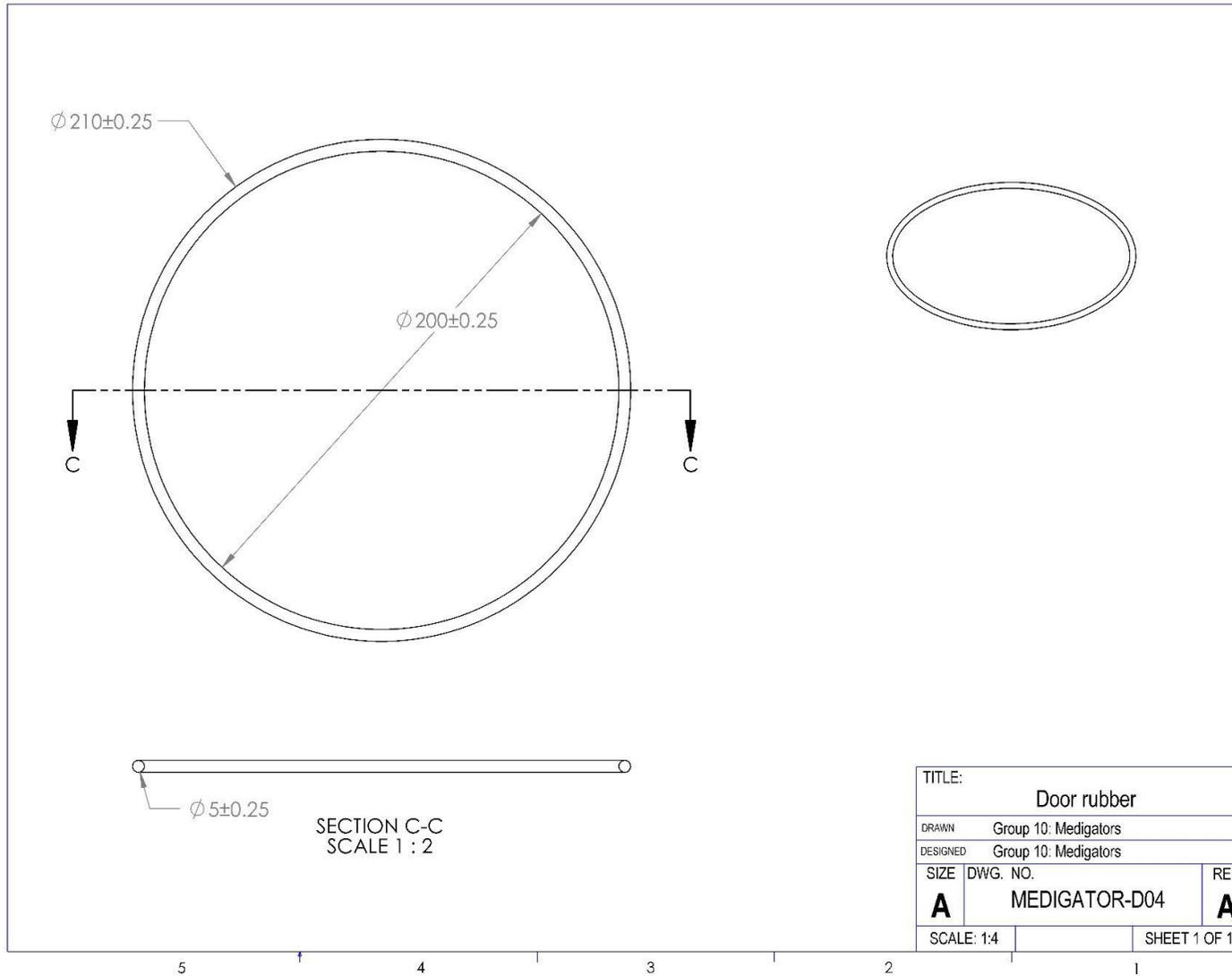






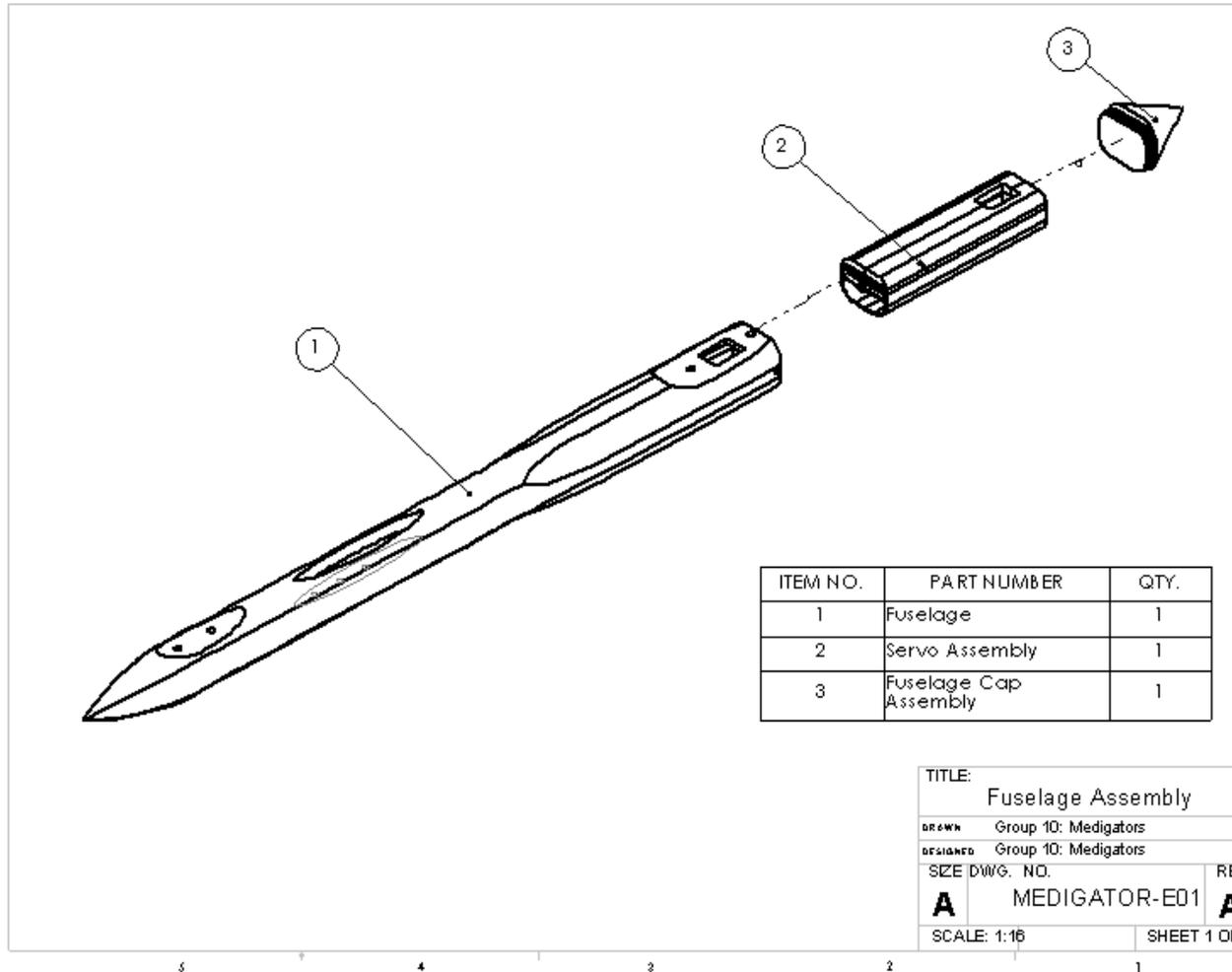
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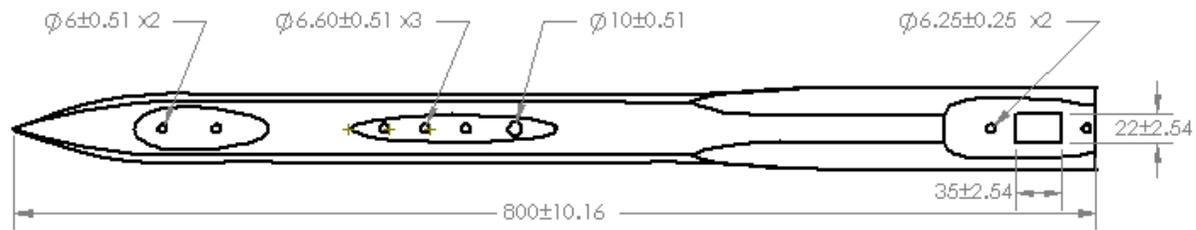






APPENDIX H FUSELAGE ASSEMBLY





TITLE:		Fuselage	
DRAWN	Group 10: Medigators		
DESIGNED	Group 10: Medigators		
SIZE	DWG. NO.	REV	
A	MEDIGATOR-E02	A	
SCALE: 1:12		SHEET 1 OF 1	

