Re-Design and Prototyping of an Electric Outboard Propulsive Leg using Additive Manufacturing Techniques

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Abstract – *The development and adoption of Additive Manufacturing (AM) technologies continues to increase in different emerging areas. One of these areas is marine industry where the demand of producing lightweight cost effective AM components has been going on for the last couple of years to increase functional efficiency. This paper goes through a case study where some critical components of an electric outboard propulsive leg have been redesigned to gain benefits from the AM technology in terms of better performance, less costly and rapid development of components, which require no tooling and other associated costs.*

Key Words: Additive Manufacturing, Propulsive Leg, Finite Element Analysis, Computational Fluid Dynamics Analysis

1. INTRODUCTION

Additive Manufacturing is considered as the next industrial revolution and technology of the future in manufacturing of intricate components while benefiting from high quality with very little time in production as compared to traditional manufacturing processes. Due to its adaptability to custom designs and well established benefits, application of AM technologies has been extended from medical to aerospace, automotive and marine engineering. Additive Manufacturing allow new innovative design to be produced with regards to material, shape and complexity of the part because these manufacturing processes eliminate the need of tooling.

Majority of constraints inherent in f current conventional manufacturing processes' are eliminated with the use of AM processes. However, AM processes have their own characteristics and requirements, which needs to be considered during the design stage to ensure the manufactured parts conform to the quality requirements.

The purpose of this paper is to review the application of AM technology in different sectors and to present their application systematically using a case study of designing and developing an electric propulsive leg. The project followed a methodical process in evaluating a current electric outboard propulsive leg design, which was achieved through the breakdown of a current propulsive leg available in the market, check/re-define the requirements for an electric propulsive leg, through market research and tools such as a QFD and FMEA. These requirements were then used as the basis for re-designing the propulsive leg in a way that it would then be possible to produce it using additive manufacturing techniques. Furthermore, this project evaluated the new design based upon the following parameters: how the additive manufactured design has improved the current design and how well the additive manufactured design stands up to the stresses placed on the propulsive leg which was achieved through computer simulation techniques such as Finite Element Analysis and Computational Fluid Dynamics. This paper presents the key project stages of design and development of the electric propulsive leg using additive manufacturing technologies further provides a methodology to use AM techniques for prototype development and the steps that should be followed for a successful new product development and for the improvements in the existing product.

2. APPLICATION OF ADDITIVE MANUFACTURING (AM) TECHNOLOGY IN DIFFERENT SECTORS

Additive Manufacturing(AM) is defined as "the process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies, such as traditional machining" [1]. Similar definitions in the literature are additive layer manufacturing, layered manufacturing, 3D printing, and free form fabrication. Common materials include: Polymers (such as Nylon, ABS and Epoxy Resin), Metals (Maraging Steel, Titanium Alloy, Stainless Steel and Aluminium) and Ceramics (Silica/Glass, Porcelain and Silicon Carbide) [2]

Gibson et al [3] defines eight key steps in the generic process of CAD to part through any AM technology:

1. Conceptualization and CAD modelling
2. Conversion to STL file format
3. Transfer and manipulation of STL file on AM machine
4. Machine setup
5. Build part
6. Removal of part and clean up
7. Post-processing of part
8. Use/Application of part

Holmström et al. [4] suggest the unique characteristics of AM production lead to the following benefits:

- No tooling is needed significantly reducing production ramp-up time and expense.
- Small production batches are feasible and economical.
- Possibility to quickly change design.
- Allows product to be optimised for function (for example optimised cooling channels).
- Allows economical custom products (batch of one).
- Possibility to reduce waste.
- Potential for simpler supply chains; shorter lead times, lower inventories.
- Design customization and optimisation.

In its early years AM was mostly applied for the fabrication of conceptual and functional prototypes, also known as Rapid Prototyping (RP). These prototypes were most commonly used as communication and inspection tools, producing several physical models in short time directly from CAD models to shorten the production development steps [5].

The advantages of AM technologies have been utilised in a variety of applications spanning a number of industrial sectors and different stages of product development. Some examples include titanium and steel aerospace parts where only 10% of the overall raw material is required when compared to the original machined components [6]. Atzeni and Salmi [7] showed the economics of additive manufacturing for end-use parts through comparing the production of landing gear aircraft assemblies through high pressure die casting (HPDC) and laser sintering. The advantages of AM have been utilised in the production of race car gear boxes [6], which facilitates the manufacture of smooth internal profile of gears providing faster gear changes and also reducing component weight by 30%. Cooper et al. [8] also showed the chances for improved functionality in their study on formula one technology through applying AM to manufacture of hydraulic component increasing efficiency of fluid flow by 50%. The applications of AM processes in creating functional ready to use consumer components have also been successful in some areas. Significant areas of success include the production of medical devices such as dental crowns and hearing aids, driven by customer requirements for individualised products since AM processes can be used for unlimited design freedom and design customization. The aerospace sector has also found a number of applications particularly in the development of jet engines where application of AM technology facilitates the reduction of number of separate components for assembly. The AM technologies also have enabled designers to design and manufacture complex assemblies as one part thereby reducing cost and time required for assembly of products as well as designing and developing tooling of some components. As an example, GE Additive have been using AM techniques to build more efficient fuel nozzles for jet engines [9] and so far produced 30,000 of them. European Space Agency (ESA) have used AM techniques to build a new thruster chamber using a platinum-rhodium alloy using a laser beam applied to a metal powder bed [10]. Since AM processes allow complex intricate designs to be developed without having any manufacturing constraints, a number of industrial sectors employed design optimisation to produce light weight strong and durable components most notably metal-based processes [11]. Other areas of AM application include automotive, jewellery, architecture and defence applications. The success and benefits of application of use of different AM technologies in different industrial sectors as shown in this section encouraged authors to redesign some important components and assemblies of electric propulsive leg considering AM processes and materials of choice.

The following sections of the paper discuss the stages of electric propulsion leg design following the AM process under seven main headings: Current Propulsive Leg Design Analysis, User Requirements for New Design, Product Design Specifications, and Additive Manufacturing Technologies for New Design, Propulsive Leg Configurations and Alternative Designs, Detailed Design, Prototyping and Evaluation through FEA and CFD Analysis.

