University of Nottingham
Department of Mechanical, Materials & Manufacturing Engineering
Group Design Project MM4GDM

Post CDR Report

Group 6A

Biomimetic Propulsion System

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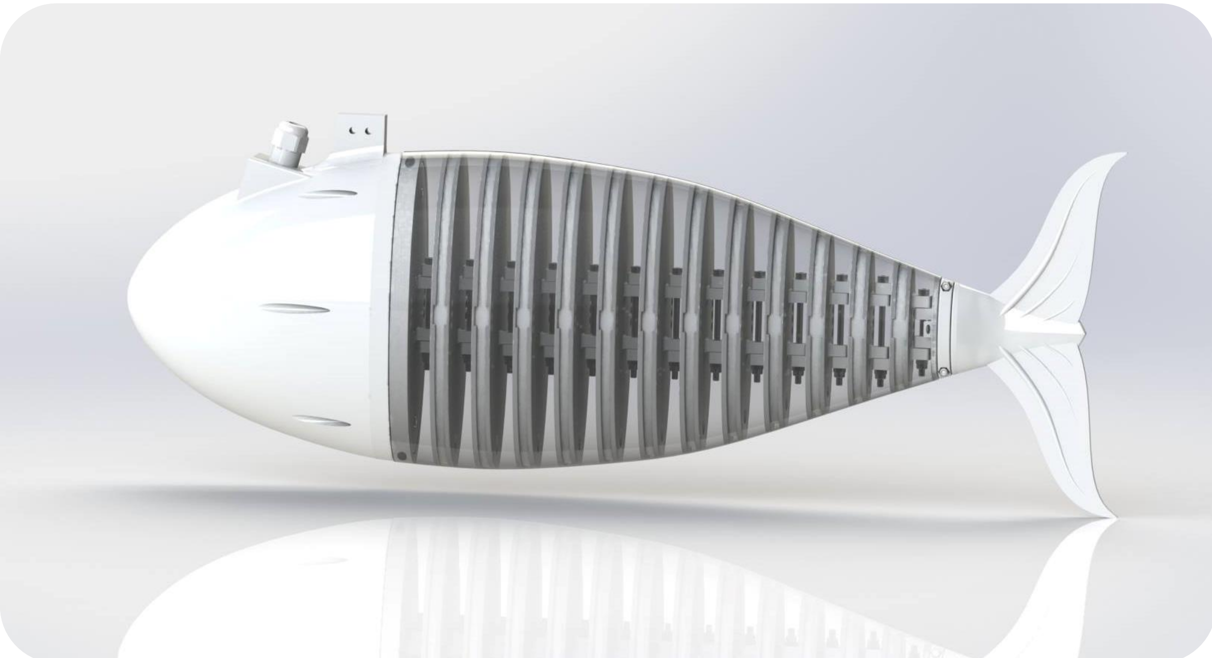

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1. Executive Summary

Abstract

This report details the design of a propulsion system that accurately mimics the sinusoidal motion of fish. Robotic fish already exist; however, most are not fully biomimetic and so, although functional, their designs do not exactly replicate the motion of fish. The primary aim of this project is to create a design that wholly replicates this motion, whilst also producing thrust.

Accurate biomimicry is to be achieved by reproducing the spine of a fish and its movement. The design incorporates 13 unique vertebrae with an elastic-antagonistic force between each; the force replicates the action of the muscles between them.

At the time of the submission of this report, compliance with most requirements has been demonstrated through design and calculations. Testing will be carried out in a water tank to refine and optimise the system, and to confirm the biomimetic accuracy and measure the thrust the system produces. It is believed that this mechanism is novel: the first of its kind.

Introduction

Robotic 'fish' are not new. However, existing projects have not placed much emphasis on biomimicry, the design of systems based on biological entities or processes. This leads to designs that, although functional, do not fully replicate the motion of a fish.

More accurate biomimetic robots have potentially extensive applications: not limited to underwater observation, and shepherding schools of fish away from environmental disaster sites. The more a robot can blend into the environment unnoticed, the less it will disturb marine life. The use of a robot would also reduce localised pollution caused by boats and people, which can damage fragile habitats such as coral reefs.

The customers' key requirements are that the design must produce at least a 3rd harmonic sinusoidal shape. It should also produce at least 9N of thrust and should be powered by a 12V power supply. These requirements have been central to the focus of the design.

To ensure the project is feasible within the available time, factors such as buoyancy, reaction surfaces and remote control which would be important considerations for a free-swimming system, were not the focus though could be considered in further iterations of the design.

This report explains the design rationale, calculations, costs, project timeline, fabrication plan, relevant risk analyses, and the health and safety considerations entailed in designing, building and testing the system.

System Requirements

Working with the customer, the requirements of the deliverable were defined and refined throughout the design process. Key requirements of the system are shown below:

- *Must produce at least 9N of thrust (Requirement 2)*
- *Must use no more than 3 actuators (Requirement 3)*
- *Must produce sinusoidal motion up to the third harmonic (Requirement 4)*
- *The housing for the electronics must not leak at water depth of 3m (Requirement 5)*
- *Must fit within a size envelope of 650 x 250 x 150mm (Requirement 8)*
- *Must exhibit piscine motion (Requirement 13)*

The following requirements were non-negotiable:

- *Must be powered by a 12V supply (Requirement 1)*
- *Cost must not exceed £500 (Requirement 9)*
- *Must exhibit a 1st order response to allow steering (Requirement 14)*

Design Description

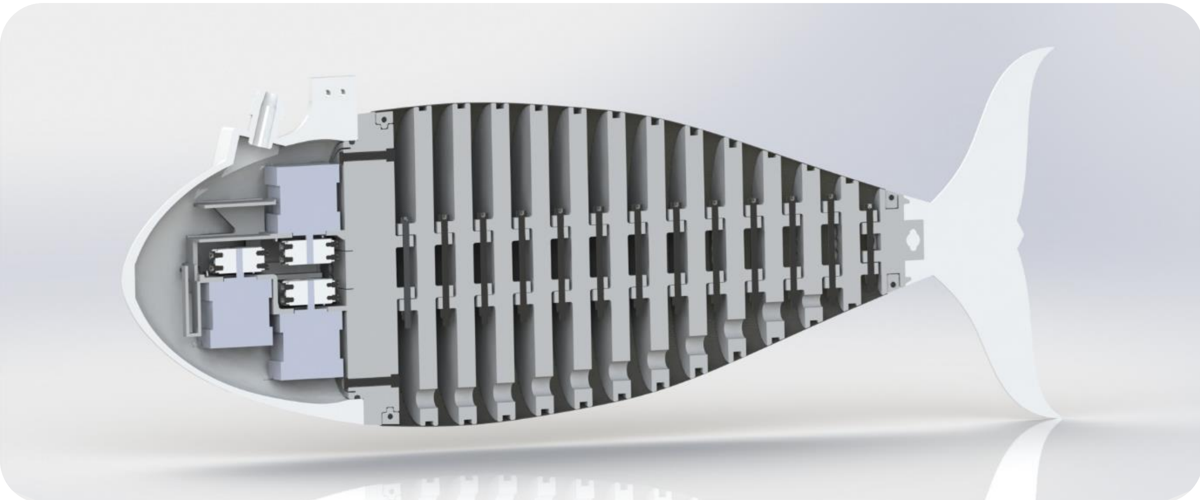


Figure 1.1: Section View of the final design

Mechanism

Sinusoidal motion is replicated using an antagonist to replicate the action of muscles between vertebrae. This is shown in Figure 1.2 below:

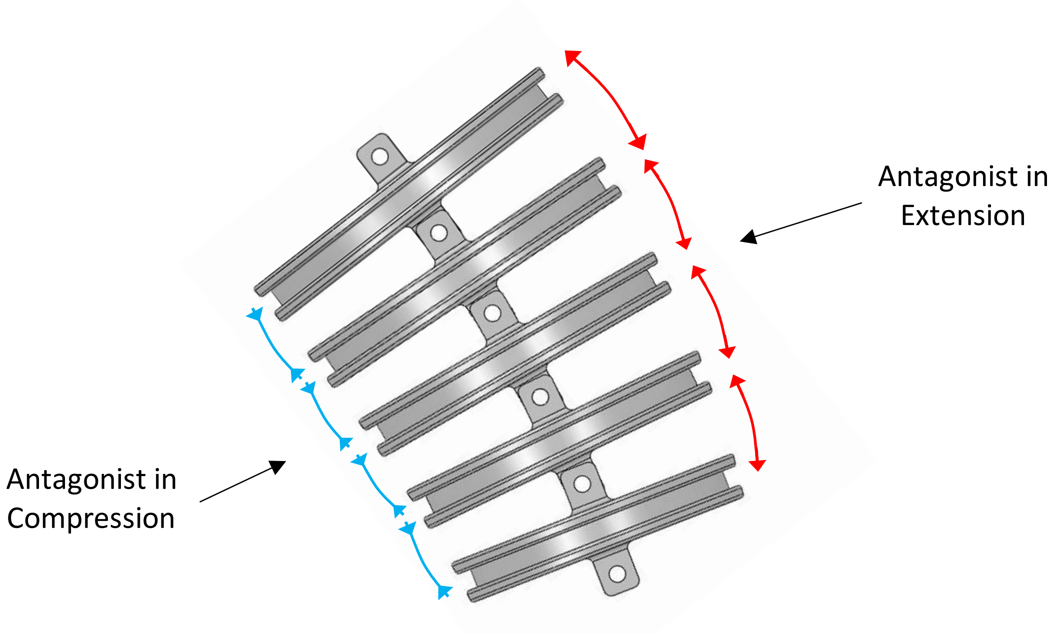


Figure 1.2: Diagram describing the action of an antagonist

As the spine is manipulated to create motion, the antagonist tries to return the vertebrae to a neutral position. This creates smooth and natural motion.

Three stepper motors pull on cords to turn the vertebrae to the right or left in an alternating pattern to produce the sinusoidal movement and resulting thrust. Two different methods of manipulating the cords to achieve the desired shapes will be trialled when the system is tested.

One pair of cords spans the length of the spine to allow for a '1st order response' that can be used to steer the system.

Overall System Shape

The shape of the design is approximately based on an Atlantic Bluefin Tuna. Tuna exhibit piscine motion and are fast swimmers, hence it is thought that replicating the shape will aid the production of thrust. This has resulted in overall dimensions of approximately 630 x 230 x 100mm, complying with Requirement 8.

Vertebrae Design

The spine is made up of 13 vertebrae with an elastic-antagonistic force between each, replicating the action of the muscles between the vertebrae and creating sinusoidal motion when actuated. The elastic antagonist force is delivered by the elastic 'skin' material which covers the skeleton and additionally keeps the system watertight:

- Due to the complex geometry of the components, the vertebrae assemblies will be 3D printed from PLA.

- The links are jointed using single M4 bolts to ensure good alignment. The maximum stress experienced by the joints in supporting the weight of the fish was found to be 2.24 MPa, which is well under the yield strength of PLA.
- A groove allows the skin to be clamped to the vertebrae using in-line cable ties, creating an antagonistic force between each link.

Head Design

The 3D printed head contains the electronics and stepper motors for controlling the product. The size of the head was dictated by the size of the stepper motors which in turn provided the profile for the fish. A back plate connects the head to the vertebrae system and provides a surface for two mounts (holding the electronics and stepper motors) to be attached. The back plate includes a recess for clamping the skin and a groove facing the head for an O-ring to ensure waterproofing (Requirement 5).

The head and its internals were designed so that:

- The stepper motors were arranged to allow for an accurate Tuna fish head profile.
- Spools with clamps on the sides could allow for the cord to be connected to the stepper motors with pre-tensioning.
- To ensure the motor mounts can support the components, simple beam bending calculations were used to approximate the stresses. Maximum stresses of 1 MPa and 2.7 MPa were found for the upper and lower mounts respectively, which are much smaller than the yield strength of PLA, 35 MPa.
- An M16 cable gland IP69K rated (waterproof for full submersion) will be mounted on the head to allow the external wires to connect to the internal circuitry.
- Exposed PLA parts will be coated to ensure they do not absorb water.

Skin

The skin will be silicone due to its elasticity and high elongation capability, allowing it to act as the antagonistic mechanism between vertebrae:

- A 1.67 reserve factor is applied to the pre-tensioning to ensure the skin is not over-stretched and is puncture resistant.
- E41 adhesive will be used as it was suggested as the optimal joining method by the supplier.

The skin was calculated to last for 3000 cycles or approximately 2.5 hours. As it is a prototype this is deemed acceptable.

The skin is attached at both the head and the tail using clamps that can be tightened to achieve a watertight seal. The clamps can be removed to allow any water to be drained from the system, with holes in each link enabling water to be drained to the rear of the design, away from the electronics. The watertight capability of the system will be confirmed before any electronics are installed.

Time Period of the Oscillation

The Strouhal number was used to understand the vortex production of fast-swimming fish such as Tuna. It was found that maximum efficiency occurs at values of around 0.2-0.4 which gives a time period of 1.38 seconds to produce maximum efficiency at 9N of thrust, however this will be verified by testing (Requirement 2).

Actuator Selection

The design uses 0.4Nm stepper motors. Calculations show that the stepper motors can provide torque at the time period required for maximum efficiency with a reserve factor of 1.25.

- Powered by a 12V power supply to comply with the Statement of Requirements (Requirement 1).
- Turned off when handled to eliminate the risk of electric shock (Requirement 12).
- Coded to produce up to the 3rd harmonic (Requirement 4) with the 1st order response used for steering (Requirement 14).
- The on-off switch (Requirement 10) and emergency stop (Requirement 11) are already incorporated and built-in to the power supply.

Cord

Nylon has been chosen due to its high fatigue strength (36 – 66 MPa at 10^7 cycles) meaning it can cope with the cyclic stresses induced by the stepper motors. The stress on the cord due to the torque being produced is 7.07 MPa which is considerably less than the yield stress of nylon.

Tail Design

The tail is made from a single piece of cast polyurethane, which is moulded through the last vertebra, using a CNC machined two-part aluminium mould.

Two resins of different stiffness will be cast and trialled to determine which produces the most thrust.

The design has been optimised by:

- Having a large surface area for the reacting surface.
- Including: a 40-degree leading edge angle, a 120-degree convex trailing edge and limited forking of the caudal fin to maximise thrust and efficiency.
- Using materials of intermediate flexibility to prevent inefficiencies caused by completely rigid or fully compliant caudal fins.

- Integrating fin rays to increase the tail strength and biomimetic accuracy of the fish appearance.

Testing Rig

The test rig has two functions, to measure the thrust of the system and to support the fish. It was designed with ease of manufacture and assembly in mind, hence most of the components are simple and made from materials readily available from the L2 stores.

- Parts submerged in water are made of aluminium to ensure corrosion resistance.
- The rig was found to experience an approximate 2.8 MPa of bending stress which is much lower than the yield strength of the steel angled bars that support it.
- The exposed materials are corrosion resistant to saline environments (including the fasteners being stainless steel); the design complies with Requirement 6.

All fasteners used in the submerged system are made from stainless steel to prevent corrosion.

The total cost of the system and test rig is less than £500.

Testing

Testing will be undertaken in a large water tank (2m x 3.5m x 3m deep). The clear glass windows of the testing tank will allow for the optical verification of the biomimicry of the system. The depth allows for testing the waterproofing of the product (Requirement 5).

The fish system will be bolted at the bottom of the mounting bar. As the fish produces thrust, the pivot bar will rotate, inducing a moment on the spring dynamometer. From this, the thrust of the fish can be obtained.

Before electronics are added to the product, a waterproofing test of the system will be carried out to ensure that there are no leaks, eliminating the risk of damage to the electronics.

Health and Safety

Manufacturing and testing of the final product have associated risks that have been mitigated:

- Health and safety have been considered for all manufactured parts, with fume hoods used for toxic materials and ensuring all members are fully trained and equipped to use machinery.
- Precautions have been set in place for testing including limiting the height the tester can go on the tank ladder, covering the tank to prevent users falling in and ensuring power is turned off during mounting to avoid accidents.

Project Potential

The technology has many potential applications and has generated opportunities for future study. This could include projects to determine exactly how fish generate propulsion, and how efficiently they do so.

Further work could include making the system autonomous or remotely controlled. Fitting it with cameras would mean it could be used for underwater observation without causing localised pollution or disruption to marine life. Potential applications range from observing and studying aquatic animals, to inspecting underwater infrastructure such as bridges, oil rigs and offshore wind turbines for damage and wear.

Biomimetic fish could also be used to divert marine life away from damaging environmental disaster sites.

Conclusions

All requirements have been achieved through design and calculations, however the thrust that the system will produce is yet to be measured.

At the time of submission of this report (25th March 2019), the final deliverable is still being manufactured and therefore has not been tested. Visual verification of the biomimicry of the system and empirical measurement of its thrust will be carried out in the week commencing April 3rd.

2. Statement of Requirements

Latest Statement of Requirements

No	Customer(s)	Requirement	Method of Demonstrating Compliance	Rank
1	User	Must be powered by a 12V power supply	Inspection/Design	N/A
2	User	Must produce at least 9N of thrust	Measurement	2
3	Designer	Must use no more than 3 actuators	Inspection/Design	2
4	User	Shall generate motion up to the 3rd harmonic	Inspection	1
5	Designer	The housing for the electronic components must not leak when submerged in water at a depth of 3m	Test	N/A
6	User	Exposed parts must use materials that exhibit corrosion resistance in a saline environment	Design	5
7	User	The design must provide a means to be drained	Inspection	N/A
8	User	Must fit within a size envelope of 650mm x 250mm (Height) x 150mm	Measurement	4
9	Designer	Cost must not exceed £500	Calculation	5
10	User	Design must incorporate an on/off switch	Test	N/A
11	User	Design must incorporate an emergency stop	Test	N/A
12	User	Design must eliminate risk of electric shock during normal handling	Inspection/Design	N/A
13	Designer	Must exhibit piscine motion	Inspection/Design	N/A
14	Designer	Must exhibit a 1st order response to allow steering	Inspection/Design	N/A

Table 2.1: Latest Statement of Requirements

Previous revisions of the Statement of Requirements are included in Appendix B.

Compliance Statement

No	Requirement	Outcome
1	Must be powered by a 12V power supply	The electronic components and actuators have been selected in accordance with this requirement (See Electronics Design on Page 46).
2	Must produce at least 9N of thrust	Compliance with this requirement will be verified by testing the finished prototype.
3	Must use no more than 3 actuators	The system has been designed to use 3 stepper motors.
4	Shall generate motion up to the 3rd harmonic	Compliance with this requirement will be verified by testing the finished prototype. This will be done by counting the number of peaks present in the vertebrae.
5	The housing for the electronic components must not leak at a water depth of 3m	Compliance with this requirement will be verified by testing the finished prototype.
6	Exposed parts must use materials that exhibit corrosion resistance in a saline environment	Throughout the design appropriate corrosion resistant materials have been used.
7	The design must provide a means to be drained	Compliance with this requirement will be verified by testing the finished prototype.
8	Must fit within a size envelope of 650mm x 250mm (Height) x 150mm	The total size of the system complies with the size envelope (see Page 24).
9	Cost must not exceed £500	The costs are not expected to exceed £500 (see Budget on Page 84).
10	Design must incorporate an on/off switch	The on/off switch on the power supply satisfies this requirement.
11	Design must incorporate an emergency stop	The on/off switch on the power supply satisfies this requirement.
12	Design must eliminate risk of electric shock during normal handling	The system only uses a 12V supply, so is unlikely to cause an electric shock.
13	Must exhibit piscine motion	The system has been designed to create piscine motion (see Page 13). Compliance with this requirement will be verified by testing the finished prototype.
14	Must exhibit a 1st order response to allow steering	The system has been designed with first order control (see Page 13). Compliance with this requirement will be verified by testing the finished prototype.

Table 2.2: Table showing compliance of the requirements

3. Design Description

System Mechanism

The propulsion system needs to produce sinusoidal shapes up to the 3rd harmonic. This motion is achieved by reproducing the spine of a fish and the elastic-antagonistic force of muscles between the vertebrae. The antagonistic force acting between adjacent vertebrae creates smooth motion, as has been verified by prototypes. The action of the antagonistic force is illustrated in Figure 3.1 below:

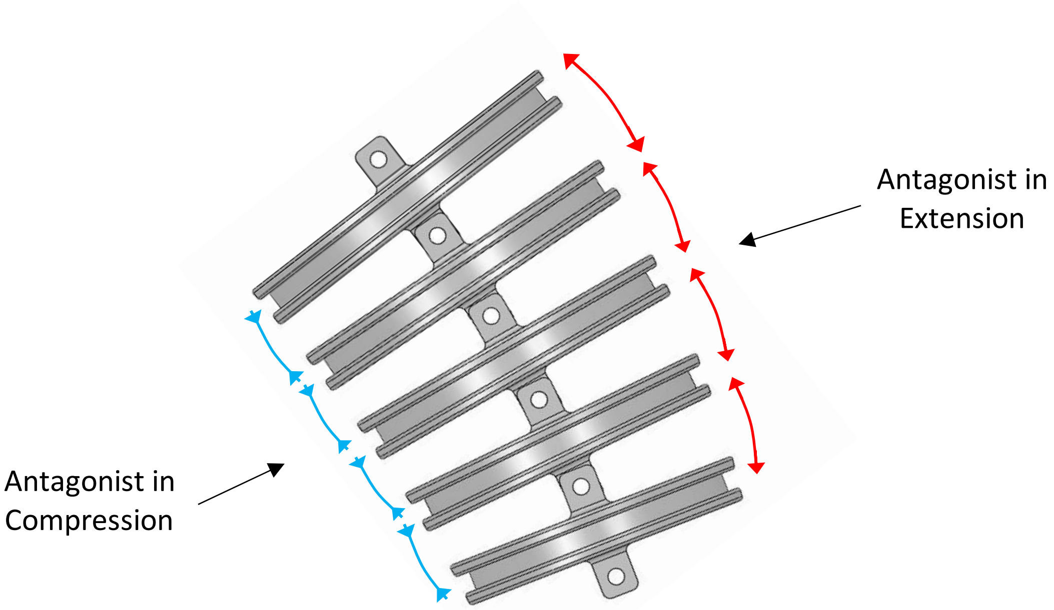


Figure 3.1: Diagram illustrating the antagonistic forces

This mechanism creates smooth and accurate sinusoidal body caudal fin motion.

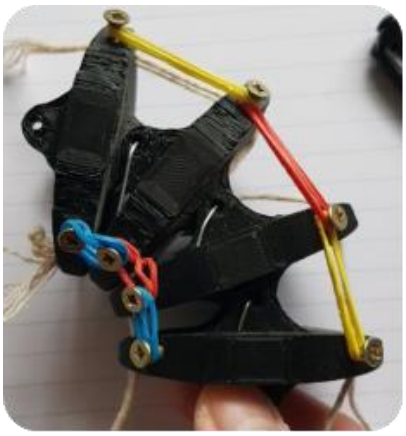


Figure 3.2: An image of a prototype that uses elastic bands as an antagonist

In the initial prototypes, this was achieved with rubber bands connected between each vertebra on both sides. Although this was successful in validating that the mechanism achieved the desired motion, it was not a long-term solution.

- Rubber bands have a low fatigue strength which means they would break frequently and also have inconsistent thicknesses which leads to different forces between vertebrae.

- A long-term solution was needed and initially springs were considered, however these would be thick and may rub and degrade the silicone skin (as discussed on Page 43).

After initial testing of the silicone sheeting, it was found that when it was pre-tensioned it provided the antagonistic forces between the vertebrae that was desired. This meant that the design could be simplified so fewer parts and less assembly time would be required.

It is therefore important to ensure that the skin is properly pre-tensioned. This calculation is shown on Page 62.

Motors turn the vertebrae left and right via cords, creating sinusoidal motion and thrust. Two different ways of programming the motors that manipulate the spine to create the biomimetic motion will be investigated: an *Antagonistic Stepper Motor system* and a *Reactive system.*

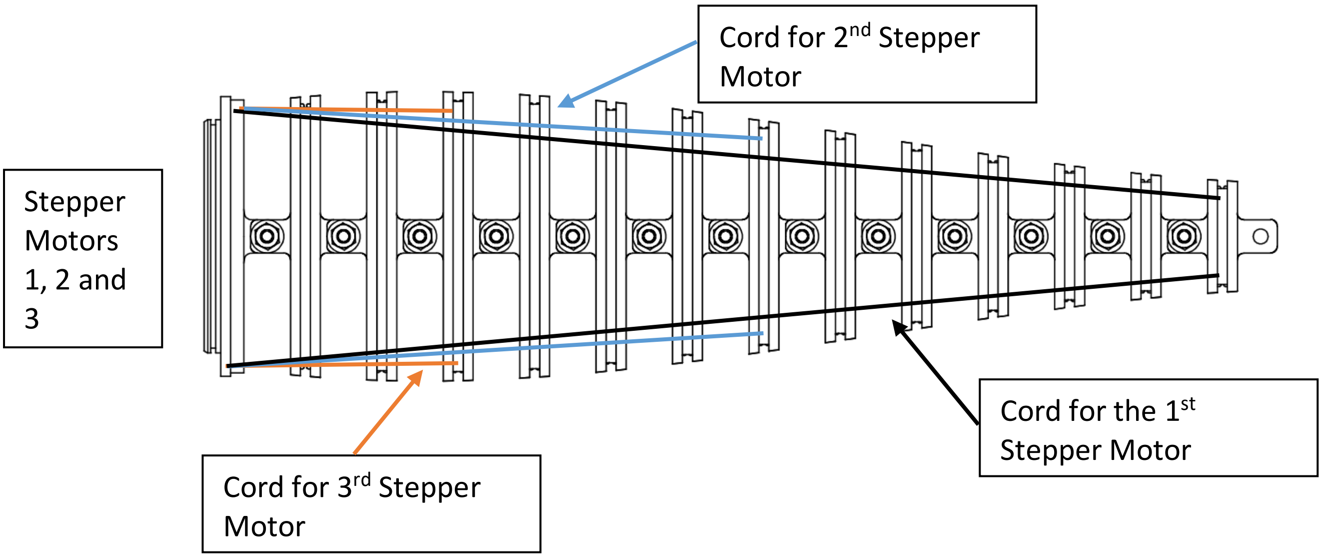


Figure 3.3: Diagram showing the cord configuration

Antagonistic Stepper Motor System

This system uses multiple motors depending on the desired harmonic to be produced. When trying to obtain the 3rd harmonic, all three stepper motors will be oscillating in opposite directions relative to their adjacent partners to produce the overall shape.

A prototype managed to produce the 2nd harmonic in *air* [1 - Video]. However, this behaviour needs to be verified when the system is submerged in water.

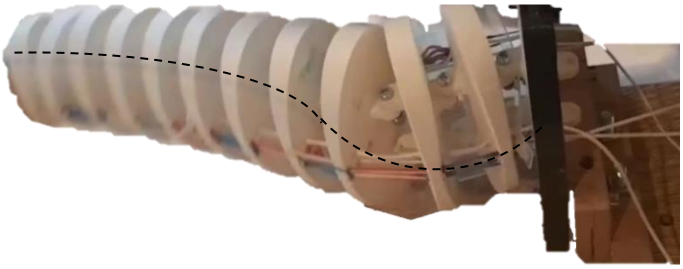


Figure 3.4: Prototype showing 2nd harmonic (two peaks present in the figure)

Reactive System

This system uses the same cord configuration, however, the harmonics are created by using a single motor and the reactive forces from the water to create the sinusoidal shape [2 - Video].

Preliminary testing for this system with reactive forces present, only at the tail, demonstrated that a sinusoidal motion can be produced. However, this will have to be verified when submerged underwater to ensure compliance.

Figure 3.5: Shape achieved using the reactive system

Head Design (BPS.01.00)

The head of the fish contains the three stepper motors, motor drivers, their respective breadboards, and the Arduino Nano. The design allows access to the USB and power supply cables whilst remaining watertight.

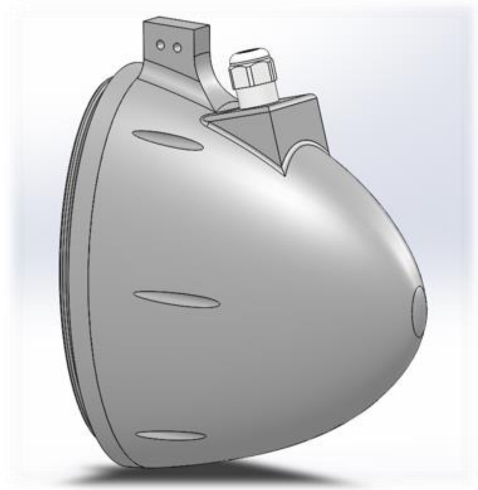


Figure 3.6: CAD model of Head Subassembly

Stepper Motor Configuration

Finding the best layout for the stepper motors inside the head was an important part of the design process. In order for the design to keep with the philosophy of the project, the stepper motors needed to be arranged in a way that allowed for an accurate head profile. Therefore, the stepper motor arrangement, as seen in Figure 3.7 below, was chosen as it allowed the head casing to slope naturally resembling that of a fish.

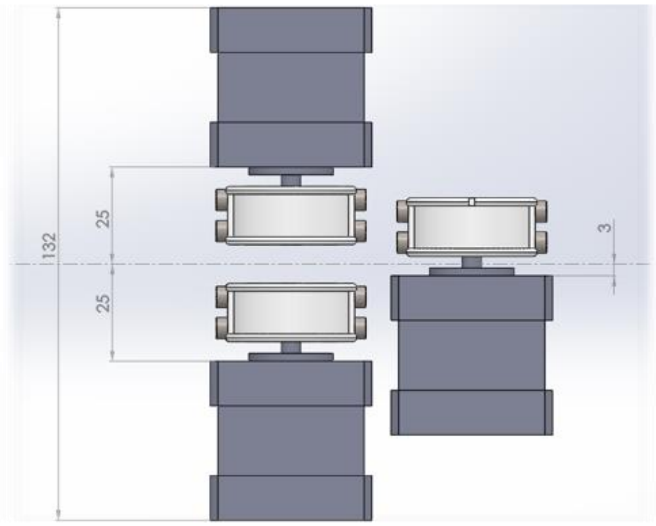


Figure 3.7: Stepper motor configuration inside the head

Motor Mounts (BPS.01.01 and BPS.01.02)

The mounting for the stepper motors and electronics has been split into an 'Upper Mount and a 'Lower Mount' to increase the ease of manufacture and assembly. Both parts will be 3D printed using PLA.

The Upper Mount holds the single upside-down stepper motor, all three motor drivers and the two breadboards.

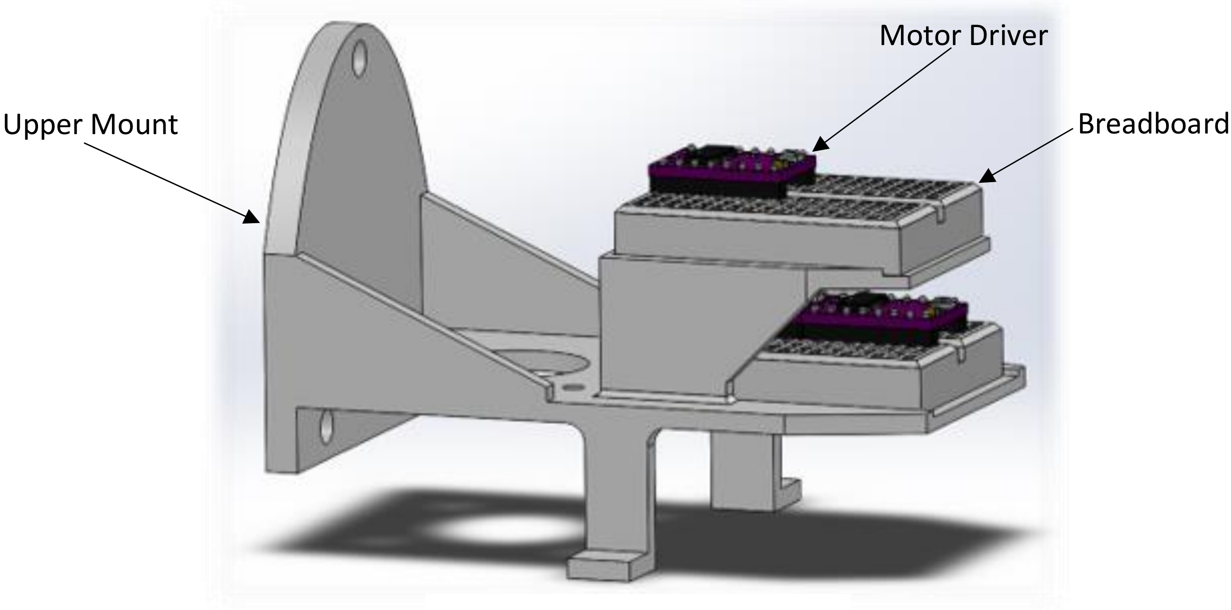


Figure 3.8: Upper Mount model

The Lower Mount holds the two bottom stepper motors, the Arduino Mount Subassembly and has flanges added to the side for better structural integrity inside the head.

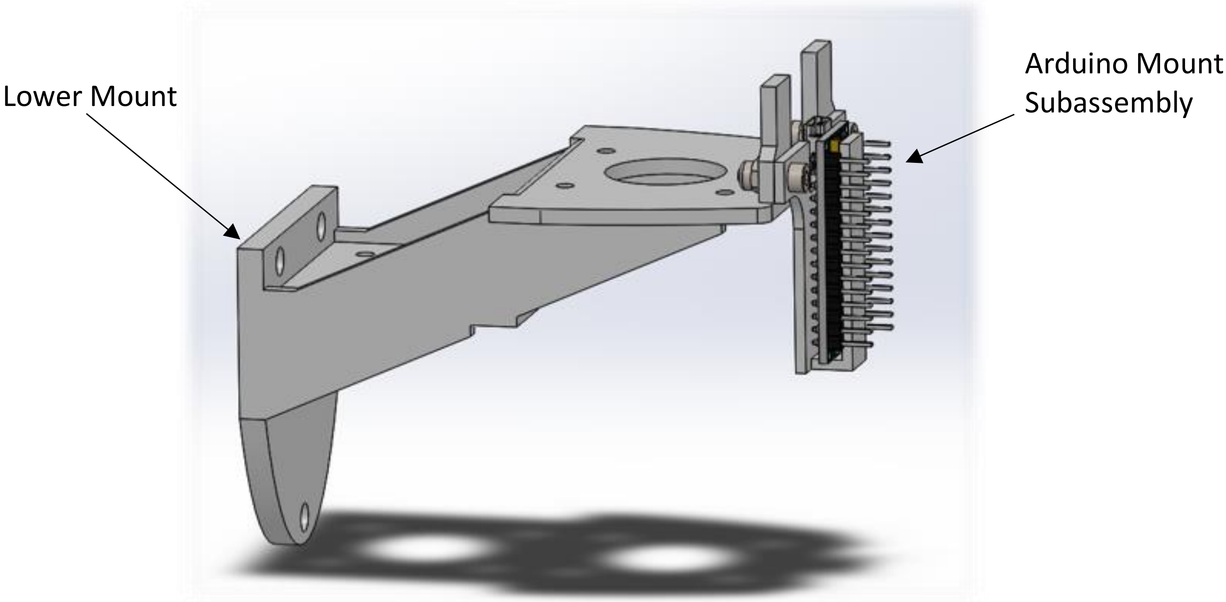


Figure 3.9: Lower Mount model

Arduino Mount Subassembly (BPS.01.03)

The Arduino Mount Subassembly holds the Arduino Nano and fixes to the Lower Mount using two M3 x 10mm bolts. The Arduino slots into the 3D printed mount as shown in Figure 3.10 below.

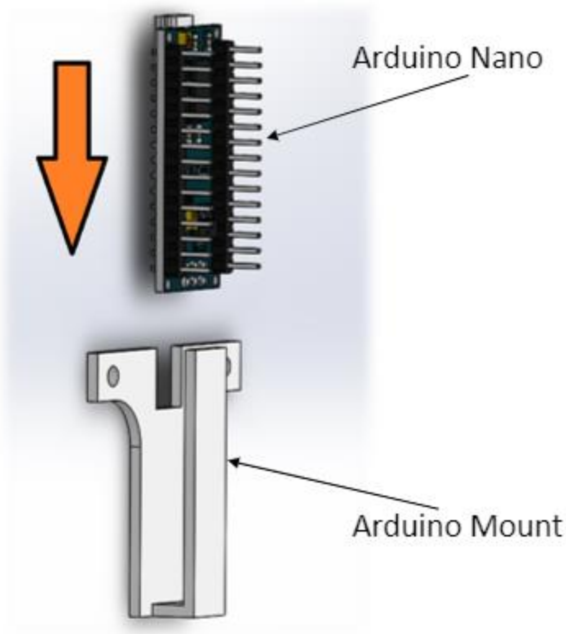


Figure 3.10: Diagram showing how the Arduino Nano assembles into the Arduino Mount

Spool Design (BPS.01.04.00)

The spools that hold the cables onto the stepper motors fit onto the stepper motor shafts via an interference fit. These spools will hold the cables with clamps on the sides of the spools which can be tightened with screws.

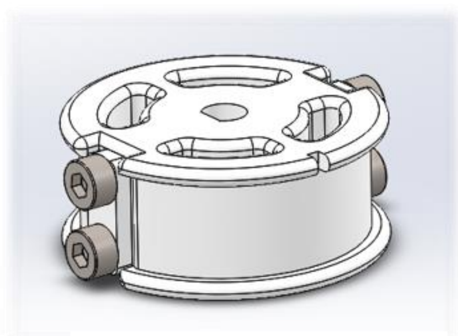


Figure 3.11: Spool model

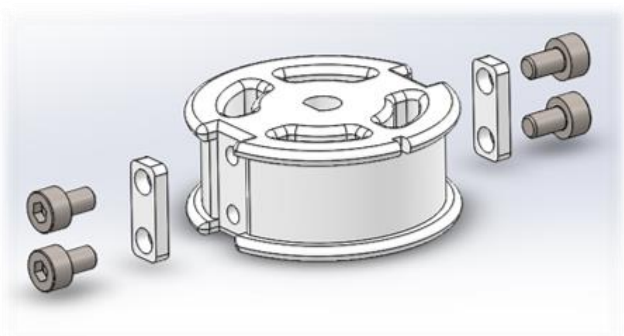


Figure 3.12: Exploded View of spool

Back Plate (BPS.01.06)

The Back Plate is the interface between the head and the body of the fish. It has a seal on either side, recesses for the motor mounts and contains the holes for the cords to pass through.