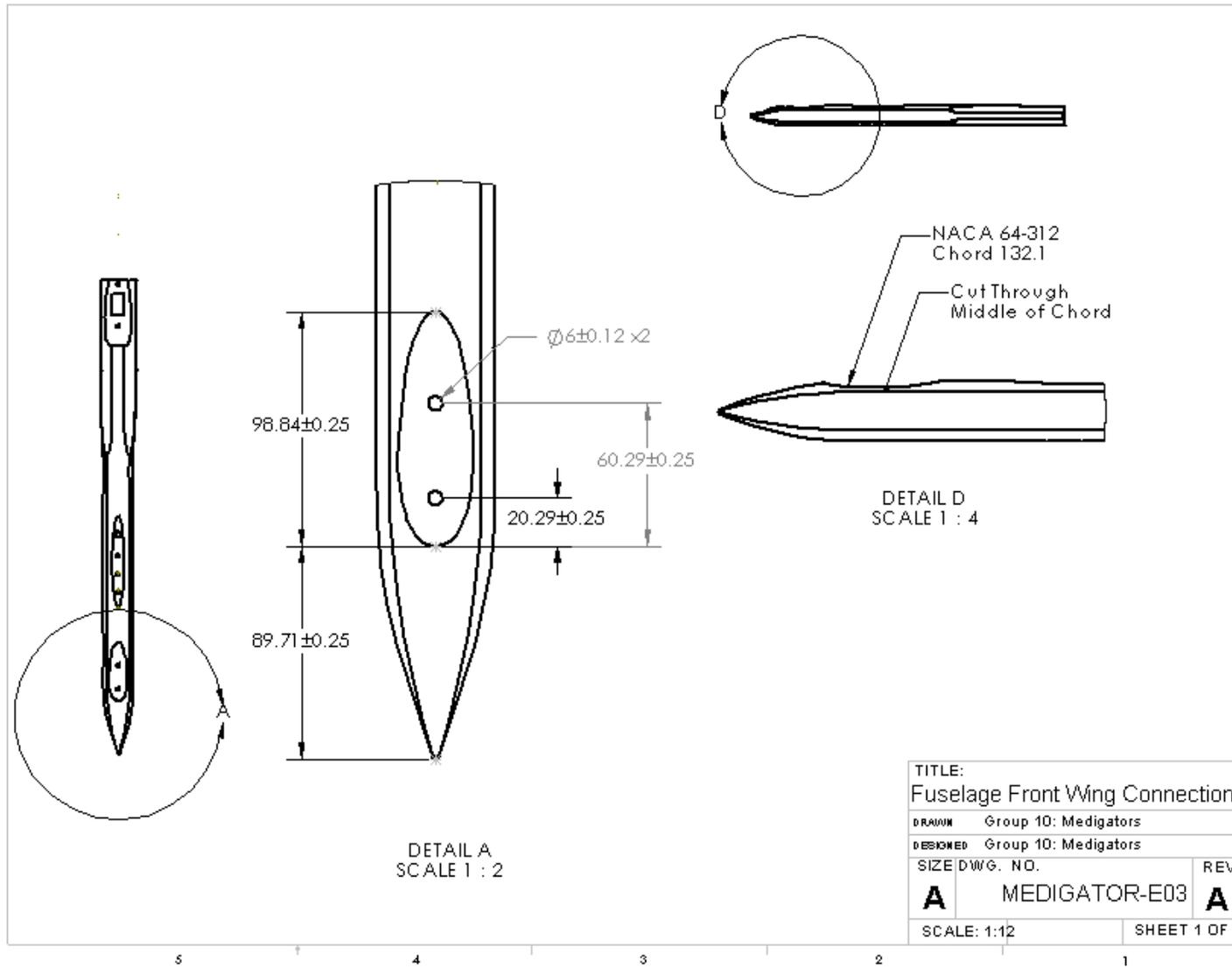
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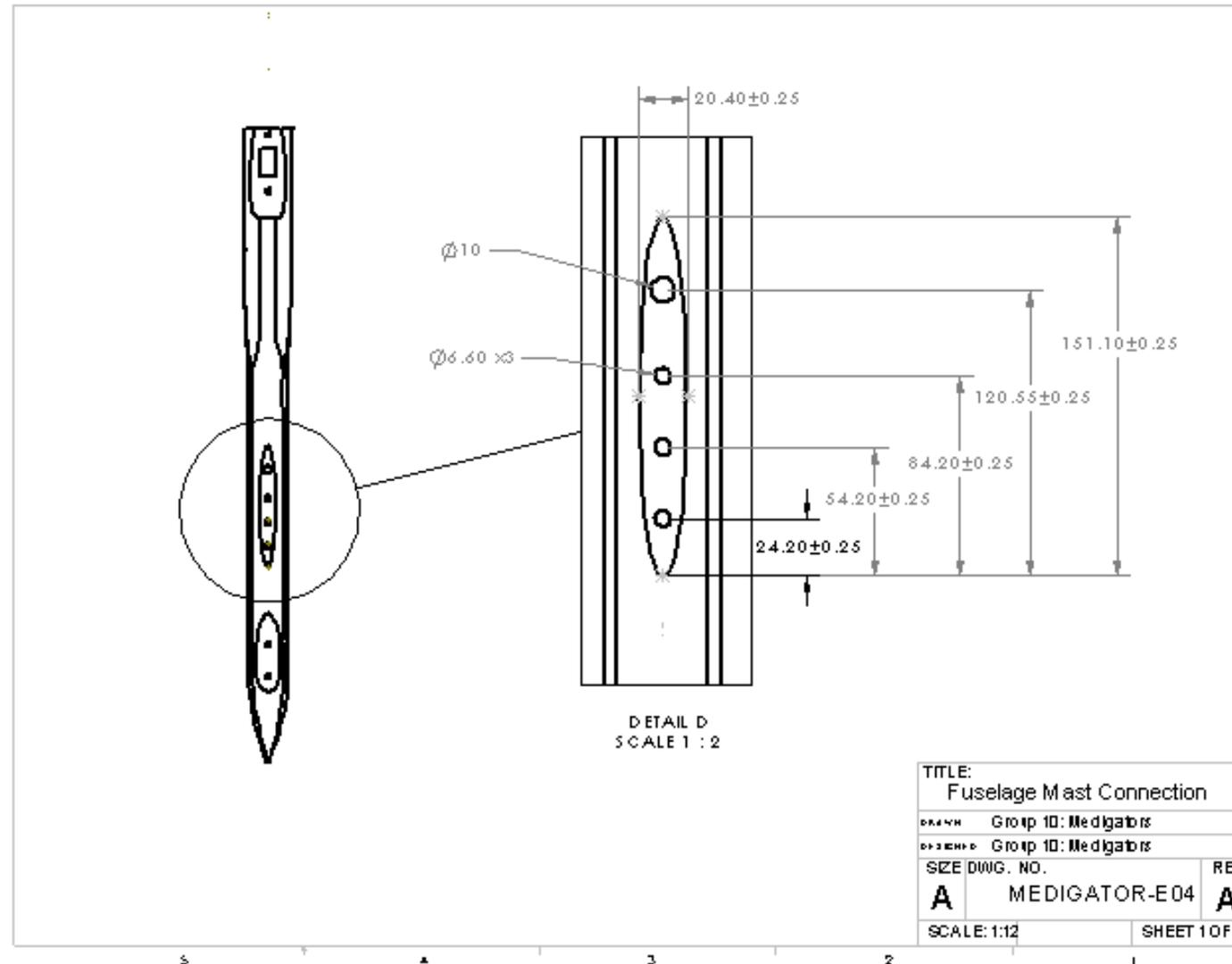
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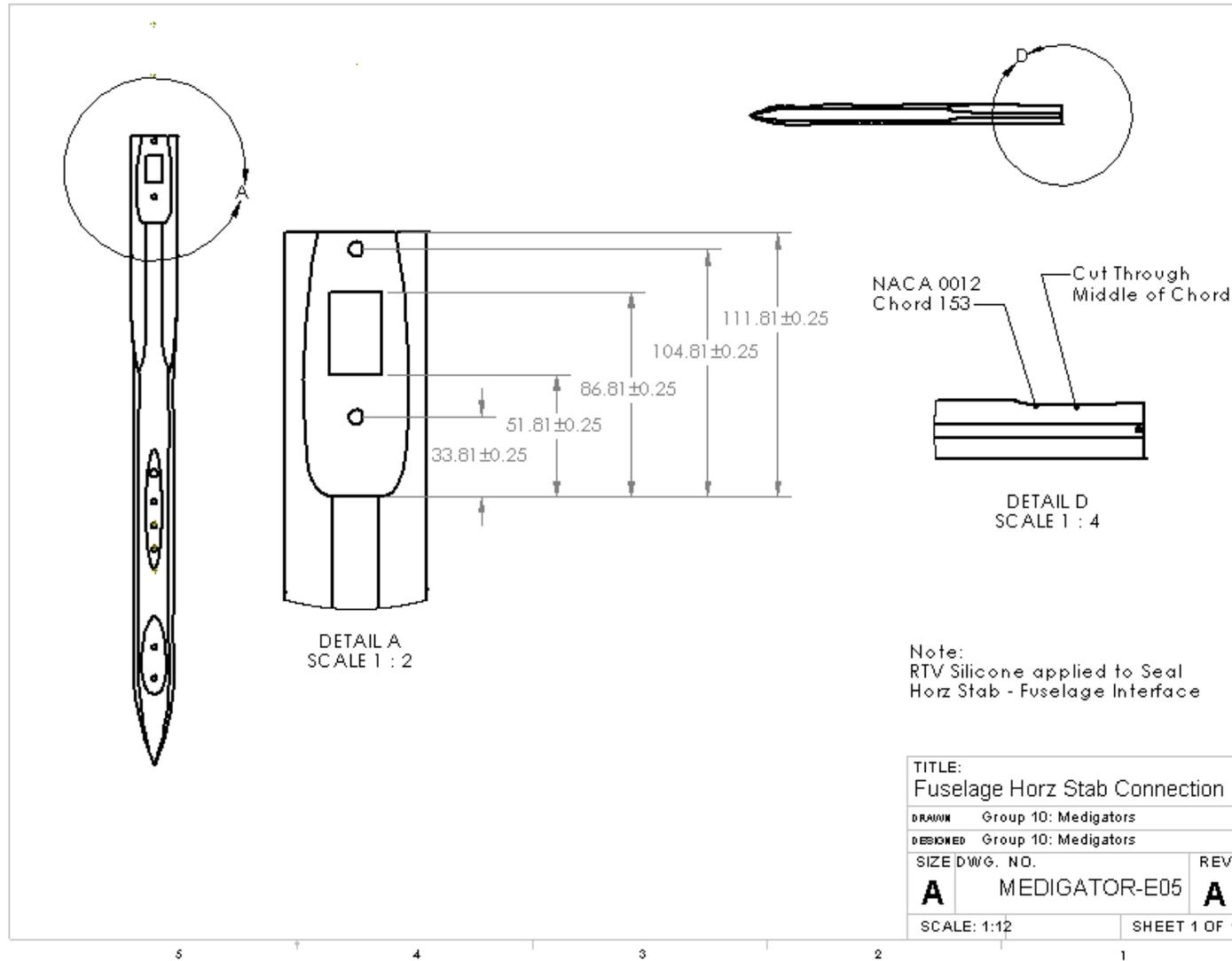
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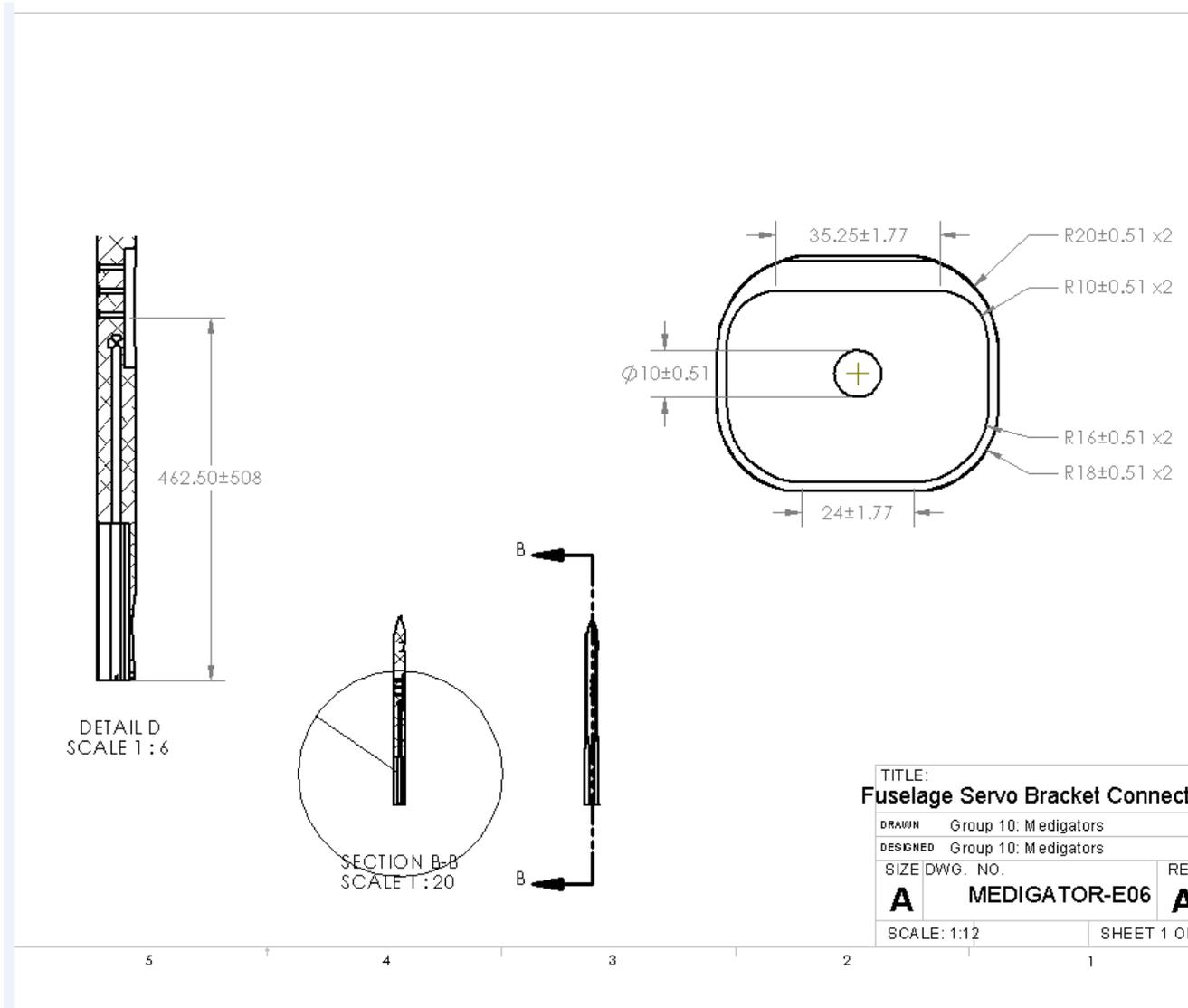