3. CURRENT PROPULSIVE LEG DESIGN ANALYSIS

The purpose of this stage of the project is to identify the technical requirements needed to create an improved design using AM techniques of the current propulsive leg. To obtain such technical requirements, two main techniques: Quality Function Deployment (QFD) and Failure Mode Effect and Analysis (FMEA) tools were used. Initial step of the project was to develop technical requirements. This section presents a high level summary of the technical requirements identified and how these impact the final performance, manufacturing possibilities and user friendliness of the new design.

3.1 Product Breakdown Structure

A typical off the shelf market available electric outboard propulsive leg as shown in Figure 1 was used merely for the purpose of identifying and analysing main functional components and subassemblies of a typical electric outboard propulsive leg which includes an electric motor that is able to produce 55 pounds of thrust. The tilt is adjustable in length and height. This outboard includes an electrical mechanism to lift and deploy the propeller. The electric motor is powered by an external 12 Volts battery, which has to be stored in the boat. The motor weights around 13kg without battery. This outboard can be used both in saltwater or freshwater.

Figure 1: A typical electric Outboard propulsive leg.

Figure 2 shows a hand drawn diagram of the propulsive leg, it is possible to see the individual features and how they are related i.e. whether they are performance related, aesthetic related or both. The product is broken down and grouped as shown in the diagram. The main sections are grouped in four different views.

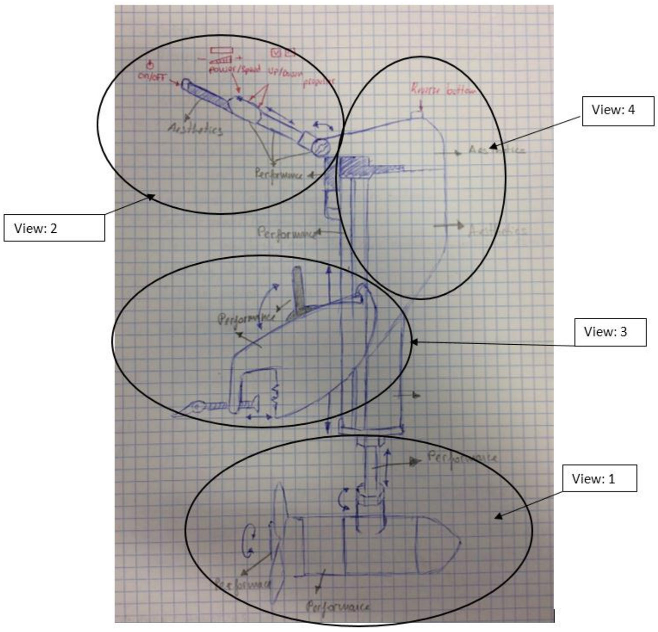

Figure 2: Sub assembly structure of propulsive leg.

View 1: Propeller subassembly. This specific subassembly of the product is designed to be the part that provides the power for the propulsive leg. It is where the motor of the propulsive leg is housed.

View 2: Telescopic tiller subassembly. This subassembly is designed to allow the user to adjust the length of the tiller when they are operating the product which then makes it easier and more comfortable for the user to operate.

View 3: Outboard Mount. The purpose of this subassembly is to allow the attachment of the propulsive leg to the transom of the boat being propelled. It uses screws and a grip mechanism to do this.

View 4: Outboard main body. This subassembly protects and covers the internal components of the propulsive leg. Furthermore, it makes the propulsive leg look aesthetically pleasing.

3.2 Current Propulsive Leg Design Analysis Summary.

A detailed QFD and FMEA analysis of the selected propulsive leg has been done. From the analysis of the current propulsive leg and the information obtained through the QFD and FMEA it is possible to identify the following areas to be improved using additive manufacturing techniques.

Main body: The systems used for functions such as steering or propeller height adjustment are areas where the design could be significantly simplified. Modifying the design in these areas would also allow the adaptation of the design to be manufactured using AM techniques. Even though the electrical components of the propulsive leg are protected by casing, during the disassembly it was possible to identify that the casing was not fully watertight. For the new design, the water resistant capabilities of the external casing was considered.

Telescopic Handle: Another area of improvement that has been highlighted through the accomplished methods would be to change the display of the outboard buttons/controls to improve the user's interface. It would also be beneficial to improve the water insulation in the buttons as there are possibilities of water going inside and damaging the electrical components.

The Propeller Subassembly: As the casing for the motor is made of one piece of cast-aluminium it has not been possible to evaluate this area in more depth. As the functions of the propeller spinning both directions are easily accomplished by the subassembly, the possibilities to redesign this area have been discarded.

Outboard Mounting: The transom mount that the selected propulsive leg features includes all the adjustments required of such component, however if the main body of the outboard was to be modified, the mounting would also need to be modified in order to adapt to the new design.

4. USER REQUIREMENTS FOR NEW DESIGN.

The next stage of the project is to define the high level user requirements for a low power propulsive leg i.e. what does the user want the product to do. This section will also identify the system requirements for a low power propulsive leg, i.e. how will the propulsive leg achieve these high level user requirements. The user/system requirements have been derived through propulsive leg research and derivation of requirements through the QFD and the FMEA. Furthermore, where user/system requirements have been met they have been linked back to the subassembly that allows the product to meet those requirement in section 3.1 (Product Breakdown Structure).

4.1 Performance

Electric outboards require to produce power enough to make a boat travel at speeds from one to three knots.

- The mount of the motor must secure the motor in the right position and resist the thrust that produced by the motor.
- The steering system of the outboard must not interfere with any component of the boat.
- The shaft of the motor is required to be long enough to be submerged at all times as well as not interfering with the transom of the boat.
- The main functions of an outboard are forward/reverse drive, speed adjustment and steering.

4.2 Environment

- As the product is going to be used in the water the electrical components must be adequately protected. This requirement is not yet sufficiently met with the current product
- The components of the outboard must have outstanding anti-corrosion properties. This requirement has been met through the materials selection choice of the propulsive leg
- Rotating parts are required to have good lubrication and abrasion resistant properties. This requirement has been met through the lubrication of correct parts, this was found through deconstruction of the propulsive leg

4.3 Usability

- To improve user friendliness, it is required of the outboard to be easily removable and transportable. This requirement has been met as the selected propulsive leg only weighs 13 Kg (maximum).
- The tiller must have an adequate angle of operation to avoid interfering with the user or boat components.
- The cables that connect the outboard to the battery in the boat must have adequate length. This requirement is not met with the current design as the battery is treated as a separate component to the current product

4.4 Health and Safety

- The electrical components in the overboard must meet the Boat safety scheme for electrical installations (BS EN ISO 10133:2001) [12]. All the electrical components in the selected propulsive leg have an external insulation layer.
- Hazardous moving parts such as propeller must not interfere with the user at any time during normal operation of the device. As it can be observed in view 1 the propulsive leg has a long extensible shaft that keeps the propeller immersed at all times during operation.
- Small open power boats must be fitted with a kill cord which, in case of the driver becoming dislodged from the helm position, will stop the motor immediately. The given propulsive leg lacks of this safety system.