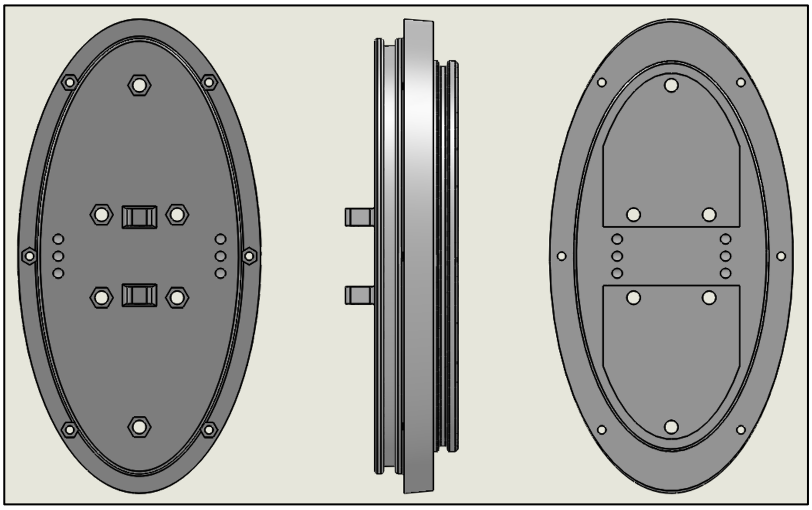


Figure 3.13: Back Plate model

The two stepper motor mounts each fit onto the Back Plate using three M5 x 35mm hex bolts. Each mount locates onto the back plate by slotting into a recess on the face as seen in Figure 3.14 below.

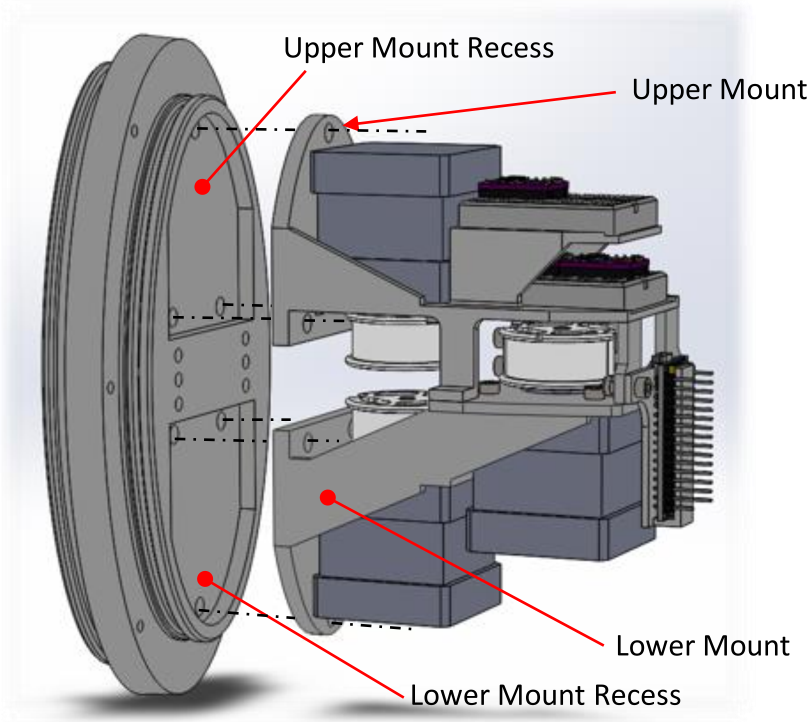


Figure 3.14: Diagram showing recesses for motor mounts and how motor mounts attach

The other side of the back plate (Figure 3.15) is what the body of the fish attaches to. It contains recesses for the M5 nuts so that they do not interfere with the mechanism of the body.

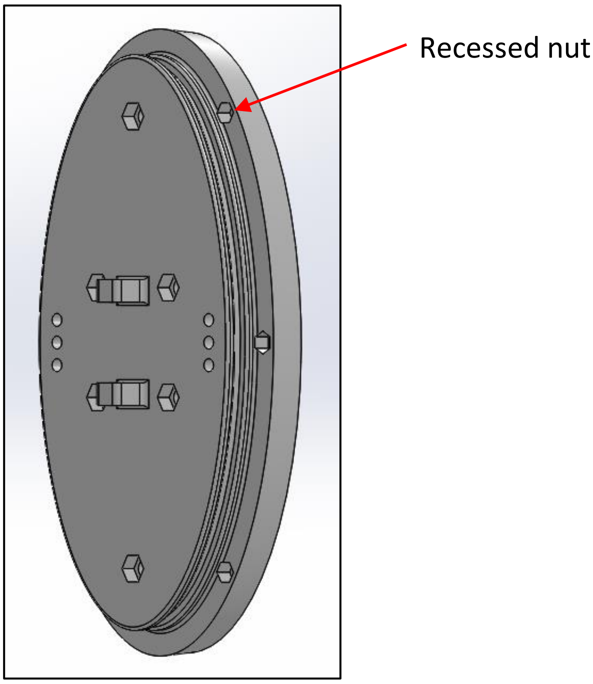


Figure 3.15: Highlighted recessed nut on Back Plate

There are two seals on the back plate. The first is located where the skin joins up to the head and the other is using an O-ring which sits in a groove between the Back Plate and Head casing. This is shown in Figure 3.16 below.

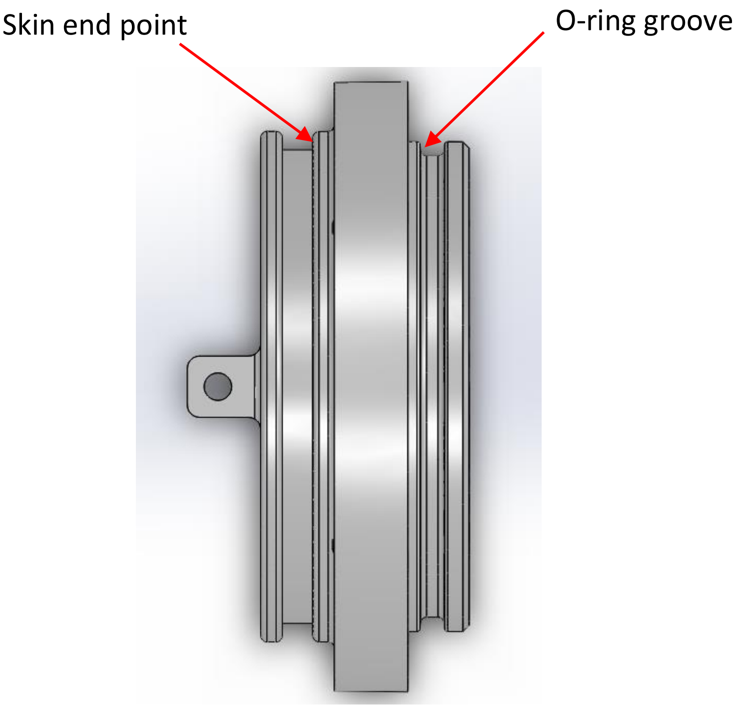


Figure 3.16: Top-down view of Back Plate showing seal locations

Head Casing (BPS.01.05)

The Head Casing fastens to the Back Plate via six M3 socket head bolts. The Head Casing design includes the mounting through holes (M4) for the test rig and a flat surface for the cable gland to be fitted.

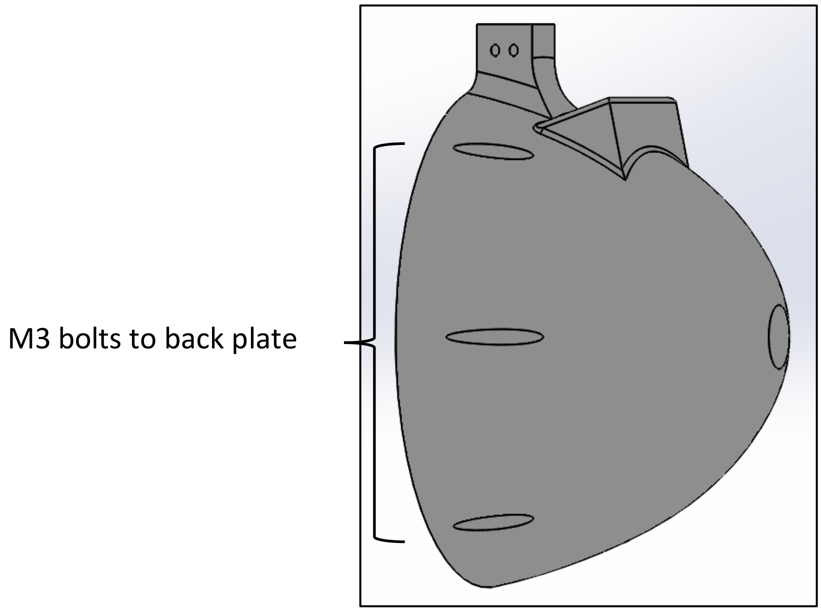


Figure 3.17: General View of Head Casing

Figure 3.18 highlights the key features of the head casing. The indents in the head were created by overestimating the size of some components and then removing any material in those areas. This was done to ensure the components fit inside the casing and to allow for larger tolerances.

The test rig fits onto the head using two M4 bolts in order to fully constrain the fish to the test rig.

The flat surface at the top of the head has been added so that a proper seal can be established between the head casing and the cable gland. This has also been done so that the cable gland is angled towards the test rig, meaning wires can be easily secured to the rig.

The ridges inside the head have been added to give extra support to the motor mounts.

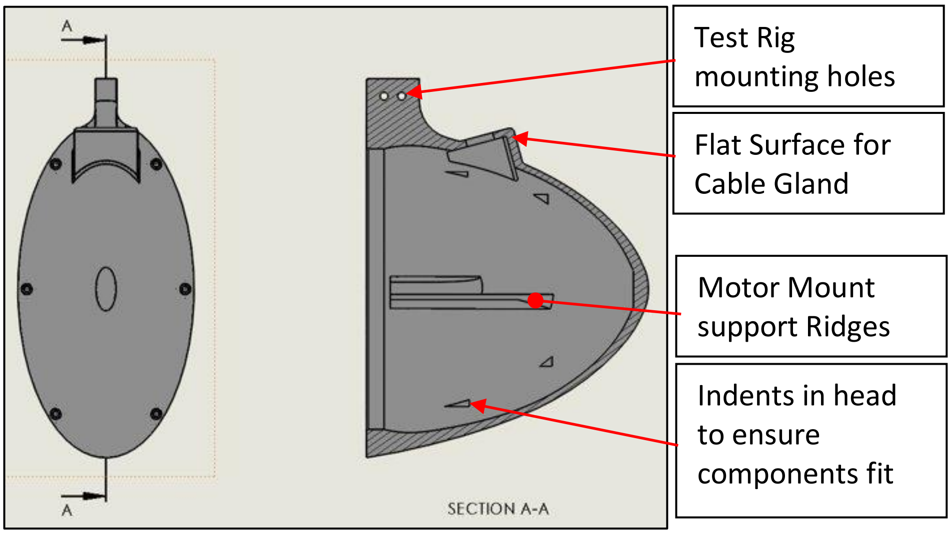


Figure 3.18: Diagram of Head Casing features

Waterproofing

The head must be fully waterproof to ensure there is no risk of damage to the electronics. As previously discussed, the Back Plate has a seal where the skin joins to the head, and an O-ring seal between the Back Plate and the Head Casing.

Because the power supply and logic for the stepper motors is provided externally, the respective wires must be able to enter the fish head without allowing water in. To achieve this, an M16 cable gland will be used, which will be fitted to the top of the Head Casing (Figures 3.18 and 3.19). The cable gland has an IP69K rating, the highest rating of the IP codes, which means it is waterproof when fully submerged under high pressures.

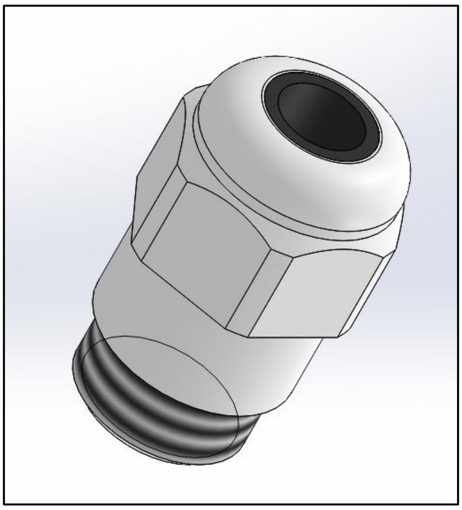


Figure 3.19: Cable Gland

The assembled elements of the Head Subassembly are shown in Figure 3.20 below:

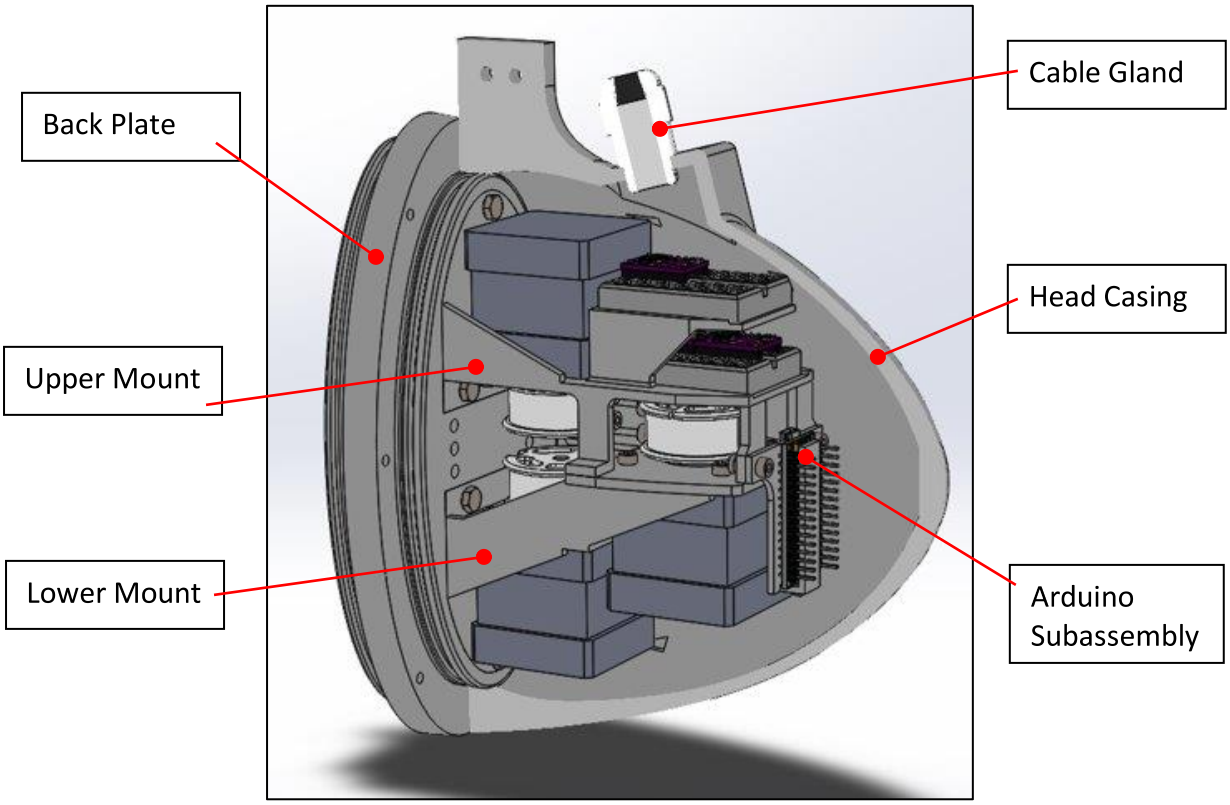


Figure 3.20: Full Head Subassembly with Head Casing and cable gland cross-sectioned to show interior

System Shape and Size

The following morphology diagram (Figure 3.21) of an Atlantic Bluefin Tuna was used to obtain the approximate proportions and shape of the system.

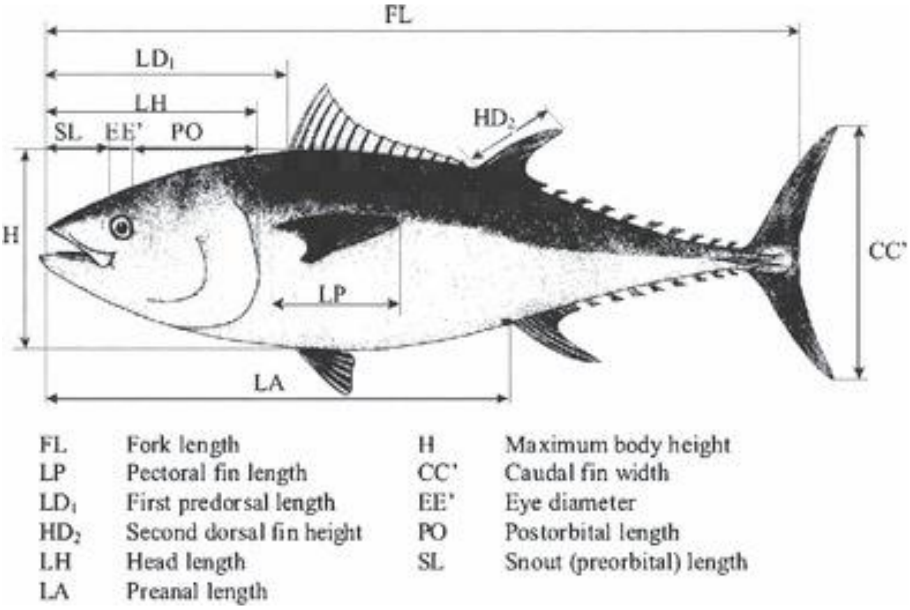


Figure 3.21: Morphometric diagram of an Atlantic Blue Fin Tuna [3]

Parameters	Range	Median	Geometric mean	95% CI
In % of fork length (FL)				
Head length (LH)	27.1–30.6	28.8	28.8	28.7–28.9
First predorsal length (LD_1)	29.3–34.5	31.8	31.9	31.7–31.0
Preanal length (LA)	57.4–65.5	62.0	61.4	61.2–61.6
Pectoral fin length (LP)	16.5–23.5	20.1	20.0	19.9–20.2
Second dorsal fin height (HD_2)	8.6–14.2	11.1	11.0	10.8–11.2
Caudal fin width (CC')	22.2–33.3	28.5	28.5	28.3–28.8
Max. body height (H)	23.5–29.4	26.9	26.9	26.8–27.0
In % of head length (LH)				
Snout length (SL)	27.5–36.0	33.2	33.1	32.9–33.2
Eye diameter (EE')	10.3–16.9	12.8	13.1	12.9–13.2
Postorbital length (PO)	50.7–59.0	53.9	53.7	53.6–53.9

Figure 3.22: Chart indicating the proportions of an Atlantic Blue Fin Tuna, based on the Total Length (FL) [3]

The overall dimensions were determined by the configuration of the stepper motors. Using their height as the approximate 'Maximum Body Height', H in Figure 3.21, the rest of the proportions were determined and they resulted in the following profile:

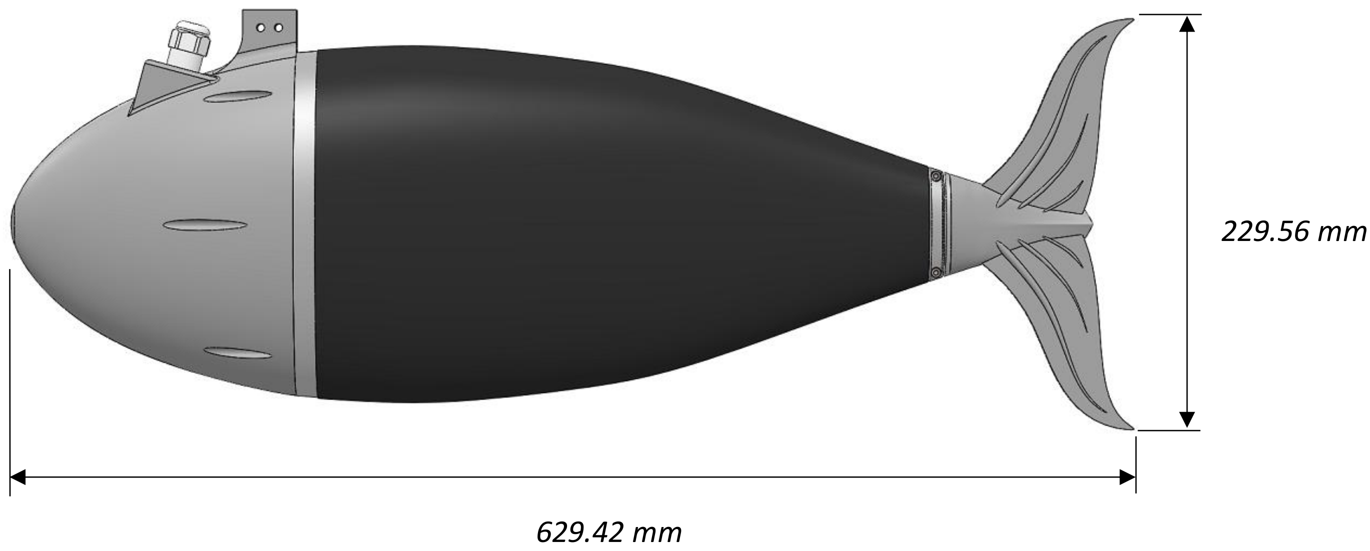


Figure 3.23: Side View demonstrating the final shape and dimensions of the system

Figure 3.24: Top View demonstrating the final shape and dimensions of the system

As shown in Figure 3.23, the resulting overall dimensions of the final design are approximately 630 x 230 x 100mm, complying with Requirement 8.

Vertebrae Design (BPS.02.00 – BPS.02.12)

The actuated body of the system consists of 13 vertebra which can pivot about each other.

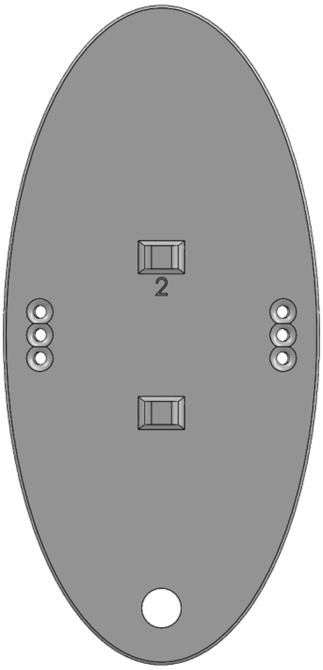


Figure 3.25: Diagram of vertebra front view

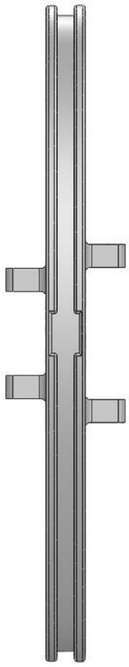


Figure 3.26: Diagram showing vertebra side view

Vertebrae Shape

The shape of the vertebrae has been designed to approximately mimic the cross section of a tuna. Each link has a unique lofted profile which when assembled creates the smooth profile of a real fish, as shown in Figures 3.27 and 3.28 below:

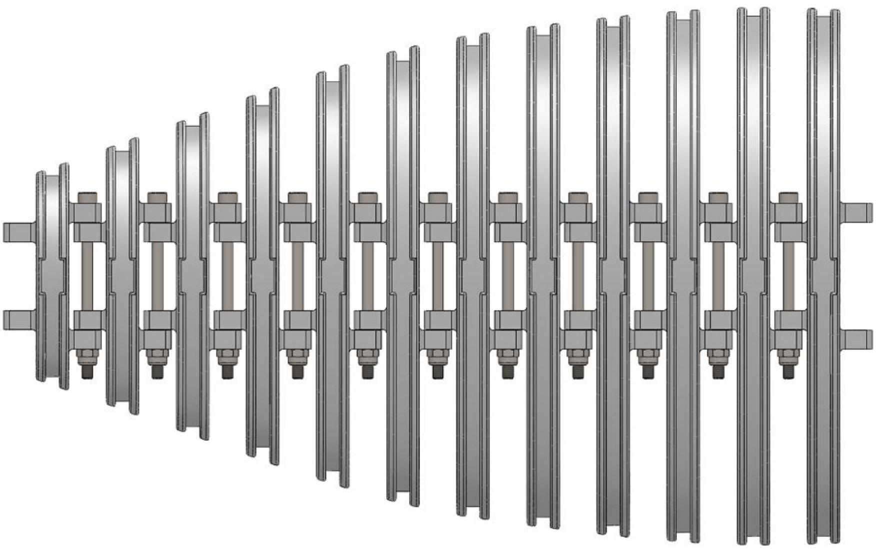


Figure 3.27: Side View of Vertebrae Assembly

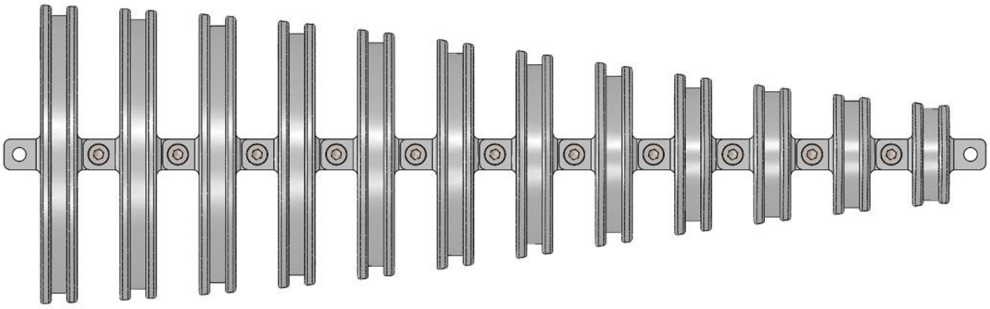


Figure 3.28: Top View of Vertebrae Assembly

Connection Between Vertebrae

A single bolt is to be used to connect adjacent vertebrae, ensuring good alignment and to reduce assembly time. The bosses that contain the through holes for the bolts have been designed so that there is clearance to allow the bolt to be securely fastened without creating any clamping force between the links, ensuring minimal friction in the joint. The bosses have also been designed with relief where they meet the body of the link, to reduce any stress concentrations. A nut with a nylon insert will be used to prevent it from coming loose.

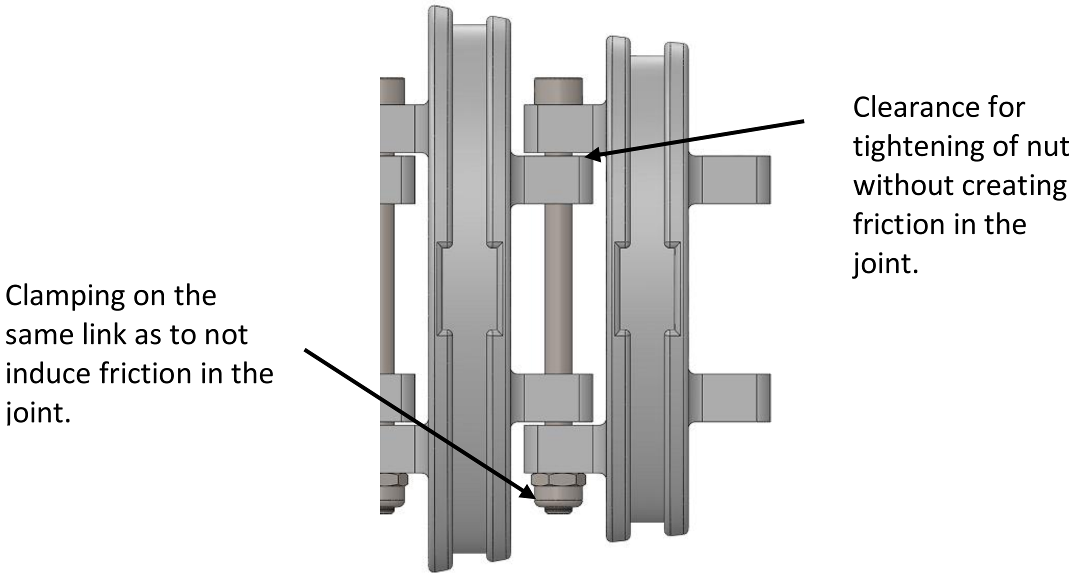


Figure 3.29: Side View of bolted connection

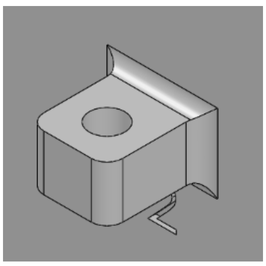


Figure 3.30: View of stress relief features on the bosses that contain through holes

At the Critical Design Review stage, attention was drawn to the fact that this method allows for unrestricted tightening of the bolt, which could result in the fracturing of the boss upon which it is clamped, if too much axial load is applied.

The solution to this problem is to use a bolt that has a shoulder which the nut could be tightened onto, or to use a circlip, removing any axial load on the vertebrae. This was investigated, however the additional time and financial cost of producing the parts for this method, in conjunction with the deliverable being a prototype system, resulted in the conclusion that the original method would be adequate, as long as care is taken to not overtighten the nut. This decision was made with, and deemed acceptable by, the customer. It is acknowledged that this is not good practice and would be an unacceptable solution for a production version of the product.

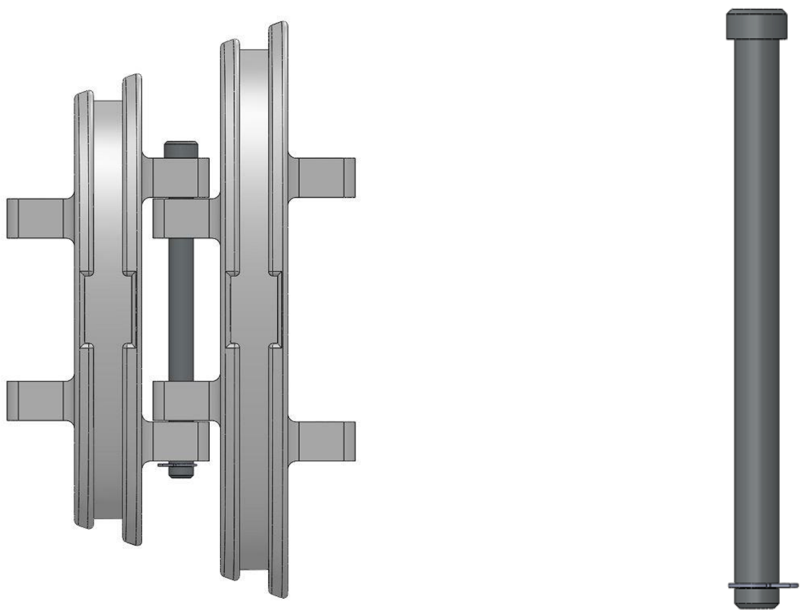


Figure 3.31: Diagram of a steel pin with a circlip

Skin Retention Features

A groove around the sides of the vertebrae constrain the cable ties which secure the skin. At the far ends of the assembly, the skin will be attached using 3D printed 'clamps' secured with bolts to create a watertight seal. Intermediate links will be attached to the skin using low profile cable ties to create the antagonistic force between adjacent links.

The groove has filleted edges to prevent any sharp corners coming into contact with the skin, reducing the risk of damaging it. A recess in the side of the groove has been created to allow the boss of the cable tie to sit flush with the vertebrae.

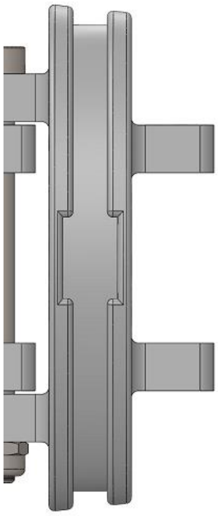


Figure 3.32: Diagram showing the skin groove

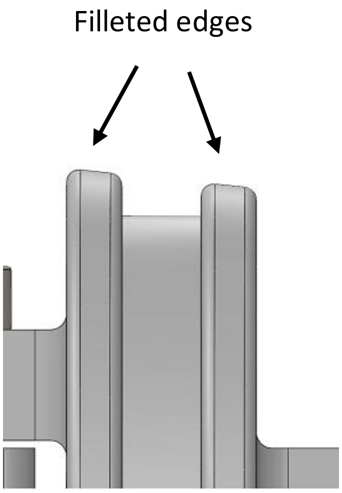


Figure 3.33: Diagram showing the filleted edges of the skin groove

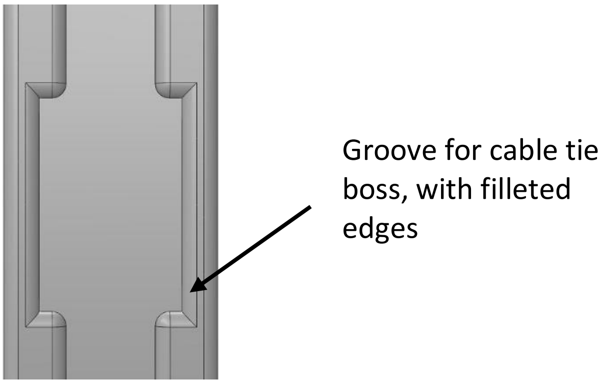


Figure 3.34: Diagram of recessed groove to fit the cable tie boss

Figure 3.35: Diagram of the cable tie boss

Cord Holes

Each vertebra has six through holes for the cords, which animate the mechanism, to pass through. These have been angled and rounded to prevent any catching of the cords as they pass between links. The holes have been positioned such that the maximum moment can be achieved, reducing the force required to manipulate them.

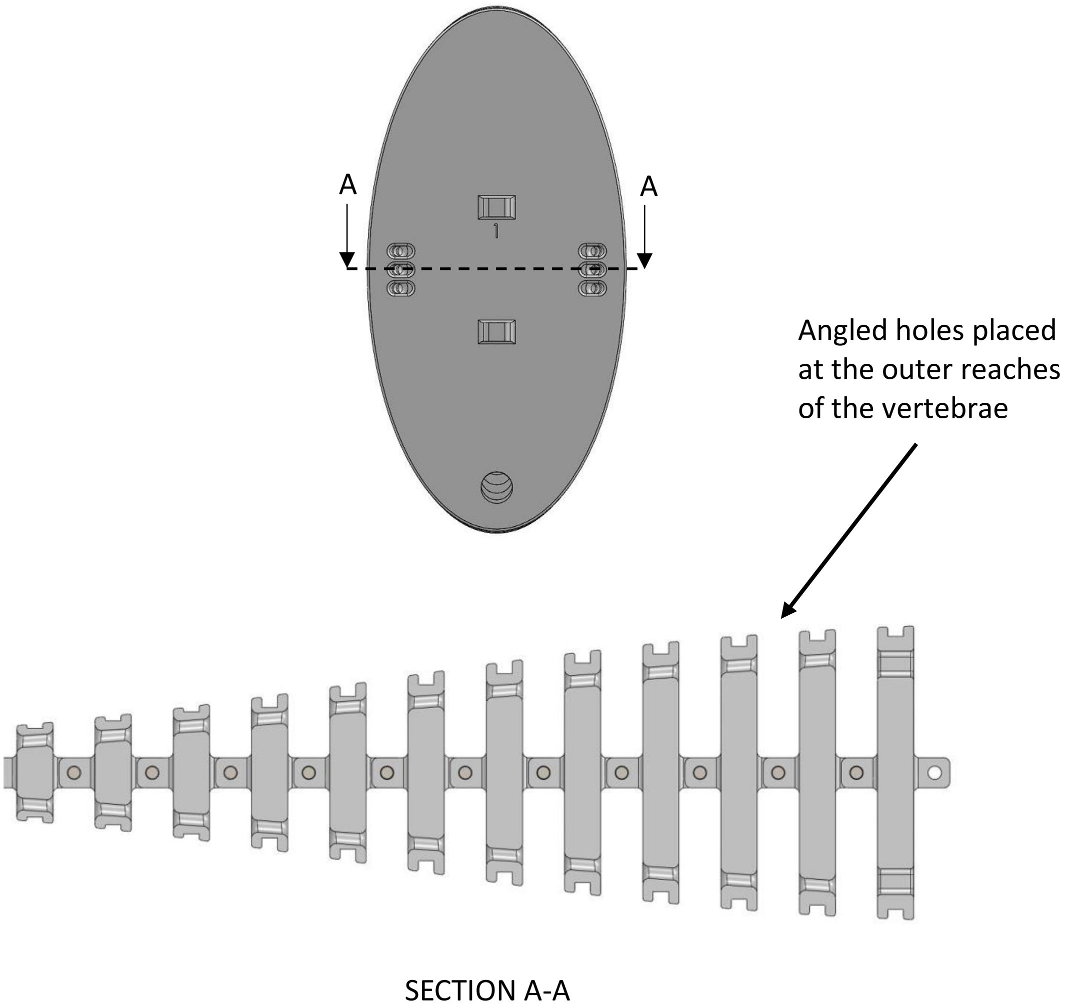


Figure 3.36: Section showing angled and rounded cord holes

Drainage Holes

In the event of seals or joins in the skin becoming compromised and allowing water into the body of the fish, holes in each link have been included to allow water to be drained out of each enclosed section. Although these holes have been included, the system needs to be watertight, so they are mainly designed for use when the watertight capability of the system is being tested.

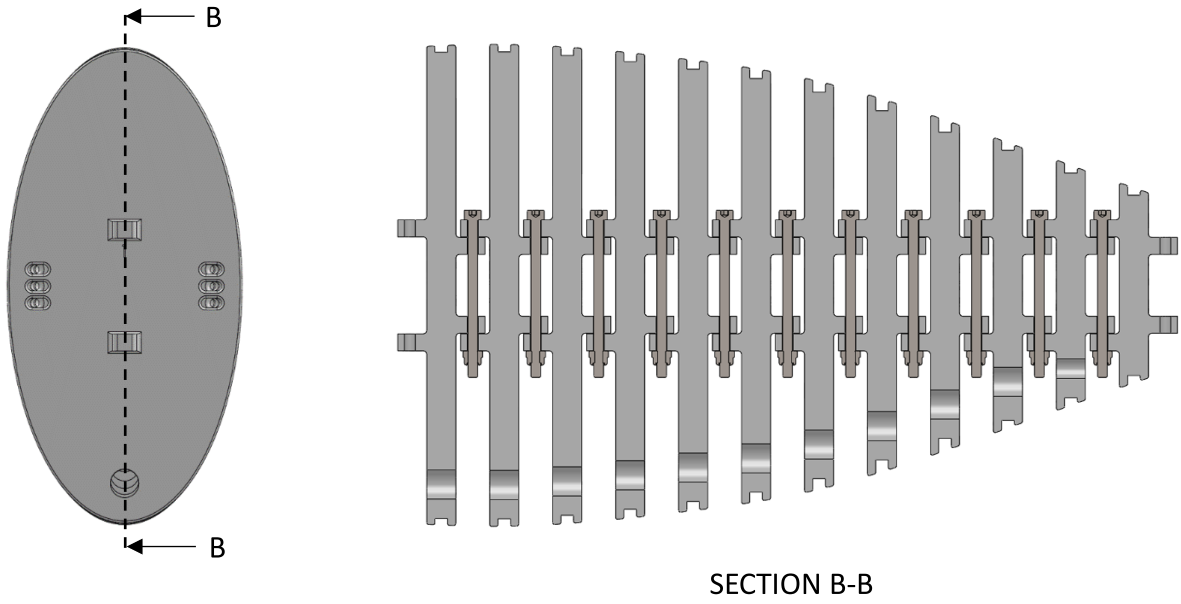


Figure 3.37: Diagram showing drainage holes

Due to the hollow nature of the 3D printed components, buoyancy of the tail section may become a problem once the system is submerged in water. If the buoyancy force is excessive and impacts the movement of the system, steel sleeves will be added around the bolts that connect the vertebrae to counteract the buoyancy force. These are illustrated in Figure 3.38 below.