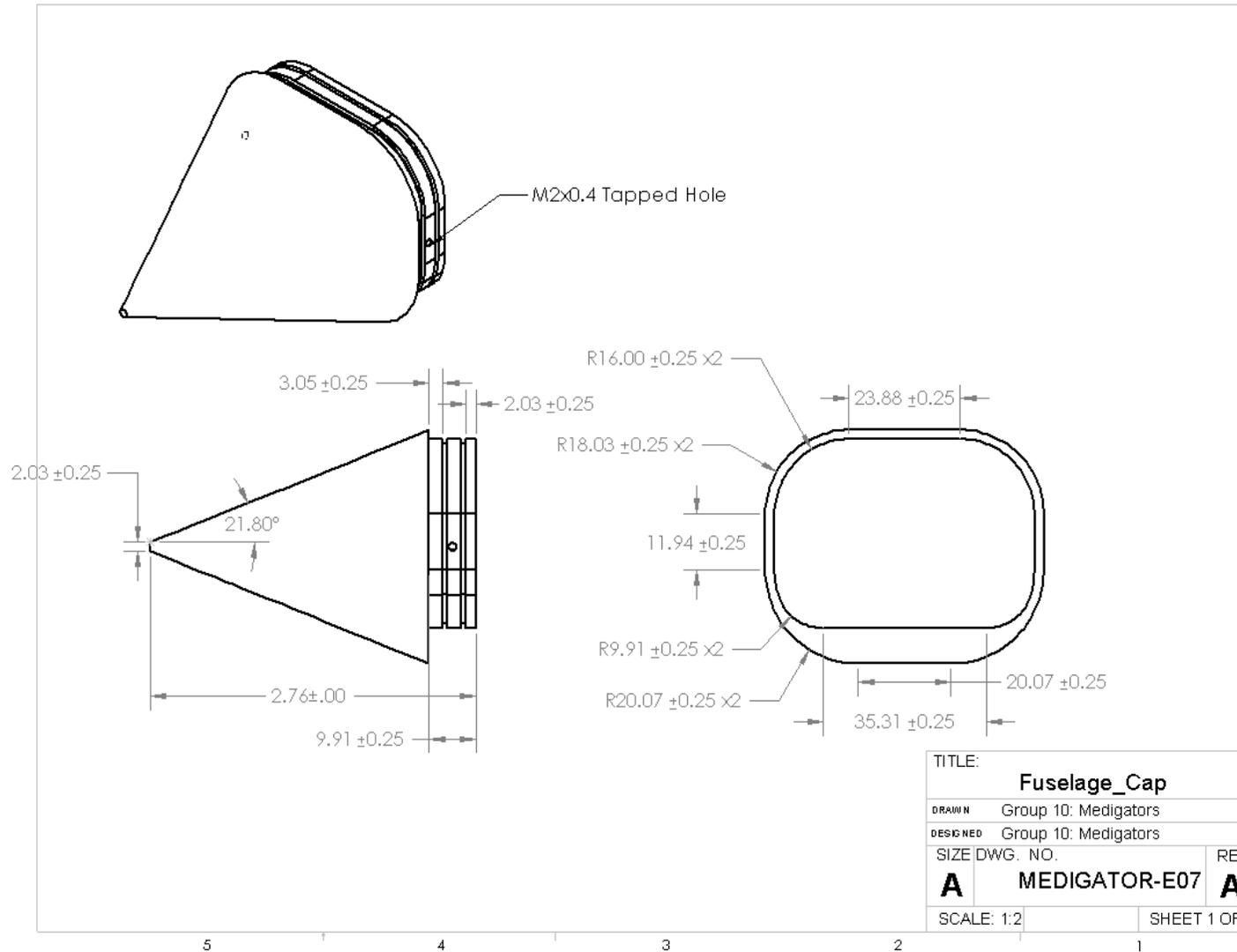
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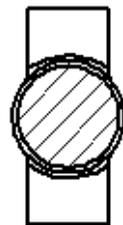
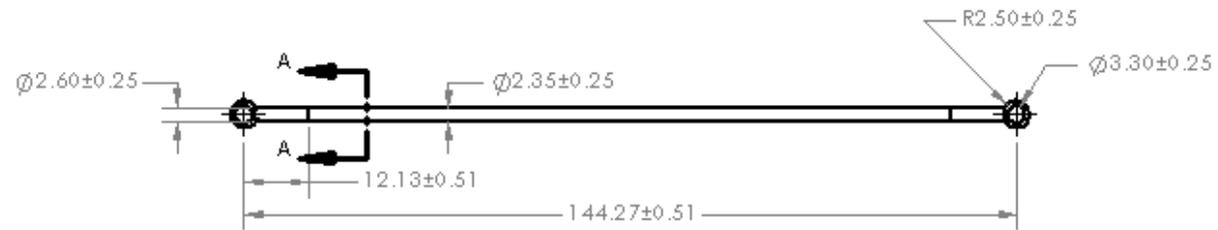