4.5 Maintenance

- The equipment should be rinsed with fresh water after every use. Ideally, the propulsive leg designed should have a system to facilitate the flush the stagnant water.
- The battery should be unplugged when not in use. The terminals of the battery can be easily unplugged when the motor is not in use.
- The battery and other connections should be kept dry at all times. To make the propulsive leg watertight it is essential that the battery and connections need to be protected by any watertight casing.

5. PRODUCT DESIGN SPECIFICATIONS FOR NEW DESIGN

Having a good design specification allows the engineer to design something that meets all of the criteria set out by the customer/user. In this case the design specification has been derived from FMEA and QFD tools. The FMEA/QFD identify a system requirement, for example the propulsive leg providing enough power to allow the boat to travel up to 3 knots. This then spawns several design specifications such as: the propulsive leg having a large enough motor, the propulsive legs propeller is designed to best utilize the power outputted by the motor and the propulsive leg having a significant enough power source. From this it is possible to derive measures to see once the product has been made if it meets the requirements e.g. a threshold measure would be the boat traveling at 3 knots and the objective measure would be the boat traveling faster than 3 knots. This process can then be repeated for all of the system requirements for the propulsive leg which will allow the identification of all the design specifications to be considered allowing informed decisions to be made within the initial design stages. Table 1 shows the full product design specifications.

Table 1: Derived Product Design Specifications

System Requirement	Design Specification	Measure
The outboard provides enough power to make the boat travel up to 3 knots.	D1: The propulsive leg has a large enough motor D2: The propulsive leg has a propeller designed to best utilize the power from the motor D3: The propulsive leg has a significant enough power source	Threshold: The boat travels up to 3 knots Objective: The boat travels faster than 3 knots
The mount of the motor must secure	D4: The mounting has a strong grip	Threshold: The trim/height of the

the motor in the right position resisting the thrust produced by the motor.	onto the boat D5: The mounting has a secure method of keeping the trim of the motor in the same place	motor remains the same during operation Objective: The trim/height of the motor remains the same during extra loading. (For example in the case of the propulsive leg colliding with something in the water)
The steering system of the propulsive leg must not interfere with any component of the boat.	D6: The tiler must be designed in a way that it is clear from parts of the boat D7: When the tiler is used to adjust the direction of the propulsive it must be clear from parts of the boat	Threshold: The steering system does not interfere with any component of the boat Objective: There is extra room surrounding the steering system for easy access
The shaft of the motor is required to be long enough to be submerged at all times as well as not interfering with the transom of the boat.	D8: The shaft is at least 1m long D9: The propulsive legs height can be adjusted through the mounting bracket	Threshold: The motor is submerged at all times Objective: The motor is able to fit on a wide variety of boats
The electrical components of the propulsive leg need to be protected from the marine environment.	D10: Electrical components are waterproofed D11: Where possible electrical components are housed above the waterline D12: Electrical components are housed within a waterproof casing	Threshold: The electrical components are mounted in such a way that they are clear from the water Objective: The electrical components are waterproofed
The components of the propulsive leg need to have good corrosion resistance	D13: The components material selected has good corrosion resistance D14: The components material selected can be treated so that the component has good corrosion resistance	Threshold: The components material can be treated to resist corrosion. Objective: The components material resists corrosion.
Rotating parts have good lubrication and abrasion resistance properties	D15: Rotating parts are lubricated D16: The material used for the rotating parts has good abrasion	Threshold: The components are lubricated Objective: The components have good self-

	resistance properties	lubricating properties
The propulsive leg needs to be easily removable and transportable	D17: The propulsive leg has a simple and easy to use attachment system to the boat D18: The propulsive leg is kept below 12 Kg	Threshold: It is possible to carry the propulsive leg with one hand Objective: It is possible to carry the propulsive leg with minimal effort
The electrical components within the propulsive leg must meet: BS EN ISO 10133:2001	D19: All the electrical components must have an external insulating layer	Objective: The propulsive leg meets BS EN ISO 10133:2001
The propulsive leg must have a way of stopping when the user is no longer in control of the vessel	D20: The propulsive leg has a kill cord	Objective: The propulsive leg stops when the user disengages the kill cord
The propulsive leg must not hold stagnant water	D21: The propulsive leg has a flushing system to remove stagnant water D22: A hose can be used to reach areas of the propulsive leg where stagnant water can build	Threshold: It is possible for the user to flush water from the propulsive leg Objective: There is nowhere on the propulsive leg where stagnant water can build up
It is possible to adjust the height of the propulsive leg	D23: There is a method of adjusting the height of the propulsive leg	Threshold: The user can adjust the height of the propulsive leg in relation to the water Objective: The user can adjust the height of the propulsive leg in relation to the water while the propulsive leg is in operation
The propulsive leg has a significant effect on the direction of the boat	D24: The tiler has a wide range of movement D25: The propulsive leg utilizes the hydrodynamic flow of the water to best suit the direction chosen by the user	Threshold: The user has an effect on the direction of the boat using the propulsive leg Objective: The user has a significant effect on the direction of the boat using the propulsive leg

6. PROPULSIVE LEG CONFIGURATIONS AND ALTERNATE DESIGNS

Having identified the less practical design features of the existing propulsive leg through QFD and FMEA, it has been possible to make some design iterations on the given propulsive leg. The aim of such iterations is to reduce the weight, improve performance, and simplifying the manufacturing process.

One of the main aims of the design iterations has been to simplify the overall design. The functions of the highlighted areas (mounting bracket, shaft, casing and tiller) have been critically analysed, allowing to create subassemblies with a significant reduction of components and therefore in weight. Five detailed conceptual design iterations were developed and thoroughly evaluated against product design specifications using Analytic Hierarchy Process (AHP) [13], a scientific design alternative selection method. A final best design alternative has been selected through this process which is explained here in further sub-sections:

6.1. Selected Design Alternative

The main advantages of choosing the design alternative shown in Figure 2 is that the shaft used for the propulsive leg is significantly simpler. As this is already mass produced, it would be easy to integrate into the assembly thereby removing the need to have a complex gearing system that the previous design encompasses. This is due to the steering system pivoting from the mounting bracket and there has been a significantly reduction in weight as compared with the current design due to the adaptation/removal of unnecessary components, which has this significantly increased the usability of the design.