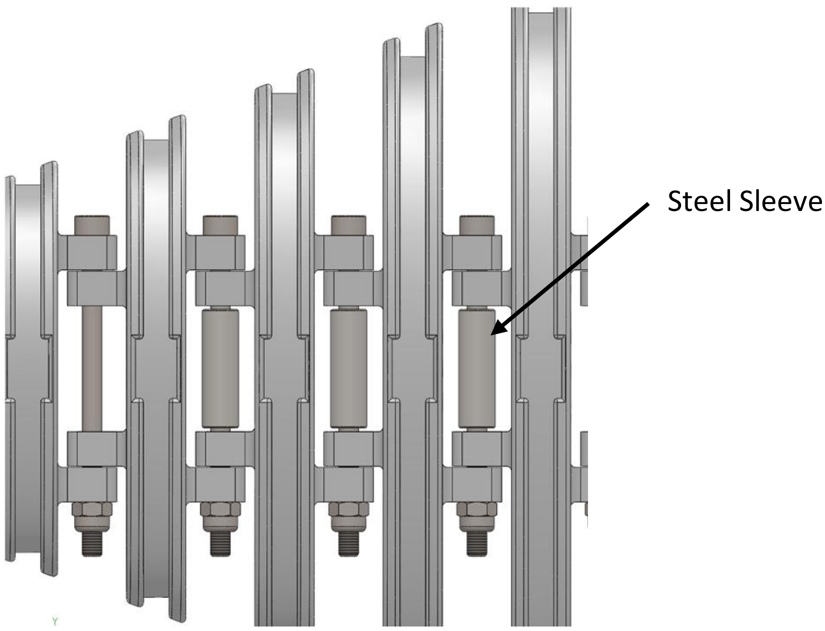


Figure 3.38: Diagram showing steel sleeves around bolts

Due to the similarity of the vertebrae parts, each one is marked with a unique number referencing the order in which they need to be assembled.

The number of vertebrae that make up the assembly has been dictated by the maximum size the system can be, and the minimum width of the vertebrae. It could be the subject of further work to optimise the number and width of the vertebrae, but this was not feasible within the constraints of this project.

Angular Restriction

During testing it became apparent that some restriction in the maximum angle of certain links results in an improved response and a more accurate replication of fish movement. Even though pictured as integral parts of the vertebrae below (Figure 3.39), in the final design these constraints will be added as separate components, allowing for the two proposed movement concepts to be tested.

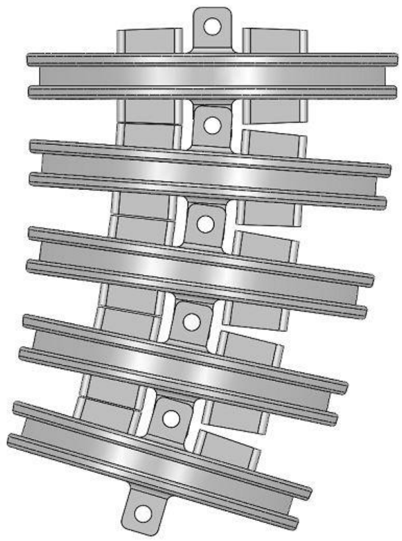


Figure 3.39: Diagram illustrating the intent of angular constraints

Clamp Design Rationale (BPS.00.01 – BPS.00.04)

At either end of the vertebrae assembly the skin must be attached so that there is no water ingress into the system. The proposed solution is to use a pair of clamps that can be tightened to compress the silicone between two surfaces to create a seal.

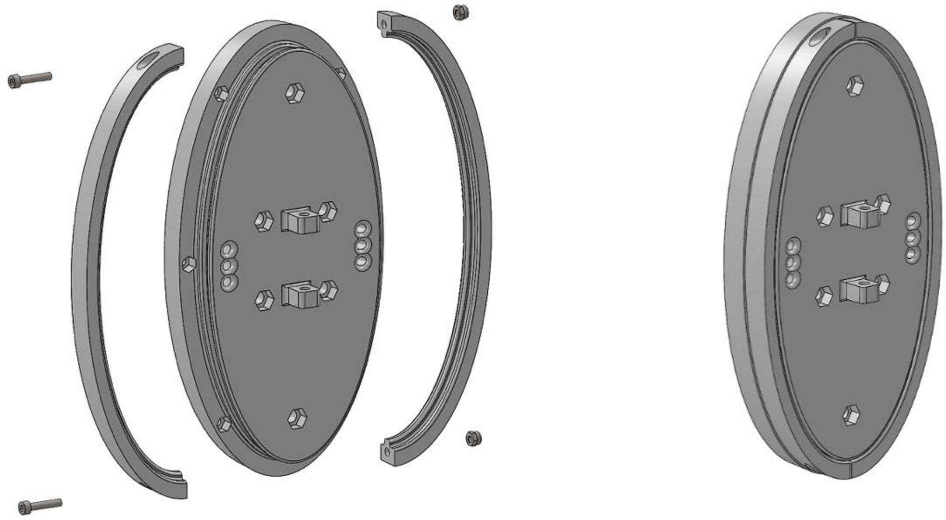


Figure 3.40: Exploded View of the Head End Clamp

At the end nearest to the head a ‘tongue and groove’ will be used, with the skin looping back over the top of the clamp, maintaining the smooth profile of the fish. The dimensions consider the tolerances that can be achieved with 3D printing.

All edges that come into contact with the skin have been filleted and will be given a smooth finish so that they do not damage the silicone. This is shown in Figure 3.41 below:

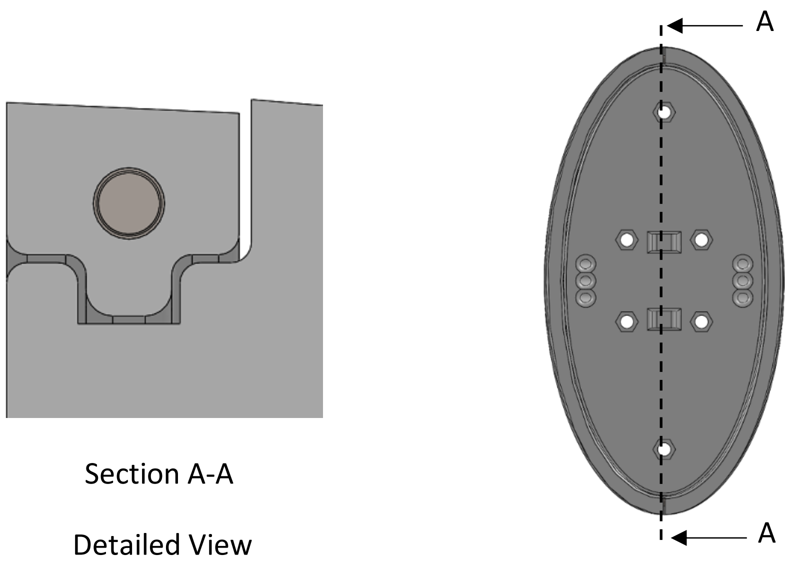


Figure 3.41: Detailed Section View demonstrating the geometry of the Head End Clamp

At the tail end the clamp will recess into the tail link (Page 42), reducing any protrusion:

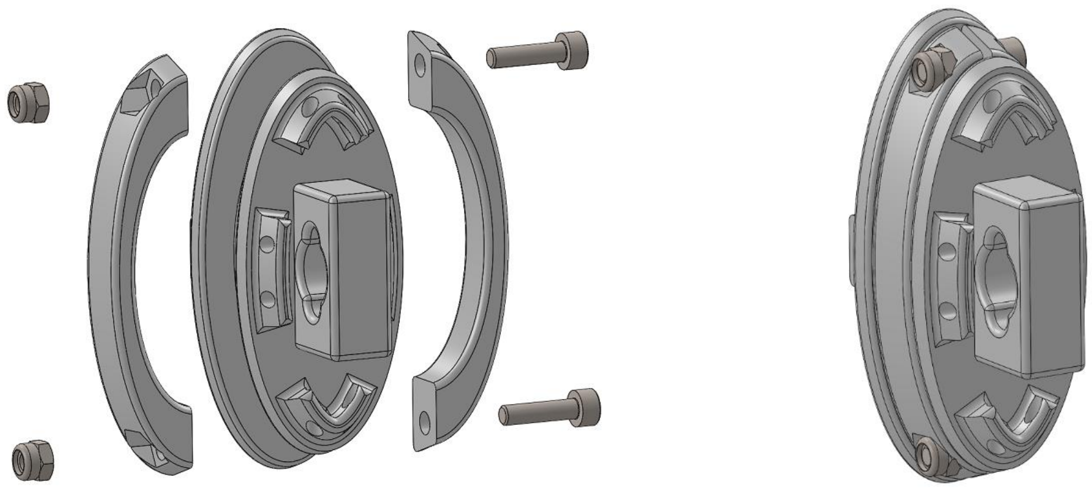


Figure 3.42: Exploded View of the Tail End Clamp

Both methods use a pair of nuts and bolts to allow clamping force to be applied. The clamps will be 3D printed using PLA, hence care has been taken to ensure that features such as holes have been oversized in the CAD model to avoid the need for alterations after the part has been manufactured.

Each pair of clamps uses a retained Nyloc nut and a countersunk M3 cap screw. These features have been designed so that they do not protrude from the surface of the clamp. They will also be made from stainless steel, so they will not corrode in a saline environment.

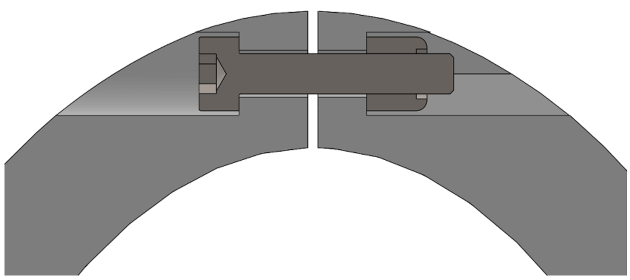


Figure 3.43: A Diagram illustrating the method of applying clamping force

Prior to installing any electronics, the integrity of the seals will be tested to verify that water cannot get into the system. Additional sealant materials may be required in order to ensure this.

Material Selection: 3D Printing

Due to the complexity of the geometry, 3D printing has been chosen as the method to manufacture the vertebrae and head components. Care has been taken to account for the precision that can be obtained using this process, and parts have been designed to minimise the amount of post-print processing that may be required. This has included accounting for the shrinkage of the holes.

The Rapid Prototyping Lab print in two materials, PLA and ABS. More materials can be used in the 3D printers however they prefer these due to their availability and ease of printing.

	PLA	**ABS**
Tensile Strength	37 MPa	27 MPa
Elongation	6%	10-50%
Biodegradable	Yes	No
Material Price	Same price for both	
Corrosion resistance: Marine Environment	All polymers are corrosion-free in salt water, though some absorb up to 5% causing swelling. (Parts will need to be finished to make them watertight)	
Other comments	• Regularly used due to its ease of use. • It requires a lower tip temperature and does not need a bed therefore printing is quicker than ABS. • It is a stiff material and will shatter by failure but has a higher tensile strength. • PLA is known for being more precise and creating a finer finish.	• Flexible material and so fails by yield and is shatter resistant. • It warps on cooling so needs to be printed onto a heated bed. • Resistant to high stresses and temperatures.

Table 3.1: Table showing the comparison between PLA and ABS for 3D printing

PLA prints faster and is cheaper than ABS, therefore, to ensure the project can be completed within the available time and within budget, PLA has been selected.

Additionally, PLA is the better choice for this project due to it being stiff with a high tensile strength. The head and vertebrae of the fish need to be stiff and so the flexibility of ABS may reduce the biomimicry of the product. PLA is often used because it is biodegradable; it is important to consider environmental factors when choosing materials, especially for a luxury product which may not be used regularly before being recycled.

Fused Deposition Modelling

The method of printing that to be used is called Fused Deposition Modelling (FDM) however, there are some issues with 3D printers that need to be considered:

	FDM
Dimensional tolerance [4]	$\pm 0.5\%$ (lower limit: $\pm 0.5mm$)
Shrinkage/warping	Shrinkage usually occurs in the 0.2-1% range.
Support requirements	Required for overhangs greater than $45°$, the supports must then be removed which can ruin the surface finish.
Finish quality	Depends on the speed that the part is manufactured. Surface will be rough and will require additional finishing before use.
Part integrity	3D printing saves material by creating a honeycomb structure within solid parts, this means that parts are lighter but also have different properties. For this project, parts have been considered as solid for weight and calculations due to parts not being subject to stresses close to their failure stress.
Printing direction	The orientation in which a part is printed effects the accuracy of certain dimensions. For location holes in the vertebrae, the part is printed so the circular hole is made upwards and not 'sideways'. Wrong orientation leads to elongation and tolerances are affected.

Table 3.2: Table showing FDM issues which need to be considered when 3D printing parts

These issues have been considered when designing and prototypes have been printed to ensure there are no problems. The surface finish for the vertebrae parts is adequate for use in this project and therefore the parts only need filing and holes drilled through to ensure they fit the tolerances. The head of the fish on the other hand needs to be watertight and aesthetically pleasing as it will be on display.

To finish the surface of the head (the materials needed are all displayed in the Budget in Section 6):

- The layers created by printing should be sanded down so they smooth out, then a white primer coat applied to the surface.
- The previous step should be repeated using increasingly fine wet and dry paper until the surface feels smooth to the touch.
- The part should then be spray-painted to desired colour and then nail varnish applied across the surface to ensure it is kept watertight.

Tail Design (BPS.03.02)

In order to ensure the propulsion system is able to produce the maximum achievable thrust with the power drawn by the stepper motors, the tail of the fish must be optimised.

Overall Size

In the System Size and Shape section on Page 24, the morphology diagram (Figure 3.21) indicates that the height of the tail, based on collected data, should be approximately 6% greater than the maximum diameter of the body section. Figure 3.21 also dictates the length of the tail. Both of these attributes will contribute towards a large surface area of the caudal fin, guaranteeing a broad reacting surface and allowing the piscine motion to take place. The shape of the peduncle of the tail was designed to taper and smoothly follow the overall desired profile.

Determining the Geometry

The optimisation of the caudal fin shape has been examined using research papers to achieve optimal values of thrust and efficiency. The critical geometric characteristics are:

- The leading edge angle of the caudal fin
- The concavity of the trailing edge of the caudal fin
- The amount of forking in the caudal fin profile

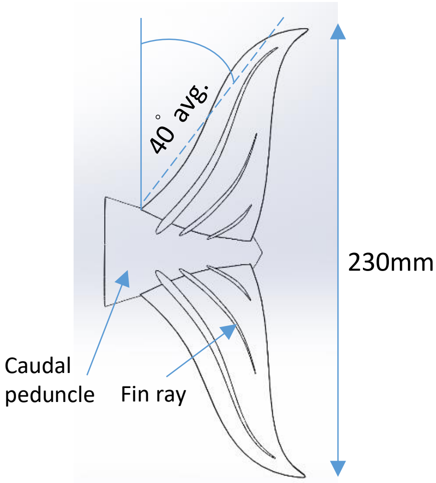


Figure 3.44: Caudal fin line drawing (CAD)

Leading Edge Angle

Figure 3.45 shows that as the leading edge angle (angle between leading edge and vertical) decreases, the amount of thrust produced by the swimmer increases, and reaches a maximum at approximately 40° [5]. Although it requires more power, this geometry produces the maximum propulsive force.

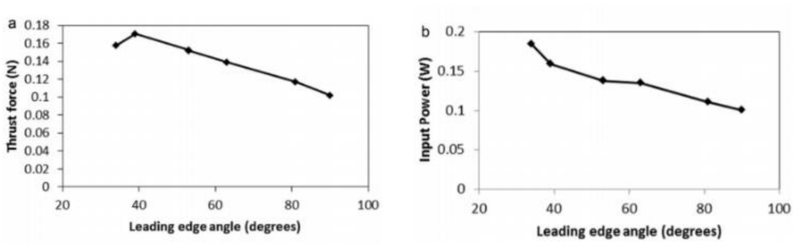
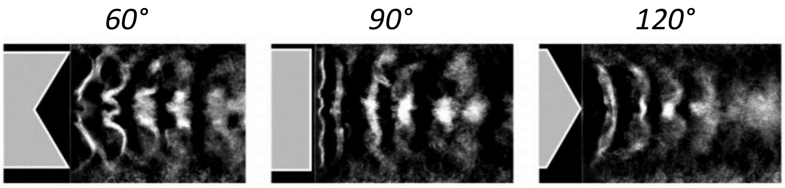


Figure 3.45: Graphs showing the effect of leading-edge angle on thrust and power [5]

Trailing Edge Concavity

A study into the 'impact of trailing edge shape on the wake and propulsive performance of pitching panels' [6] has shown that using a convex trailing edge for the caudal fin greatly improves the thrust coefficient and also the efficiency of the resulting propulsion.



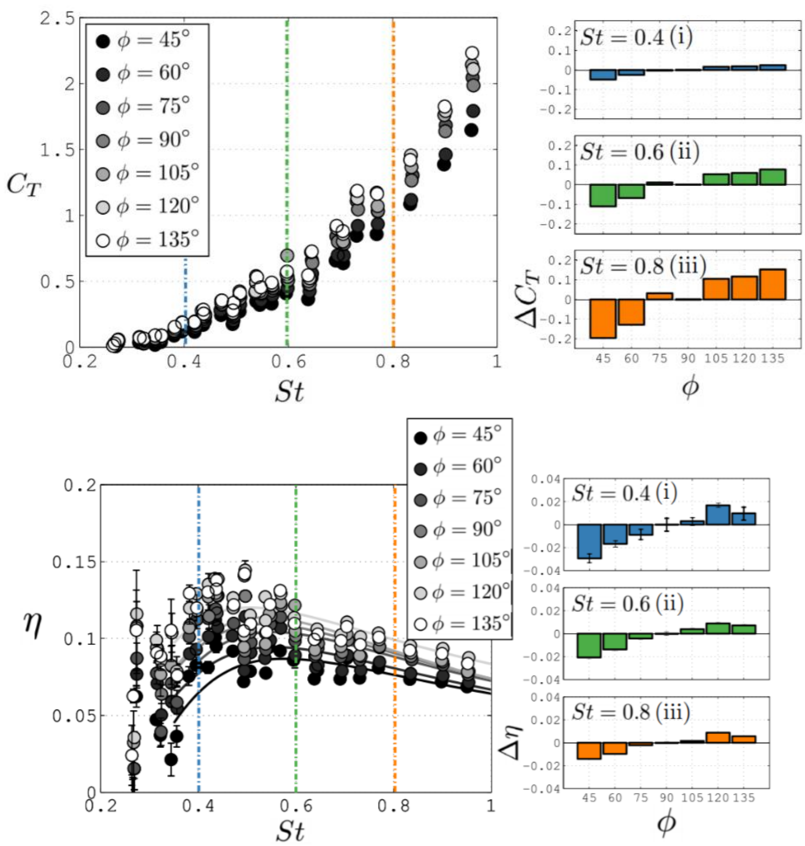
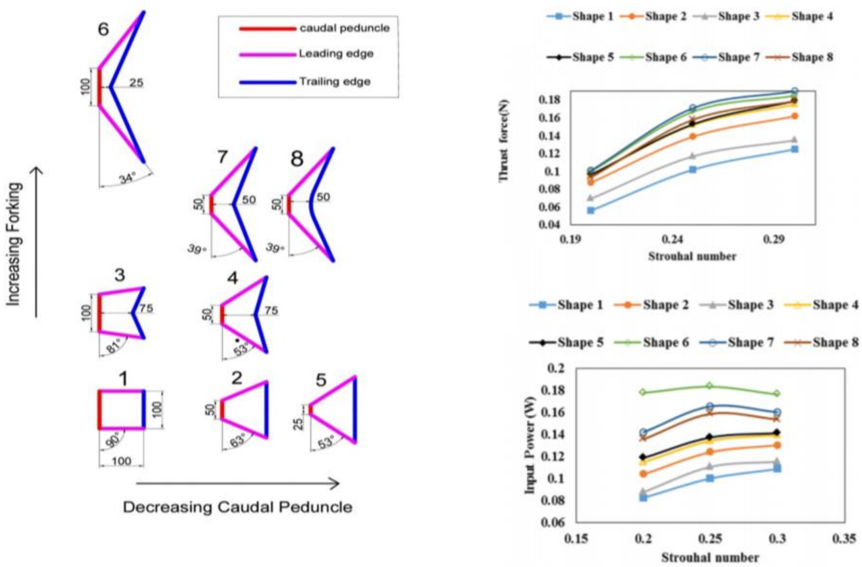


Figure 3.46: (a) Illustration of 3 different angles of trailing edge pitching panels (60°, 90° and 120°); (b) Graph showing the effect of trailing edge concavity on the thrust coefficient C_T across a range of Strouhal numbers; (c) Graph showing the effect of trailing edge concavity on the propulsive efficiency η across a range of Strouhal numbers [6]

From Figure 3.46(b) and (c), it can be seen that the 120° trailing edge geometry illustrated in Figure 3.46(a) performs much better across a range of Strouhal numbers (Pages 45 and 65) in terms of thrust production and efficiency (C_T and η respectively). Figure 3.46(a) also shows the less optimal 60° concave pitching panel and the square (90°) shape. For concave shapes, the efficiency is reduced by up to around 3% in comparison to the square trailing edge case, whereas for convex shapes the efficiency is improved by 2% for the case ϕ = 120 and St = 0.4. These findings influenced the caudal fin design; the tail model incorporates a 120° trailing edge.

Profile Forking

The amount of ‘forking’ in the geometry of the caudal fin is closely linked to the performance of the tail and consequently the system as a whole.



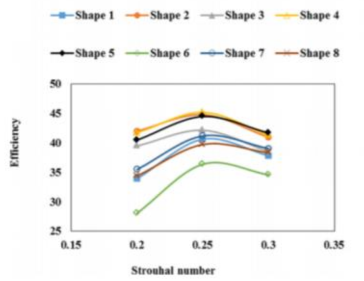


Figure 3.47: (a) Diagram depicting a variety of caudal fin shapes with different degrees of forking; (b) Graphs showing the effect of caudal fin geometry on thrust and propulsive efficiency [5]

In Figure 3.47(a), a wide range of shapes have been selected with differing degrees of forking and peduncle heights. The term ‘forking’ refers to the degree to which the two opposing points of the fin diverge from the central axis. Figure 3.47(b) shows how shapes 4 and 7 produce the largest quantities of thrust force at the highest levels of efficiency across a range of Strouhal numbers. These factors all lead towards the optimal design for the fish tail (Figure 3.44).

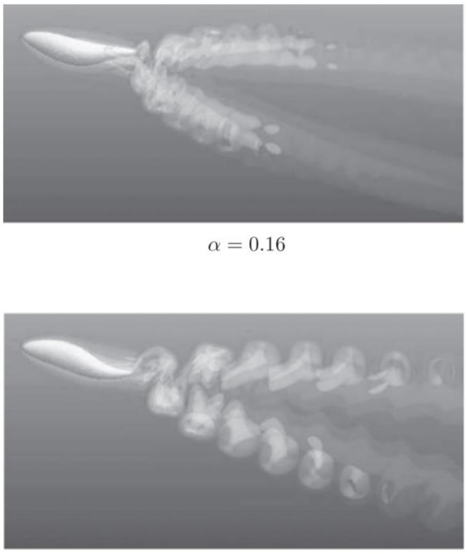
Other Features Regarding Shape

Fin rays are included in the design to improve the strength of the caudal fin and to increase the biomimetic accuracy of the appearance of the fish (Figure 3.44).

The thickness of the caudal fin is to be constant, unlike the tapering nature of the caudal peduncle. This characteristic is restricted by the minimum casting thickness of the manufacturing method discussed in the Tail Manufacture section (Page 41).

Material Selection

Further studies into the optimal flexibility of the caudal fin of biomimetic swimmers have found that the highest propulsive efficiency is achieved with a tail of ‘intermediate flexibility’ and that ‘neither excessive rigidity nor compliance are conducive to efficient propulsion’. Taking this further, it is observed that ‘rigid caudal fins lead to excessive lateral forces that increase power consumption without generating thrust, whereas highly flexible caudal fins produces negative thrust during significant portions of the stroke.' [7]



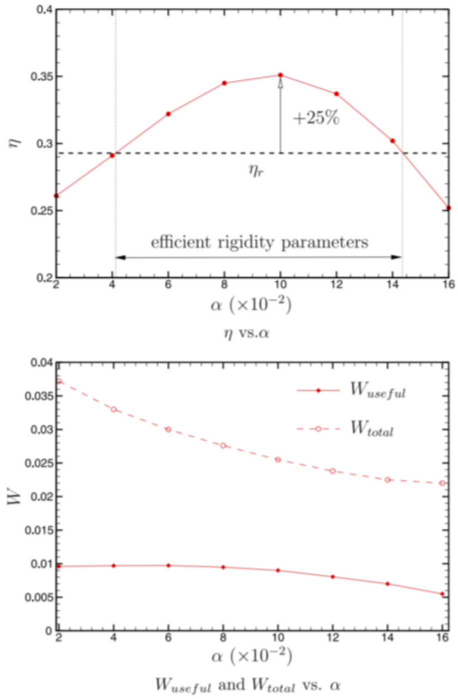


Figure 3.48: (a) Vorticity snapshots of caudal fins with relatively stiff and optimal rigidity parameters, α; (b) Graphs showing the effect of caudal fin flexibility on overall efficiency. They indicate a maximum efficiency η at intermediate stiffness [7]

Figure 3.48(b) shows how a caudal fin with a rigidity parameter midway between fully compliant and fully stiff will lead to increased efficiency of the swimming body as there is more useful work produced per Joule of total work done by the system. Figure 3.48(a) illustrates the vorticity snapshot of a stiff caudal fin (α = 0.16) in comparison to an optimised tail of intermediate flexibility (α = 0.10).

With this knowledge, an extensive comparison of potential materials was completed and samples of flexible material were ordered from local suppliers.

Material	**Process for manufacture**	**Flexibility**	**Price/kg**	**Comments**
Formlabs Photopolymer Resin	Outsourced Additive Manufacture	Provides some flex but quite rigid	£100+	Very poor toughness and failed after basic flexibility testing
PLA	Additive Manufacture	Rigid	~£16	Brittle

Polycraft T4 Silicone Rubber 40 Shore A	Casting	Very compliant	£27	Would not hold up under its own weight
Polytek PT Flex 60 Shore A Liquid Casting Rubber (LCR)	Casting	Compliant	£19	Would not hold up under its own weight
Polytek PT Flex 70 Shore A LCR	Casting	Intermediate stiffness	£19	Very suitable
Polytek PT Flex 85 Shore A LCR	Casting	Firm yet slightly flexible	£19	Very suitable
DuroFlex 85 PU LCR	Casting	Firm, yet slightly flexible	£19	Poor return to original shape

Table 3.3: Material selection for the manufacture of the caudal fin

Based on the findings from the material comparison (Table 3.3), Polytek PT Flex 70 and 85 were selected, as these cured resin samples provided intermediate flexibility. Given the low expense, both resins could be used to cast separate tail models to compare performance. It was guaranteed by the chosen supplier (MB Fibreglass) that the cured resins would have a long life after being submerged in salt water, and that the moulded tail would withstand the fatigue stresses associated with its piscine motion oscillations.

Tail Manufacture (BPS.03.03)

For the manufacture of the tail, a mould would need to be produced in order to cast the resin to give the required shape. The original tail part was subtracted from a cuboid and cut in half to give one half of the proposed tail mould (shown in Figure 3.49).

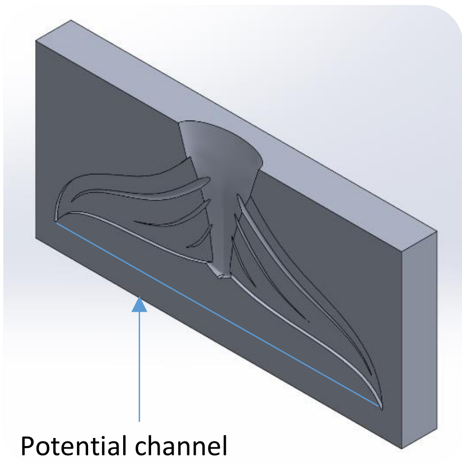


Figure 3.49: CAD model of one half of the proposed mould (locating dowels to be added by technician at their request)

The mould is to be made using two 6082 grade aluminium blocks (120mm x 260mm x 1”) using a CNC machine and the file was approved and booked for manufacture by the technicians in the workshop.

Aluminium was chosen as the material for the mould:

- It will last longer than silicone or PLA moulds, provide a much higher surface finish for the tail and can be machined to a much higher level of precision and accuracy than if using additive manufacture.
- It is non-porous and will therefore allow much easier mould separation than PLA.
- Silicone moulds often deform the shape of the moulded part due to the compression applied when the resin is curing.
- The build volumes of the 3D printers available were found to be too small to produce the mould in its desired form.

Although the use of bubble channels, such as between the two points of the caudal fin, were considered in order to avoid defects, the very low viscosity of the chosen resins meant that this was not necessary. Mould release spray will be used to increase the ease of removing the finished part from the aluminium mould.

Connection to the Final Tail Link (BPS.03.01)

The final aspect of the tail to be considered was the method by which the tail should be attached to the rest of the fish body. Figure 3.50 depicts the CAD part which will be used as the final link in the chain of vertebrae.

- The link will be clamped in place above the tail mould (Figure 3.49)
- It incorporates an extruded plug feature which allows the resin in the tail mould to cure around the link and secure the tail in place.
- A ring of extruded bosses with through holes is used to ensure the resin is bonded right up to the vertebra surface.
- The link includes two bosses to tie off the cords running through the length of the fish and space for the skin to be clamped around the final link, waterproofing the entire body section.

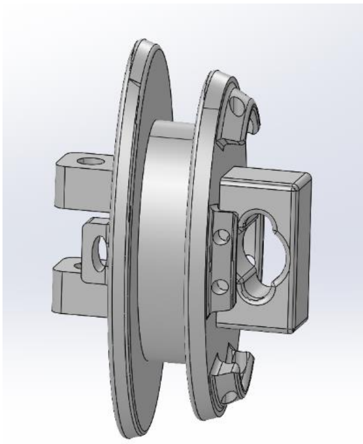


Figure 3.50: CAD model of final vertebra to be fixed to tail

Skin Design

The skin material covers the vertebrae to keep the system watertight, and also acts as the antagonist between each vertebra. To act as the antagonist, the material needs to provide suitable elasticity and strength and also be capable of being stretched without tearing or breaking. This was difficult to determine numerically, therefore materials were evaluated experimentally.

Several companies that supply polymers in sheet form were contacted and they supplied samples of different materials/thicknesses as shown in Table 3.4. The materials were chosen, in part, due to being reasonably priced for the quantity required and also because they were stocked by trusted suppliers.

Sample Supplier (Company)	Material	Thickness (mm)	Price per m	Comments
Polymax PROTEK	SBR – Black 70° Shore	2.00	£13.96	• Originally chosen for the product, the minimum thickness available for SBR was 1mm; this was too thick and did not have high elongation before failure. • The sample for 1mm tore after simple stretching and twisting
Polymax PROTEK	SBR – Black 70° Shore	1.00	£10.37	
Silex Silicones	Silicone – White 60° Shore	0.50	£17.19	• The two silicone samples showed improved performance with high elongation and resistance due to puncturing despite the thin thickness. • The 0.3mm silicone appeared to stretch considerably more than the 0.5mm sample and was more flexible in its movement.
Silex Silicones	Silicone – Translucent 60° Shore	0.30	£17.29	
Thames Valley Supplies	Latex – Brown	0.45	£61.95	• Latex is more expensive than the other two elastomers and the properties do not justify the cost. • The samples had excellent elongation to failure, however the material was more prone to puncture than the silicone.
Thames Valley Supplies	Latex – Translucent	0.33	£45.92	

Table 3.4: Comparing six elastomer samples for their use as a flexible skin

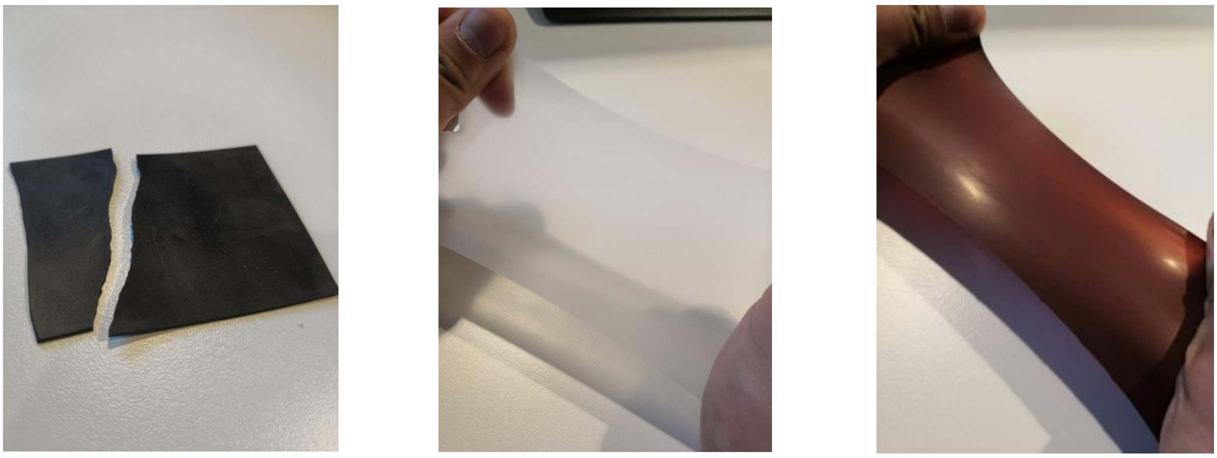


Figure 3.51: Pictures of three sample under tension to show their elongation capabilities. From left to right: SBR - 70° Shore, Silicone - 60° Shore and Latex

- SBR is no longer the best choice for the project due to it not being available in thin enough sheet form.
- Latex has a high at risk of puncture and can cause allergic reactions for some users.
- Silicone samples tested had the elasticity, elongation and flexibility desired for the skin material.

The manufacturing method for the skin requires that the silicone can be attached to itself. Several products were investigated and the company supplying the silicone sheeting were contacted to discuss the products they recommended. Table 3.5 shows the different products that were investigated to join the silicone sheeting to itself.

Sample Supplier (Company)	Product	Type	Comments
Smooth-On	Sil-Poxy	Silicone Adhesive	• Provides a strong and flexible bond. • Sil-Poxy takes 24 hours to fully cure which is considerably longer than the other products and is regularly used to seal silicone moulds made from thicker silicone.
Sleeve-It	369 Self Fusing Silicone Tape	Silicone Tape	• Silicone tape was a cheap alternative which was considered due to creating a tight seal with minimal time and effort. • Although the tape is strong, the seal created is not permanent so the waterproofing of the product would be compromised. • Additionally, the tape does not create a professional aesthetic for the product.
Silex Silicones	E41 - Translucent	Silicone Adhesive	• The E41 adhesive creates a tight seal and will be suitable as long as it is connected at a point of minimal elongation. • The Silex 400+ Primer Kit limits the curing time but it does not offer a better seal for the increased cost.
Silex Silicones	Silex 400 + Primer Kit	Instant Bonding Adhesive	

Table 3.5: Comparing methods for joining silicone to silicone

Silex Silicones recommended E41 silicone adhesive for use with the 0.3mm silicone chosen.
- E41 claims to have an elongation to failure of 500% which is exceptionally high and as the recommended choice from the supplier of the skin material it was agreed upon by the group to follow their expertise.
- The other adhesives were considerably more expensive which made the E41 a better choice.

The budget will show:
- 2m x 1.2m of black 0.3mm silicone sheet 60° Shore was ordered alongside E41 silicone adhesive and a 5m roll of silicone tape.
  - Translucent, despite being discussed, was not chosen because the inner workings of the product should be encased and not viewable for the proposed market.
  - The final product will only use about a quarter of the amount of silicone sheet ordered. However, after consultation with the customer, it was

decided that extra material should be ordered to test and ensure the final product works effectively.
- Silicone tape was ordered for the testing of prototypes due to its low cost and ability for instant use.

In order to manufacture the skin, an initial skin length needed to be calculated (as shown on Page 64). The final value for the initial length will be obtained after testing the final 3D printed parts. This will make sure that the skin fits perfectly to the final model.

- The skin sheet is cut to the correct length and then folded and attached to itself using silicone adhesive. This is then left to cure for 12 hours to produce a skin tube.
- The tube will then be pulled over the vertebrae and clamped at both ends to ensure pre-tension is kept along the skin.

Time Period to Produce Maximum Thrust Efficiency

It is important to consider the way a fish produces thrust in order to best replicate the movement of a fish. The oscillating body of a fish, as its tail reaches its maximum sideways deflection, creates a vortex. As the vortex drifts away, another vortex forms spinning in the opposite direction as the tail reverses direction. The continuous lateral undulations of the body create a staggered array of interconnected vortex rings which propels the fish forwards. Optimal thrust and efficiency are achieved by controlling the periodicity of the vortices in the wake, which can be found to be related to the **Strouhal** number.

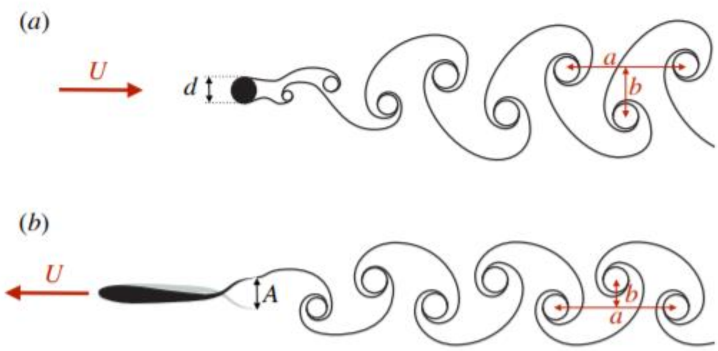


Figure 3.52: Illustration showing alternating vortex shedding behind a cylinder versus alternating vortex shedding behind a swimming fish [8]

The calculations on Page 65 show that, using the Strouhal number, the time period for one oscillation (peak to peak displacement) for optimal efficiency can be found. It is likely that this might change during testing in order to achieve maximum thrust.

Electronics Design

Actuator Selection

Three rotational bipolar steppers motors were chosen to control of the cords that actuate the system. Stepper motors were chosen because they can turn forwards and backwards an accurate number of steps without any positional feedback. Stepper motors of the size NEMA 17 were found to be the smallest motors that produced an appropriate amount of torque [9]. This was supported by preliminary trials.

To ensure the stepper motors could comfortably provide the torque needed by the system, the reserve factor (the ratio between the torque needed to accelerate the system and the torque provided by the motor) was calculated. Details of the reserve factor calculations can be found on Page 71.

The equations in the calculations section uses values for a HS174401 NEMA 17 0.4 Nm motor [10] which exhibits a higher torque than the motor used in the preliminary trials.

Microcontroller Selection

For the control of the stepper motors, Arduino microcontrollers were deemed the most appropriate due to their straightforward interface, control and electronics assembly.

A comparison was made between the Nano and the Uno, as both are the smallest and most commonly used Arduino microcontrollers. Both use the same Atmega328 chip and also have sufficient number of pins to control the three drivers needed to run the stepper motors (9 pins required in total).

The Nano is one of the smallest Arduino boards (18.5 x 43.2mm) and is the cheaper of the two. Its small size allows for higher flexibility spatially in terms of the configuration of the electronics. Its disadvantages however are that it requires soldering of the pins before it can be connected to external peripheral devices.