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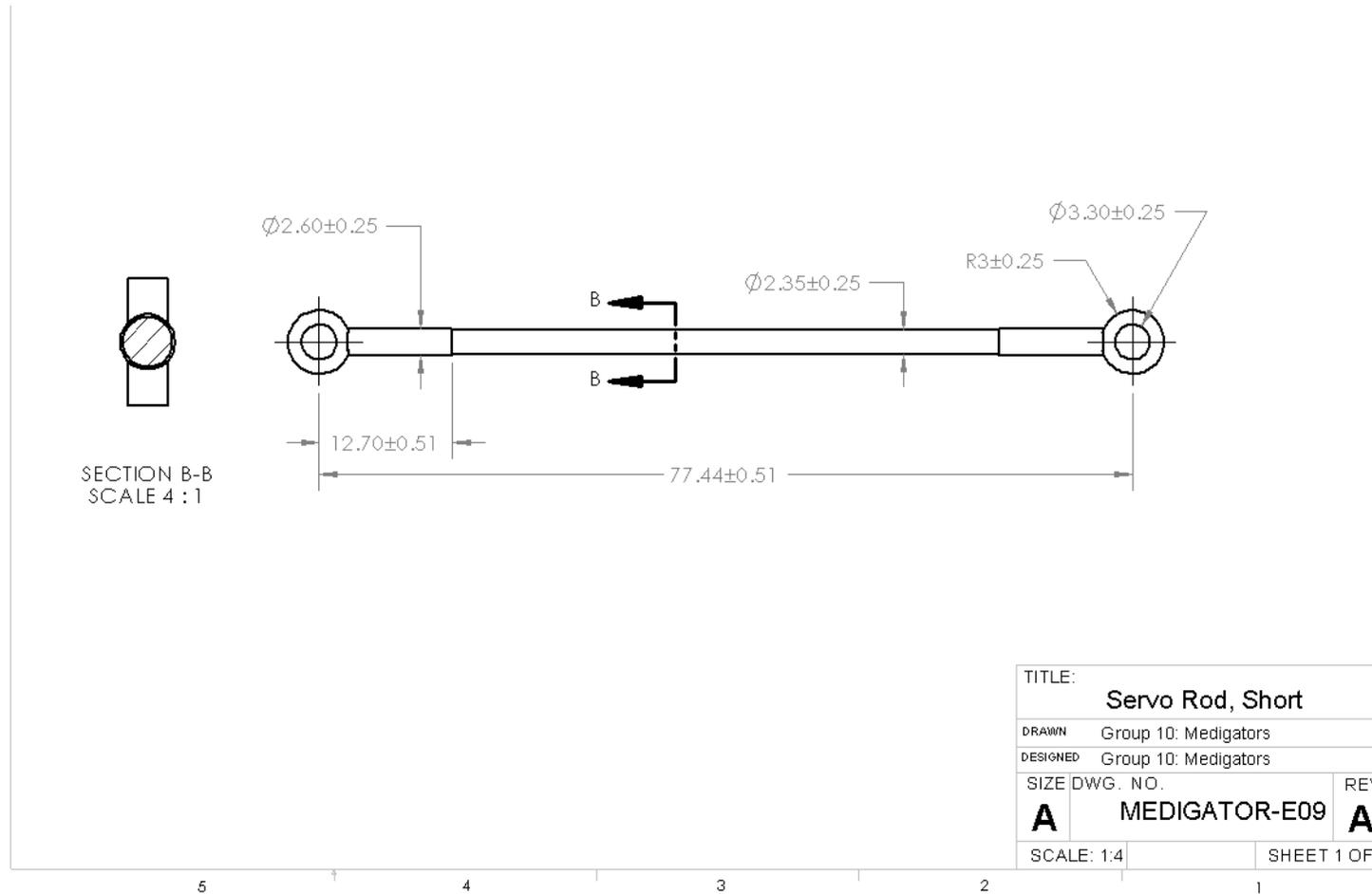


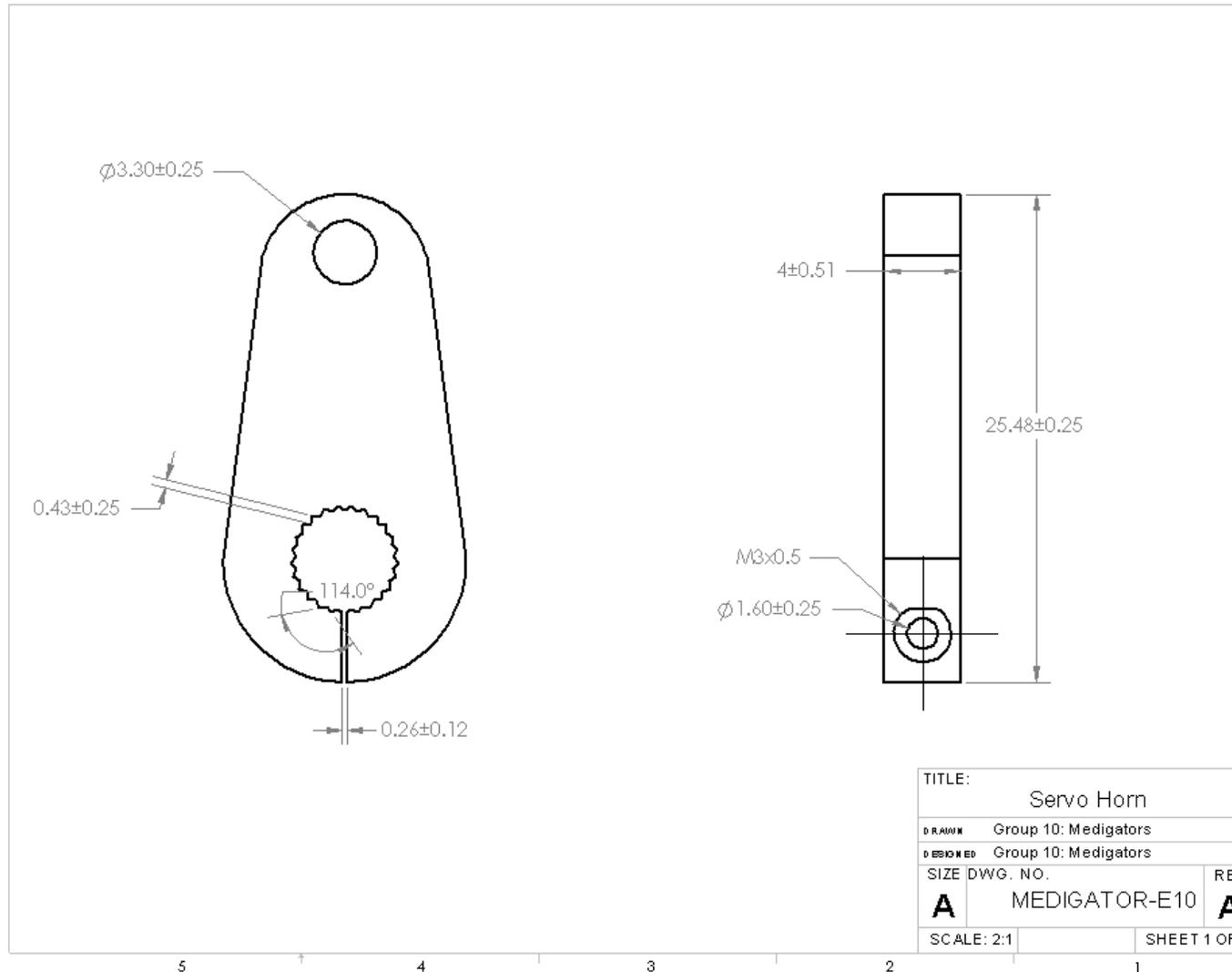
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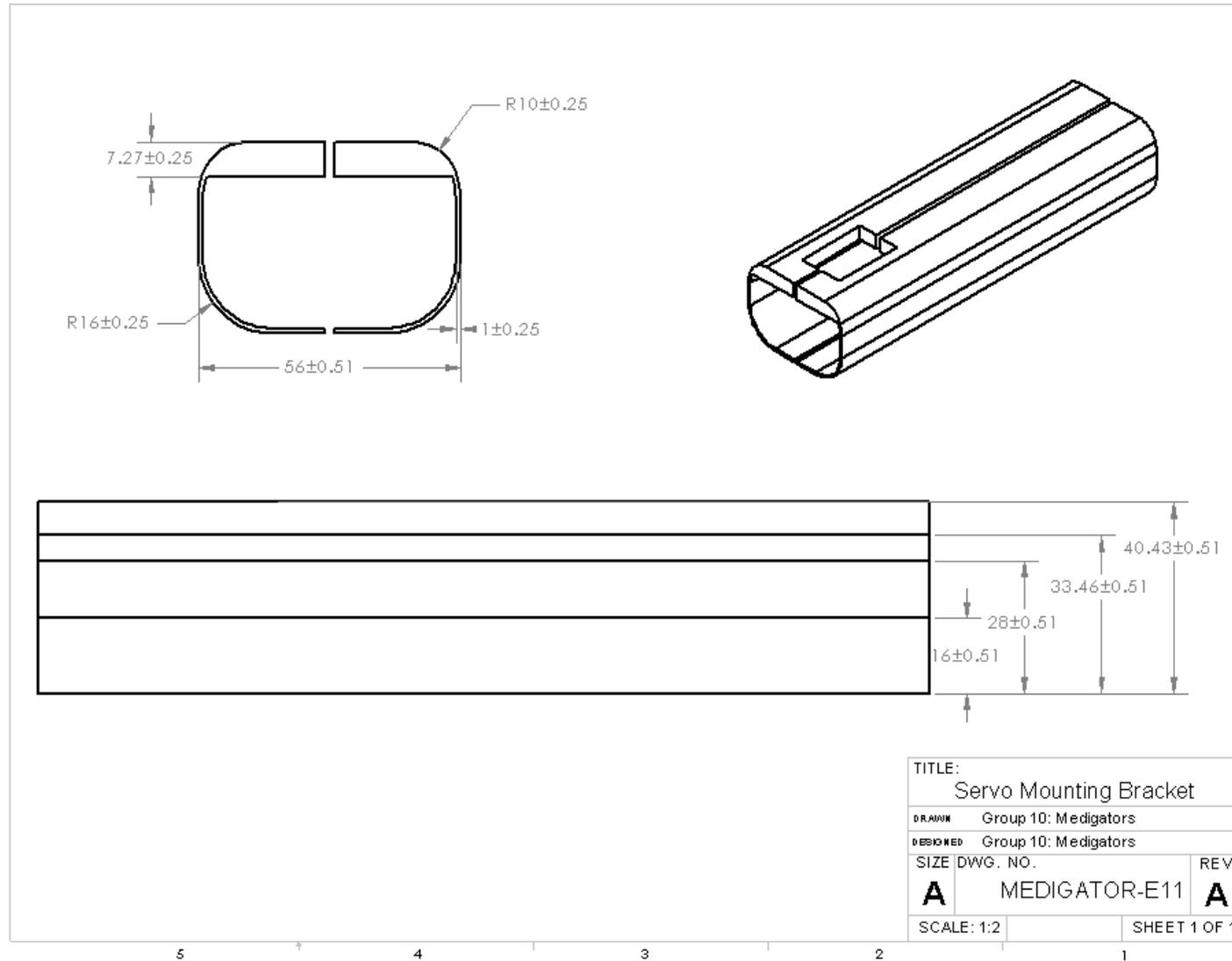