The selected design is a circular shaft that comes out of the main casing, which has the following benefits:

- Simplicity of the circular shaft allows a significant reduction in weight.
- There is no need for internal gearing systems for steering, as the new shaft would pivot around the mounting bracket.
- It offers a possibility to use commercial extrusions of lightweight materials such as carbon fibre for the shaft with a very low cost.

6.2. Mounting Bracket in the Selected Design

The mounting bracket of the given propulsive leg has a solid transom mount and incorporates a mechanism that allows several positions of trim adjustment. The area where the mounting bracket is in contact with the shaft of the propulsive leg has been redesigned. Figure 3 shows the design of the modified mounting bracket.

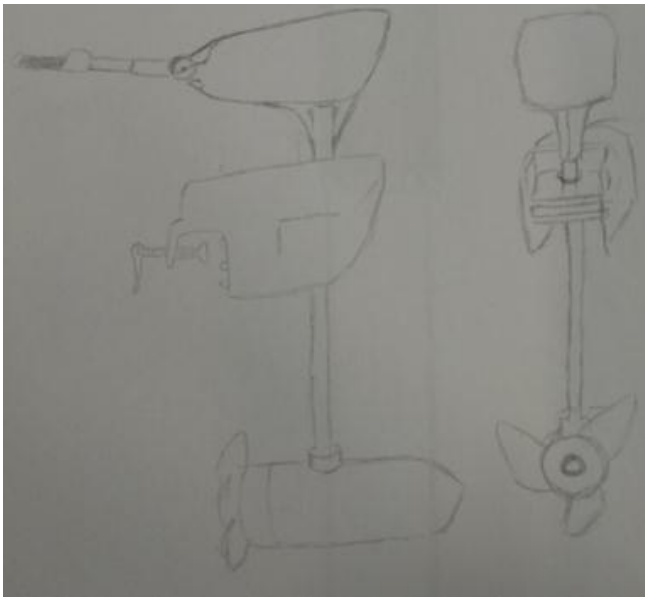

Figure 2: Full Assembly of Selected Design Alternative

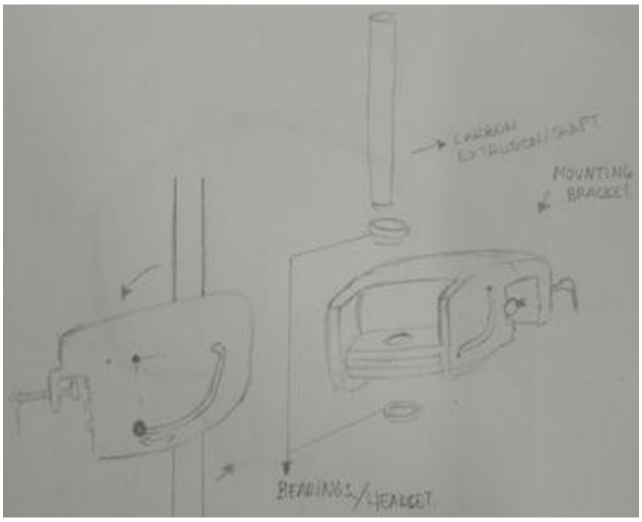

Figure 3: Mounting Bracket of Selected Design

The mounting bracket (Figure3) allows a much simpler steering system, which consists of two sets of bearings housed in the case, such bearings would allow the shaft to pivot around the mounting bracket without the need of gear systems. This has enabled a significant reduction in weight, manufacturing costs, and it is easier to lube, clean or replace for maintenance.

6.3. Casing in the Selected Design

Located on top of the propulsive leg is the top casing (Figure 4). The aim of this subassembly is to house all the electrical components of the propulsive leg. The new design consists of two main components:

Base: The bottom part of the assembly connects the shaft to the tiller. It is required that this component to have a solid structure in order to hold the weight of the outboard. It is also required of this component to have an adequate area to attach all the electrical components of the propulsive leg.

Casing: The aim of the casing is to isolate the electrical components from water. It is required of this component to be light and adapt perfectly to the base in order to make the entire subassembly watertight. A small display with battery charge LED indicator could also be located in this component.

The new casing design will have a big impact in the ease of manufacture and a high reduction is costs and weight. The amount of components in this subassembly has been reduced from 5 components in the existing propulsive leg, to only 2: base and casing. The simplicity of the shapes chosen for this components will allow to make the entire subassembly watertight in a much easier way.

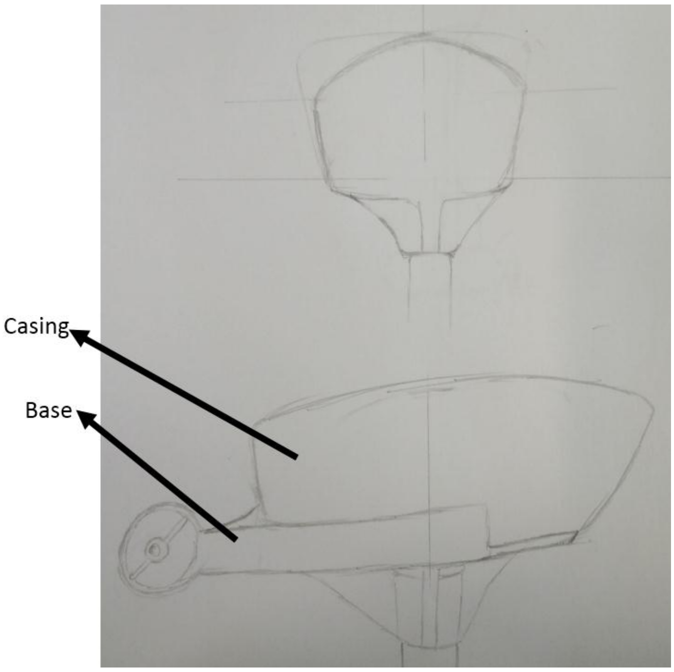

Figure 4: Casing of Selected Design

6.4. Tiller in the Selected Design

The tiller of the given propulsive leg features length adjustment through a telescopic mechanism, such tiller also includes a pivot point at the end where is in contact with the casing. With the aim of incorporating such features, the tiller has been redesigned (Figure 5) reducing the amount of components and incorporating the outboard controls in the handle.