The Uno is roughly 3 times the size of the Nano (68.6 x 53.3mm), however it is more advantageous in terms of ease of use, as the majority of shield boards are catered for it. It has the disadvantage of having a larger board size which makes it more difficult to arrange inside the head that allows for a more realistic fish profile.

Figure 3.53: Image of an Arduino Uno

The board chosen was the Nano as its small size allows for the head to be a more compact, allowing for a greater length of actuated spine, which creates a more realistic representation of a fish.

Figure 3.54: Image of an Arduino Nano

Stepper Motor Driver Selection

The DRV8825 stepper motor driver was chosen due to its small size (15.2 x 20.3mm), and its current capabilities – it can deliver a continuous current per phase of 1.5A but can reach up to 2.2A with a heat sink making it suitable to control the 1.7A HS4401 0.4 Nm motor.

Figure 3.55: Image of a DRV8825 driver

It is very similar to the driver used in the preliminary testing (A4988) in terms of size and function however it exhibits better heat dissipation allowing it to have a higher current limit, making it more suitable for the project.

DRV8825 Current Limit Setup

From the manufacturer's specification [11], the current limit must be set at or below the current rating of the stepper motor. This is done by measuring the voltage between the potentiometer and ground. This current limit can be calculated using the following equation:

$$Current\ Limit = V_{ref} \times 2 \tag{1}$$

Electronics Arduino Schematic

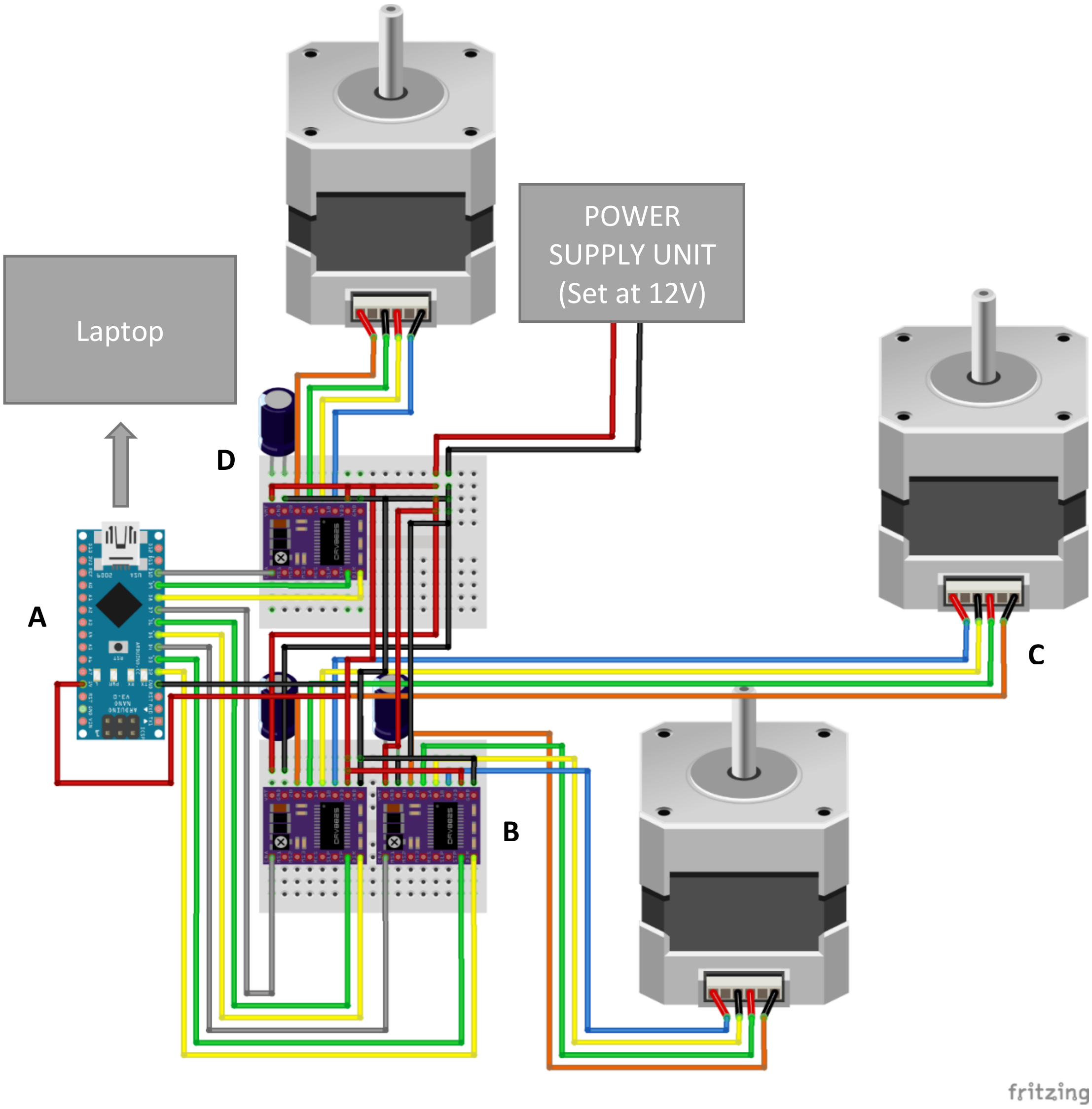


Figure 3.56: Schematic of the electronics wiring

Components	
A	Arduino Nano
B	DRV8825 Stepper Driver
C	1.7A NEMA 17 Bipolar Stepper Motor (HS174401)
D	100µF Capacitor

Table 3.6: Table indicating the components in Figure 3.56

Notes on the Electronics

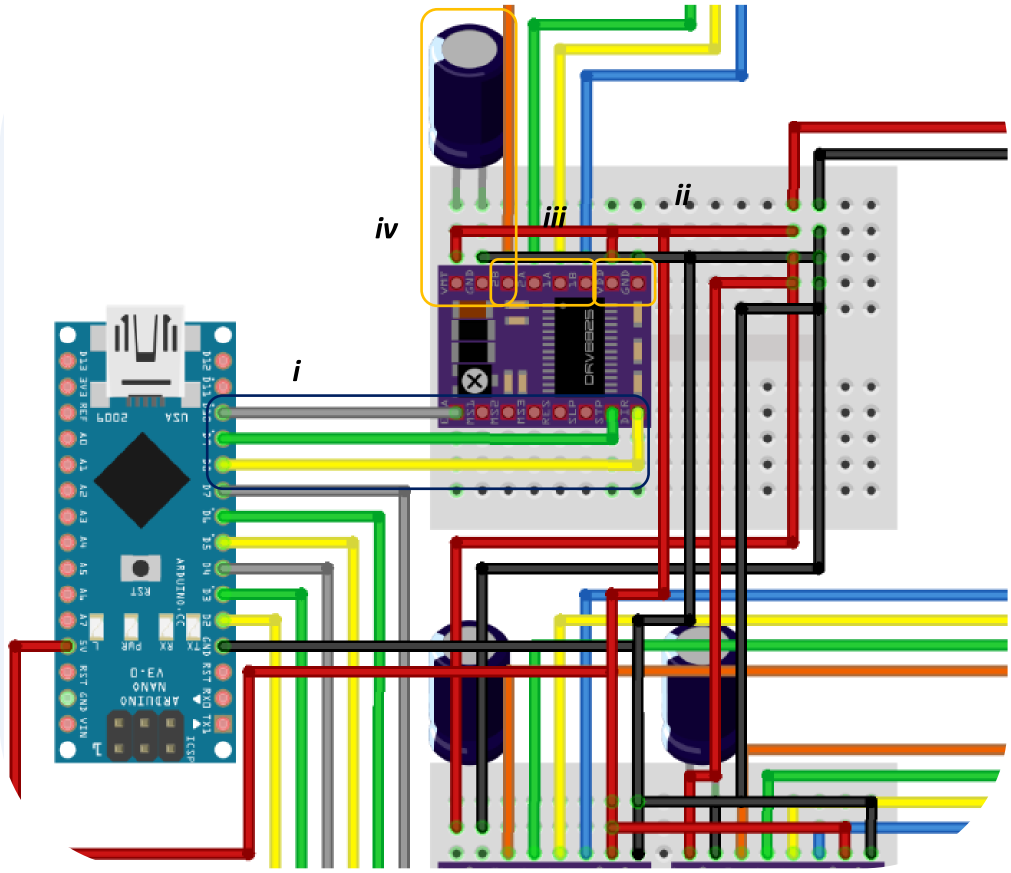


Figure 3.57: Close-up view of driver board pin connections

Schematic Notes		
Enable, Step and Direction Pins	*i*	• *Each driver needs three pins from Nano.* • *Enable line allows the disablement of the current to the inactive motors removing their holding torque.*
Driver V_{cc} and GND Pins	*ii*	• *Uses the 5V logic output from the Nano to power the DRV8825 driver.*
Driver Stepper Motor Pins	*iii*	• *Four pins on the driver connect to the four leads that powers the coils of the stepper motors.*
Stepper Motor Power Pins	*iv*	• *Stepper motors must be powered externally by the 12 V power supply with a 100µF capacitor to protect the driver from voltage spikes.*

Table 3.7: Table explaining purpose of driver board pins

Summary of the Control Program

The program that controls the stepper motors allows both the Antagonistic and the Reactive systems to be tested. Each motor configuration state is assigned to a number which can be changed via the serial monitor using the keypad.

The motor states and the actual values in the code (such as the maximum rotational position the stepper motors will travel) will be refined through iterative testing to obtain the required biomimetic piscine locomotion and maximum thrust.

There is also a reset state which will set the stepper motors back to their defined zero position. This will be used in between active state changes to ensure the motors do not become desynchronised from each other.

Example States			
Reset State	State 1 (First Harmonic)	State 2 (Second Harmonic through Antagonistic Motor system)	State 3 (Second Harmonic through Reactive system)
Reset	Active	Active	Inactive
			
Reset	Inactive	Active	Active
			
Reset	Inactive	Inactive	Inactive
			

Table 3.8: Table indicating on/off state of each stepper motor for each programmed mode

The code uses the *AccelStepper* library. The step per time algorithm (by David Austin) which has linear velocity ramping (constant accelerations).

Fastener Material Selection

Throughout the design, stainless steel fasteners have been used due to their superior corrosion resistance compared to plain steel. In a production version of the system, stainless steel would only be required where fasteners are exposed to water to reduce costs. However, as this is a prototype and its water tightness is yet to be verified, stainless steel has been used throughout.

Test Rig Design (RSA GA)

The test rig has two functions: to measure the thrust that will be produced by the robotic fish and to mount and support it, as buoyancy and the reactive forces from water were not required to be considered in the project.

An emphasis on the ease of manufacture and assembly was applied to the design of the rig. This was achieved by using materials and components readily available from the L2 stores. The rig must attach to the 50mm hollow square bar that spans the width of the testing tank.

There are five main parts to the test rig: the mounting of the rig to the 50mm hollow square bar; the pivot mechanism and its connection to the dynamometer; the dynamometer mount and the mounting connection to the head of the fish.

Mounting of the Rig (RSA 3 and RSA 4)

The test rig will have two angled steel bars mounted to the hollow bar crossing the tank. Flexing and bending in the transverse direction is undesirable, hence angled bars were selected over flat bars. Steel has been chosen for these components as it has a high modulus which will reduce bending and it is also relatively inexpensive. Rust and corrosion are also not of concern as these components are above the water.

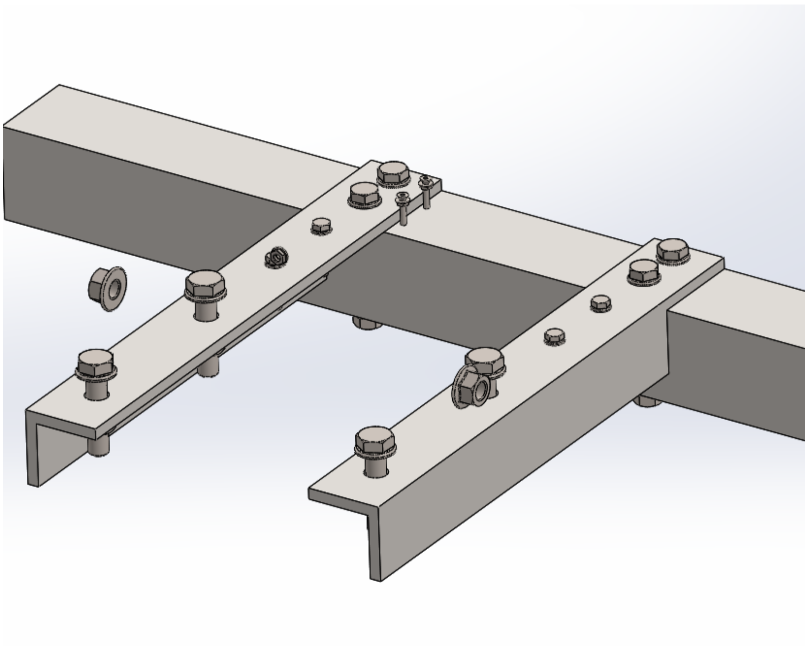


Figure 3.58: View of 40x40x6mm test rig angled bars

Pivot Mechanism

To limit the friction around the pivot point, rolling element bearings were chosen over plain bearings. The design incorporates two pillow block bearings mounted on the protruding arms which will support a welded assembly of an aluminium pivot rod (*RSA 5*) and bar (*RSA 6*).

As the mounting bar will be welded and submerged in water, aluminium is used as it can be welded and has good corrosion resistance.

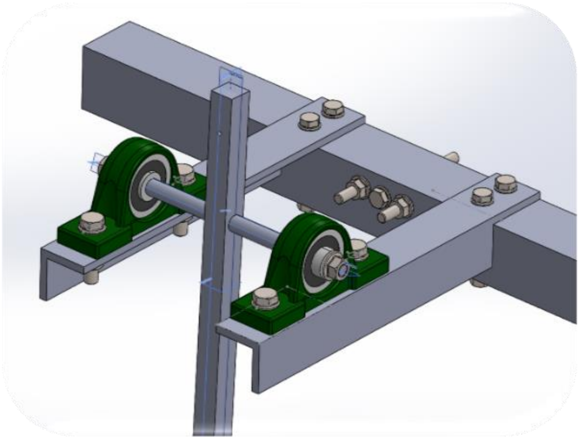


Figure 3.59: View of test rig pivot mechanism

Dynamometer Mount (RSA 1 and RSA 2)

Three different spring Newton meters will be used: 5N, 10N and 20N maximum capacity meters all having the same dimensions. A high-resolution electronic gauge was considered, however as it is placed above the water tank, and is more expensive, it was not selected.

Figure 3.60: Image of the dynamometer to be used for testing

The main objective of the dynamometer mount is to allow gauges to be easily swapped during testing. For ease of manufacture, the mounting structure has been designed to be produced out of readily available sheet steel through metal sheet folding. The mount is designed to be made from two parts that have simple geometry for ease of manufacture.

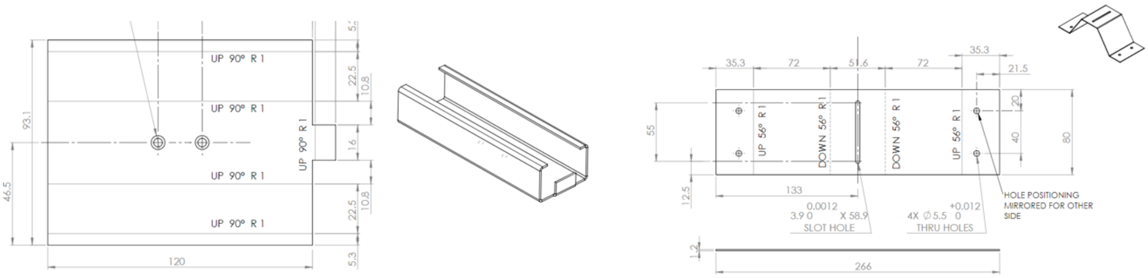


Figure 3.61: Drawings of Upper and Lower parts of the mount

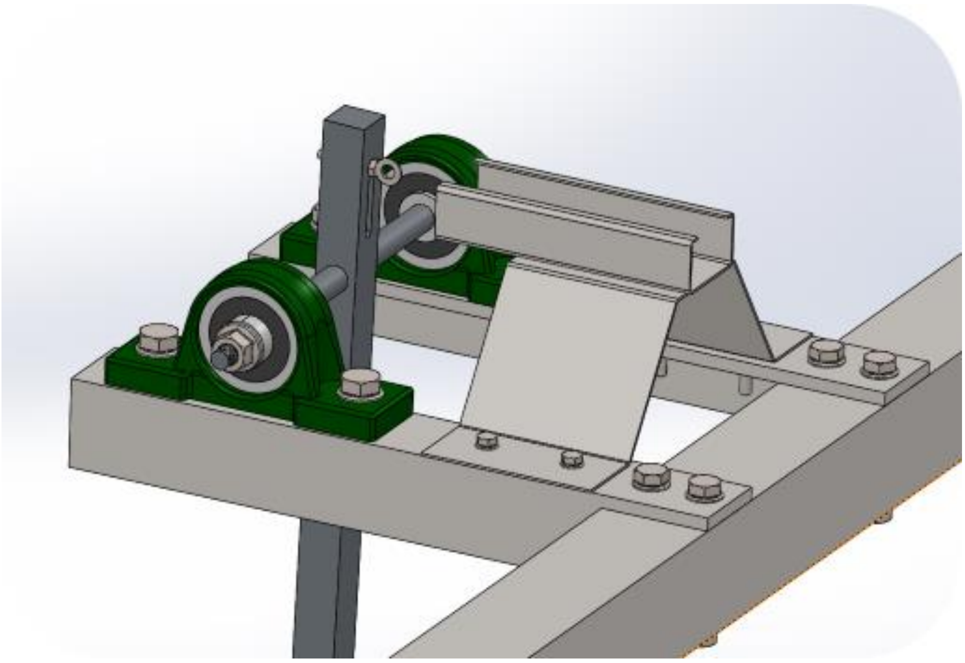


Figure 3.62: 3D model of the testing rig assembly

Pivot Connection to the Dynamometer (RSA 5 and 6)

Since the test rig will most likely need adjusting during and after installation, the connection is designed so that the hook connected to the dynamometer can be changed in height (a threaded hook (*RSA 7*) slotted on the mounting bar – Figure 3.62).

The hook (*BOM 23 in RSA GA*) will be made by welding a washer to an M4 bolt.

There is a slot in the bottom part of the dynamometer mount to allow axial adjustment of the upper mount (Figure 3.63).

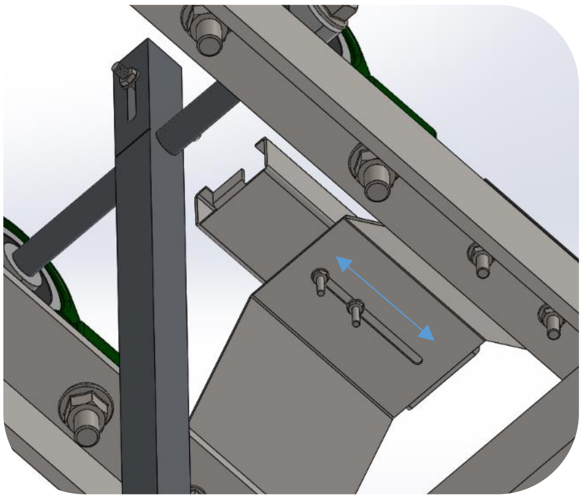


Figure 3.63: Image showing axial adjustment of the upper mount part

Fish Head Mount (RSA 6)

Due to the nature of the pivoted design, the fish will swing in a radial direction rather than a direct linear motion. One solution for this would be to have the fish pivoted at the bottom of the pivot bar so that as the bar rotates, the fish would stay horizontal. The problem with this however, is that if the pivot is not at the centre of gravity, it will cause a tipping in either side of the fish which would lead to higher uncertainty and unreliability in the test results. Due to the hollow nature of the components, CAD models cannot give accurate values for the centre of gravity.

The Newton meters that will be used have a maximum reach of 5-6cm, hence, it is assumed that the rig will experience negligible angular rotation and displacement. This led to the design of the fish head having a fixed bolted connection to the pivot swing bar (*RSA 6*).

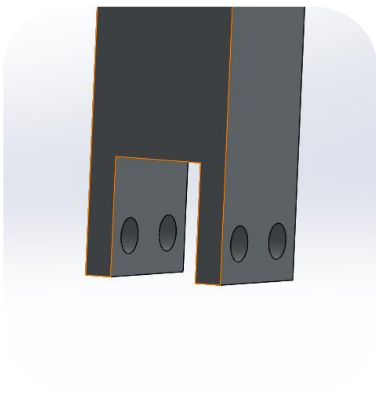


Figure 3.64: Image of the connection to the head casing at the end of the pivot swing bar

Cord Material Selection

A thin cord is used to manipulate the vertebrae assembly to produce propulsion. The material selection for this part is detailed in this section.

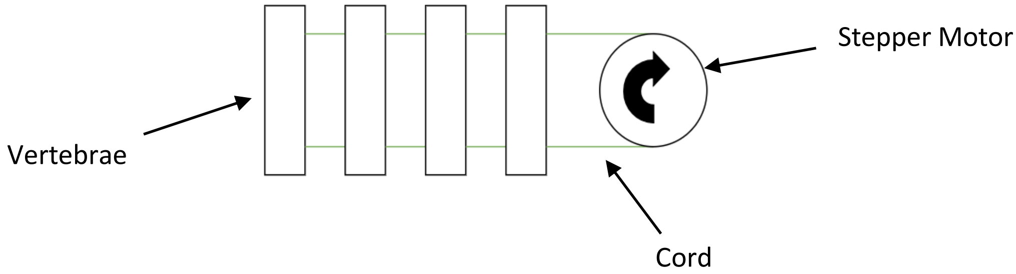


Figure 3.65: Diagram indicating the cord-vertebrae-motor mechanism

Desirable Properties

- Has a yield strength greater than 14.04 MPa (This accounts for a reserve factor of 2, Page 72).
- Resistant to abrasive wear.
- Will not degrade in a saltwater environment.
- Suitable flexibility.
- High fatigue strength.
- Must be available in a diameter < 4mm.

Nylon was chosen as it exhibits adequate strength, has a low coefficient of friction, is rot resistant and is not adversely affected by wetting and drying cycles. It is also available in a diameter smaller than 4mm and exhibits the appropriate flexibility. Other synthetic rope materials used in marine applications were considered, however nylon exhibits the best fatigue strength, allowing for the greatest life in service as shown in Table 3.9 below:

Property	Polyamide (Nylon)	Polypropylene	Polyester
Yield Strength (MPa)	50 – 94.8	20.7 – 37.2	33 - 40
Ability to cope in a salt water environment	Acceptable	Excellent	Excellent
Fatigue strength at 10^7 cycles (MPa)	36 - 66	11 – 16.6	16.6 – 35.8

Table 3.9: Table comparing the properties of different synthetic fibres commonly used [12] in marine settings [13]

Steel cable was considered, however, due to the abrasive nature of steel on plastic, it was discounted. Cotton has also been discounted due to potential rot and degradation as a result of water absorption.

At the Critical Design Review stage, the reviewers suggested using a carbon fibre cord. It would exhibit the strength required and is not affected by salt water. However, as shown in Table 3.10 below, it could not be sourced at a price that would make it a financially acceptable alternative to nylon cord:

Material	Supplier	Cost	Cost per metre
Nylon Braided Cord 1.8mm (55m) [14]	Amazon	£6.99	£0.13
Carbon Fibre Cord 2mm (100m) [15]	Dyneema	£64.21	£6.42

Table 3.10: Table comparing the costs of nylon and carbon fibre cords

4. Calculations

Motor Frame Calculations

To ensure the upper and lower mounts can support the components (mainly the stepper motors) a simple beam bending calculation can be carried out by assuming the mounts to be simple cantilever beams (ignoring the complex geometries of the parts). The symbols used in this section are defined in Table 4.1 below.

Symbol	Variable	Unit
δ	Deflection	m
σ	Stress	Pa
F	Force	N
L	Length	m
E	Modulus	Pa
I	Second Moment of Area	m^4
M	Moment	Nm
Y	Distance from neutral axis	m

Table 4.1: Table showing list of variables used in calculations

Material Properties of PLA[16] [17]: $E = 3.5\ GPa, \quad \sigma_y = 35\ MPa$

Each stepper motor weighs approximately 300g and so will each exert a downwards force of roughly 3N.

Lower Mount

Max. Deflection:

$$\delta = \frac{FL^3}{3EI} = \frac{6\ \times (76 \times 10^{-3})^3}{3 \times 3.5 \times 10^9 \times 1.26 \times 10^{-10}} = 2\ mm \tag{2}$$

Max. Stress:

$$\sigma = \frac{My}{I} = \frac{((3 \times 29 \times 10^{-3}) +\ (3 \times 22 \times 10^{-3}) + (3 \times 25 \times 10^{-3})) \times 1.5 \times 10^{-3}}{1.26 \times 10^{-10}} = 2.7\ MPa \tag{3}$$

The maximum stress experienced was much lower than the yield stress so is acceptable. However, the deflection calculated is quite large and so FEA was carried out on the part to see what the actual deflection would be. The FEA showed that the part would experience a max. deflection of 0.214mm and a maximum stress or 1.56MPa. This supports the calculations above as the added chamfers that were ignored in the initial calculations would provide added rigidity, giving a lower deflection.

Upper Mount

Max. Deflection:

$$\delta = \frac{FL^3}{3EI} = \frac{3 \ \times (29 \times 10^{-3})^3}{3 \times 3.5 \times 10^9 \times 1.26 \times 10^{-10}} = 0.055 \ mm \tag{4}$$

Max. Stress:

$$\sigma = \frac{My}{I} = \frac{3 \times 29 \times 10^{-3} \times 1.5 \times 10^{-3}}{1.26 \times 10^{-10}} = 1 \ MPa \tag{5}$$

The deflection is small and since this calculation ignores the added support provided by the chamfers on the part, the maximum deflection will be smaller than calculated. The maximum stress experienced by the part is small and so the part will not fail either, hence there is no need for further calculations.

Fatigue Life of Mounts

The motor mounts will experience a load cycle due to the force that the cords exert on the mount as the fish moves from side to side. The force on the cords has been calculated to be 22.2N (see Page 72).

Due to the complex geometry of the part, FEA was used to find what stress this would exert on the mounts. The maximum stress exerted on the motor frames (Upper and Lower) was found to be less than 6MPa.

A research paper found on the fatigue life of PLA stated that 'an approximation to the fatigue limit for PLA parts manufactured using a honeycomb infill with 75% density, 0.5 mm of nozzle diameter, and 0.3 mm of layer height has been detected at around 45 MPa.'[18]. Therefore, for the small stresses experienced by the mounts, the parts should not fail by fatigue for the life of this project.

Vertebrae Stress Calculations

The critically stressed areas for the 3D printed vertebrae are the small bossed joints which connect each of the vertebrae together with a single bolt. This is the thinnest segment and will be subjected to the highest loads. In order to test whether the 3D printed material (PLA) is able to withstand these forces, Finite Element Analysis (FEA) has been used.

FEA has been used for this part due to the complex geometry. Hand calculations were performed but due to vertebrae being connected in the series and being loaded through multiple pins at varying heights the simplified calculations differed hugely from those found from FEA.

- The highest loads on the pin joints can be assumed to be if the fish is held at the head section allowing the weight to hang down.
- The largest stress values will therefore be seen on the first set of pins (vertebra closest to the head). This can then be modelled as a cantilever beam.

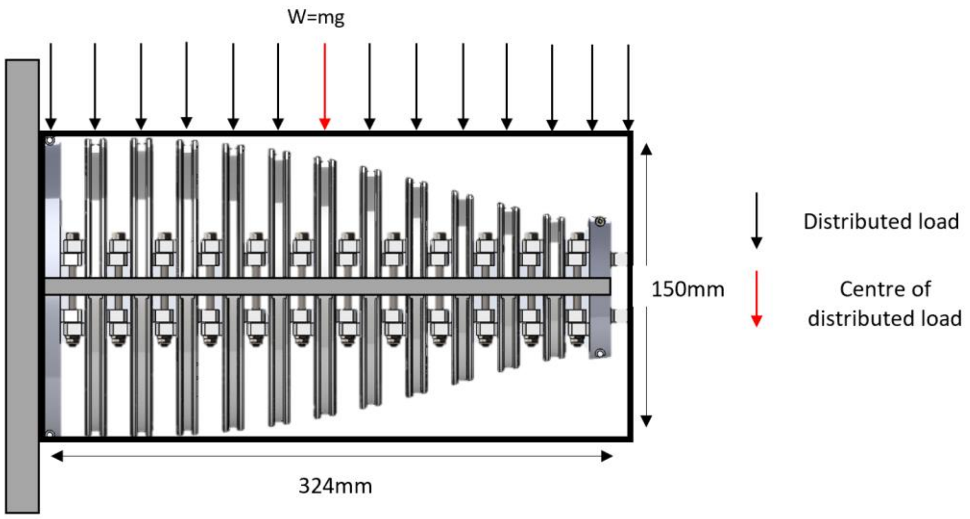


Figure 4.1: Side view showing the fish vertebrae modelled as a cantilever to understand the weight distribution across the segment

Assuming the vertebrae segment as a rectangle it can be modelled that the centre of mass of the segment is in the centre of the beam. SOLIDWORKS Simulate was used to analyse the stress on the pin jointed area using FEA and the material property was set to PLA.

A fine mesh is needed at the points of interest (pin jointed holes), due to the stress gradients changing dramatically in these areas. This increases computation time but ensures that the part is well modelled and, due to the small size of the part, the computation time was not excessive.

- An example of the finer mesh used can be seen in Figure 4.2. Two meshes were used to compare the different stresses computed and understand the reliability of the analyses:

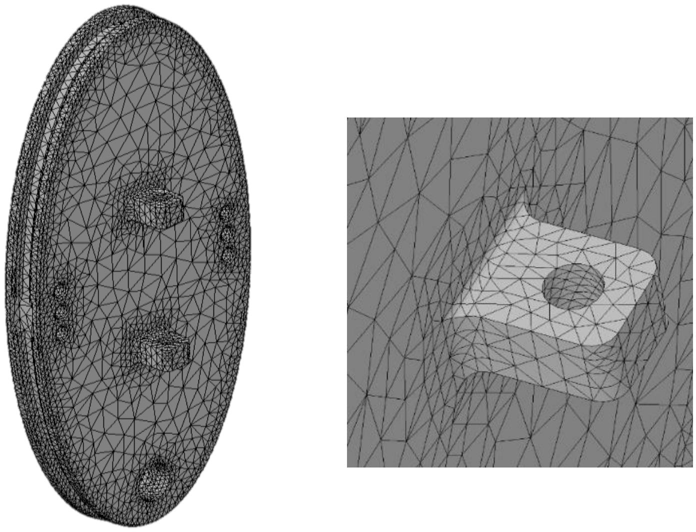


Figure 4.2: Image showing the finer mesh applied to the largest vertebra for FEA analysis

In order to analyse the vertebra, loads and constraints needed to be applied to the model. The back of the largest vertebra was constrained in place as a wall and the force was applied at a distance of 162mm from this edge. The load (weight) was then set to be applied only through the two pin jointed holes as shown on the model. The mass was calculated from the volume presented in SOLIDWORKS.

$$V = 1121683.95\,mm^3 = 1.122 \times 10^{-3}\,m^3$$

$$\rho_{PLA} = 1250\,kg/m^3$$

For the assumption of the weight of the segment it has been assumed that the parts are made from solid PLA.

$$M = \rho_{PLA} \times V = 1.403\,kg \tag{6}$$

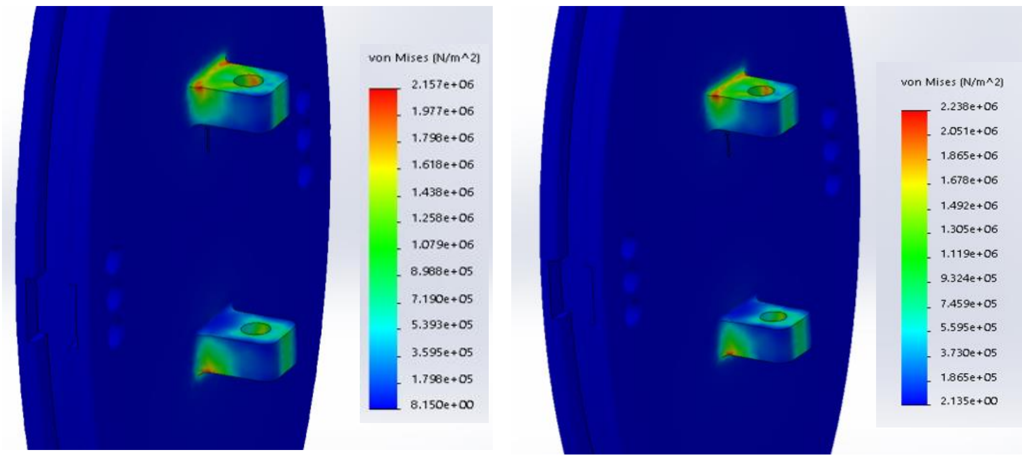


Figure 4.3: FEA analysis showing von Mises stress on two meshes. Left: a fine mesh around the holes with standard sizing for global meshing; Right: a fine mesh around the holes with small sizing (fine mesh) for the global meshing

$$\therefore W = Mg = 1.403 \times 9.81 \approx 14N \quad (7)$$

14N of force was applied at the set distance from the front edge of the vertebra, showing if the pin joints will withstand the force applied to it due to its own weight. Safety factors can then be determined to ensure that it will not fail.

14N was applied through the two pin jointed holes. The two analyses computed in Figure 4.3 above both show a similar peak von Mises stress. This shows that the two results are very similar and so are reliable for the load applied. The maximum von Mises stress found is 2.24MPa. This can be considered as an underestimate due to the pin joints not being solid PLA as they are 3D printed, however the stresses are considerably lower than the yield strength and therefore this is not an issue to be concerned with.

- The yield strength for PLA is 35MPa [17]. This is considerably larger than the von Mises stresses shown and therefore it can be said that the pin joint will be able to withstand the forces applied.

Skin Calculations

The skin surrounding the vertebrae of the fish is subject to cyclic stresses. Therefore, the material chosen for the skin needs to be able to withstand these loads for a reasonable lifetime whilst also fulfilling the functions previously stated.

- The elastomer material is unlikely to fail by yielding due to its large elongation to failure, therefore it can be assumed that if it fails it will be due to crack propagation.

Figure 4.4 below shows how it has been assumed the skin material will be stressed. Although the motion of the fish is closely matched to sinusoidal, the skin can be said to be stretched along the length of the fish and therefore the stressing can be modelled as a simple tensile test of the material:

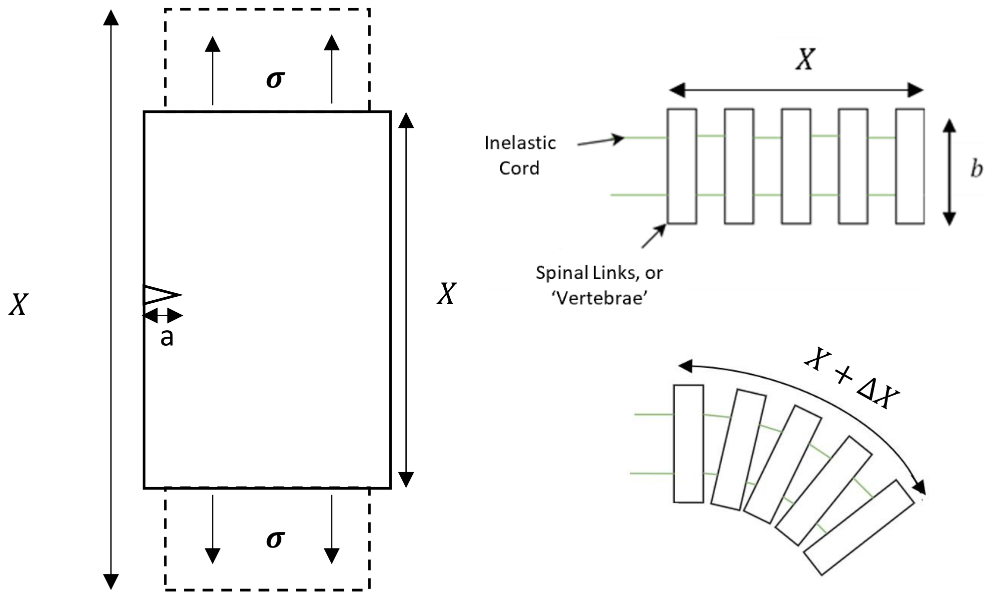


Figure 4.4. Diagram showing the assumption that the stresses on the skin can be best modelled as simple tensile loading

Crack propagation can be used to analyse how long it will take for a crack to grow to a critical size. As can be seen in Figure 4.4, the crack is assumed to start along the edge of the elastomer where the material has been cut. This is because cutting may result in very small tears and imperfections.

- The critical crack size is calculated from the stress intensity factor K_{IC} (SIF). The SIF can be calculated using the Young's modulus and critical strain energy release rate G_{IC} of the material.

- The G_{IC} is found experimentally. The values for silicone, the chosen skin material, have been found from *Thorup, 2012* [20]. Alongside this, the exponent constant, m, and constant C_2 were also found, used later in the Paris equation (Equation 10).

$$E_{Silicone} = 15\ MPa \qquad G_{IC} = 38.4\ KJ/m^2$$

$$K_{IC} = \sqrt{EG_{IC}} = 0.76\ MN\ m^{\frac{-3}{2}} \tag{8}$$

$$a_c = \frac{1}{\pi}\left(\frac{K_{IC}}{\sigma_{max}}\right)^2 = a_c = \frac{1}{\pi}\left(\frac{0.76}{10}\right)^2 = 1.84 \times 10^{-3} m = 1.84\ mm \tag{9}$$

Where: Y = Geometric constant (1.1) for a crack propagating from an edge
σ_{max} = Max. tensile stress of the material (10MPa for silicone)
a_c = Critical crack size, the size of crack which will cause failure

Knowing the critical crack size will give the cyclic loading to reach failure and therefore the number of cycles that the skin will be able to withstand.

To do this, the Paris equation must be integrated to attain an equation for the number of cycles to failure:

$$\frac{da}{dN} = C_2\lambda^m \quad \rightarrow \quad N = \int \frac{da}{C_2\lambda^m}$$

$$N = \frac{1}{\left(1 - \frac{m}{2}\right) C_2 Y^m \sigma^m \pi^{\frac{m}{2}}}\left[a_c^{1-\frac{m}{2}} - a_o^{1-\frac{m}{2}}\right] \tag{10}$$

Where: $m = 0.3 \qquad C_2 = 1.2 \times 10^{-7}$

Before the equation is integrated, there is a term: $\lambda = K_{max}^2 - K_{min}^2$. This equation considers the cyclic loads applied to the material, however cracks only increase for tensile stresses and therefore because the skin is being applied to a compressive-tensile cycle it only needs to consider the stress in one direction.

- Equation reduces to $\lambda = K_{max}^2$, where K_{max} is the SIF due to the maximum stress applied to the skin. One cycle can be considered as the movement of the body from fully extended in one direction to the other side and back.