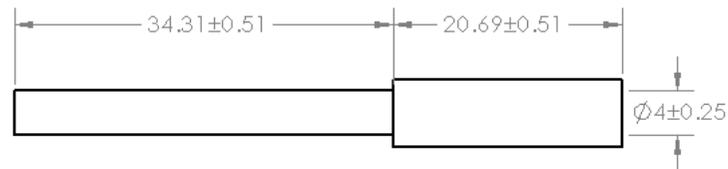
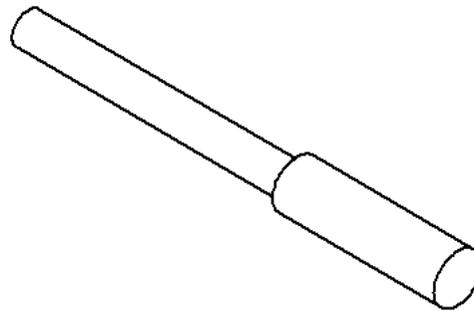
SECTION A-A
SCALE 8 : 1

TITLE:	
Servo Rod, Long	
DRAWN Group 10: Medigators	
DESIGNED Group 10: Medigators	
SIZE DWG. NO.	REV
A	MEDIGATOR-E08 A
SCALE: 1:4	SHEET 1 OF 1









TITLE:		
Servo Mounting Rod		
DRAWN	Group 10: Medigators	
DESIGNED	Group 10: Medigators	
SIZE	DWG. NO.	REV
A	MEDIGATOR-E12	A
SCALE: 1:1	SHEET 1 OF 1	

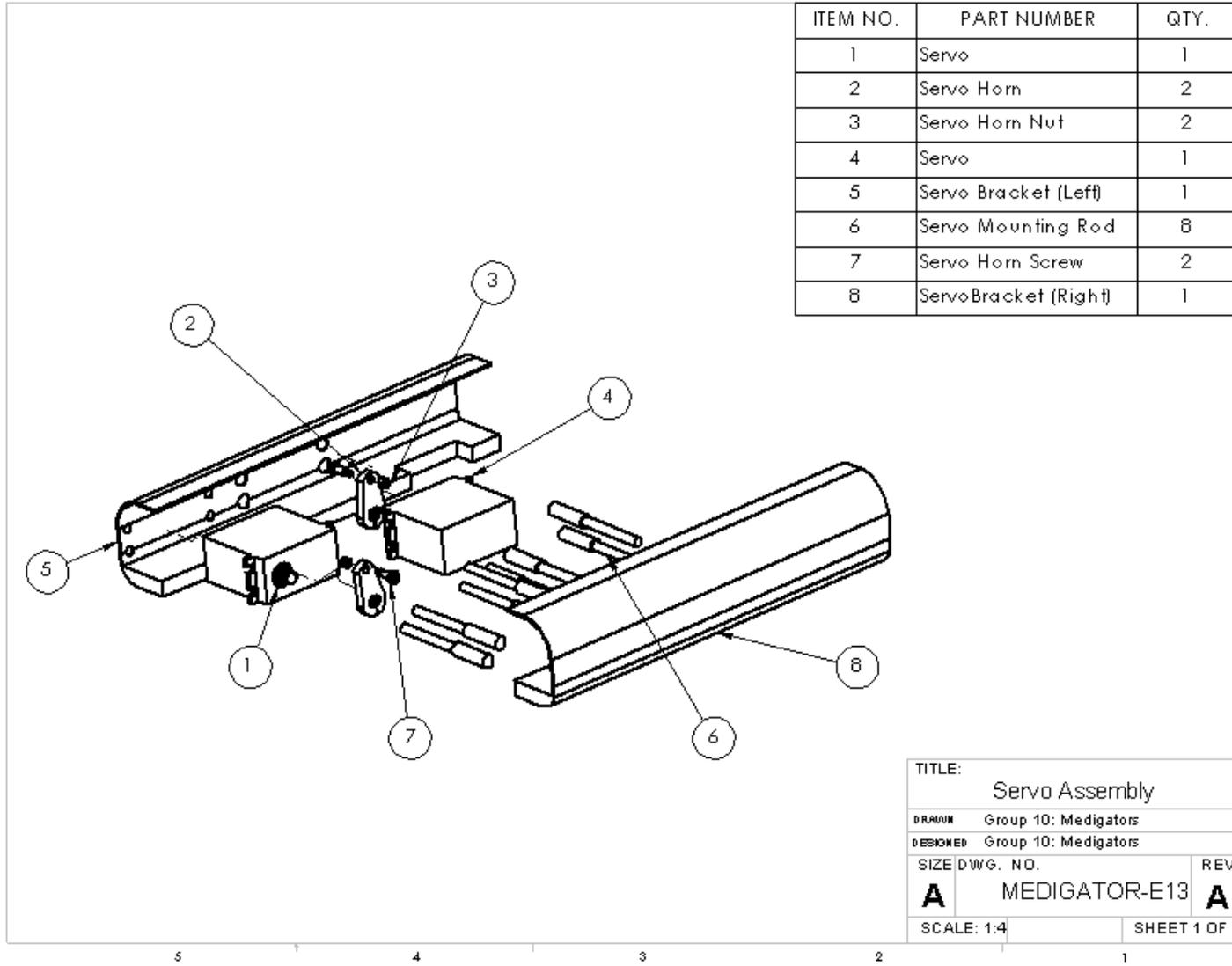
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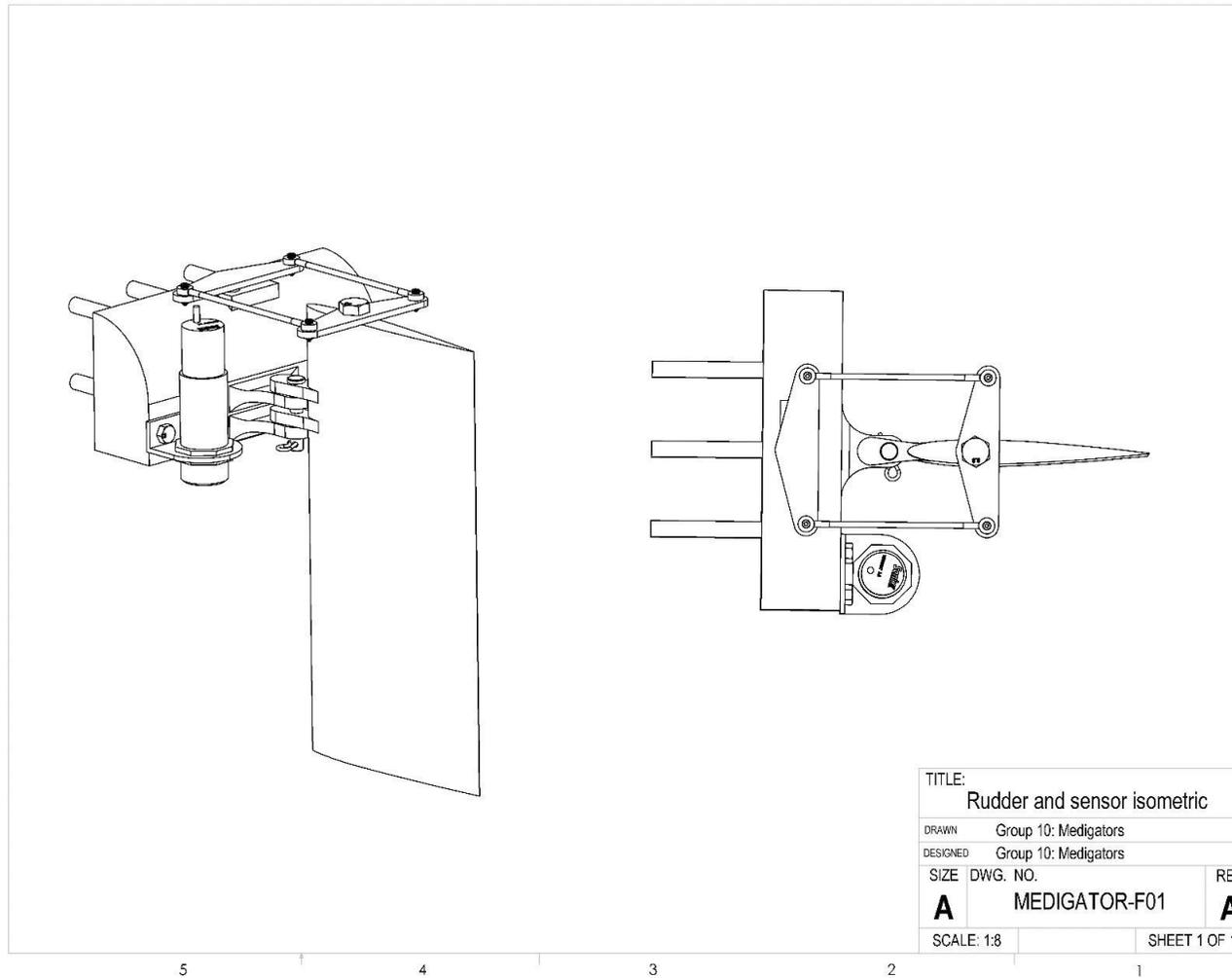