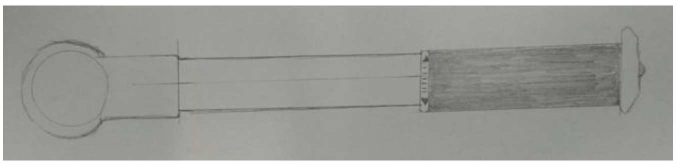

Figure 5: Tiller of Selected Design

The tiller design allows the telescopic mechanism staying inside the grip area, providing a much cleaner look. This design also incorporates a twisting throttle to manage the power of the outboard. As the electrical height adjustment has been suppressed, the amount of buttons have been reduced to one allowing a much more minimalistic design and reducing the possibilities of water going inside electrical components. The new design reduces the amount of components from the original design from 5 to only 3.

7. Material Selection

7.1. Shaft and Tiller Material

It is possible to see through the materials selection comparison tables derived from the AHP that the best material that is possible to produce using additive manufacturing techniques is ABS. This is because it allows the balance of good mechanical properties such as: medium strength, very high impact strength, high tensile strength and stiffness and excellent high and low temperatures performance with the density (Absmaterial.com, 2016). However, the mechanical properties are not as good stainless Steel, which is generally used in the manufacture of propulsive leg. As the propulsive leg uses low power and the strength requirements are not so high, ABS was considered as one of the main materials for design. This is because it is significantly more cost effective to additively manufacture parts using ABS rather than using metals. To ensure the propulsive leg will have sufficient strength using ABS, the design calculations were carried out and confirmed with FEA.

7.2. Mounting Bracket Material

Looking at the material comparison tables derived from the AHP, it is possible to see that the selected material (ABS) fares well when put up against the current material - Polypropylene. The only issues that are possible to see from section 8.2 is that the UV stability for ABS is poor when compared with Polypropylene. However it is possible to obtain ABS that has good UV stability when it is treated. (The other negative of using ABS when compared with the current Polypropylene is that the density is higher. However given that the new design will have significant weight reductions this should be compensated for. This was verified using FEA calculations.

8. DETAILED DESIGN OF PROPULSIVE LEG

A detailed thorough analysis has been done to identify all of the main forces that are going to be placed upon the propulsive leg. It has allowed for the identification and confirmation as to whether the dimensions of new parts parts/assemblies will be capable of withstanding the forces applied. Given that the calculations have shown that the parts are well up to the job of withstanding the forces, being twice as strong as required or more, this has led to a high FOS for all of the parts. Therefore, the information obtained from these calculations confirm that the new conceptual designs produced are durable enough and this was further confirmed via the FEA simulations.

Once the design calculations have been completed it was then possible to use a CAD software to allow the full design of the propulsive leg to be made. Through the 3D modelling package the individual parts that have been redesigned can be made and then assembled in one file to show the full concept design. Figure 6 shows the result of compiling all of the re-designed parts into one assembly.

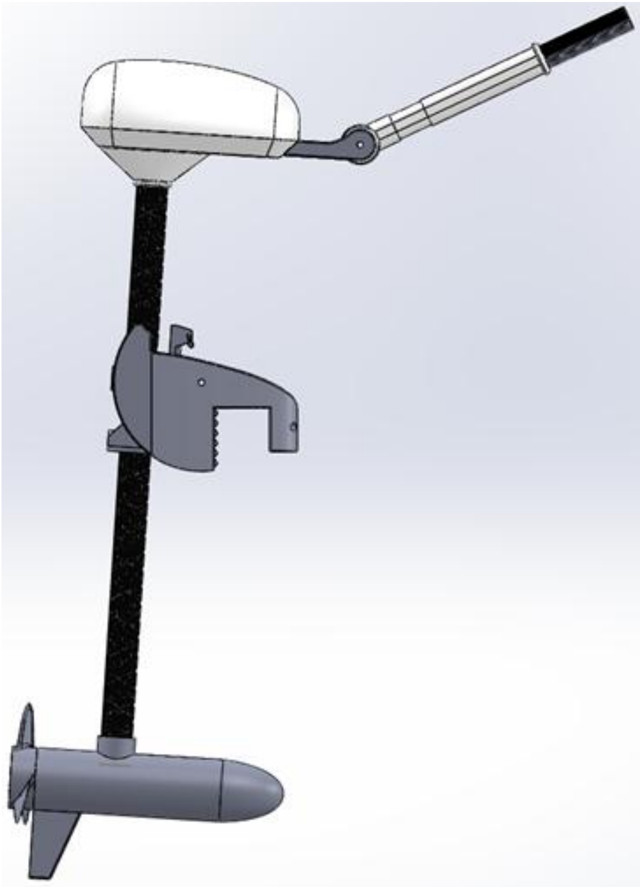

Figure 6: New Propulsive Leg Design Assembly CAD Model

Looking at figure above it is possible to see the key changes in design, the aluminum extruded shaft has been replaced with a lightweight smaller carbon fiber shaft. The tiler assembly has been replaced with a simplified tiler, which allows the changing of speed and direction via the handle on the tiler. It is also possible to see that the mounting bracket holds the shaft using two bearings, which allows the user to rotate the entire assembly and the propulsive leg is enabled to change the direction of the craft.

8.1. Mounting Bracket

Figure 7 shows the new design of the mounting bracket. Key features of the design are as follows: There are multiple grooves along the curved edge, which allow the user to choose from a wide range of trim adjustments. There are two screw holes at the front of the mounting bracket which is where the user can tighten up the mounting bracket where it attaches to the transom which then presses the grooved edges of the mounting bracket to the transom of the boat ensuring a full attachment. The final main change in design of the mounting bracket is that it is wider where the shaft goes through the mounting bracket, thereby allowing the correct sized shaft to attach to the mounting bracket and allow enough room for rotation.