The maximum force applied to the system is difficult to simulate analytically due to the odd movement of the fish. Therefore, the force can be simplified:

- The fish is required to create a force of at least 9N and, taking the propulsion system to only be 30% efficient, the applied force should be assumed to be at least 30N.
- A safety factor of 2 in included due to the uncertainty of the project: $F = 60N$.
- To attain the maximum cyclic stress, the side of the fish must be considered as the area to which this force is applied.

$$\sigma = \frac{F}{A} = \frac{F}{X \times b} = \frac{60}{0.15 \times 0.324} = 1234.6\ Pa \tag{11}$$

The integrated Paris equation also requires an initial crack size to be propagated to give the time that it takes to grow to a critical size. For this example, the initial size has been taken as an $a_0 = 0.5mm$ crack on the edge. This is larger than what should be present for the final product but this assumption ensures that the product lasts its intended life time.

$$N = \frac{1}{\left(1 - \frac{0.3}{2}\right)(1.2 \times 10^{-7})1.1^{0.3}1234.6^{0.3}\pi^{\frac{0.3}{2}}}\left[0.00184^{1-\frac{m}{2}} - 0.0005^{1-\frac{m}{2}}\right]$$

$$N = 948313(3.17 \times 10^{-3}) = 3006\ cycles \qquad (12)$$

Equation 12 shows that the silicone skin used for the project should last for roughly 3000 cycles. As this is a prototype the skin is not expected to last for long periods of time.

Assuming that the body of the fish is moving at roughly 20 cycles per minute, it can be expected for the skin to be durable for about 2.5 hours.

After this time the fish would need to be reskinned to ensure structural integrity and renew the watertight seal created by the silicone.

Skin Tensioning Safety Factor

For the skin to act as the antagonistic mechanism between each vertebra it must be pre-tensioned and tightened along each vertebra.

- The skin material selected is shore 60° 0.3mm thickness silicone which can withstand up to 400% elongation before failure and can therefore be stretched up to 5 times its original length before failing.

- To ensure that the silicone is not subject to these maximum strains, a safety factor is applied. A maximum of 200% elongation was chosen for the design meaning that the material can be stretched up to 3 times its initial length.

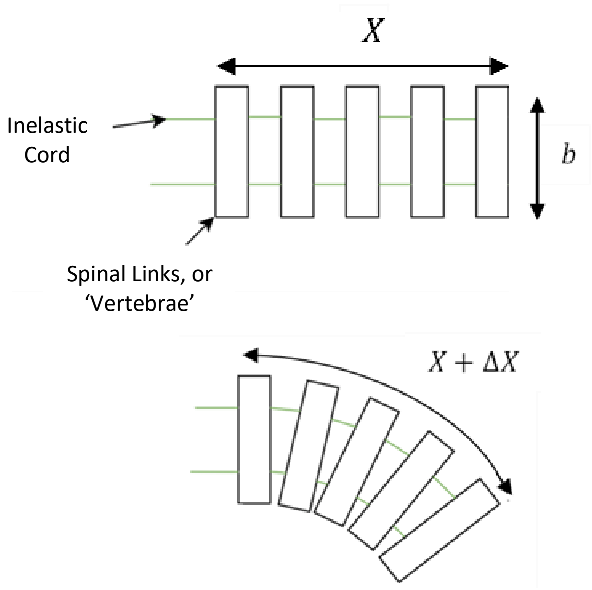


Figure 4.5: Diagram indicating change in length of the skin

- $3x$ is the maximum length limit the silicone can stretch to, therefore, the initial sock length needed so pre-tension can be applied would be:

$$\frac{x + \Delta x}{3} \qquad (13)$$

- Where $x + \Delta x$ is the length of the vertebrae when at maximum deflection to one side

- This results in a safety factor of 1.67 which is adequate to ensure the skin is not over stretched

Period of Oscillation for Maximum Efficiency

The Strouhal number is a dimensionless number, representing the ratio of unsteady and steady motion. For thunniform swimmers (fast-swimming fish like Tuna), the Strouhal number has been found to produce maximum efficiency in the range between 0.2-0.4[21].

The Strouhal number can be used to estimate the period of each oscillation required for maximum efficiency. This was used as a rough guide when programming the stepper motors to produce the maximum efficiency.

$$St = \frac{fA}{U} \tag{14}$$

The Strouhal number which will be used is 0.2. This is because it leads to a more reasonable oscillation time period. The oscillation frequency, f, is to be determined and A is the peak-to-peak oscillation amplitude (the distance between when the tail is fully extended in one direction to the other). This has been taken to be 0.2m and U is the flow rate which needs to be calculated.

The fish can be assumed to be an elliptical cylinder with a ratio of 4:1 to determine the coefficient of drag of the fish ($C_d = 0.35$) [22]. Using this, the equation for drag can be used to calculate the flow rate. To use this equation, it has also been assumed that the drag is equal to the desired thrust to be produced, therefore the drag has been taken to be 9N:

$$C_D = \frac{D/A}{\frac{1}{2}\rho U^2} \quad \rightarrow \quad U = \sqrt{\frac{D/A}{\frac{1}{2}\rho C_D}}$$

$$U = \sqrt{\frac{9/(0.65 \times 0.15)}{\frac{1}{2} \times 997 \times 0.35}} = 0.727 m/s \tag{15}$$

Knowing all the constituents required to calculate the Strouhal number, the oscillation frequency can be found and therefore the time per oscillation required for the program can be obtained:

$$f = \frac{St \times U}{A} = \frac{0.2 \times 0.727}{0.2} = 0.727\ Hz \qquad (Rearranged\ 14)$$

$$T = \frac{1}{f} = 1.38s\ per\ oscillation \tag{16}$$

Electronics Calculations

Stepper Motor Reserve Factor Relating to the Torque Needed to Accelerate the System

The time period used in the code is based on the oscillation time period calculated above (Equation 16).

The program uses the *AccelStepper* library which is based on the Austin algorithm which creates a linear velocity ramping (constant acceleration).

The result of the constant accelerations due to the algorithm means that as it reaches the neutral (zero position – position B) from one end (position A), it experiences a positive acceleration. It then decelerates from position B to the other end (position C). It induces the same pattern when it returns back to position A. The whole time period *T* can then be split up into four constant acceleration parts.

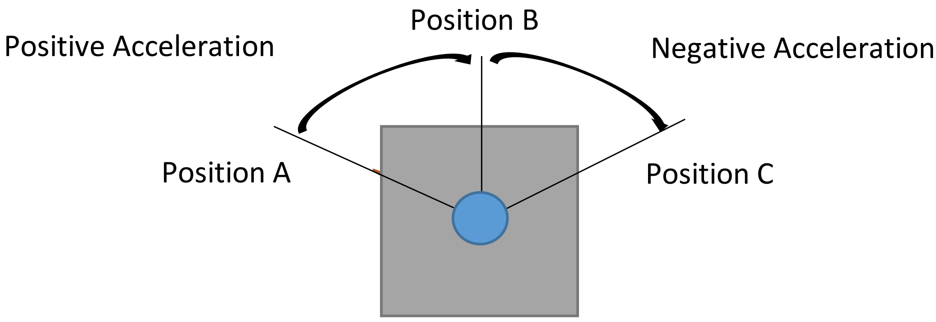


Figure 4.6: Diagram illustrating stepper motor acceleration

Division of the time period by four to obtain the torque needed to accelerate the system to maximum speed (in the positive acceleration) or back to zero (in the negative acceleration).

$$t = \frac{T}{4} \tag{17}$$

Acceleration needed to reach the desired x position at each quarter part (each will have the same magnitude) in steps per second^2.

$$a = \sqrt{\frac{2x}{t^2}} \tag{18}$$

Conversion to rads^{-2}. NEMA 17 has 1.8 degrees per step.

$$\alpha = \frac{a \times 2\pi \times 1.8}{360} \tag{19}$$

The maximum velocity in steps per second.

$$v = at \tag{20}$$

Assumptions Relating to the Moment of Inertia of the Fish Vertebrae

The formulation assumes that the body of the fish stays rigid when it moves (thus a more oscillating motion rather than undulation) during the first harmonic. The moment of inertia at the centre of mass is therefore taken from the 3D CAD SOLIDWORKS model of the second 3D printed prototype. This is then referred to the motor to calculate an effective total moment of inertia.

Using the 2nd prototype itself to support the assumption:

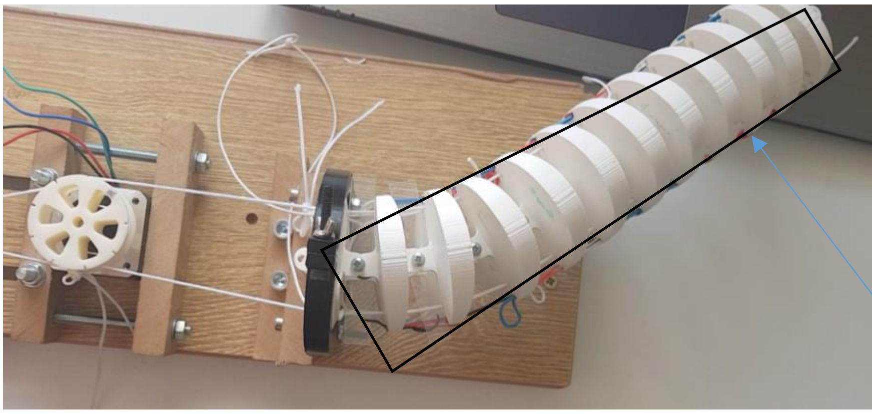


Figure 4.7: Upper peak of the first harmonic

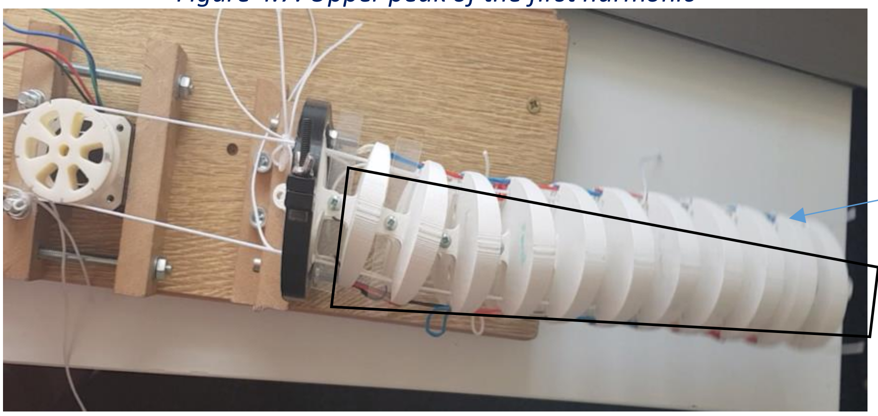


Figure 4.8: Neutral position

Rigid Body Assumption during the First Harmonic to approximate the Moment of Inertia in air

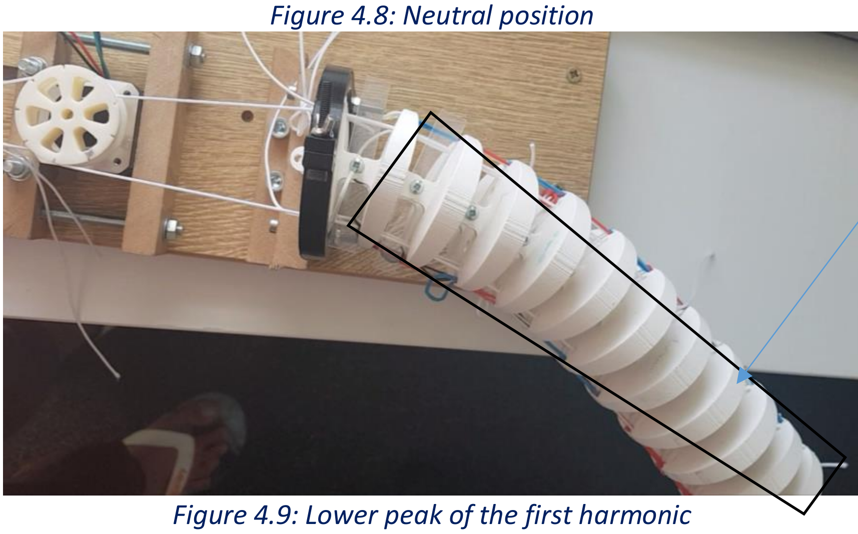


Figure 4.9: Lower peak of the first harmonic

By assuming the first link functions similarly to belt drives, the effective gear ratio is simply the ratio of the radius of the first link to the ratio of the cord spool:

$$n = \frac{R_{FirstLink}}{R_{MotorSpool}} \tag{21}$$

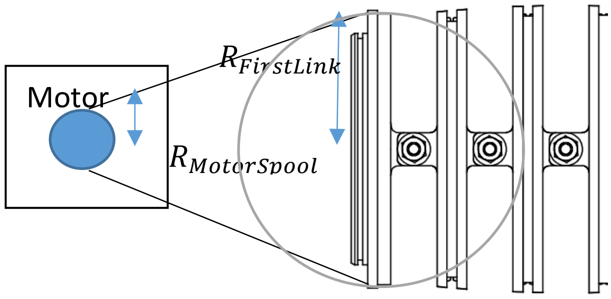


Figure 4.10: Diagram illustrating effective gear ratio

Equation 22 relates the moment of inertia at centre of mass to the end link which is then referred to the motor:

$$J_{referred} = \frac{J_{system}}{n^2} = \frac{J_{At\ centre\ of\ mass} + J_{At\ End\ Link}}{n^2} \tag{22}$$

Where $J_{At\ End\ Link}$ is the parallel axis theorem:

$$J_{At\ End\ Link} = ml^2 \tag{23}$$

Where l is the distance from the centre of mass to the centre of the very first link.

Subsequently summing vertebrae inertia with the motor inertia:

$$J_{total} = J_{motor} + J_{referred} \tag{24}$$

The maximum torque needed to operate the system per every accelerating and decelerating quarter (occurs four times every period):

$$T_{min} = J_{total}\alpha + T_{drag/friction} \tag{25}$$

$$Reserve\ Factor = \frac{Torque\ provided\ by\ motor\ at\ max.speed}{Approximate\ torque\ required\ to\ accelerate\ the\ system} \tag{26}$$

The Torque-Speed graph for the HS174401 motor is non-existent so Figure 4.11 is for a **similar** Bipolar Stepper Torque-Speed Curve as an **approximate reference.**

The 0.4 Nm motor runs off 1.7A rather than 1.5A per phase, hence the graph is closer to the pre-owned 1.5 0.35 Nm 17HS13 stepper motor.

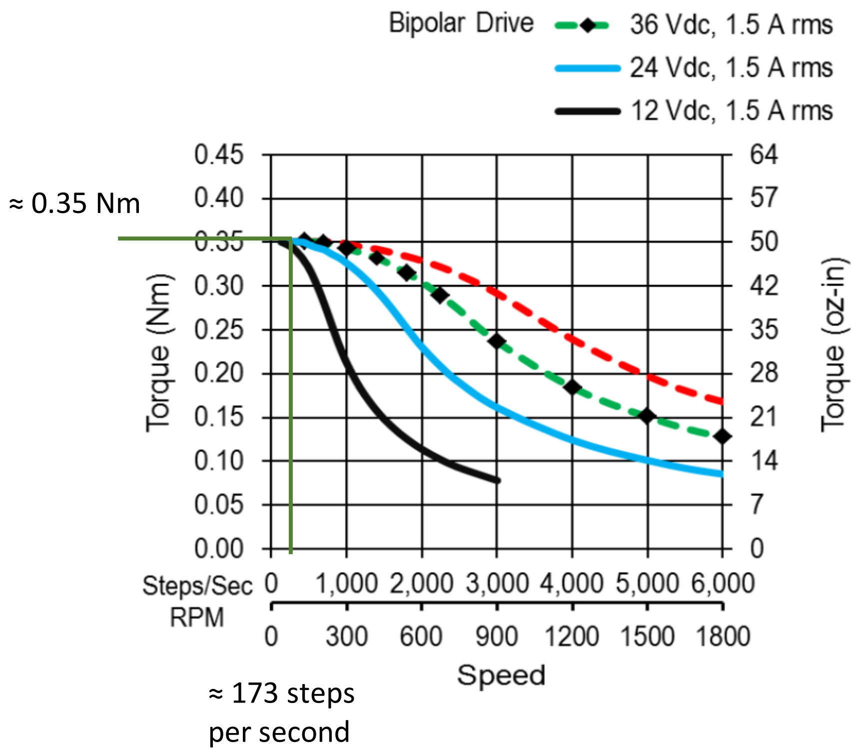


Figure 4.11: Stepper motor torque-speed curve [24]

Initial Conditions to Calculate the Reserve Factors		
Condition	Value	Notes
$T\ (seconds)$	1.38	The time oscillation needed to obtain optimum efficiency for a fish with a peak amplitude of 20cm.
$x\ (in\ steps)$	30	Due to the mechanism, the distance the motor rotates had to be iteratively obtained during the initial trial with the pre-owned 17HS13 stepper to achieve an amplitude of approximately 20cm.
$T_{drag/friction}\ (N)$	0	Zero as the test was done in air and not in water.
$J_{At\ centre\ of\ mass}\ (kgm^2)$	0.0568	Moment of Inertia of the Second Prototype obtained

		from SOLIDWORKS (Material ABS).
$J_{motor}\ (kgm^2)$	0.0000052	Moment of Inertia of the HS174401 0.4Nm Motor [23].

Table 4.2: Table of values used to calculate reserve factor of stepper motor torque

Approximate Reserve Factor to Accelerate the Second Prototype		
$Equation\ 17$	Quarter Time Period *(s)*	0.345
$Equation\ 18$	Stepper Motor Acceleration (*steps per second*^{2})	504
$Equation\ 19$	Angular Acceleration (*rads*$^{-2}$)	15.84
$Equation\ 20$	Maximum Velocity (*steps per second*)	173
$Equation\ 21$	Link (Gear) Ratio	2
$Equation\ 22$	Referred Moment of Inertia (*kgm*^{2})	0.01420
$Equation\ 24$	Total Moment of Inertia (*kgm*^{2})	0.01421
$Equation\ 25$	Minimum Torque Needed *(Nm)*	0.225
$Equation\ 26$	Reserve Factor	1.56

Table 4.3: Table of equations used to calculate reserve factor of stepper motor torque for the second prototype

As shown in table 4.3, a 0.35Nm stepper motor can produce the torque required to actuate the system when it is moving in air with a reserve factor of 1.53. Since the graph used for the calculation is for a 0.35Nm stepper motor, the actual reserve factor will most likely be higher, as a 0.4Nm motor has been selected for the final design.

Assumptions and factors such as Rigid Body Motion, the greater drag force the system will experience when moving in water and the difference in the mass of the vertebrae between the CAD and real system (CAD does not consider the parts to have hollow in-fill) will impact the reserve factor. These factors are difficult to consider within the calculations, hence the obtained reserve factor is more of an estimate rather than an absolute known value.

Stepper Motor Reserve Factor for the Final Fish Design

Using the same formulation as above, the same calculations were performed for the reserve factor of the latest fish vertebrae with the polyurethane tail included. Moment of inertia, again, was taken directly from the 3D SOLIDWORKS model using the correct materials (PLA for the vertebrae and polyurethane for the tail).

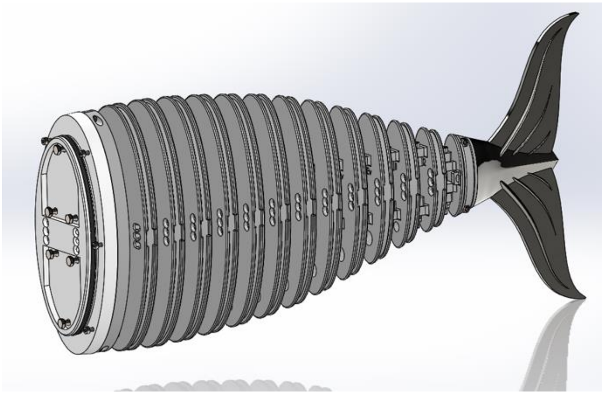


Figure 4.12: Final Vertebrae Design

Approximate Reserve Factor Needed to Accelerate the Final Design		
$Equation\ 17$	Quarter Time Period *(s)*	0.345
$Equation\ 18$	Stepper Motor Acceleration (*steps per second*^{2})	504
$Equation\ 19$	Angular Acceleration (*rads*$^{-2}$)	15.84
$Equation\ 20$	Maximum Velocity (*steps per second*)	173
$Equation\ 21$	Link (Gear) Ratio	2
$Equation\ 22$	Referred Moment of Inertia (*kgm*^{2})	0.0175
$Equation\ 24$	Total Moment of Inertia (*kgm*^{2})	0.0176
$Equation\ 25$	Minimum Torque Needed *(Nm)*	0.28
$Equation\ 26$	Reserve Factor	1.25

Table 4.4: Table of equations used to calculate reserve factor of stepper motor torque for the final design

Similarly to the prototype results, a single 0.4Nm stepper motor can support the fish in air, however will have to be physically tested submerged underwater to verify the locomotion and thrust propulsion.

Cord Calculations

The maximum torque that can be supplied by the stepper motor dictates the maximum force that can be applied to the cord and is calculated below:

$$T = Fd \tag{27}$$

T = Torque (Nm), F = Force (N), d = Distance at which the force acts (m)

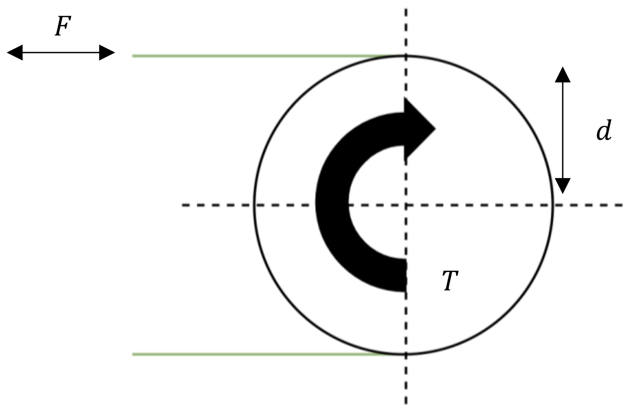


Figure 4.13: Diagram showing the force exerted on the cord

The maximum torque the stepper motors are rated for is 0.4 Nm, and the radius of the spool is 0.018m, hence using equation 27, the maximum force the cord will experience can be calculated:

$$T = 0.4\ Nm, \quad d = 0.018\ N$$

$$F = \frac{T}{d} = \frac{0.4\ Nm}{0.018\ m} = 22.2\ N$$

Using the maximum force exerted by the stepper motor, and assuming the diameter of cord is 2mm, the maximum stress can be calculated:

$$\sigma = \frac{F}{A} \tag{28}$$

σ = Stress (MPa), A = Area (m^2)

$$A = \pi r^2 \tag{29}$$

r = Radius (m)

Hence the stress on the rope can be calculated:

$$A = \pi \cdot 0.001^2 = 3.14 \cdot 10^{-6}\, m^2$$

$$\sigma = \frac{22.2\, N}{3.14 \cdot 10^{-6}\, m^2} = 7.07\, MPa$$

To comply with the reserve factor of 2, the yield stress of the material must be greater than 14.14 MPa.

Test Rig Calculations

Test Rig Thrust Measurement Calculation

The thrust produced by the system is measured using a couple. One end is connected to the fish and the other to a spring dynamometer as shown in figure 4.14. Assuming very small angular displacement, then as the fish produces thrust, it will produce a force on the dynamometer. Using basic moment formulation, the equation for the thrust can be obtained.

$Equation\ 30$:

Uses the results from the Newton meters to obtain the thrust.

$$Thrust = \frac{F_{dynamometer} \times L1}{L2} \tag{30}$$

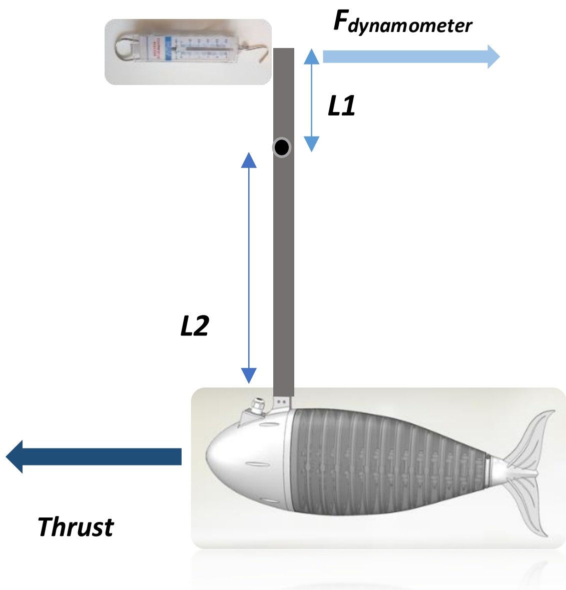


Figure 4.14: Diagram showing how the thrust of the system will be measured

Test Rig Angled Bars Stressing Calculations

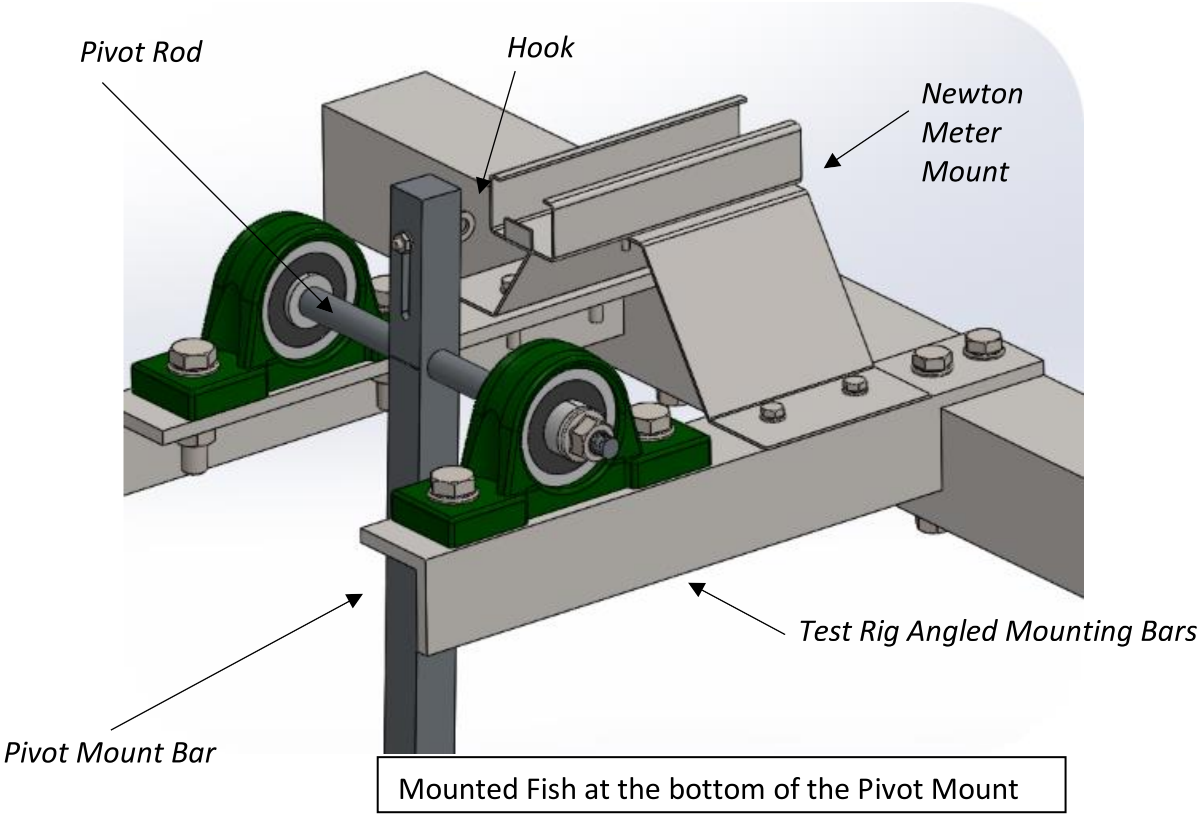


Figure 4.15: Components of the Test Rig Assembly

From Figure 4.15, it can be seen that each of the two angled mounting bars would experience bending moments (relative to their mountings) from the weight of the whole pivoted fish system, the Newton meter mount and the weight of the pillow block bearings with an additional torsional component due the loads being placed in between the two angled bars.

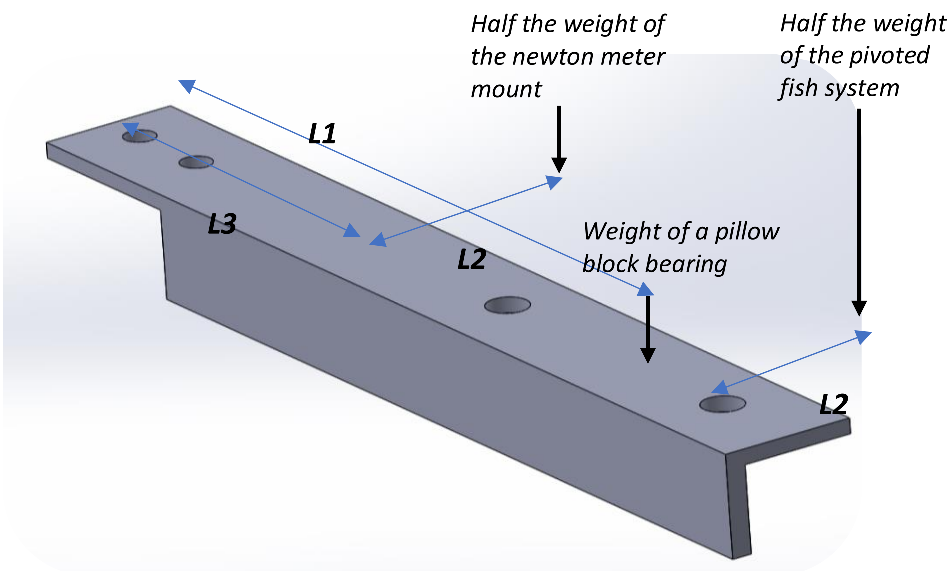


Figure 4.16: Image showing loads applied on each angled mounting bar

Due to the angled geometry of the mounting bars, one way to accurately calculate the stresses caused by the loads would be to first create a simpler hand-drawn analytical model, and if the resulting reserve factor is of concern, then it can be compared to an FEA model to find the suitable mesh size to then be able to numerically compute the stresses on the actual mounting components.

Thus, if the simpler model is created for only a single mounting bar due to symmetry and having all the weight of the components summed together at the very open end to make it a cantilever scenario (omitting the torsional component in process), then a rough approximation of the stresses can be calculated.

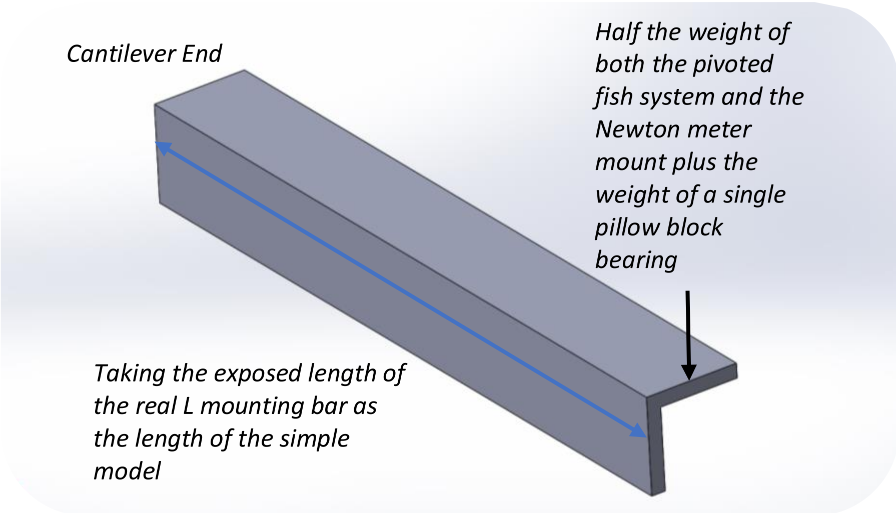


Figure 4.17: Simplified cantilever model

Approximate force applied on the model angled mount:

The values are taken from the CAD models and Datasheets

Component	**Material**	**Density**	**Volume**	**Quantity**	**Mass**
		kgm^{-3}	m^3		kg
Pivot Rod	Aluminium	2700	$2.38x10^{-5}$	1	0.06
Pivot Mount	Steel	7800	$1.07x10^{-4}$	1	0.83
Pivot Hook Puller	Steel	7800	$2.31x10^{-6}$	1	0.02
NEMA 17 Motor				3	0.90
Head Mount and Internals	PLA	1050	$8.35x10^{-4}$	1	0.88
Fish Vertebrae	PLA	1050	$1.29x10^{-3}$	1	1.35
Fish Tail	Silicone	1500	$4.36x10^{-5}$	1	0.07
Arduino Nano				1	0.01
DRV8825 Driver				3	0.07
Pillow Block Bearing					0.63
Newton Meter Mount Rig	Steel	7800	$3.28x10^{-5}$	1	0.26
Total Mass (kg)					5.07
Force (N)					49.74
Force on each L mount (N)					24.87

Table 4.5: Table summarising the force applied to angled bar due to the weight of the components

Use of Asymmetrical Bending Mechanics on the Simplified Angled Mount to Calculate the Maximum Tensile Bending Stress

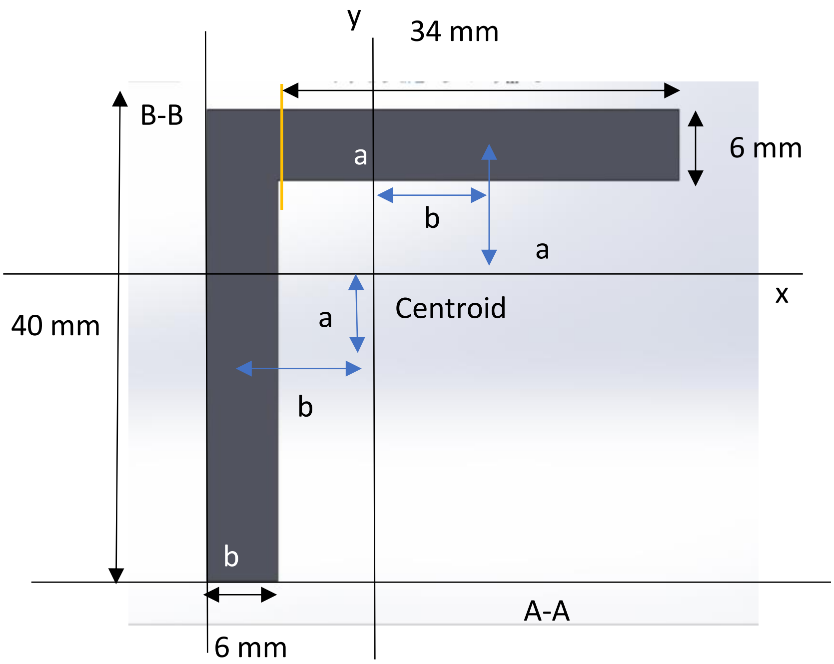


Figure 4.18: Figure showing the location of the centroid

F = 24.87N

L = 250mm

Since the L mount is made of steel, the yield is taken as 300MPa (lowest value taken from CES)

Position of centroid relative to A-A axis

$$\bar{y} = \frac{(A\,\bar{y})_a + (\,A\bar{y})_b}{Total\ A} \tag{31}$$

Position of centroid relative to B-B axis

$$\bar{x} = \frac{(A\,\bar{x})_a + (\,A\bar{x})_b}{Total\ A} \tag{32}$$

2nd and Product Moments of Area:

Second Moment of Area relative to A-A

$$I_{xx} = (I_x + Ab^2)_a + (I_x + Ab^2)_b \tag{33}$$

Second Moment of Area relative to B-B

$$I_{yy} = \left(I_y + Aa^2\right)_a + \left(I_y + Aa^2\right)_b \tag{34}$$

Product Moment of Area

$$I_{xy} = (Aab)_a + (Aab)_b \tag{35}$$

Location of the Principal Axes and Principal Moment of Area through Mohr's Circle:

Due to the symmetric shape, the Mohr's Circle will have a distinct shape:

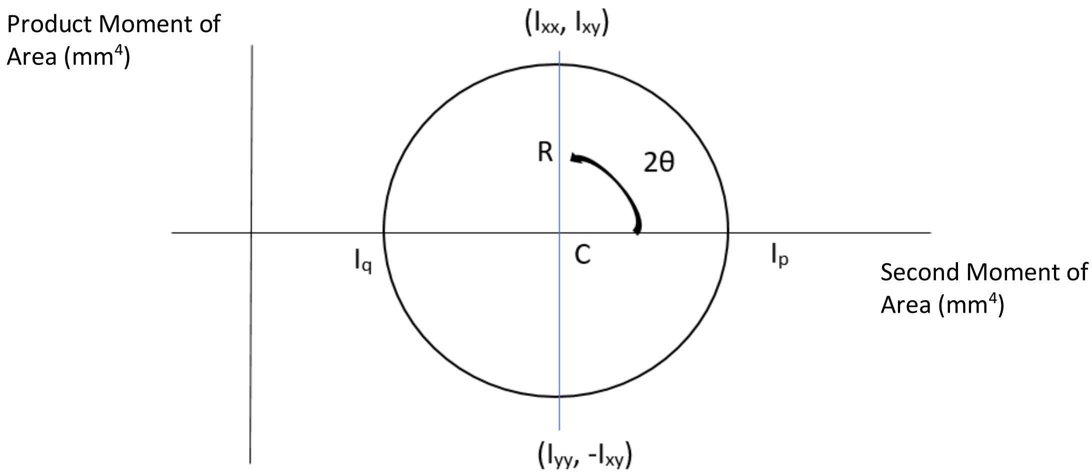


Figure 4.19: Mohr's Circle to determine the Principal Axes and Moments

Principal Second Moment of Area relative to the P axis

$$I_p = C + R \tag{36}$$

Principal Second Moment of Area relative to the Q axis

$$I_q = C - R \tag{37}$$

Angle of the principal axes relative to the x and y axes:

$$\theta = \frac{90}{2} \tag{38}$$

Maximum Bending Moment Present in the L Mounting Bar Model

Bending moment about the x axis

$$M = FL \tag{39}$$

Bending moment resolved to the P direction

$$M_p = Mcos(45) \tag{40}$$

Bending moment resolved to the Q direction

$$M_q = Msin(45) \tag{41}$$

which leads to:

$$M_p = M_q \tag{42}$$

Position of the Neutral Axis

$$\alpha = tan\left(\frac{I_p}{I_q}\right)$$

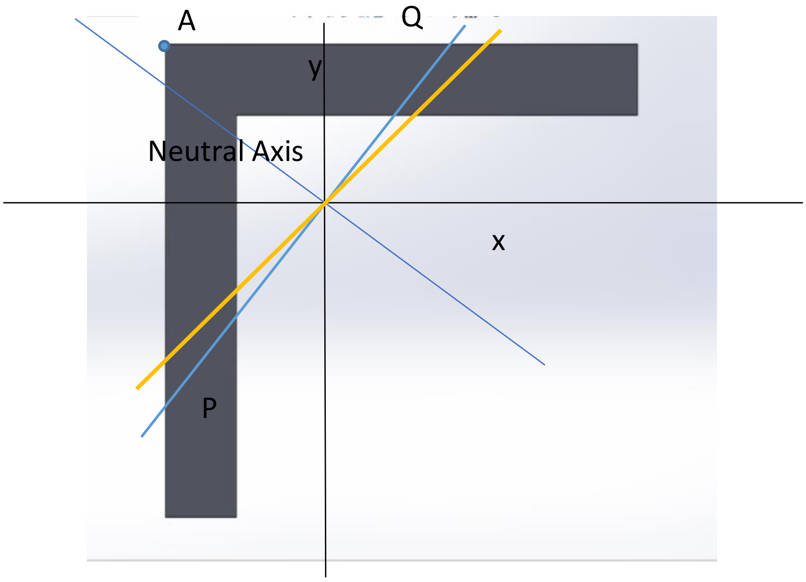


Figure 4.20: Figure showing the location of the angled bar maximum tensile moment at Position A

Coordinate relative to axis P

$$P = xcos\theta - ysin\theta \tag{43}$$

Coordinate relative to axis Q

$$P = xcos\theta + ysin\theta \tag{44}$$

Bending Tensile Stress at Position A

$$\sigma_{bA} = \frac{M_p Q}{I_p} - \frac{M_q P}{I_q} \tag{45}$$

Asymmetrical Bending Variables		
$\bar{y}$	*mm*	Position of centroid relative to the A-A axis
$\bar{x}$	*mm*	Position of centroid relative to the B-B axis
I_{xx}	*mm⁴*	Second Moment of Area relative to A-A
I_{yy}	*mm⁴*	Second Moment of Area relative to B-B
I_{xy}	*mm⁴*	Product Moment of Area
P		Principal Axis P
Q		Principal Axis Q
I_p	*mm⁴*	Principal Second Moment of Area relative to the P axis
I_q	*mm⁴*	Principal Second Moment of Area relative to the Q axis
C	*mm⁴*	Centroid of the Mohr's Circle
R	*mm⁴*	Radius of the Mohr's Circle
F	*N*	Loads due to the components on the Test Rig (**24.87**)
L	*mm*	Value of the exposed length of the protruding bars (**250**)
M	*Nmm*	Bending moment in the cartesian axes
M_p	*Nmm*	Bending moment in the P axis
M_q	*Nmm*	Bending moment in the Q axis
$Coordinate\ of\ P$	*mm*	Cartesian coordinates resolved to axis P
$Coordinate\ of\ Q$	*mm*	Cartesian coordinates resolved to axis Q
$Coordinate\ of\ A$	*mm*	Position of the maximum bending stress position relative to the P and Q axis
a	*mm*	Vertical distance of discrete shape centroid to overall shape centroid
b	*mm*	Vertical distance of discrete shape centroid to overall shape centroid

Table 4.6: Table defining the variables used in Equations 31-45

Angled Bar Stress Calculations		
$Equation\ 31$	*x Position of Centroid (mm)*	27.2
$Equation\ 32$	*y Position of Centroid (mm)*	12.2
$Equation\ 33$	*Second Moment of Area relative to A-A (mm^4)*	64480.1
$Equation\ 34$	*Second Moment of Area relative to B-B (mm^4)*	64480.1
$Equation\ 35$	*Product Moment of Area (mm^4)*	37491.7
$Equation\ 36$	*Principal Second Moment of Area relative to the P axis (mm^4)*	101972.1
$Equation\ 37$	*Principal Second Moment of Area relative to the Q axis (mm^4)*	26988.1
$Equation\ 38$	*Angle of the principal axes relative to the x and y axes (degrees)*	45
$Equation\ 39$	*Bending moment about the x axis (Nmm)*	6225
$Equation\ 40$	*Bending moment resolved to the P direction (Nmm)*	4401.7
$Equation\ 41$	*Bending moment resolved to the Q direction (Nmm)*	4401.7
$Equation\ 42$	*Position of the Neutral Axis (degrees relative to P)*	75.2
$Equation\ 43$	*Coordinate relative to axis P (mm)*	-17.2
$Equation\ 44$	*Coordinate relative to axis Q (mm)*	0
$Equation\ 45$	*Bending Tensile Stress at Position A (MPa)*	2.80

Table 4.7: Table showing the maximum bending stress on the *simplified* model

Although the model is more simplified than the actual test rig angled mounting bars, the maximum *approximate* bending stress obtained is approximately 100 times less than the yield of steel (300 MPa).