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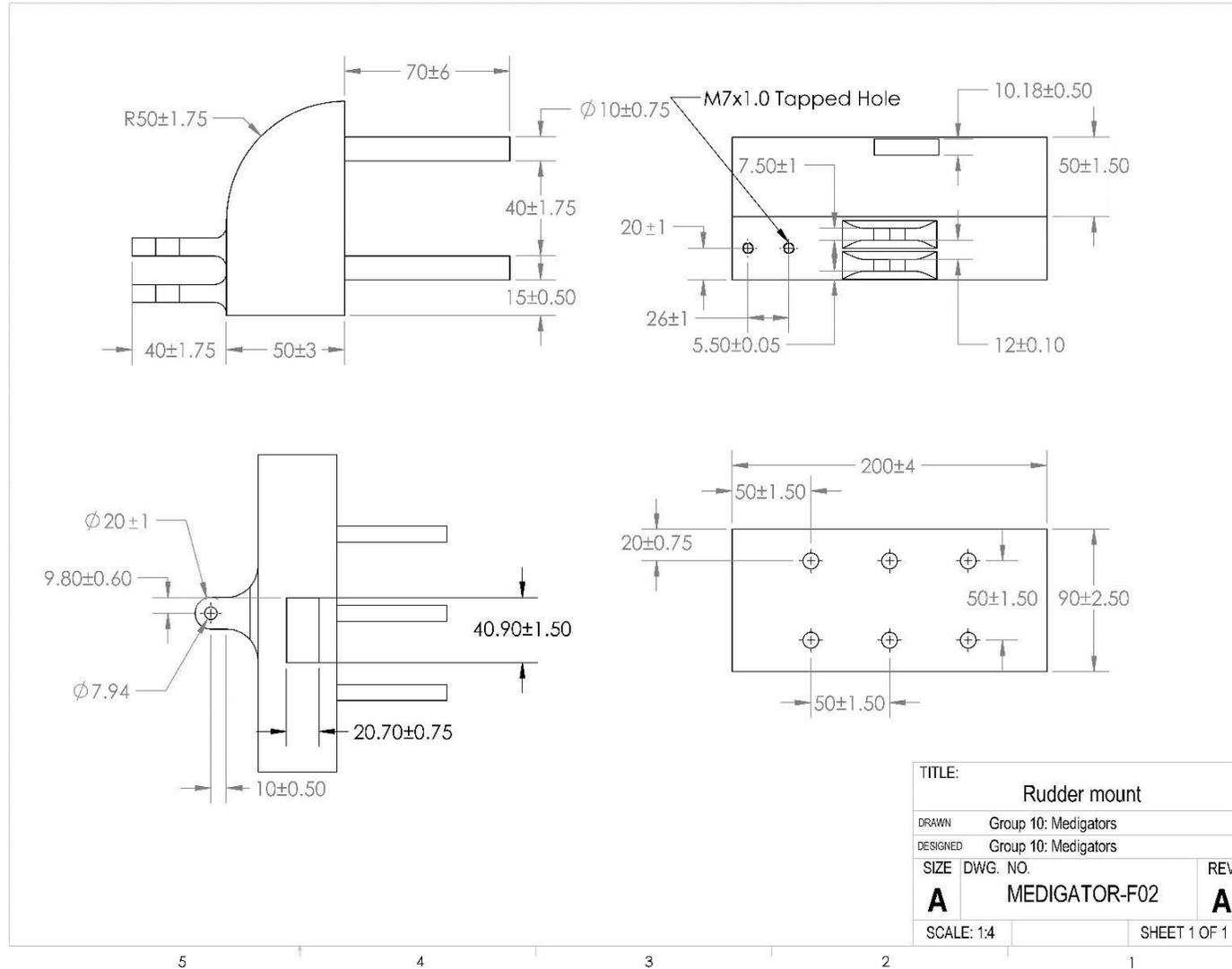


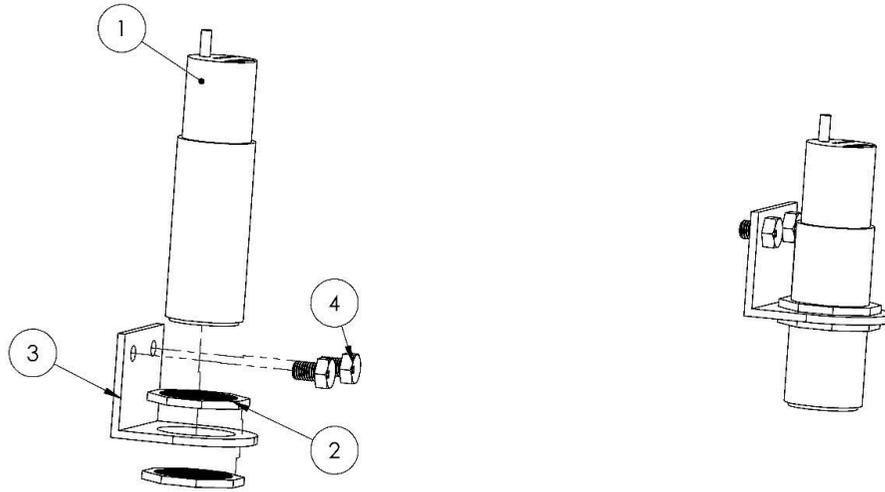
APPENDIX I RUDDER AND SENSOR ASSEMBLY





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ITEM NO.	PART NUMBER	QTY.
1	ToughSonic-14-ultrasonic-sensor	1
2	30mmNut	2
3	SensorBracketMount	1
4	M7-1.0x10	2

TITLE: SensorAssemblyExploded Drawing		
DRAWN Group 10: Medigators		
DESIGNED Group 10: Medigators		
SIZE	DWG. NO.	REV
A	MEDIGATOR-F03	A
SCALE: 1:2		SHEET 1 OF 1