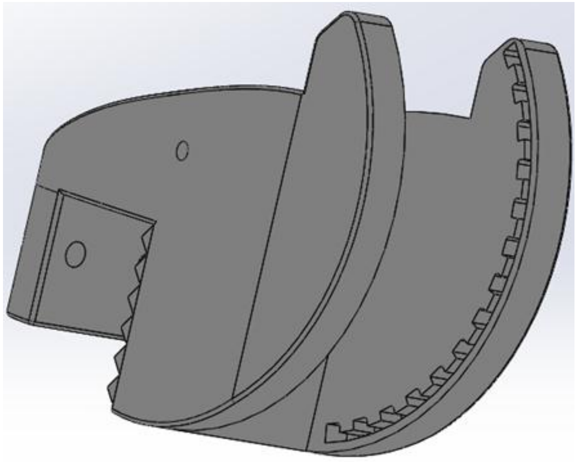

Figure 7: Mounting Bracket Design

8.2 Trim Mounting Design

Figure 8 shows the design of the trim mounting. This part has been designed so that the shaft which attaches the whole propulsive leg can run through it. It is then possible to mount this shaft onto two bearings which are housed within this component which then allow the shaft to pivot within the trim mounting allowing the user to adjust the direction. Other key features on this component is the jamming assembly mount which allows the user to adjust the position of the trim mount within the mounting bracket to achieve the desired motor trim.

8.3. Shaft Redesign

The shaft was another key area of re-design, this was because the previous propulsive leg shaft had to deal with a multiple amount of systems for things such as the propeller height adjustment and the steering gearing system. Given that our new design does not incorporate these features because it has been identified within the previous stages of the project they are not required. Key points with this design is that it is a commercially available size of carbon fiber shaft which can be easily and economically sourced. There is a notch at the top of the shaft where it attaches to the tiler

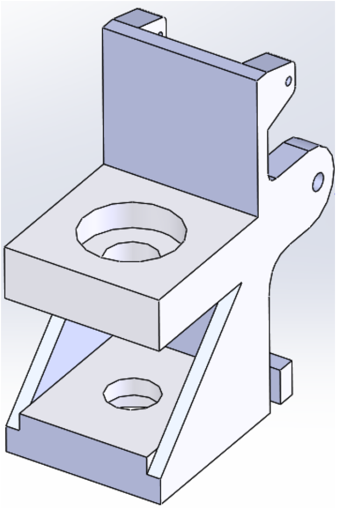

Figure 8: Trim Mounting Design

8.4. Pivoting Tiller Redesign

The joint between the tiller and the bottom part of the casing is a pivoting point that is used to adjust the height of the tiller. For an optimum steering it is fundamental that this feature can be locked at any height. To achieve so, the internal shaft has been redesigned including twelve round slots that are coincident with other twelve round protuberances as the figure 9 displayed below shows.

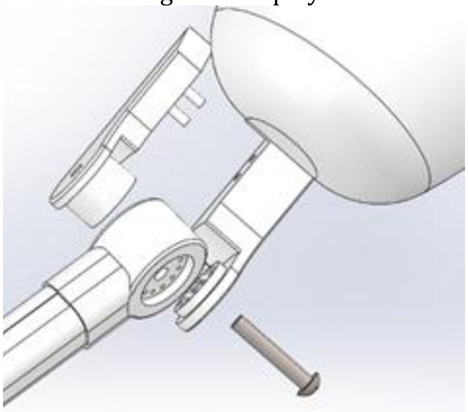

Figure 9: Pivoting Tiller Design

This mechanism reduces the amount of components from the original design from 5 components to only 3 providing the same performance.

8.5. Electronics Housing

The cables and other electrical components that the outboard feature are in charge of transporting the user's input to the electric motor. It is fundamental that the electronics are completely isolated from the water as if they get wet a short circuit could occur. To achieve so the design (Figure 10) allows to guide the cables inside the tiller and the bottom part of the casing. The top part of the casing is also watertight and has room to include circuit boards.

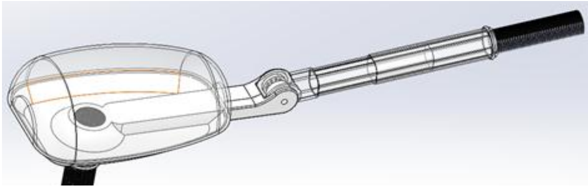

Figure 10: Electronics Housing Design

8.6 Design Table Summary

Table 2 below summarizes how the newly designed additive manufactured propulsive leg fares against the conventionally manufactured propulsive leg.

Table 2: Comparison of Existing and Newly Designed Propulsive Leg

Propulsive Leg Type	Weight	Ease of Use	Ease of Manufacture	Environmental Impact	Economic Impact
Existing Propulsive Leg	13.6 KG	A wide variety of controls, is heavy and requires the user to use their free hand to make adjustments to the propulsive leg.	Sub-assemblies which require manual assembly after manufacture with 20 + components. Make for a time consuming and expensive assembly process.	More material wastage due to using conventional manufacturing techniques such as injection moulding and hot extrusions. Furthermore the energy to run the machinery is significantly higher than it would be to run the machinery for an additively manufactured part.	Labour has to be sourced from other countries because it is cheaper than labour within the UK. This means that jobs are lost within the UK.
Newly Designed Propulsive Leg	10.69 KG	All of the controls are on the tiler grip, which means the user does not have to use their free hand to make any adjustments. Significantly easier to mount because it weighs 3 KG less.	A total of 6 components make, due to the advantages of being able to produce assemblies using additive manufacturing processes fare for a significantly less laborious and cheaper manufacturing process.	Less environmental impact than a conventionally additively manufactured propulsive leg. Due to additive manufacturing requiring less energy to run the machine and producing less waste.	Because additive manufacturing is an autonomous procedure it is cheaper to run which means that jobs can be created within the UK boosting the economy.

9. PROTOTYPING OF FINAL DESIGN

9.1 Virtual Prototyping

A full working prototype has been tested in a CAD software motion simulation to ensure that all the components and subassemblies of the newly designed propulsive leg work/perform as designed according to the product design specifications. This functional prototyping evaluation using motion simulation validates the intended functionality of propulsive leg components and subassemblies.

9.2 Prototyping using Additive Manufacturing Technique

Figure 11 shows the entire assembly of propulsive as a downscaled visual prototype. The whole prototype has been made using digital ABS, this is because it is the material that has been decided to be used for the manufacturing of visual prototype through additive manufacturing. The tiler grip has been made from Tango Family material which is a flexible material which will allow the tiler to better represent what the full product would be like. Throughout the project a scaled down version of the propulsive leg has been made so that it was possible to further check the functionality of the propulsive leg. This allowed a confirmation that the design shown in the AM built prototype is OK to have a full working prototype made with the correct additive manufacturing materials as specified above.