5. Overview of the Arduino Code

This section contains examples of the code used to control of one of the motors.

Each stepper motor used will have to be first created as an AccelStepper object:

```
AccelStepper stepperN(AccelStepper::DRIVER, Step1, Dir1);
```

Figure 5.1

Values for the allowable maximum speed, acceleration and the position to and from have to be initially defined:

```
stepperN.setMaxSpeed(500); //the p
stepperN.setAcceleration(500);
stepperN.moveTo(StepperNStroke);
```

Figure 5.2

The motor states can be changed using a simple 'if' loop with functions for receiving integer data though the serial monitor:

Functions to take in information via the serial monitor were taken from programs created by Dr Jones.

```
recvWithEndMarker(); //Written by Dr. Jones
convertNewNumber(); //Written by Dr. Jones

if (dataNumber == 1)
{
  SwitchCase1();
  digitalWrite(EnableLine,LOW);
}
else if (dataNumber == 0)
{
  SwitchCaseOff();
  digitalWrite(EnableLine,HIGH);
}
```

Figure 5.3

*Writing HIGH to the Enable Line is a key factor in the mechanism of the motors. This line of code **turns off** the **holding torque** for the motor which would mean that if one motor is to be active and the other two are not, there would be **no resistance from other two** which avoids desynchronization of the active motor.*

The motor controls the cord by rotating from one position to the other which is achieved by having the value of the destination reverse in magnitude when the motor has reached its step destination:

```
void SwitchCase1()
{

  if (stepperN.distanceToGo() == 0)
  {
    stepperN.moveTo(-stepperN.currentPosition());
    //when it gets to 2000, reverse the step amount so i
  }
  stepperN.run();

}
```

Figure 5.4

The reset state position is then achieved by programming the steppers to return to the initial zero position whenever 0 is entered through the serial monitor:

```
void SwitchCaseOff()
{
  if (stepperN.currentPosition() > 0)
  {
    stepperN.moveTo(0);
    if (stepperN.currentPosition() != 0)
    {
      stepperN.runToPosition();

    }
    stepperN.moveTo(-StepperNStroke);
    dataNumber = -1;
  } else
  {
    stepperN.moveTo(0);
    if (stepperN.currentPosition() != 0)
    {
      stepperN.runToPosition();
    }
    stepperN.moveTo(StepperNStroke);
    dataNumber = -1;
  }

}
```

Figure 5.5

6. Budget

Product Code	Component	Lead/Delivery Time (Working Days)	Supplier	Quantity	Delivery Costs	Unit Cost	Tax	Total Cost
	Skin							
-	0.3mm Silicone Sheet Translucent	*Received*	Silex Silicones	1	£ 13.20	£ 20.75		£ 33.95
-	0.3mm Silicone Sheet Black	*Received*	Silex Silicones	1	*Included above*	£ 20.75		£ 20.75
-	Silicone Adhesive	*Received*	Silex Silicones	1	*included above*	£ 15.95		£ 15.95
-	Belt-Ty In-line Cable tie	7	Reichelt Elektronik	80	£ 4.16	£ 0.23	£ 0.20	£ 27.07
-	Premium Black amalgamating rubber tape	7	Amazon (Gocableties)	1	£ -	£ 4.99		£ 4.99
	Electronics and Actuators							
-	TopDirect 5PCS Nema 17 Stepper Motors (Pack of 5)	5	Amazon	1	£ -	£ 34.00		£ 34.00
-	Elegoo Nano For Arduino Nano V3.0 (Pack of 3)	5	Amazon	1	£ -	£ 10.99		£ 10.99
-	HiLetgo DRV8825 Stepper Motor Drivers (Pack of 5)	5	Amazon	1	£ -	£ 7.99		£ 7.99
-	10m USB Extension	5	Amazon	1	£ -	£ 12.99		£ 12.99
-	Rhinocables USB 2.0 A Male to Mini B 5m	5	Amazon	1	£ -	£ 2.50		£ 2.50
-	Elegoo 120pcs Multicoloured Dupont Wire	5	Amazon	1	£ -	£ 6.99		£ 6.99
-	100 microF Capacitors	-	Electronics Stores	3	£ -	£ 0.02		£ 0.06
-	Elegoo 6PCS Mini Breadboard	5	Amazon	1	£ -	£ 6.99		£ 6.99
	Vertebrae Assembly							
-	Vertebrae Links (Average Cost)	-	RP UoN	14	£ -	£ 4.55		£ 63.70
-	Vertebrae Clamps (Pair)	-	RP UoN	2	£ -	£ 0.70		£ 1.40
HNN-M4-A2	M4 Stainless Steel Nyloc Nut	3	Accu	14	£ 2.95	£ 0.09	£ 0.20	£ 5.05
SSC-M4-65-A4	M4x65 Stainless Steel Cap Screw	3	Accu	14	*Included above*	£ 0.35	£ 0.20	£ 5.88
SSC-M3-16-A2	M3 x 16 Stainless Steel Cap Screw	3	Accu	10	*Included above*	£ 0.13	£ 0.20	£ 1.56
HNN-M3-A2	M3 Stainless Steel Nyloc Nut	3	Accu	8	*Included above*	£ 0.11	£ 0.20	£ 1.06
-	Nylon Cord (1.8mm White Braided Lift Shade Cord)	5	Amazon	1	£ -	£ 6.99		£ 6.99
SSC-M4-50-A2	M4x50 Stainless Steel Cap Screw	1	Accu	2	*Included above*	£ 0.23	£ 0.20	£ 0.46
SSCF-M3-12-A2	M3 x 12 Stainless Steel Cap Screw	3	Accu	3	*Included above*	£ 0.13	£ 0.20	£ 0.39
SSB-M3-6-A2	M3 x 6 Socket Button Screws	3	Accu	16	*Included above*	£ 0.11	£ 0.20	£ 1.76
	Head Assembly							
-	Back Plate	-	RP UoN	1	£ -	£ 8.03		£ 8.03
-	Head Case	-	RP UoN	1	£ -	£ 12.37		£ 12.37
-	Motor Frame (Set of 2)	-	RP UoN	1	£ -	£ 4.43		£ 4.43
-	Spool	-	RP UoN	3	£ -	£ 0.70		£ 2.10
-	Spool Clamps	-	RP UoN	6	£ -	£ 0.05		£ 0.30
OR110x3	110mm ID x 3mm O-ring	-	Nottingham Bearing Company	1	£ -	£ 2.22		£ 2.22
365-8422	Llap Skintop M16 Cable Gland IP69K (Pack of 5)	5	RS Components	1	£ -	£ 7.58		£ 7.58
SSC-M3-16-A2	M3x16 Stainless Steel Cap Screw	3	Accu	6	*Included above*	£ 0.13	£ 0.20	£ 0.94
HNN-M3-A2	M3 Stainless Steel Nyloc Nut	3	Accu	6	*Included above*	£ 0.11	£ 0.20	£ 0.79
-	Primer	5	Amazon	1	£ -	£ 9.00		£ 9.00
SSC-M5-35-A4	M5 x 35 Stainless Steel Cap Screw	3	Accu	6	*Included above*	£ 0.20	£ 0.20	£ 1.20
HNN-M5-A2	M5 Nyloc Nut	3	Accu	6	*Included above*	£ 0.13	£ 0.20	£ 0.78
SSCF-M3-10-A2	M3 x 10 Stainless Steel Cap Screws	3	Accu	2	*Included above*	£ 0.13	£ 0.20	£ 0.26

	Tail Assembly						
QL5678	Polytek PT-Flex 85 PU Casting Rubber (500g)	4	MB Fibreglass	1	£ 7.99	£ 10.00	£ 17.99
QL3809	Polytek PT-Flex 70 PU Casting Rubber (500g)	4	MB Fibreglass	1	*Included above*	£ 10.00	£ 10.00
-	White Pigment	4	MB Fibreglass	1	*Included above*	£ 5.00	£ 5.00
-	3D printed Moulding Link	-	RP UoN	1	£ -	£ 1.40	£ 1.40
-	Aluminium Block (1 inch x 120mm x 260mm)	-	*Unused Material Kindly Donated by L2*		£ -	£ -	£ -
	Test Rig						
MJ-A08009	Steel BDMS Angle (m)	-	L2 Stores	0.6	£ -	£ 5.79	£ 3.47
MJ-B04010	3/4 Inch Square Steel Tubing (m)	-	L2 Stores	1	£ -	£ 9.34	£ 9.34
MJ-A02002	4mm Steel Round (m)	-	L2 Stores	0.2	£ -	£ 0.86	£ 0.17
MJ-A01006	Steel Sheet 1.2mm (m^2)	-	L2 Stores	0.4	£ -	£ 17.71	£ 7.08
750-8933	12mm ID Pillow Bearing	5	RS Components	2	£ -	£ 11.65	£ 23.30
MH-F01076	M10 Steel Nut	-	L2 Stores	6	£ -	£ 0.15	£ 0.90
MH-D09064	M10x45 Bolt	-	L2 Stores	4	£ -	£ 0.70	£ 2.80
MH-E01017	M10 Plain Washer	-	L2 Stores	8	£ -	£ 0.14	£ 1.12
MH-D09044	M8x65	-	L2 Stores	4	£ -	£ 0.22	£ 0.88
MH-D09050	M8x80	-	L2 Stores	3	£ -	£ 0.30	£ 0.90
MH-F01062	M8 Steel Nut	-	L2 Stores	7	£ -	£ 0.07	£ 0.49
MH-E01015	M8 Plain Steel Washer	-	L2 Stores	14	£ -	£ 0.04	£ 0.56
-	20Nm Dynamometer	5	Amazon	1	£ -	£ 10.99	£ 10.99
	Prototyping Spend	*This includes protoyping that has occurred before CDR*					
-	3D Printing Prototyping	-	RP UoN				£ 20.00
	Miscellaneous Costs						
-	Epoxy Glue	-	L2 Stores	1	£ -	£ 7.29	£ 7.29
-	Wet and Dry Paper (Various Grades) (Sheets)	-	L2 Stores	3	£ -	£ 0.85	£ 2.55
						Total Cost:	**£ 449.71**

Table 6.1: Table showing the costs of manufacturing the final deliverable and test rig

3D Printed Components	
Part	Cost
Vertebrae Links (Average Cost)	£ 63.70
Vertebrae Clamps (Pair)	£ 1.40
Back Plate	£ 8.03
Head Case	£ 12.37
Motor Frame (Set of 2)	£ 4.43
3D printed Moulding Link	£ 1.40
Spool	£ 2.10
Spool Clamps	£ 0.30
Prototyping Spend	£ 20.00
Total	£ 113.73
A spool of PLA filament is £39	
Spools of PLA required	2.916
Prices for 3D printed components have been optained from RP	

Table 6.2: Table showing the costs of the 3D printed components and the number of spools of PLA filament required

Budget (continued)

The total cost, including VAT and delivery charges comes to £449.71, resulting in approximately £50 for any contingency costs. An effort has been made to source components from reputable suppliers at the lowest possible price.

The current cost of the project represents a significant increase compared to the estimate in the PDR report. This is primarily due to the increase in size of the final system, resulting in an increased amount of PLA filament required, as well as the addition of the costs associated with the tail and test rig assemblies.

Table 6.2 shows that 3 spools of PLA are required to replace the material that will be used to manufacture the 3D printed parts for the final deliverable. The budget also accounts for the filament used to manufacture any prototype parts.

7. Project Timetable

Overall Project Gantt Chart

GANTT CHART

	Task Mode	Task Name	Duration	Start	Finish	Predecessors	% Complete
1		1 RPR	10 days	Mon 01/10/18	Wed 10/10/18		100%
2		2 Concept Generation	20 days	Thu 11/10/18	Tue 30/10/18	1	100%
3		3 Concept Evaluation & Selection	6 days	Wed 31/10/18	Mon 05/11/18	2	100%
4		4 PDR Presentation Preperation	10 days	Tue 06/11/18	Thu 15/11/18	3	100%
5		5 PDR Presentation	0 days	Fri 16/11/18	Fri 16/11/18	4	100%
6		6 Post PDR Report Writing	14 days	Sat 17/11/18	Fri 30/11/18	5	100%
7		7 Post PDR Hand In Date	0 days	Fri 30/11/18	Fri 30/11/18	6	100%
8		8 Detailed Design	89 days	Mon 19/11/18	Fri 15/02/19	5	100%
9		8.1 Actuator Selection	75 days	Mon 19/11/18	Fri 01/02/19	4	100%
10		8.2 Head/Electronics Containment Design	15 days	Fri 01/02/19	Fri 15/02/19	9	100%
11		8.3 Program Design	89 days	Mon 19/11/18	Fri 15/02/19	4	100%
12		8.4 Electronics Design	89 days	Mon 19/11/18	Fri 15/02/19	4	100%
13		8.5 Caudal Fin Design	89 days	Mon 19/11/18	Fri 15/02/19	4	100%
14		8.6 BackBone Design	89 days	Mon 19/11/18	Fri 15/02/19	4	100%
15		~~9 Christmas Vacation and Exam Period~~	~~44 days~~	~~Fri 14/12/18~~	~~Sat 26/01/19~~		~~0%~~
16		10 Finalised Detailed Design	0 days	Fri 15/02/19	Fri 15/02/19	11,12,13,14,10	100%
17		11 CDR Presentation Prep	15 days	Fri 15/02/19	Fri 01/03/19	8,11,12,13,14	100%
18		12 CDR Presentation	0 days	Mon 04/03/19	Mon 04/03/19	17	100%
19		13 CDR Report	15 days	Mon 11/03/19	Mon 25/03/19		0%
20		13.1 CDR Report Writing	12 days	Mon 11/03/19	Fri 22/03/19	18	0%
21		13.2 CDR Hand In Date	0 days	Mon 25/03/19	Mon 25/03/19	20	0%
22		14 Manufacture and Assembly	31 days	Mon 04/03/19	Wed 03/04/19	18,12	0%
23		14.1 Head Manufacture + Assembly	26 days	Mon 04/03/19	Fri 29/03/19	18	0%
24		14.2 Tail Manufacture and Assembly	26 days	Mon 04/03/19	Fri 29/03/19	18	0%
25		14.3 Vertebrae Manufacture and Assembly	26 days	Mon 04/03/19	Fri 29/03/19	18	0%
26		14.4 Clamp Manufacture and Assembly	25 days	Mon 04/03/19	Thu 28/03/19	18	0%
27		14.5 Skin Manufacture	26 days	Mon 04/03/19	Fri 29/03/19	18	0%
28		14.6 General Assembly	2 days	Mon 01/04/19	Tue 02/04/19	23,24,25,27	0%
29		15 Testing	2 days	Thu 04/04/19	Fri 05/04/19	28,22	0%
30		~~16 Contingency Time~~	~~5 days~~	~~Mon 08/04/19~~	~~Fri 12/04/19~~		~~0%~~
31		17 Final Submission Preperation	6 days	Sat 06/04/19	Thu 11/04/19	29	0%
32		18 Final Submission Hand In	0 days	Fri 12/04/19	Fri 12/04/19	31	0%
33		19 Exhibition	3 days	Tue 11/06/19	Thu 13/06/19		0%

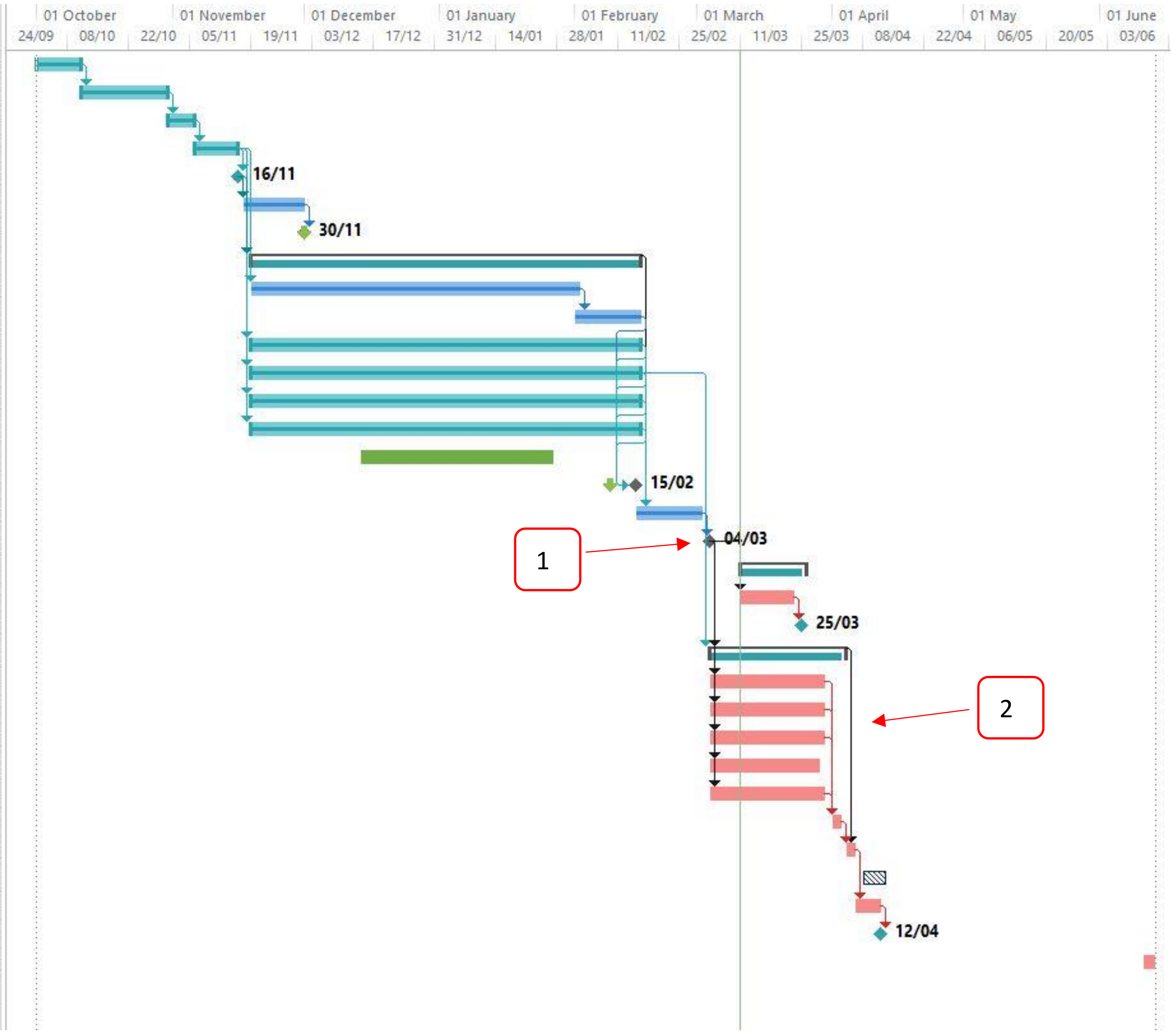


Figure 7.1: Biomimetic Propulsion System Project Gantt chart

Fabrication Plan

GANTT CHART

	Task Name	Duration	Start	Finish	Predece	Person(s) Completing Task	Total Time (Hrs)
1	**Order Forms**	**10 days**	**Mon 11/03/19**	**Fri 22/03/19**			
2	Order Forms Sent off	0 days	Mon 11/03/19	Mon 11/03/19		Alex D	
3	All Parts Delivered	0 days	Fri 22/03/19	Fri 22/03/19	2	Alex D	
4	**Head Manufacture and Assembly**	**20 days**	**Mon 04/03/19**	**Fri 29/03/19**			
5	**Back Plate Manufacture**	**7 days**	**Mon 04/03/19**	**Tue 12/03/19**			
6	3D Print	6 days	**Mon 04/03/19**	Mon 11/03/19		RP UoN	
7	Remove support material and finish	1 day	**Tue 12/03/19**	Tue 12/03/19	6	Fraser	4
8							
9	**Head Casing**	**18 days**	**Mon 04/03/19**	**Wed 27/03/19**			
10	3D Print	6 days	Mon 04/03/19	Mon 11/03/19		RP UoN	
11	Remove Support Material and Finish	3 days	Tue 12/03/19	Thu 14/03/19	10	Alex S	5
12	Prime and Sand	3 days	Fri 22/03/19	Tue 26/03/19	11,3	Alex D	10
13							
14	Electronics Test	3 days	Fri 22/03/19	Tue 26/03/19	3	Elijah	8
15							
16	**Motor Frame Manufacture**	**12 days**	**Mon 04/03/19**	**Tue 19/03/19**			
17	3D Print Frame	11 days	Mon 04/03/19	Mon 18/03/19		RP UoN	
18	3D Print Arduino Mount	11 days	Mon 04/03/19	Mon 18/03/19		RP UoN	
19	Remove support material and finish	1 day	Tue 19/03/19	Tue 19/03/19	18,17	Alex S	3
20							
21	Assemble Electronics and Actuators to Frame	2 days	Wed 27/03/19	Thu 28/03/19	16,14	Elijah, Alex S	3
22	Assemble Frame to the Backplate	1 day	Fri 29/03/19	Fri 29/03/19	21	Elijah, Alex S	3
23							
24	**Vertebrae Manufacture and Assembly**	**20 days**	**Mon 04/03/19**	**Fri 29/03/19**			
25	3D Print Vertebrae	16 days	Mon 04/03/19	Mon 25/03/19		RP UoN	
26	Remove Support Material and finish	3 days	Tue 26/03/19	Thu 28/03/19	25	Group	9
27	Assemble Vertebrae Together	1 day	Fri 29/03/19	Fri 29/03/19	26	Fraser	2
28							
29	**Tail Manufacture and Assembly**	**20 days**	**Mon 04/03/19**	**Fri 29/03/19**			
30	3D Print Attachment Link	14 days	Mon 04/03/19	Thu 21/03/19		RP UoN	
31	CNC Mould	14 days	Mon 04/03/19	Thu 21/03/19		**Technician Time**	
32	Removal Support Material and Finishing Attachment Link	2 days	Fri 22/03/19	Mon 25/03/19	30	Josh	4
33	Mould Tail	4 days	Tue 26/03/19	Fri 29/03/19	31,32,3	Josh	6
34							
35	**Clamp Manufacture and Assembly**	**19 days**	**Mon 04/03/19**	**Thu 28/03/19**			
36	3D Print	16 days	Mon 04/03/19	Mon 25/03/19		RP UoN	
37	Remove Support Material and Finish	1 day	Tue 26/03/19	Tue 26/03/19	36	Fraser	3
38	Prime and Sand	2 days	Wed 27/03/19	Thu 28/03/19	37,3	Alex D	5
39							
40	**Skin Manufacture**	**4 days**	**Mon 25/03/19**	**Thu 28/03/19**	**3**		
41	Cut Skin to Size	1 day	Mon 25/03/19	Mon 25/03/19	3	Alex D	2
42	Bond skin into a sock	1 day	Tue 26/03/19	Tue 26/03/19	41	Alex D	0.5
43	Cure Time	1 day	Wed 27/03/19	Wed 27/03/19	42	-	12
44							
45	**General Assembly**	**3 days**	**Mon 01/04/19**	**Wed 03/04/19**			
46	Connect Head and Vertebrae Assemblies	1 day	Mon 01/04/19	Mon 01/04/19	24,4,16,9	Group	4
47	Assemble Tail to Vertebrae	1 day	Mon 01/04/19	Mon 01/04/19	29	Group	4
48	Attach Skin to Body	1 day	Mon 01/04/19	Mon 01/04/19	40,35	Group	4
49	Dry Testing of Operation	1 day	Tue 02/04/19	Tue 02/04/19	48	Group	4
50							
51	**Test Rig Manufacture**	**20 days**	**Mon 04/03/19**	**Fri 29/03/19**		**Technician Time / E**	
52	Left and Right Arms	1 day	Mon 18/03/19	Mon 18/03/19		Technician Time	
53	Holes in Cross Beam	1 day	Tue 19/03/19	Tue 19/03/19		Technician Time	
54	Newton Meter Mounts	1 day	Wed 20/03/19	Wed 20/03/19		Technician Time	
55	Hook	1 day	Thu 21/03/19	Thu 21/03/19		Elijah	
56	Pivot Rod/Bar	1 day	Fri 22/03/19	Fri 22/03/19		Elijah	
57	Weld and Assemble	1 day	Mon 25/03/19	Mon 25/03/19	3,56	Technician Time	
58							
59	Fill Water Tank	5 days	Wed 27/03/19	Tue 02/04/19		**Technicians**	
60	Testing	3 days	Wed 03/04/19	Fri 05/04/19	49,51	Group	
61							
62	~~Contingency Time~~	~~5 days~~	~~Mon 08/04/19~~	~~Fri 12/04/19~~	~~60~~		

GANTT CHART

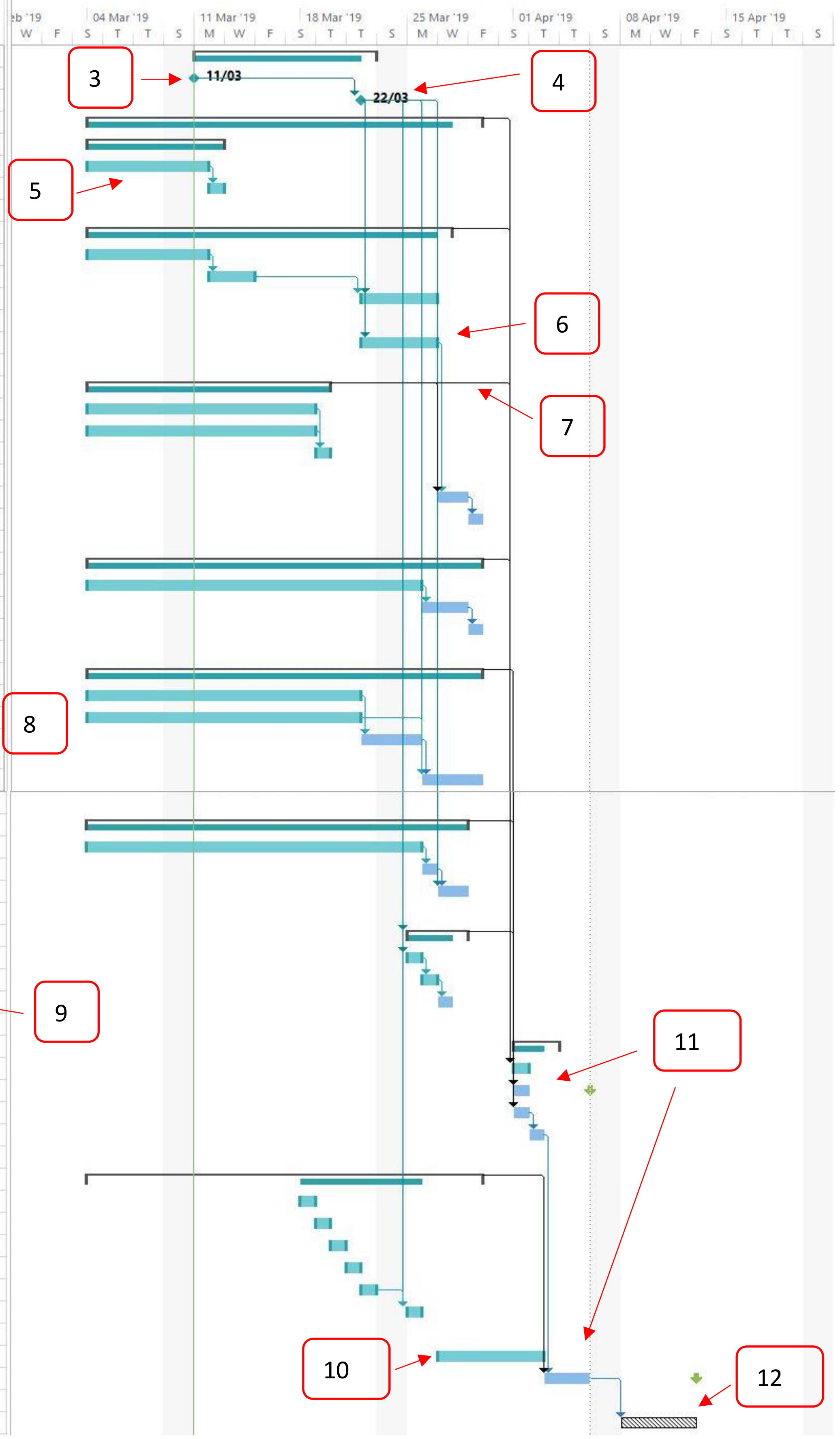


Figure 7.2. Biomimetic Propulsion System Fabrication Gantt chart

For both the Gantt charts shown above, key dates and processes have been highlighted and will be explained below. These aspects have been stated due to their timings having knock-on effects on the rest of the project. Therefore, it can be seen that the plan has been produced thoroughly to account for problems and risks if they arise.

Biomimetic Propulsion System Project Plan (Figure 7.1)

1. After CDR review was completed and passed, manufacturing could commence. This was on 4th March and hence the fabrication plan starts on 4th March.

2. The remainder of the project plan takes into account the manufacture, assembly and testing of the product. This will be explained in more detail in the fabrication plan however the key milestones of the fabrication plan have been stated in the project plan. The exhibition is the last day on the project plan.

Biomimetic Propulsion System Fabrication Plan (Figure 7.2)

3. 11th March all remaining order forms were sent off by Alastair Campbell Ritchie for purchasing. The parts required all had delivery times of 5 days or less. 2 weeks has been given for the purchasing and delivery of these parts.

4. 22nd March all orders should have been delivered. Most other processes can commence without the order parts (3D printed parts), however the remainder have been given the delivery of the orders as a predecessor so that they are set to only commence once orders arrive.

5. All 3D printed parts files were taken to the RP Lab straight after passing CDR review. This way they could be printed as soon as possible. The technicians gave rough timings for when our parts would be available. These have been used in the fabrication plan for the maximum time it would take to 3D print and the order in which the parts have been printed has been shown on the plan.

6. Electronics test cannot commence until ordered parts are delivered.

7. Some parts (Print Frame) have been set to be manufactured as soon as possible. The overall process (Motor Frame Manufacture) has been given a longer period than needed, this is so that contingency time can be considered. These parts need to be completed anytime within the time frame specified.

8. Where technician time is being used, it has been clearly stated. This is for the CNC of the tail mould and some parts of the test rig. The rest is being manufactured either through 3D printing or by the members of the group. Each part has been given an owner who will be in charge of manufacturing/assembling this part.

9. The timings needed have been clearly identified. E.g. the time needed for the silicone adhesive to cure. Additionally, overestimates for the time to manufacture each part have been included to ensure that if problems arise there is time to spare.

10. The group have been advised that the water tank to be used for testing needs 5 days to fill, therefore this has been added into the plan.

11. Assembly and testing have been placed in the same week, with the first two days for assembling the product and the last 3 days for testing. All parts will be reviewed along the way and tested for tolerances and fits. It is because of this that the group are certain that 2 days of assembly time is adequate.

12. After testing the product, there is a week's contingency time before the final deliverable is due. This leaves time for any alterations and fixes needed after testing and also gives the members of the group time to analyse the test results and produce the final documentation. If needed, this time can also be used for any manufacturing or testing still to be completed, however an effort will be made to avoid this.

8. Risk Analysis and Mitigation (FMEA)

Process Step	Potential Failure Mode	Potential Failure Effect	SEV	Potential Causes	OCC	Current Process Controls	DET	RPN	Action Recommended
What is the step?	In what ways can the step go wrong?	What is the impact on the customer if the failure mode is not prevented or corrected?	How severe is the effect on the customer?	What causes the step to go wrong (i.e. how could the failure mode occur)?	How frequently is the cause likely to occur?	What are the existing controls that either prevent the failure mode from occurring or detect it should it occur?	How probable is detection of the failure mode or its cause? 10 = most difficult to detect	Risk priority number calculated as SEV x OCC x DET	What are the actions for reducing the occurrence of the cause or for improving its detection? Provide actions on all high RPNs and on severity ratings of 9 or 10.
SOLIDWORKS engineering drawings for manufacturing	Loss of CAD files/ engineering drawings	Delay in the manufacture and presentation of final product	5	Files are not saved regularly and in a logical order	3	SharePoint Drive and autosave features	5	75	-
	Loss of access to software		8	University or student contract runs out	1	University system	2	16	-
	Inaccurate drawings with not enough/wrong dimensions	Product does not assemble	6	Concept has not been reviewed accurately	6	Peer review and CAD assemblies	8	288	Ensure the final designs have been reviewed by academics and peers. Make sure that tolerances have been included and are well dimensioned on the drawings
Purchasing of materials and components	Incorrect equipment bought	Loss of money and final deliverable is not available on time	9	Bad communication between designer and person responsible for parts/cutting list and ordering	2	Peer and customer review to ensure parts ordered are the ones wanted	6	108	Ensure all chosen products have been reviewed by academics and peers to ensure that they are suitable for the purpose intended
	Materials are not delivered on time		9	Supplier is unreliable or delivery times not taken into account	6	Use trusted suppliers, monitor Gantt chart and delivery estimates	2	108	Ensure products are bought from trusted suppliers and if late ordering occurs that the delivery times are clearly stated.
Additive manufacture of linkage system and rigid head	Unable to be additively manufactured quickly due to high demand of services	Set back in time before deliverable should be available	7	Not keeping in contact with the rapid prototyping lab to know their schedule and the time to print the parts needed	4	Regular conversations with the rapid technicians in rapid prototyping	5	140	Book a time slot in advance to use the 3D printers and ensure final designs are completed and assessed before then
	Faulty equipment	Set back in time before deliverable should be available and/or poor quality deliverable	8	Attempted equipment use without presence of trained operator, improper prior use	5	Regular machine maintenance, integrated alerts and failsafes	3	120	Ensure operators are well trained using machine equipment and that the parts to be manufactured are clearly dimensioned
	Poor tolerances	Poor quality deliverable	5	Faulty machinery, printed to a lower quality due to time constraints	7	Peer review, inspection of machine tolerances and minimum layer heights	7	245	All manufactured parts should have clear engineering drawings with written tolerances and dimensions. Book a time slot in advance to use the 3D printers.
Machining of designed components	Part is too difficult to be machined	Loss of money and final deliverable is not available on time	6	Lack of communication with the technician	5	Regular meetings with the technicians	2	60	-
	Part is machined incorrectly	Loss of money and possible set back in project lead time	3	Poorly communicated process sheets, unskilled or inattentive operator	3	Inspection by machine operator, peer review	3	27	-
Development of servo-operating code	Bugged code	Final deliverable does not work as intended	5	Code doesn't work due to complexity of system	4	Peer review/ academic consultation and regular testing	2	40	-
	Loss of access to software	Set back in time before deliverable should be available	8	University or student contract runs out	1	University system, subscription alerts	2	16	-
Assembly of bungee cord-links-cable system	Part does not fit	Set back in time before deliverable should be available	7	Tolerances have not been applied to all parts	4	Peer review	3	84	-

Fitting of architecture to outer body	Part does not fit	Set back in time before deliverable should be available	7	Tolerances have not been applied to all parts	4	Peer review	3	84	-
Fastening of various components	Not enough space for assembly	Set back in time before deliverable should be available	7	Tolerances have not been applied to all parts	4	Peer review	3	84	-
Preparation of testing environment	Equipment is not available for testing	Product is unable to be properly tested	8	Lack of time given to build test rig and to fill the tank with water	5	Regular meetings with the technicians	2	80	-
Testing and data collection of working deliverable	Unable to record data required	Product is unable to be properly tested due to testing equipment not working	5	Testing equipment does not work adequately with the product submerged in water	4	Discussions with technicians and adequate tolerances	3	60	-
		The product does not turn on and provide motion	10	The product is not sealed/wired correctly	3	Design features implemented to ensure that product is water tight	6	180	Careful assembly of the parts and testing to ensure tight fits have been met. Testing in air first, then slowly testing before full submerged test is undertaken. If issues arise, work to fix the issues before further testing continues
Maintenance of working deliverable	Product is unable to be disassembled without failure	Product is deemed unusable after initial use	3	Product fails to achieve its intended life time	5	Peer review and technician support when assembling	4	60	-
Assessed demonstration of working deliverable	Product does not fulfil its function	Product is deemed unusable	3	Product fails to achieve its intended life time	4	Peer review and technician support when assembling	9	108	Careful assembly of the parts and testing to ensure tight fits have been met. Ensure video recordings of the product working in air and also in testing are available.