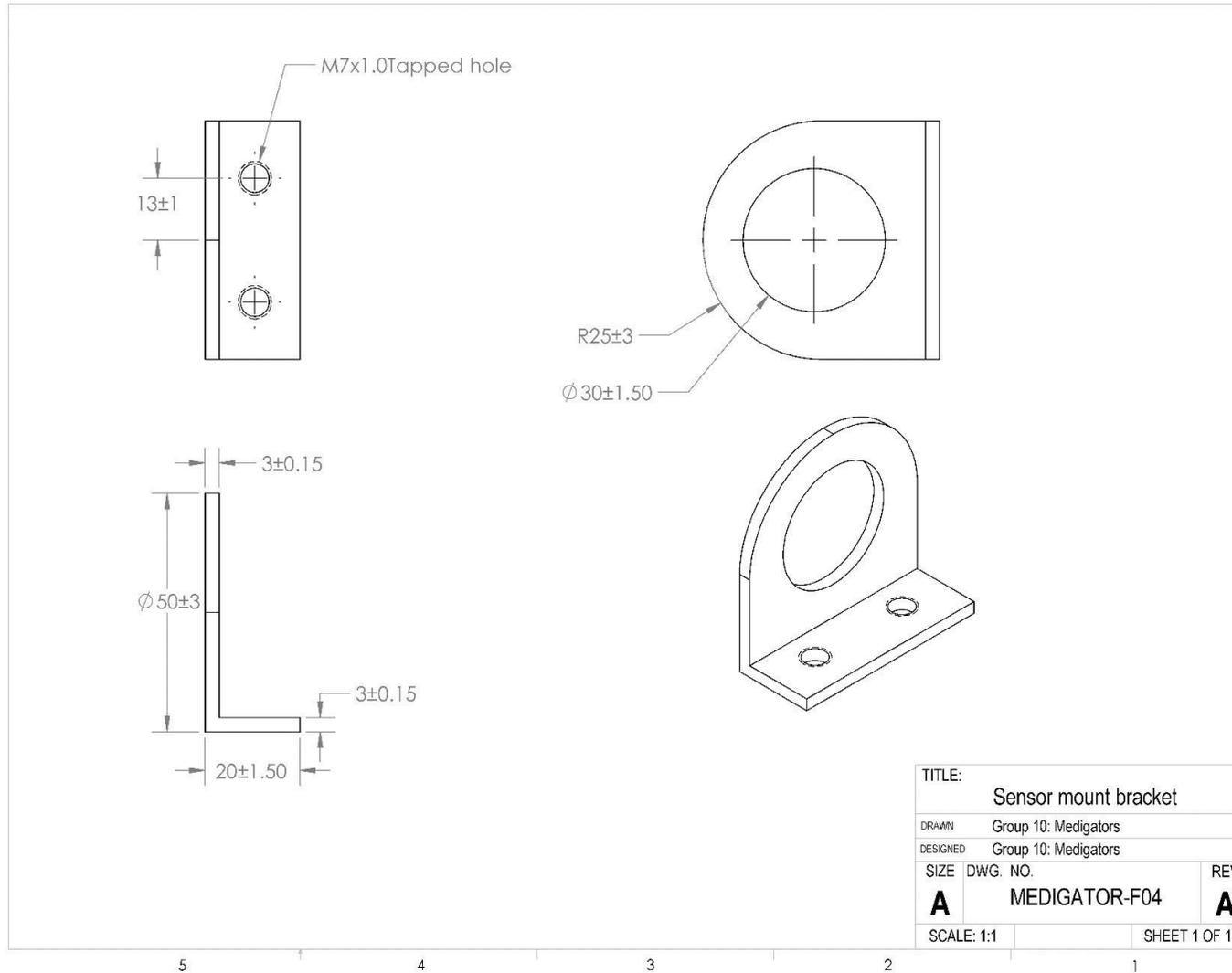
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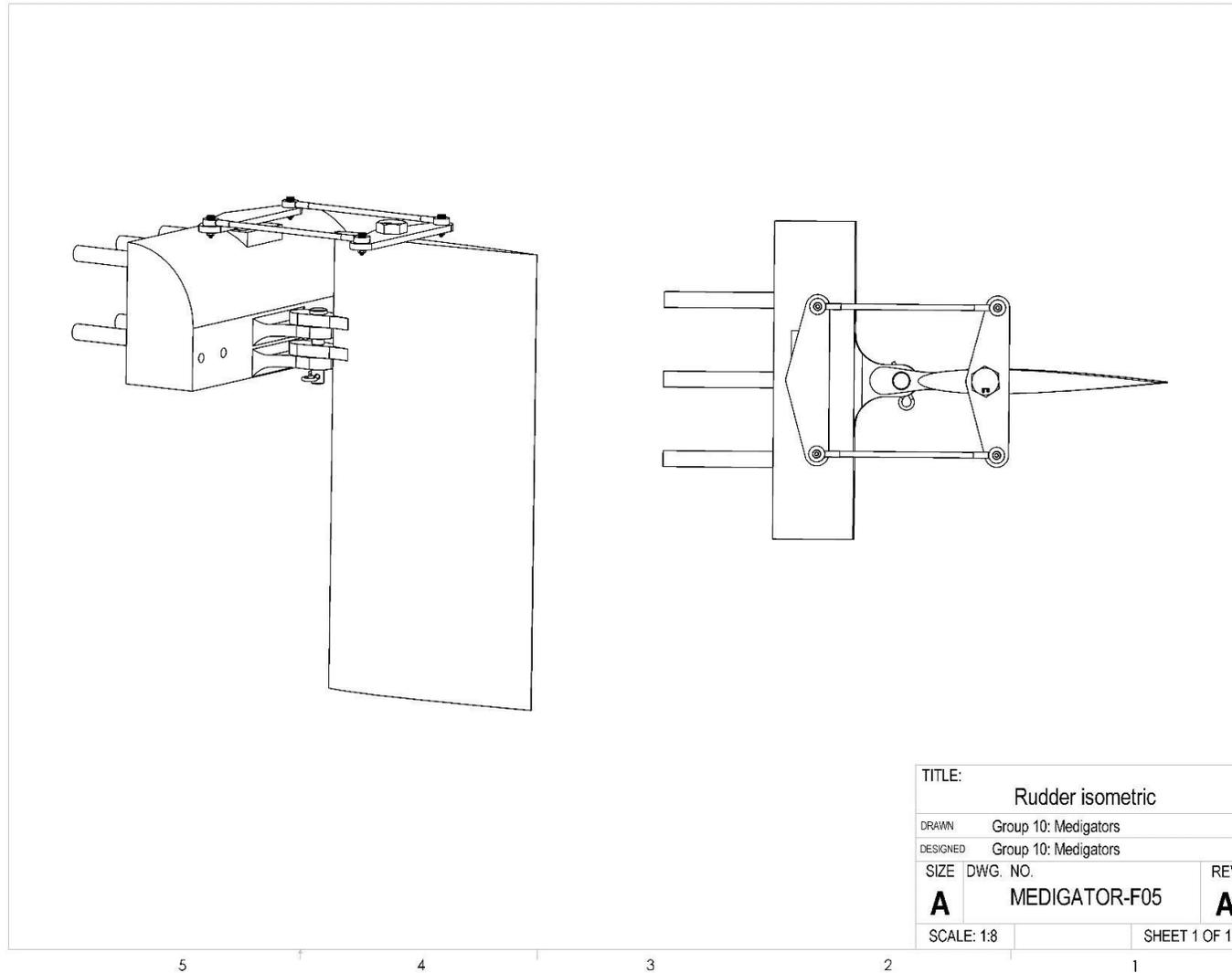
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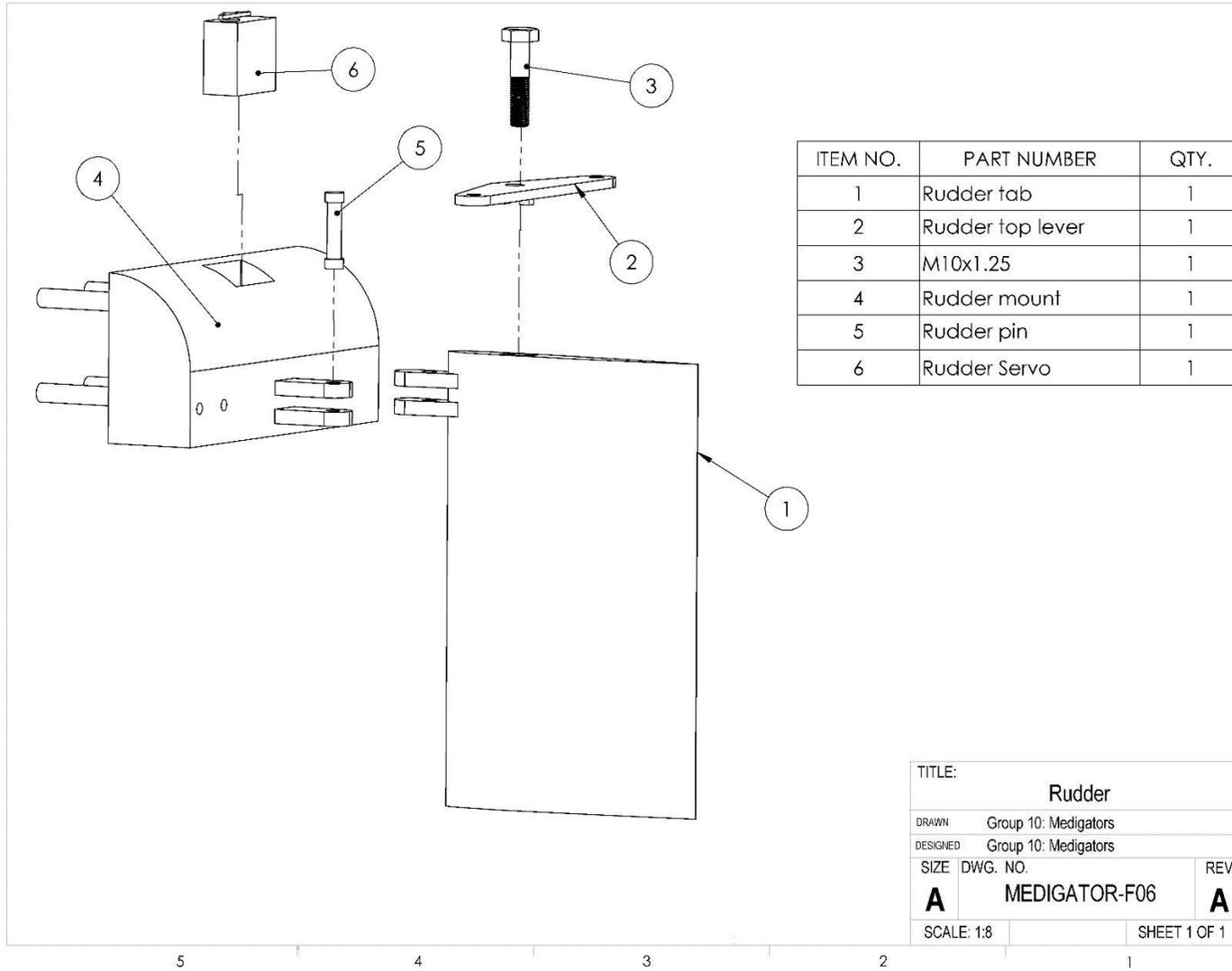
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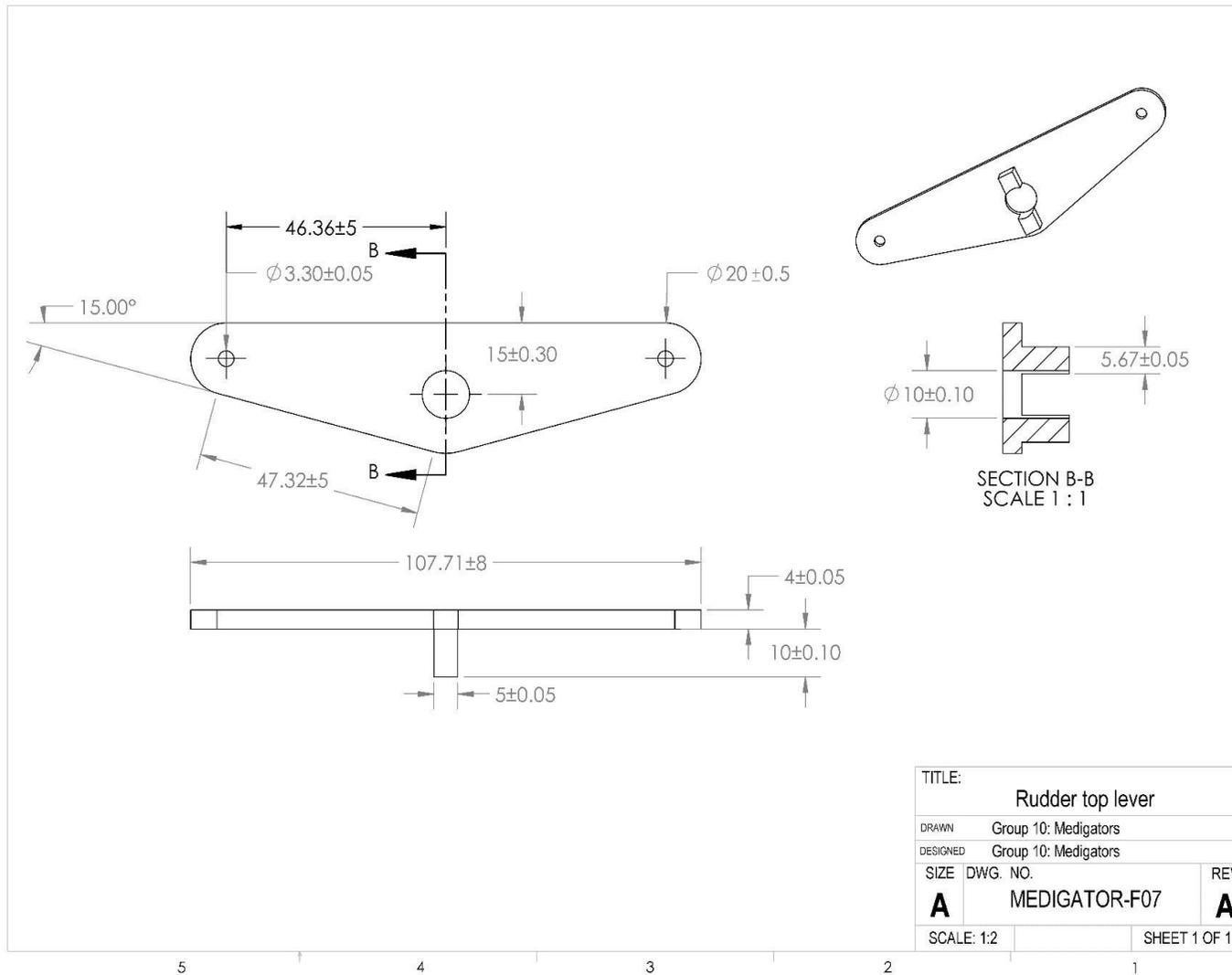