Figure 11: Full Visual AM built Prototype

10. EVALUATION THROUGH FINITE ELEMENT ANALYSIS (FEA) OF NEW DESIGN

Finite Element Analysis (FEA) method has been used to confirm that the design calculations were correct and that the parts that have been re-designed, when subjected to the loads applied by the propulsive leg would withstand the forces applied. FEA is a method of structural analysis. Within a Computer Aided Engineering (CAE) software, it is possible to constrain parts/assemblies that have been designed, calculate that correct loads that are going to be applied to these parts, select the area the loads are going to be applied to and then run the simulation to see what effect the loads have on the component/assembly. It is then possible to view the component in a multitude of ways for example it is possible to view the components' simulation results in terms of the factor of safety, it is possible to view the components simulation results in terms of the maximum von misses stress and so on.

10.1 FEA of Trim Mounting

The trim mounting was identified as a main area of stress as it is responsible to allow the adjustment of the trim of the propulsive leg and it takes all the weight of the propulsive leg (excluding the weight of the mounting bracket). Therefore, it was important to perform FEA on the trim mounting to ensure the design calculations were correct and it was strong enough to withstand the forces. Figure 12 shows the trim mounting bracket after it has gone through the FEA process. Key features to note are that it has been constrained in the middle bolt's hole and the bottom where it jams into the mounting bracket, this is to simulate the same loading condition that it would have when working. Furthermore it has a load applied to the internal circular faces (represented by the purple arrows) to simulate the force applied by the motor.

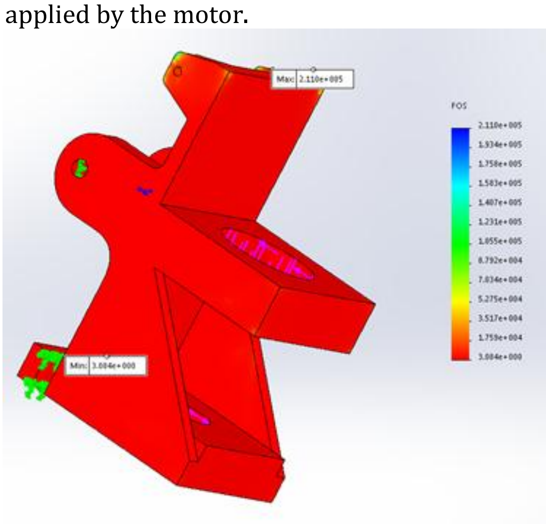

Figure 12: Trim Mounting FEA

10.2 FEA of Mounting Bracket

Given that the mounting bracket is taking the entire load of the propulsive leg and it is responsible for transferring the force produced by the motor of the propulsive leg to the boat. It was identified as a key area for design calculations and FEA analysis. Figure 13 shows the mounting bracket's FEA results, specifically for the factor of safety. It is possible to see that the minimum factor of safety is 2 and that the load has been applied where the trim mounting attaches to the mounting bracket. Furthermore, it is possible to see that it has been constrained in a way that it would attach to the transom of the boat as shown by the green arrows.

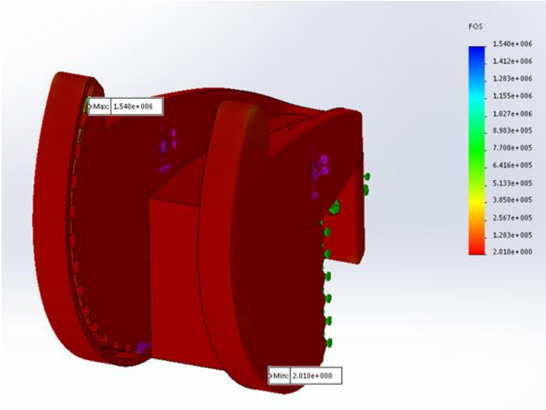

Figure 13: Mounting Bracket FEA

10.3 FEA of Mounting Bracket Jammer

The mounting bracket jammer is responsible for ensure that the propulsive leg stays in the trim position that the user decides they would like it to be in. It is the connecting part of the trim adjustment assembly. Because of this a significant amount of load goes through the mounting bracket jammer. Therefore, it is important to ensure through FEA techniques that it is able to withstand these loads.

As this part failed during the initial FEA attempts, it has been re-designed to include a stainless steel rod that goes through the weakest part of the mounting bracket jammer to ensure a safe design. Figure 14 shows the FEA results for the mounting bracket jammer.

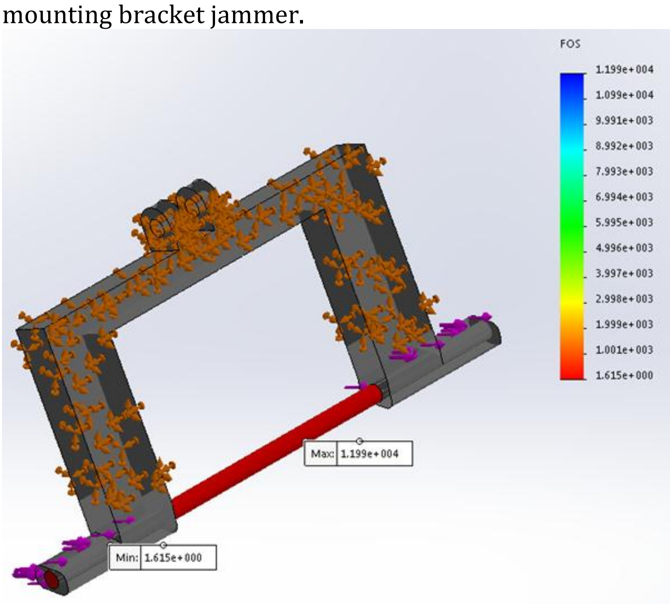

Figure 14: Mounting Bracket Jammer FEA

11. EVALUATION THROUGH COMPUTATIONAL FLUID DYNAMICS (CFD) ANALYSIS OF NEW DESIGN

Computational fluid dynamics (CFD) analysis allows the simulation of fluid, either liquid or gas, when it is passing through or around an object. CFD allows the ability to predict the impact of such flows on the product whereas before manual calculations would be very time-consuming and costly.

11.1 Flow Trajectories Analysis

Figure 15 shows the flow trajectories of the water when it is passing past the propulsive leg. This figure allows us to see in which areas the flow of water is going faster and in which areas the flow of water slows. It is also possible by using the flow trajectory lines to see the direction of flow. For example, it is possible to see that there is a lot of resistance and flow changes in the water where the motor is passing through but the newly designed shaft does not produce much resistance due to its slim profile.