Table 8.1: Revised FMEA table focusing on the manufacture and testing of the deliverable

FMEA (continued)

An FMEA (Failure Mode and Effects Analysis) was used to find potential problems which may arise due to manufacturing and testing and discuss the best methods to mitigate these risks. As shown in Table 8.1 each process was analysed to show how it may affect the project health and was given a severity value (1-10) for how it may affect the customer.

The severity could then be multiplied by the frequency of occurrence and the probability of being detected to give the Risk Priority Number (RPN) of each process. Any process with an RPN higher than 100 is considered to be high risk and therefore actions needed to be taken to ensure they did not occur. The processes with the highest risk were found to be:

- Inaccurate drawings and tolerances so the final product does not assemble accurately. This has been mitigated throughout the design process by 3D printing prototypes to test the critical parts and frequently meeting with technicians to discuss the processes for manufacturing and the engineering drawings produced.

- Parts ordered are not the correct parts or are not delivered on time. An extensive budget (Table 6.1) was used to accurately track the parts being ordered and this was cross-referenced with all drawings to ensure the parts were correct. The parts being supplied by outside companies were chosen beforehand so they could be ordered as soon as the Critical Design Review was passed to ensure lead times were considered. The times for parts to be ordered by the finance department and delivered were all considered in the fabrication Gantt chart and contingency time was left in case unforeseen problems arose.

- The waterproofing of the product is not adequate and so the product fails to work. Regular design meetings and peer review have been used to ensure standards are followed. The product will be tested without the electronics added to ensure a watertight seal before the final product is assembled and tested.

Despite many of the processes not having high RPNs, all stages have been considered during design and manufacturing through peer review, meetings with technicians and academics and an iterative design process to ensure the product should be completed on time and to a high standard.

9. Health and Safety Risks

The final product needs to be manufactured and tested in a safe environment to ensure the safety of the group members, technicians and others involved. The processes required and the risks arising from these have all been considered and the steps to mitigate these risks stated to be followed. The manufacturing and process risk assessment forms for both manufacturing and testing can be found in Appendix C.

All group members have been trained to use the machinery in L2 workshop and know the placements of all emergency stops. The training ensures that members are aware of the risks from sharp implements and swarf when machining materials. The risk assessment was also used to highlight the materials which required COSH assessment.

The silicone E41 adhesive and the PT Flex resin both require a fume hood due to hazardous fumes. These are to also be handled with care and disposed of appropriately. The procedures, in case of emergency, have all been reviewed with the health and safety officer to ensure safety.

The product will require thorough verification of its watertight capability as the casing that contains the electronics will be submerged in water. The product is following waterproofing standards to ensure that water does not leak into the head, however if this does happen the users should not be at risk. During mounting the power supply will be turned off and the power supply being used is only 12V.

A limit has been set as to the height the tester can reach on the step ladder to mitigate risk of them falling into the tank and a covering will be used on the top of the tank.

The safety of everyone involved is of utmost importance and the risk assessments show that these risks have been mitigated as best possible.

10. References

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[2]	*https://uniofnottm.sharepoint.com/sites/MM4GDMProject/Shared%20Documents/Forms/Ordered%20View.aspx?web=1&FolderCTID=0x01200003B9D6EC0F559F40B9665DDE36AAB00E&id=%2Fsites%2FMM4GDMProject%2FShared%20Documents%2FDHF%2F8%2E%20Compliance%2FPreliminary%20Test%20Videos*
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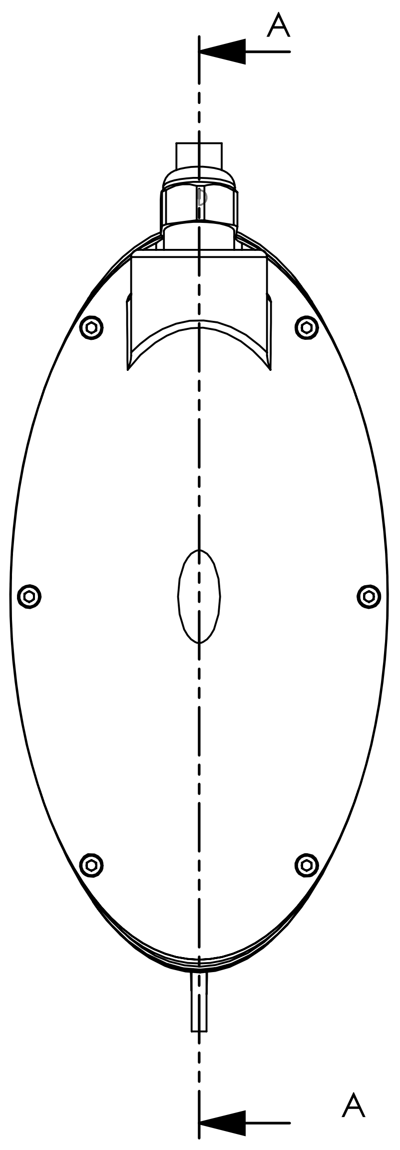
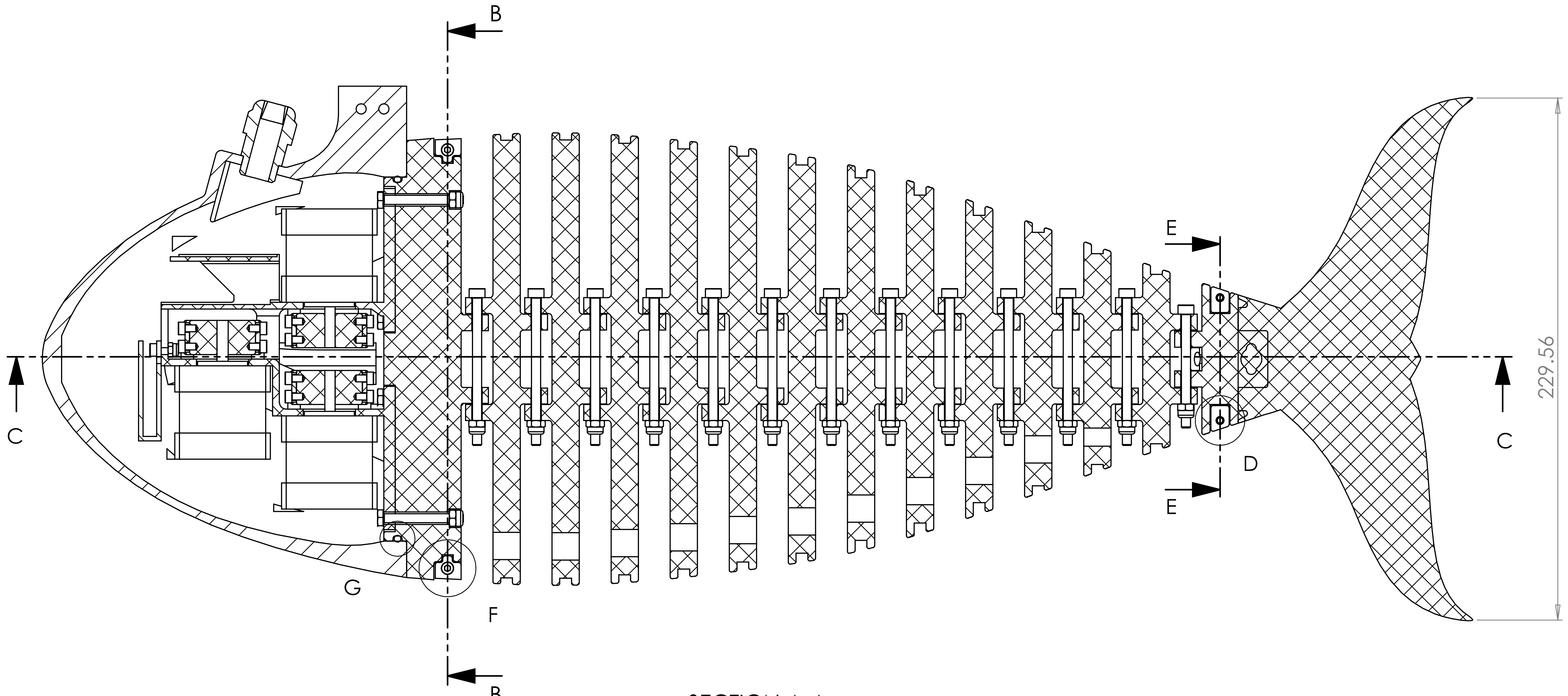
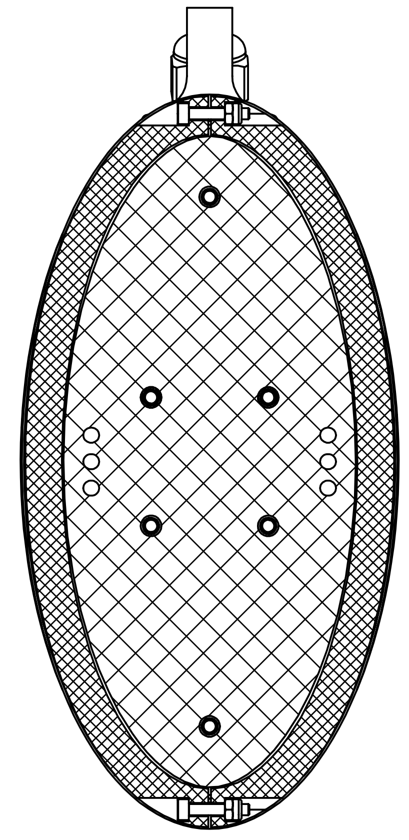
Table 10.1: Table of references

11. Appendix A – Detailed and General Assembly Drawings





SECTION A-A



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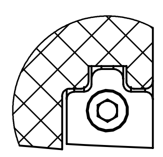

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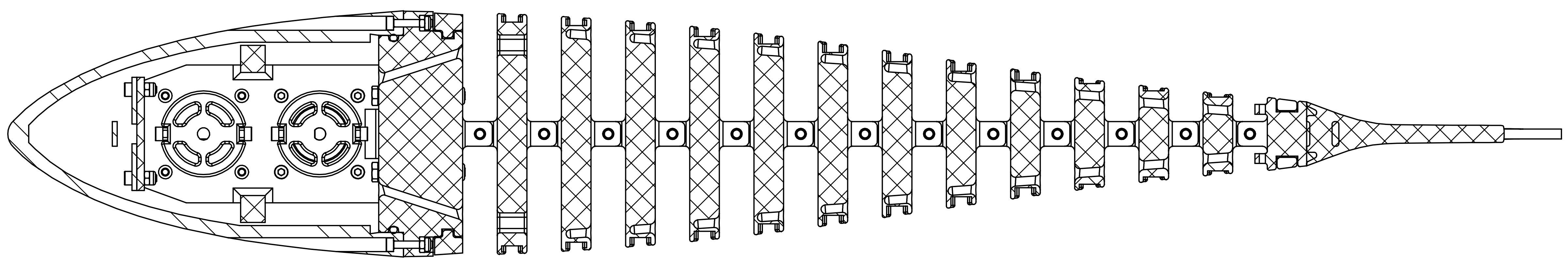

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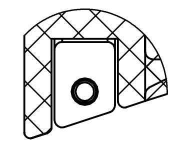

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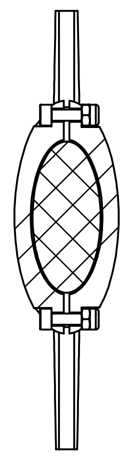
SCALE 1 : 1



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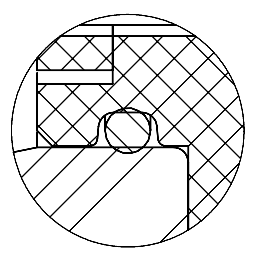
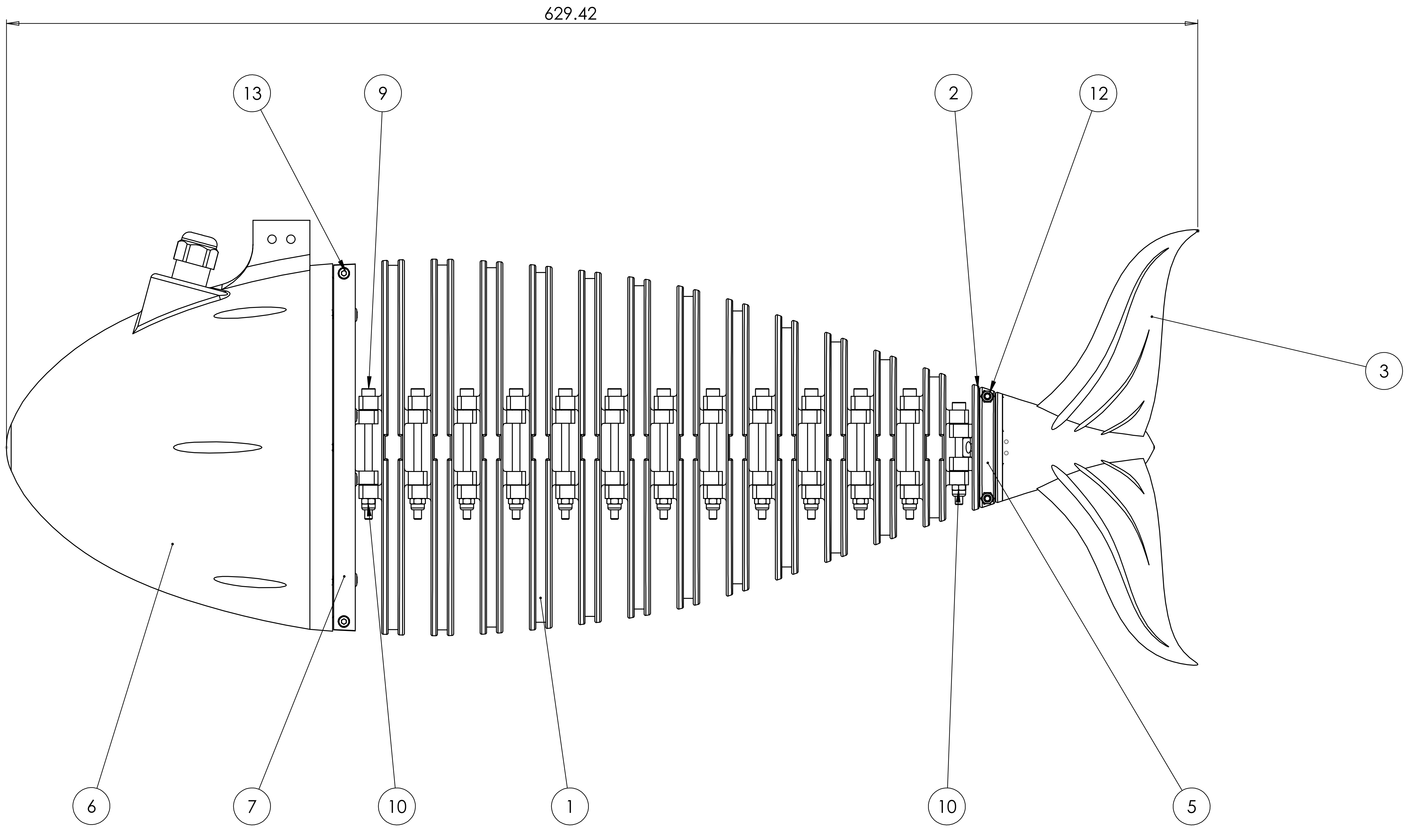


DETAIL G
SCALE 2 : 1

ITEM	DRAWING NO.	Description	MATERIAL	VENDOR	QTY.
1	BPS.02.00	Vertebrae Assembly	-	-	1
2	BPS.03.01	Vertebrae Tail Mould Link	PLA	RP UoN	1
3	BPS.03.02	Tail	Polytek PT-Flex 70 PU Casting Rubber	-	1
4	BPS.00.01	Small Skin Clamp Side 1	PLA	RP UoN	1
5	BPS.00.02	Small Skin Clamp Side 2	PLA	RP UoN	1
6	BPS.01.00	Head Assembly			1
7	BSP.00.03	Large Skin Clamp Side 1	PLA	RP UoN	1
8	BPS.00.04	Large Skin Clamp Side 2	PLA	RP UoN	1
9	-	M4 x 65 Cap Screw	Stainless Steel	Accu	1
10	-	M4 Nyloc Nut	Stainless Steel	Accu	2
11	-	M4 x 50 Cap Screw	Stainless Steel	Accu	1
12	-	M3 Nyloc Nut	Stainless Steel	Accu	4
13	-	M3 x 16 Cap Screw	Stainless Steel	Accu	2
14	-	M3 x 12 Cap Screw	Stainless Steel	Accu	2

University of Nottingham

TOLERANCE LINEAR: ± 0.5 ANGULAR: ± 1°	Biomimetic Propulsion System			
ALL DIMENSIONS ARE IN MILLIMETRES	ISSUE DATE 01/03/19	REVISION 1	DRAWN BY FK	DRAWING NO. BPS.00.00
DRAFTING STANDARD BS 8888	MODULE MM4GDM	SCALE 1:2	SIZE A2	SHEET 1 of 2



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2	BPS.03.01	Vertebrae Tail Mould Link	PLA	RP UoN	1
3	BPS.03.02	Tail	Polytek PT-Flex 70 PU Casting Rubber	-	1
4	BPS.00.01	Small Skin Clamp Side 1	PLA	RP UoN	1
5	BPS.00.02	Small Skin Clamp Side 2	PLA	RP UoN	1
6	BPS.01.00	Head Assembly			1
7	BSP.00.03	Large Skin Clamp Side 1	PLA	RP UoN	1
8	BPS.00.04	Large Skin Clamp Side 2	PLA	RP UoN	1
9	-	M4 x 65 Cap Screw	Stainless Steel	Accu	1
10	-	M4 Nyloc Nut	Stainless Steel	Accu	1
11	-	M4 x 50 Cap Screw	Stainless Steel	Accu	2
12	-	M3 x 12 Cap Screw	Stainless Steel	Accu	2
13	-	M3 x 16 Cap Screw	Stainless Steel	Accu	2
14	-	M3 Nyloc Nut	Stainless Steel	Accu	4

University of Nottingham

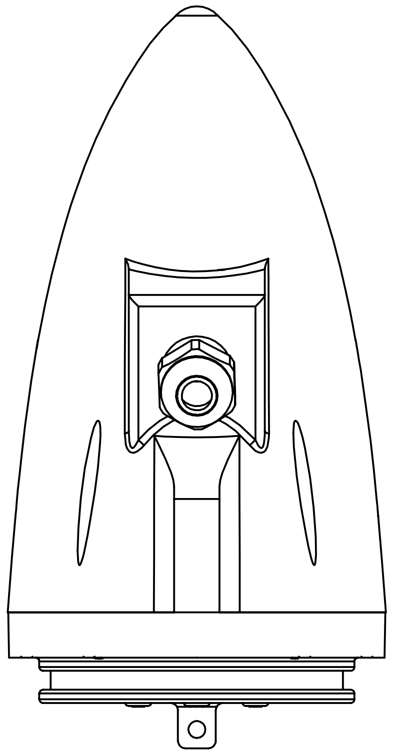
TOLERANCE
LINEAR: ± 0.5
ANGULAR: ± 1°

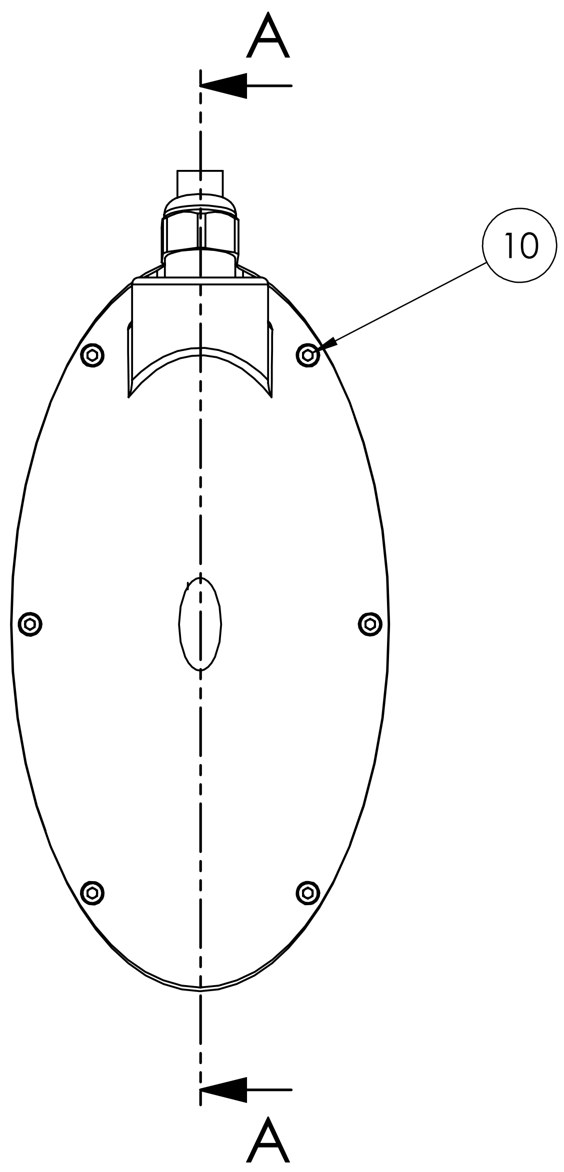
Biomimetic Propulsion System

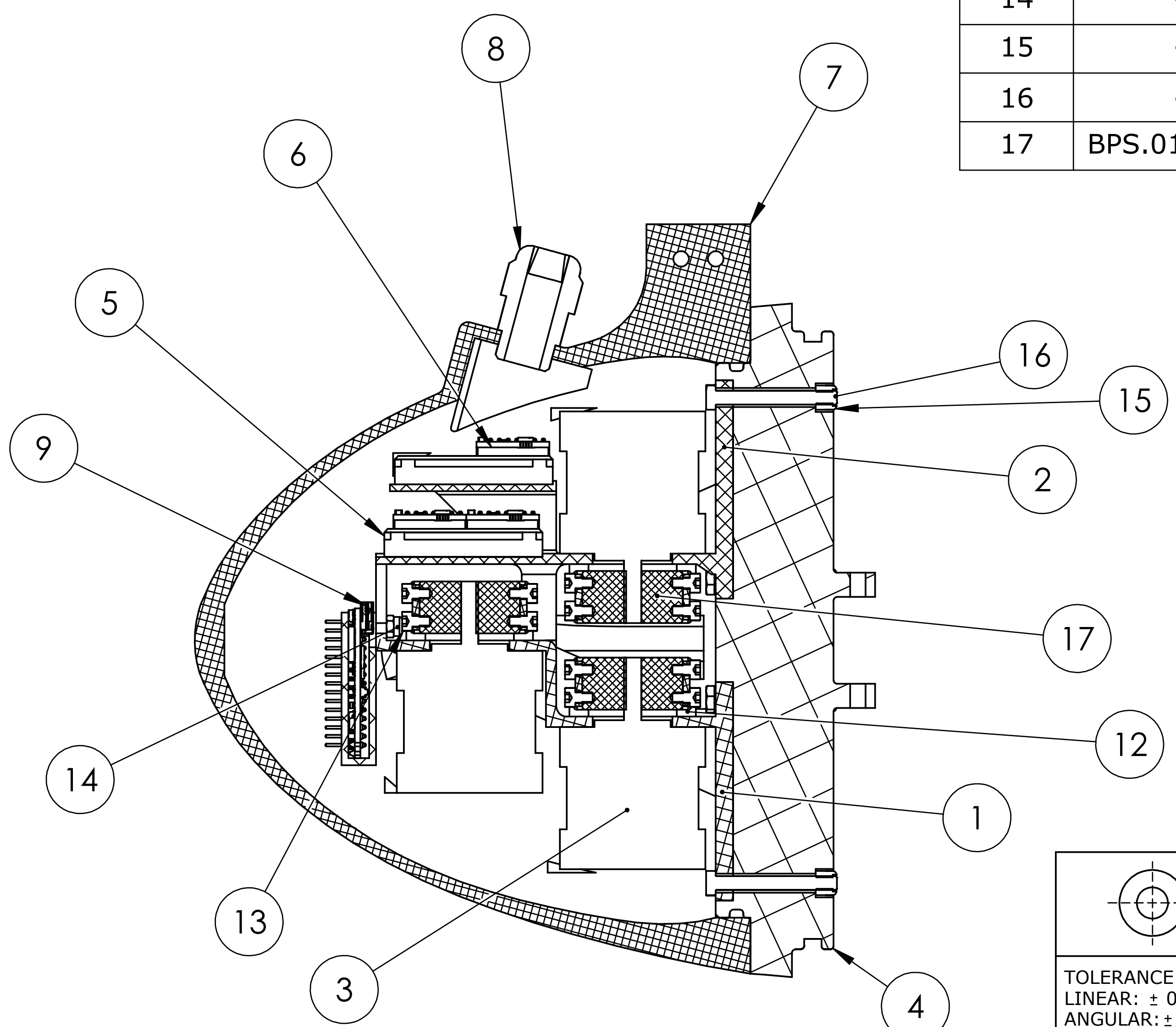
ALL DIMENSIONS ARE IN MILLIMETRES	ISSUE DATE 01/03/19	REVISION 1	DRAWN BY FK	DRAWING NO. BPS.00.00
DRAFTING STANDARD BS 8888	MODULE MM4GDM	SCALE 1:2	SIZE A2	SHEET 2 of 2

DO NOT SCALE

ITEM	DRAWING NO.	MATERIAL	Description	QTY.
1	BPS.01.01	PLA	Motor Frame Lower	1
2	BPS.01.02	PLA	Motor Mount Upper	1
3	-	-	Stepper Motor	3
4	BPS.01.04	PLA	Head Casing Back Plate	1
5	-	ABS	Breadboard	2
6	-	-	DRV 8825 Motor Driver	3
7	BPS.01.05	PLA	Head Case	1
8	-	-	Cable Gland	1
9	-	-	Arduino Nano	1
10	-	Stainless Steel	Socket Head Screw M3 x 16	6
12	-	Stainless Steel	M3 x 5 Socket Head Screw	11
13	-	Stainless Steel	M3 Hex Bolt	2
14	-	Stainless Steel	M3 Nyloc Nut	8
15	-	Stainless Steel	M5 Nyloc Nut	6
16	-	Stainless Steel	M5 x 35 Hex Bolt	6
17	BPS.01.04.00	-	Spool Sub-Assembly	3







SECTION A-A

TOLERANCE LINEAR: ± 0.5 ANGULAR: ± 1°	University of Nottingham UK | CHINA | MALAYSIA Head Assembly

ALL DIMENSIONS ARE IN MILLIMETRES	ISSUE DATE	REVISION	DRAWN BY	DRAWING NO.
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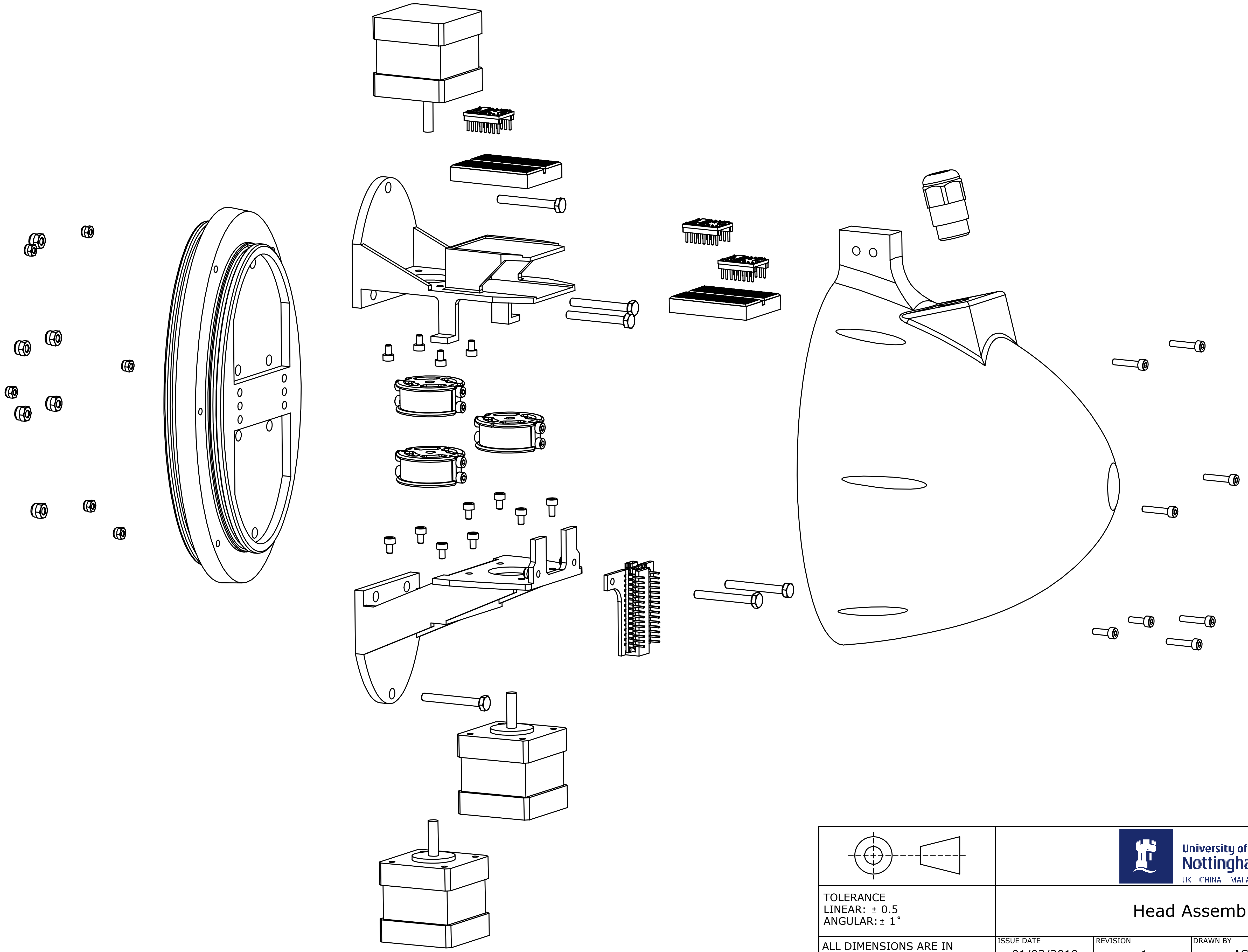
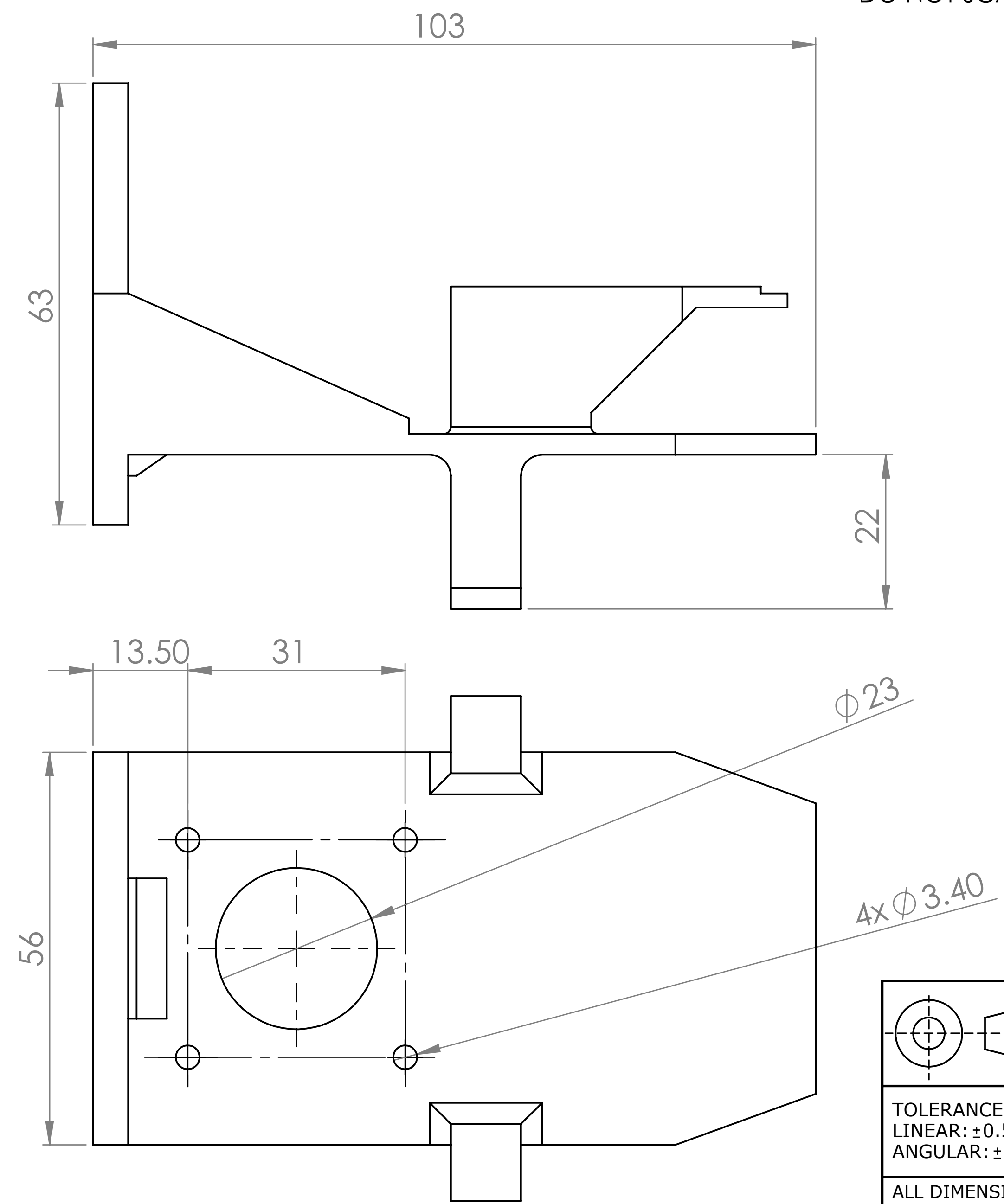
DRAFTING STANDARD BS 8888	MODULE MM4GDM	SCALE 1:2	SIZE A3	SHEET 1 of 2

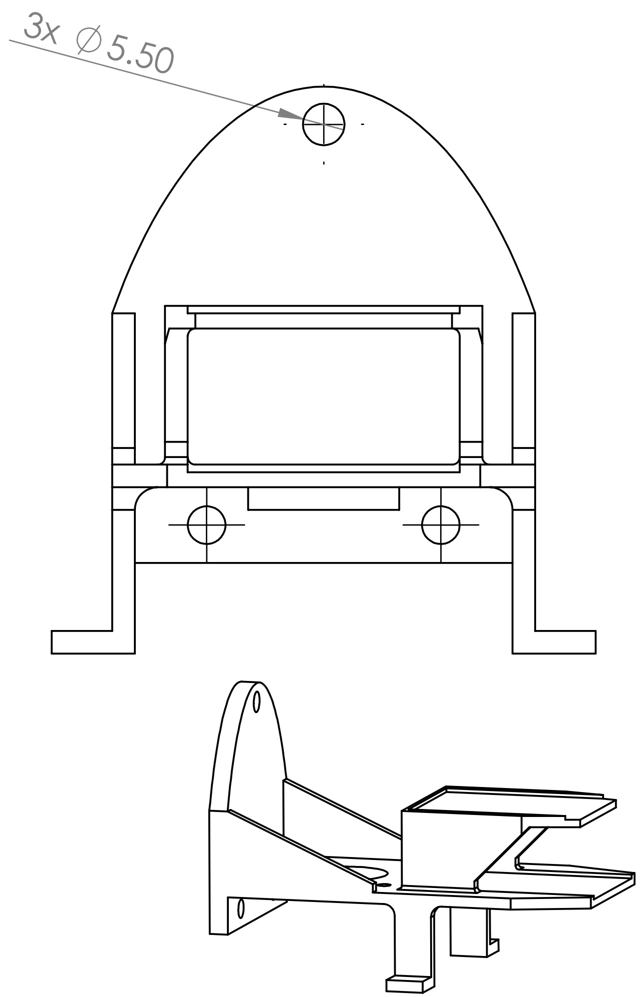
DO NOT SCALE



TOLERANCE LINEAR: ± 0.5 ANGULAR: ± 1°	Head Assembly
ALL DIMENSIONS ARE IN MILLIMETRES	ISSUE DATE 01/03/2019 · REVISION 1 · DRAWN BY AS · DRAWING NO. BPS.01.00
DRAFTING STANDARD BS 8888	MODULE MM4GDM · SCALE 1:2 · SIZE A3 · SHEET 2 of 2