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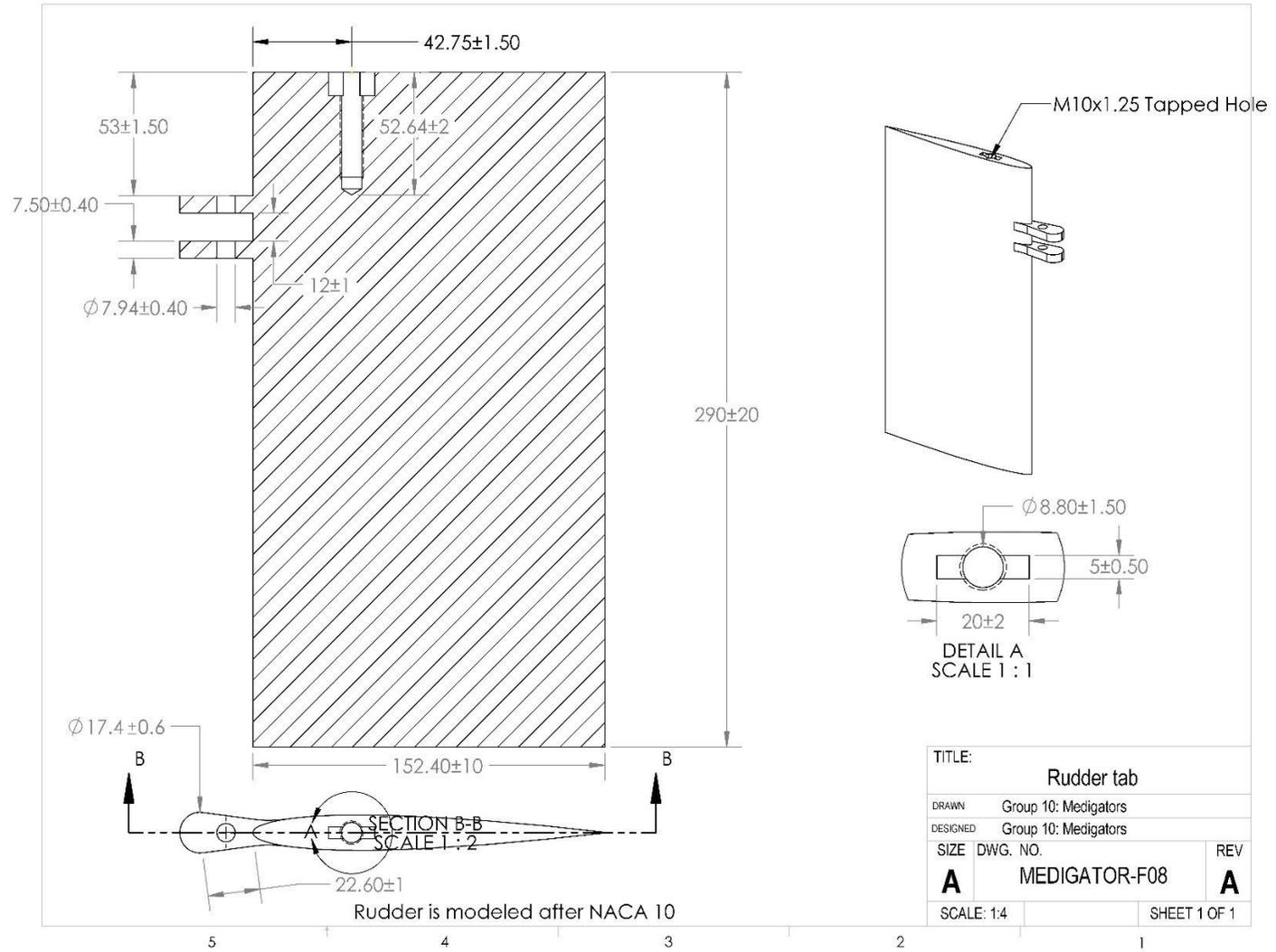
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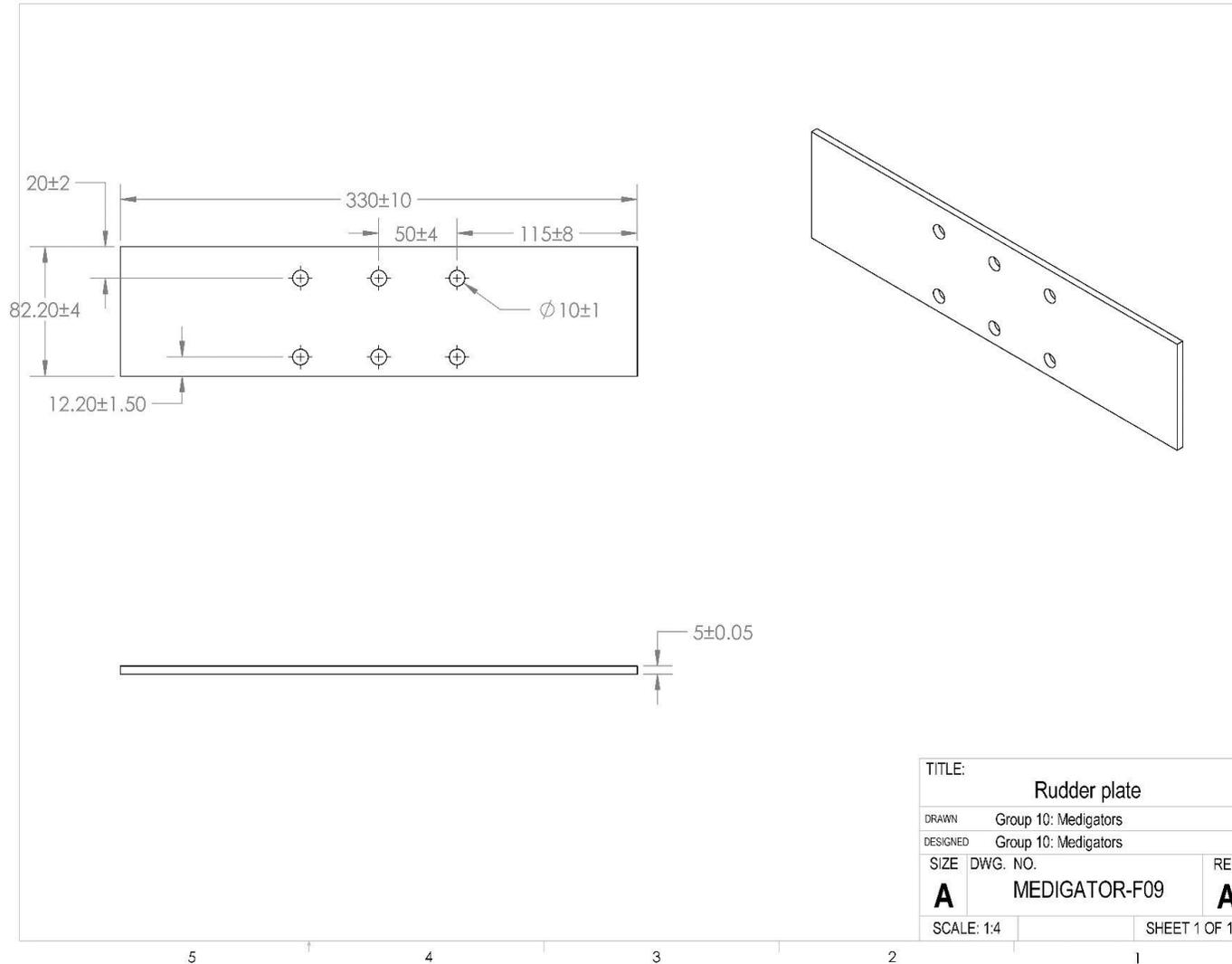














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APPENDIX J MAST