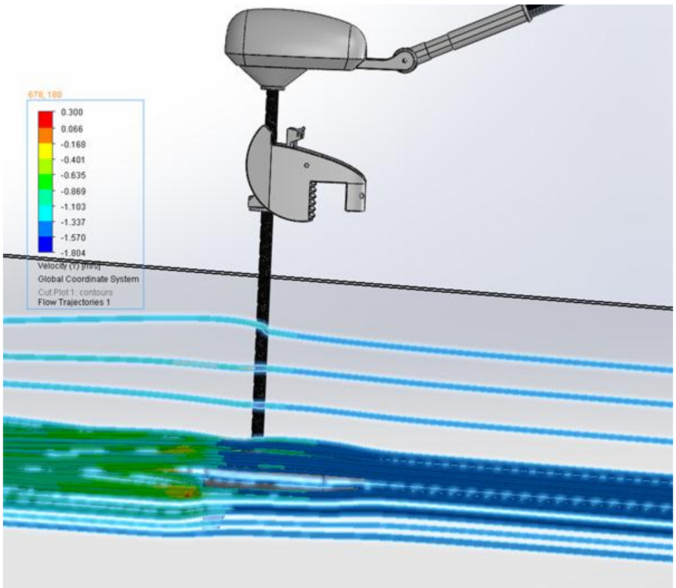

Figure 15: Flow Trajectories Plot

11.2 Velocity Profile Analysis

The velocity cut plot tool allows us to look at the speed of the flow of the water as the propulsive leg passes through the water on a specific plane and visually see using a color chart how the speed of the water changes due to the profiles of the parts being put through the water. For example: Figure 16 shows the velocity cut plot for the propulsive leg and it is possible to see from this figure that the water slows a little when the shaft goes through the water but it is not a significant difference to the original speed (3 Knots or 1.54 meters/sec).

11.3 Surface Pressure Analysis

The pressure surface plot (Figure 17) allows us to view the effect of the water pressure on the propulsive leg as it passes through the water at its maximum speed of 3 knots or 1.54 meters/sec. This is an important plot because it allows us to view which areas of the part are going to be under the most amount of stress due to the resistance of the water. This enables better optimization of the design. In this case figure 44 shows that there is a small amount of pressure build up on the shaft but nothing significant and due to the high factor of safety on the shaft it is not necessary to change the design due the pressure on the shaft.

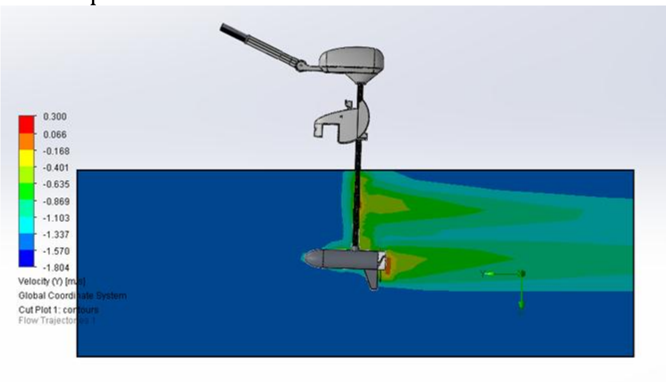

Figure 16: Velocity Cut Plot

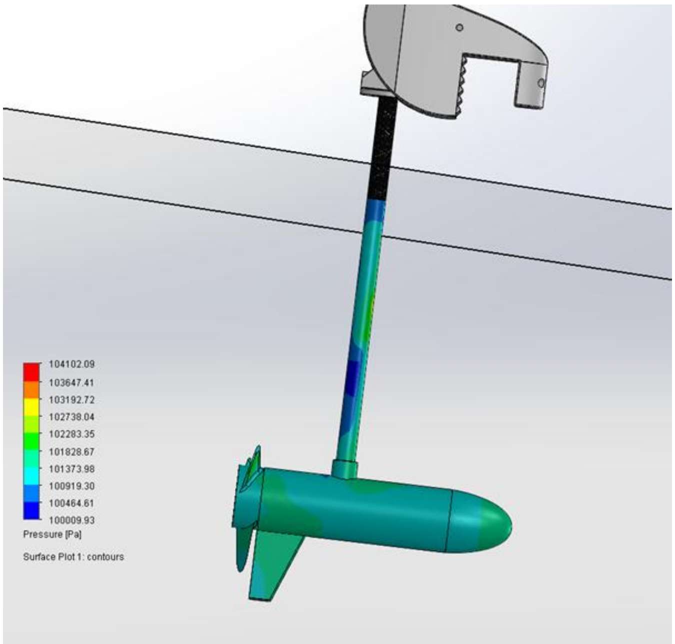

Figure 17: Surface Pressure Plot

12. CONCLUSIONS

This project has shown the findings and the processes used for creating the final design of the propulsive leg in order to use additive manufacturing processes. The build process of the propulsive leg was modelled using a CAD software and the evaluation process of the design was carried out using FEA and CFD techniques.

From the findings of the project reported in this paper, it is possible to see that the initial concept design would work fully and significantly improve the current design within the following areas: ease of use, ease of manufacture and reduction in weight as detailed below:

12.1 Ease of Use

The new design concept for the propulsive leg has ensured ease of use for the following reasons: the introduction of tiler and throttle control allowed the user to adjust the speed of the propulsive leg and the propeller direction without having to use their free hand as it is significantly lighter than the design of existing propulsive leg. It is a lot easier to adjust the trim and its lighter weight made it possible to attach it to the transom of the boat more easily.

12.2 Ease of Manufacture

Given that the propulsive leg is made through additive manufacture techniques the complex assemblies of the tiler and the mounting bracket now do not require assembling. The only manual assembly that needs to take place is being able to attach the major subassemblies together. For example attaching the mounting bracket to the trim adjustment part with a bolt. Given that there has been a reduction in the assembly features means that there is going to be a reduction in the assembly time and therefore the assembly cost, which increases productivity of manufacturing the propulsive leg.

12.3 Reduction of Weight

The new design weighs a total of 10.69 Kg and the old design weighs a total of 13.6 Kg, which shows a 20% reduction of weight.

12.4 Scope of Further Work

The next stage of this project would be to critically evaluate the prototype that has been produced and see what areas are needed for improvement/optimization. It would then be reasonable to produce another prototype to confirm the findings. The usability of the propulsive leg and fitting in the necessary electrical systems would be required in order to create a fully working prototype.

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