DO NOT SCALE





3D VIEW SCALE 1:2

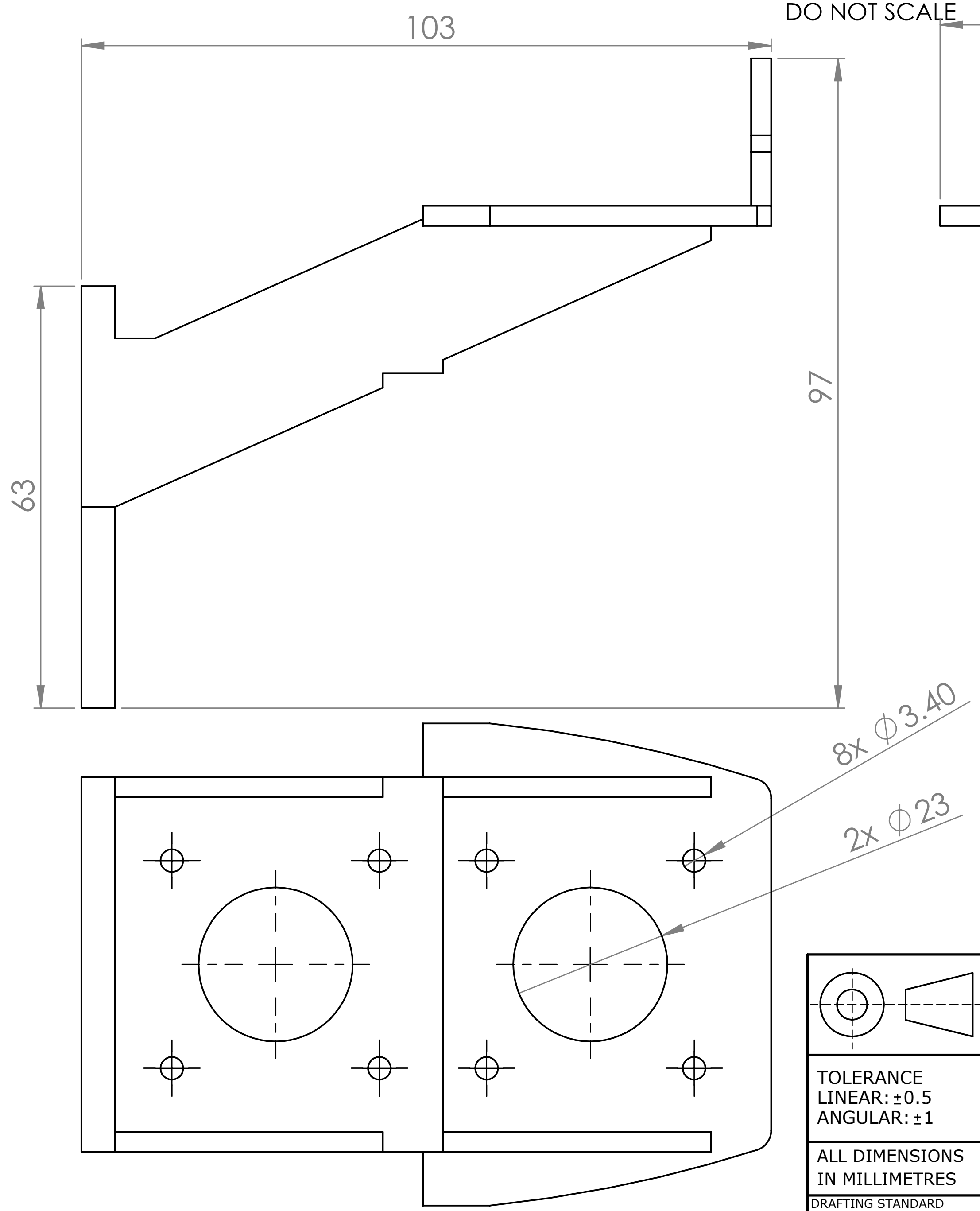
University of Nottingham
UK | CHINA | MALAYSIA

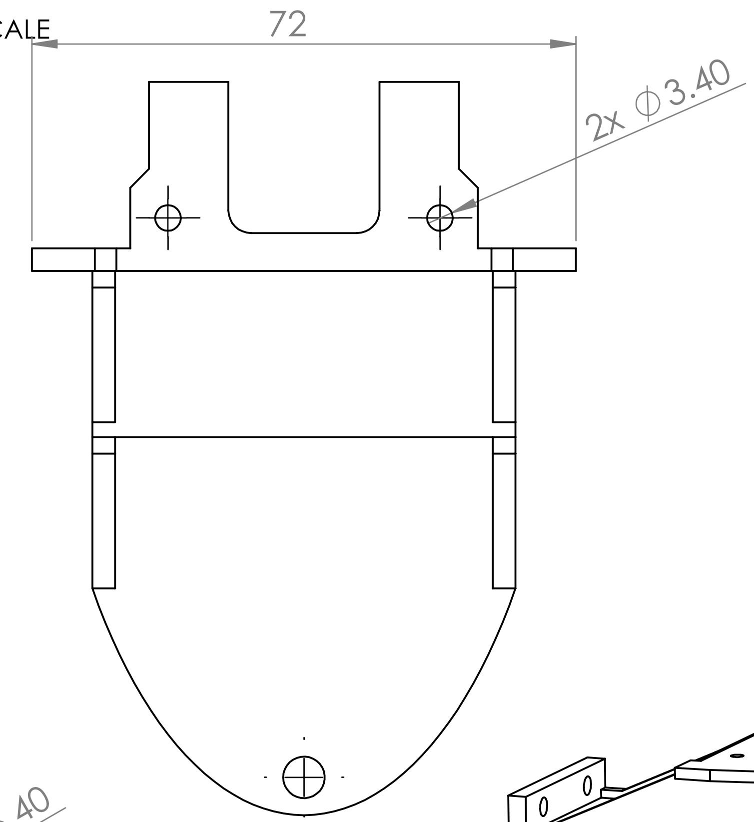
TOLERANCE
LINEAR: ±0.5
ANGULAR: ±1

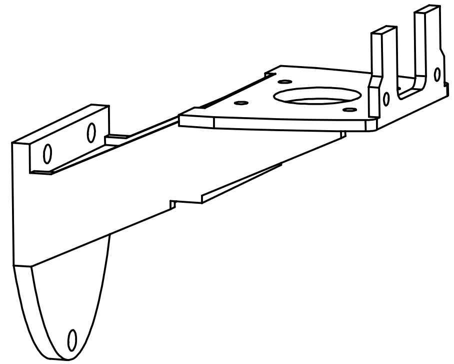
Stepper Motor Mount (Upper)

ALL DIMENSIONS IN MILLIMETRES	MATERIAL CODE -	PROCESS 3D Print	ISSUE DATE 28/02/2019	REV 1	DRAWN BY AS	DRAWING NO. BPS.01.01
DRAFTING STANDARD 8888	MATERIAL PLA		MODULE MM4GDM	SCALE 1:1	SIZE A4	SHEET 1 of 1

DO NOT SCALE







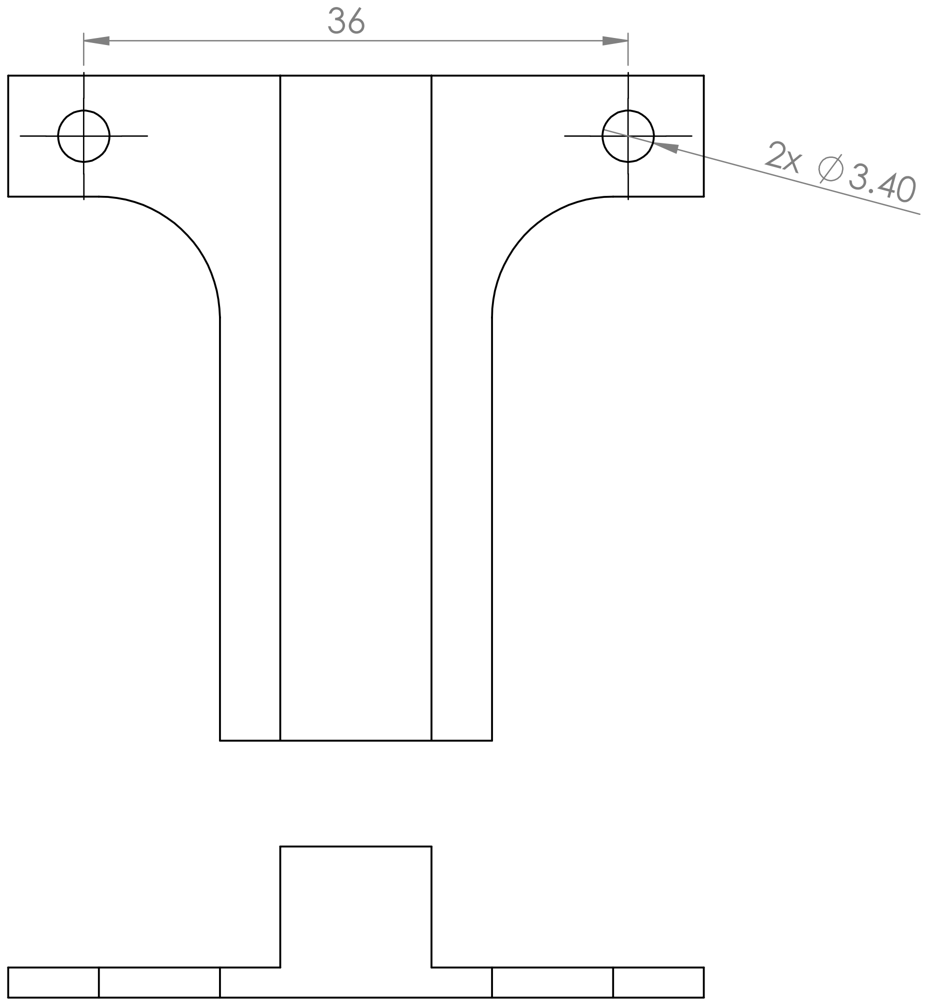
3D VIEW SCALE 1:2

University of Nottingham
UK | CHINA | MALAYSIA

Stepper Motor Mount (Lower)

TOLERANCE LINEAR: ±0.5 ANGULAR: ±1						
ALL DIMENSIONS IN MILLIMETRES	MATERIAL CODE -	PROCESS 3D Print	ISSUE DATE 20/03/2019	REV 1	DRAWN BY AS	DRAWING NO. BPS.01.02
DRAFTING STANDARD 8888	MATERIAL PLA		MODULE MM4GDM	SCALE 1:1	SIZE A4	SHEET 1 of 1

DO NOT SCALE



TOLERANCE LINEAR: ±0.5 ANGULAR: ±1	Arduino Mount					
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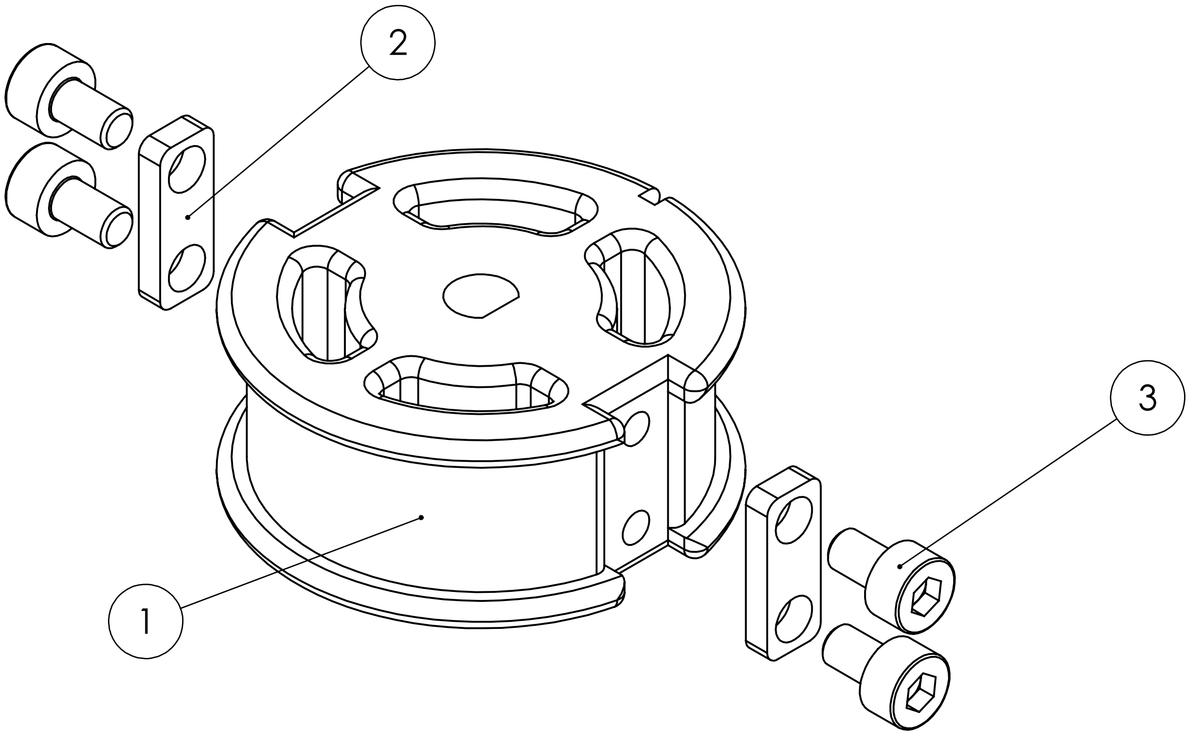
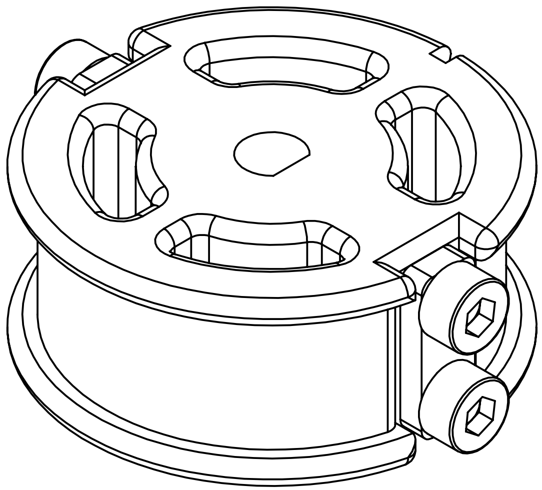
DRAFTING STANDARD 8888	MATERIAL PLA		MODULE MM4GDM	SCALE 2:1	SIZE A4	SHEET 1 of 1

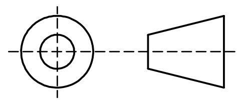
University of Nottingham
UK | CHINA | MALAYSIA

ITEM	DRAWING NO.	Description	MATERIAL	QTY.
1	BPS.01.04.01	Stepper Spool	ABS	1
2	BPS.01.04.02	Spool Clamp Plate	ABS	2
3	-	ISO 4762 M3 x 5	Stainless Steel	4





DO NOT SCALE



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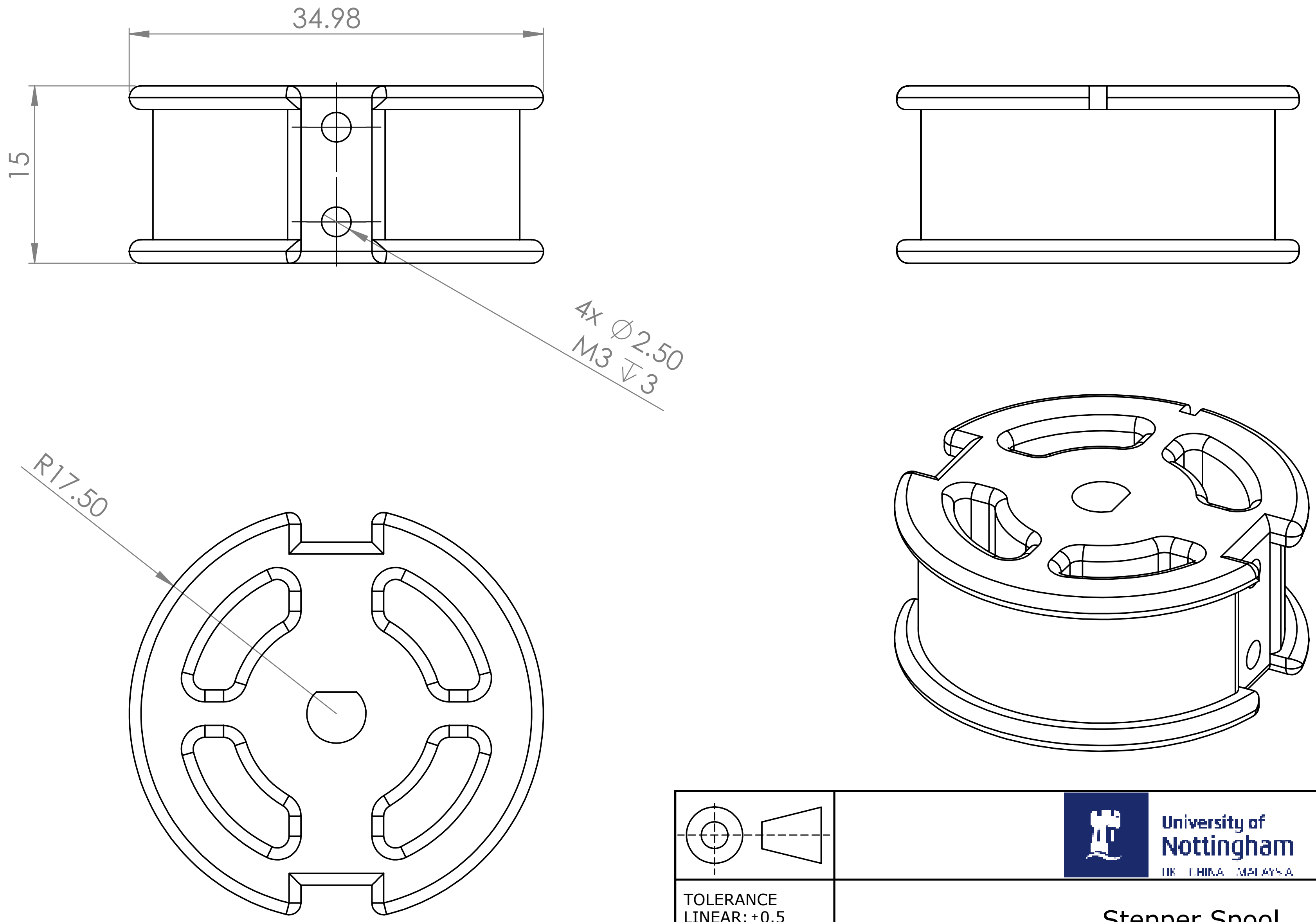
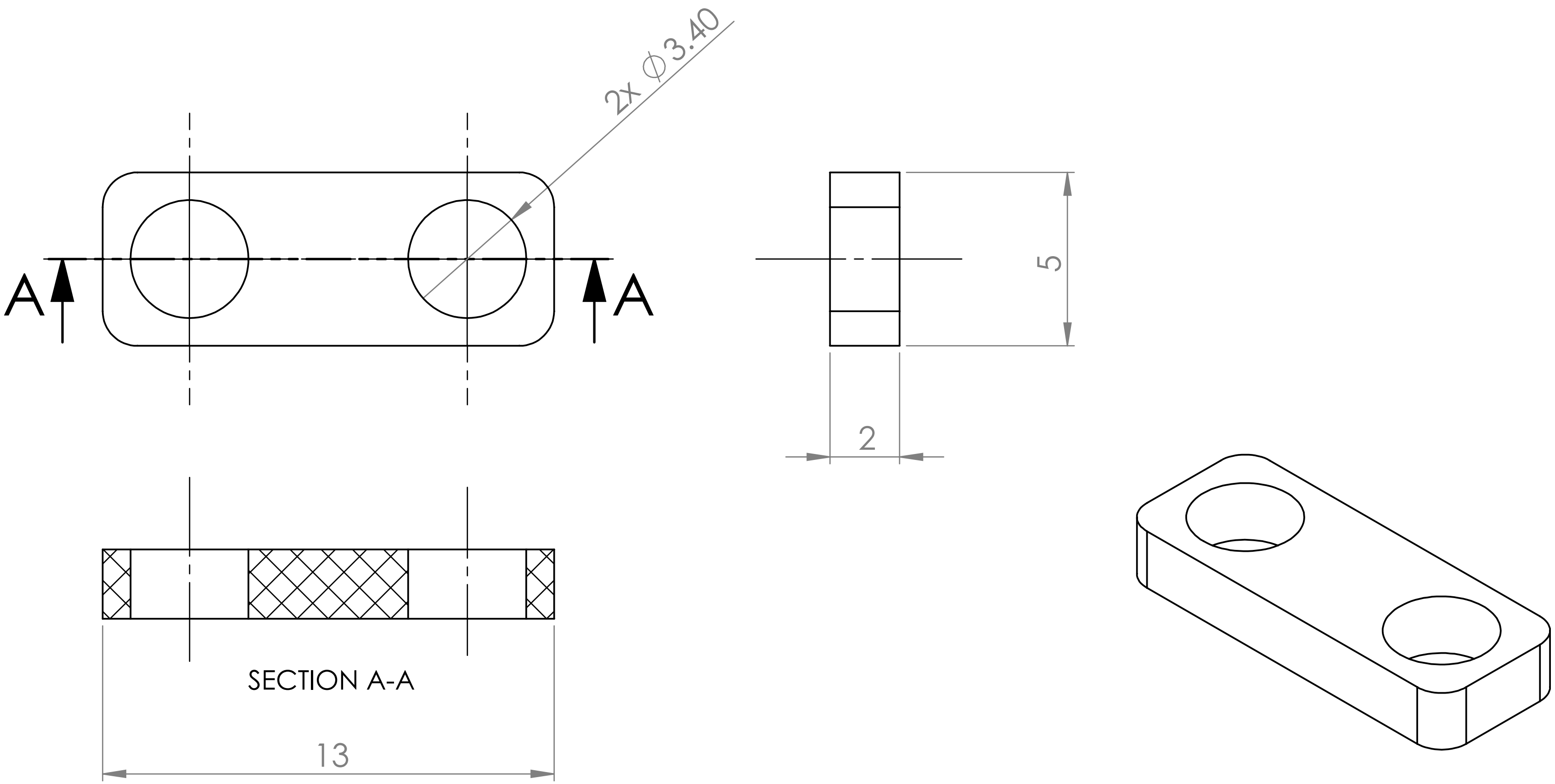
TOLERANCE LINEAR: ± 0.5 ANGULAR: ± 1°	Spool Sub-Assembly			
ALL DIMENSIONS ARE IN MILLIMETRES	ISSUE DATE 20/03/2019	REVISION 1	DRAWN BY AS	DRAWING NO. BPS.01.04.00
DRAFTING STANDARD BS 8888	MODULE MM4GDM	SCALE 2:1	SIZE A4	SHEET 1 of 1

DO NOT SCALE



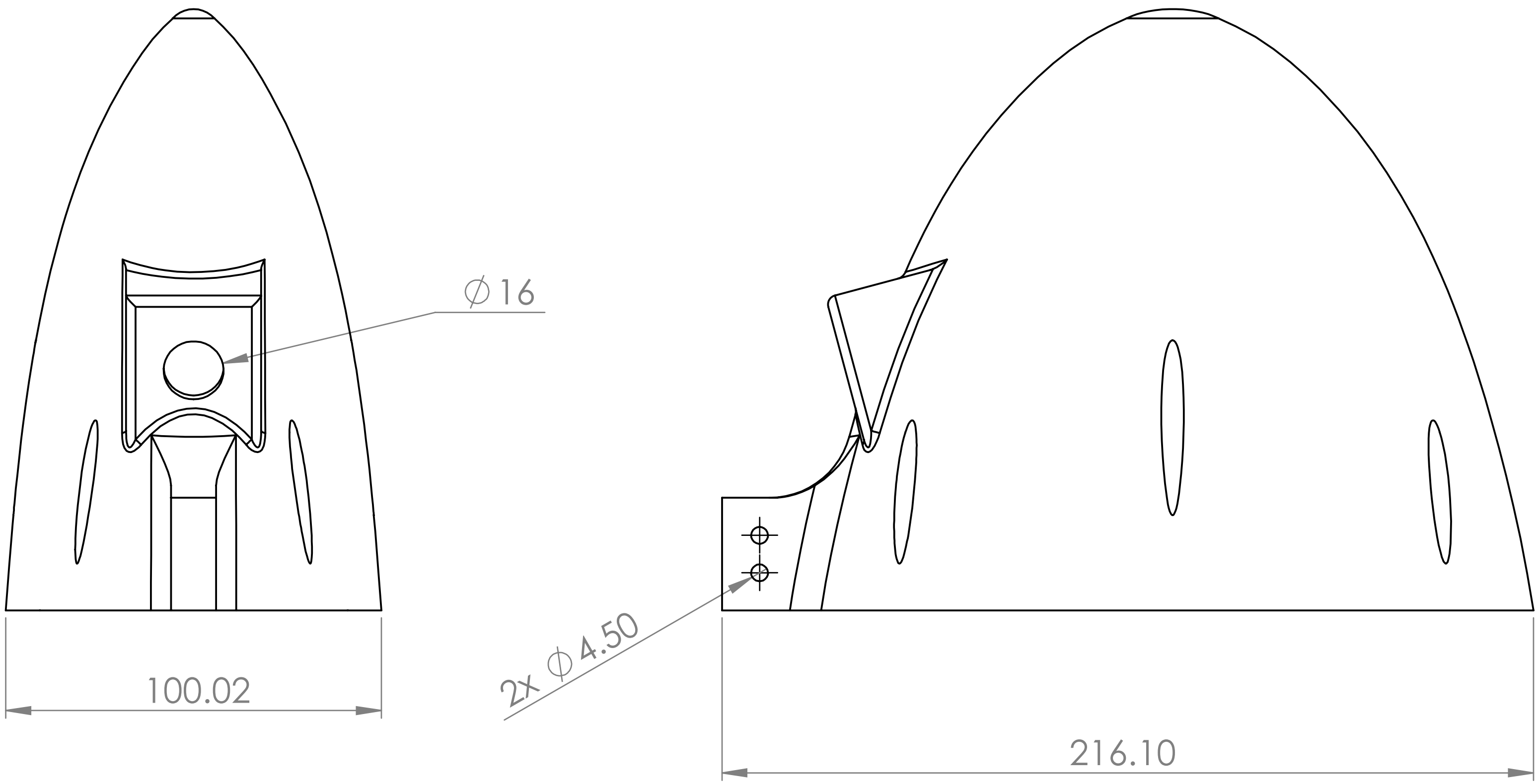
	University of Nottingham UK | CHINA | MALAYSIA					
TOLERANCE LINEAR: ±0.5 ANGULAR: ±1	Stepper Spool					
ALL DIMENSIONS IN MILLIMETRES	MATERIAL CODE -	PROCESS 3D Printed	ISSUE DATE 20/03/2019	REV 1	DRAWN BY EA	DRAWING NO. BPS.01.04.01
DRAFTING STANDARD 8888	MATERIAL PLA		MODULE MM4GDM	SCALE 2:1	SIZE A4	SHEET 1 of 1

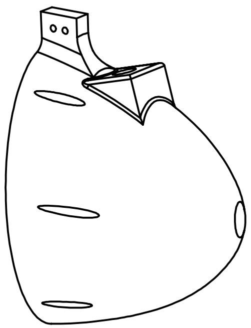
DO NOT SCALE



TOLERANCE LINEAR: ±0.5 ANGULAR: ±1	Spool Clamp Plate					
ALL DIMENSIONS IN MILLIMETRES	MATERIAL CODE -	PROCESS 3D Print	ISSUE DATE 20/03/2019	REV 1	DRAWN BY AS	DRAWING NO. BPS.01.04.02
DRAFTING STANDARD 8888	MATERIAL PLA		MODULE MM4GDM	SCALE 5:1	SIZE A4	SHEET 1 of 1

DO NOT SCALE

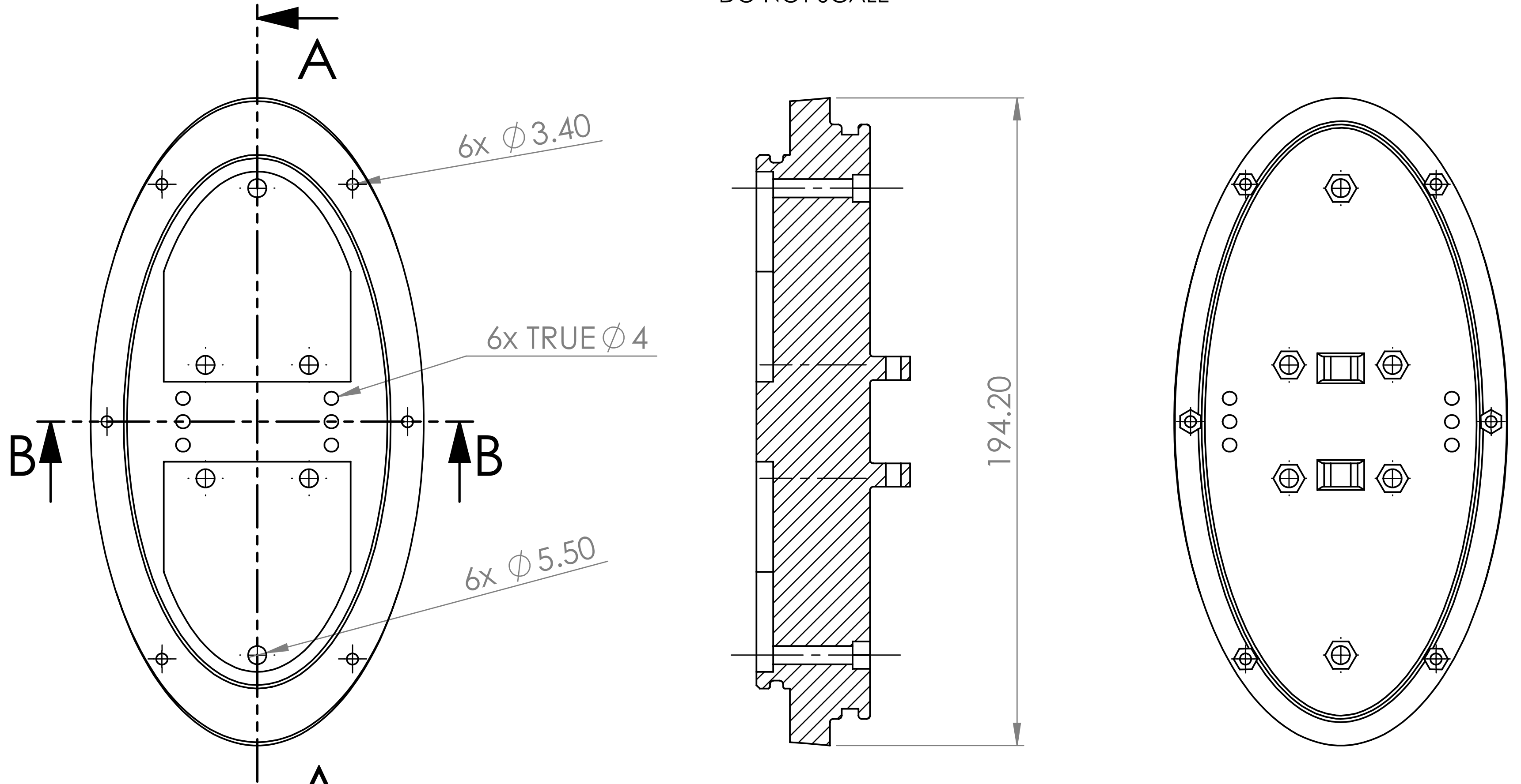


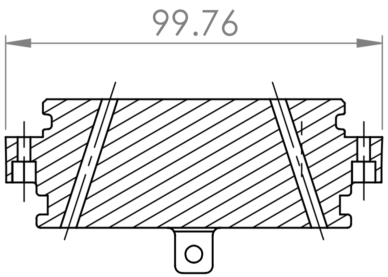


View 2 Scale 1:5

TOLERANCE LINEAR: ±0.5 ANGULAR: ±1	Head Case					
ALL DIMENSIONS IN MILLIMETRES	MATERIAL CODE -	PROCESS 3D Print	ISSUE DATE 01/03/2019	REV 1	DRAWN BY AS	DRAWING NO. BPS.01.05
DRAFTING STANDARD 8888	MATERIAL PLA		MODULE MM4GDM	SCALE 1:2	SIZE A4	SHEET 1 of 1

DO NOT SCALE





SECTION B-B

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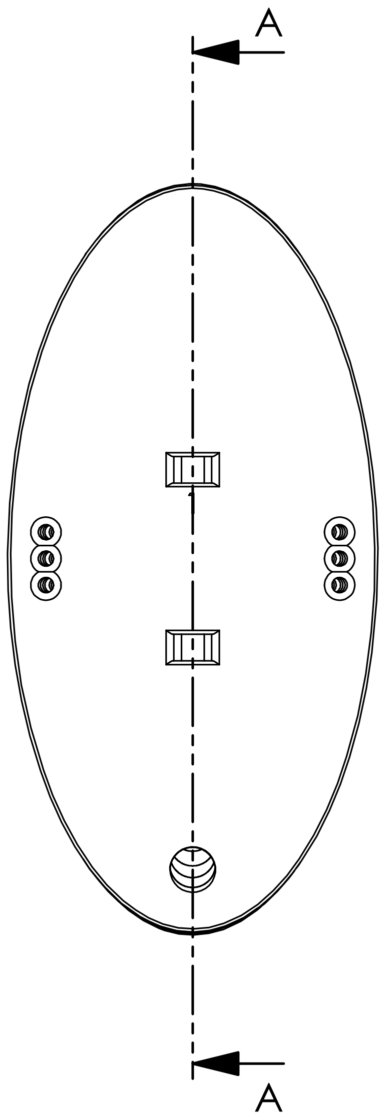
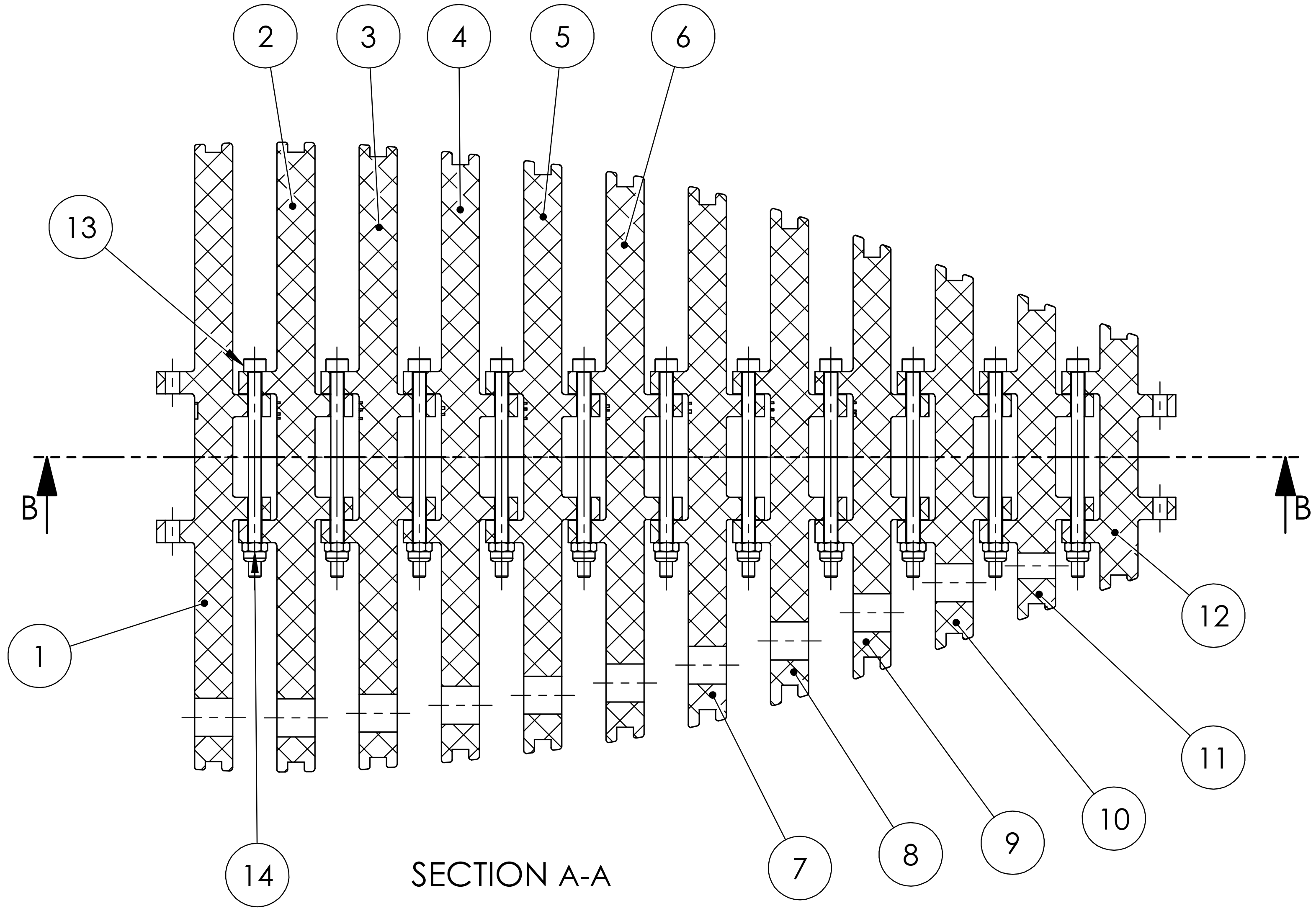
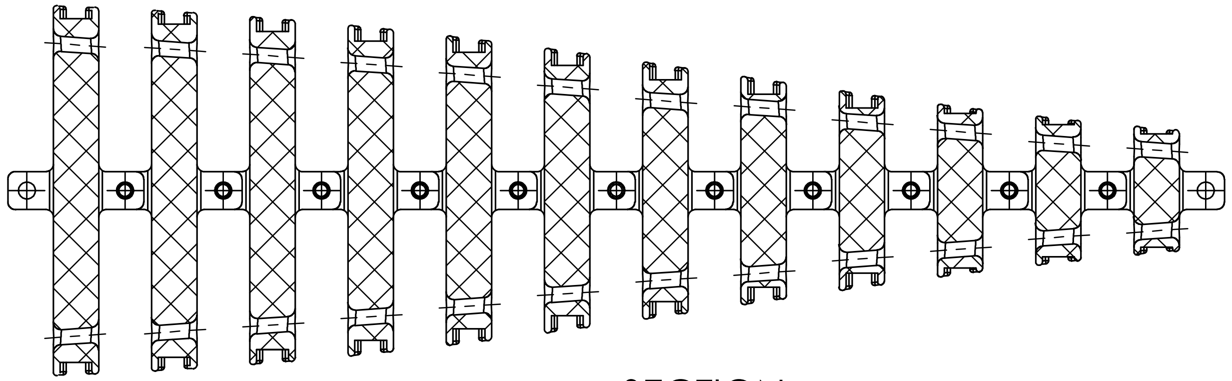
TOLERANCE LINEAR: ±0.5 ANGULAR: ±1	Head Casing Back Plate					
ALL DIMENSIONS IN MILLIMETRES	MATERIAL CODE -	PROCESS 3D Print	ISSUE DATE 20/03/2019	REV 1	DRAWN BY AS	DRAWING NO. BPS.01.06
DRAFTING STANDARD 8888	MATERIAL PLA		MODULE MM4GDM	SCALE 1:2	SIZE A4	SHEET 1 of 1

DO NOT SCALE





SECTION A-A



SECTION B-B

ITEM	DRAWING NO.	Description	MATERIAL	VENDOR	QTY.
1	BPS.02.01	Vertebrae Link 1	PLA	RP UoN	1
2	BPS.02.02	Vertebrae Link 2	PLA	RP UoN	1
3	BPS.02.03	Vertebrae Link 3	PLA	RP UoN	1
4	BPS.02.04	Vertebrae Link 4	PLA	RP UoN	1
5	BPS.02.05	Vertebrae Link 5	PLA	RP UoN	1
6	BPS.02.06	Vertebrae Link 6	PLA	RP UoN	1
7	BPS.02.07	Vertebrae Link 7	PLA	RP UoN	1
8	BPS.02.08	Vertebrae Link 8	PLA	RP UoN	1
9	BPS.02.09	Vertebrae Link 9	PLA	RP UoN	1
10	BPS.02.10	Vertebrae Link 10	PLA	RP UoN	1
11	BPS.02.11	Vertebrae Link 11	PLA	RP UoN	1
12	BPS.02.12	Vertebrae Link 12	PLA	RP UoN	1
13		M4 x 65 Cap Screw	A4 Stainless Steel	Accu	11
14		M4 Nyloc Nut	A2 Stainless Steel	Accu	11

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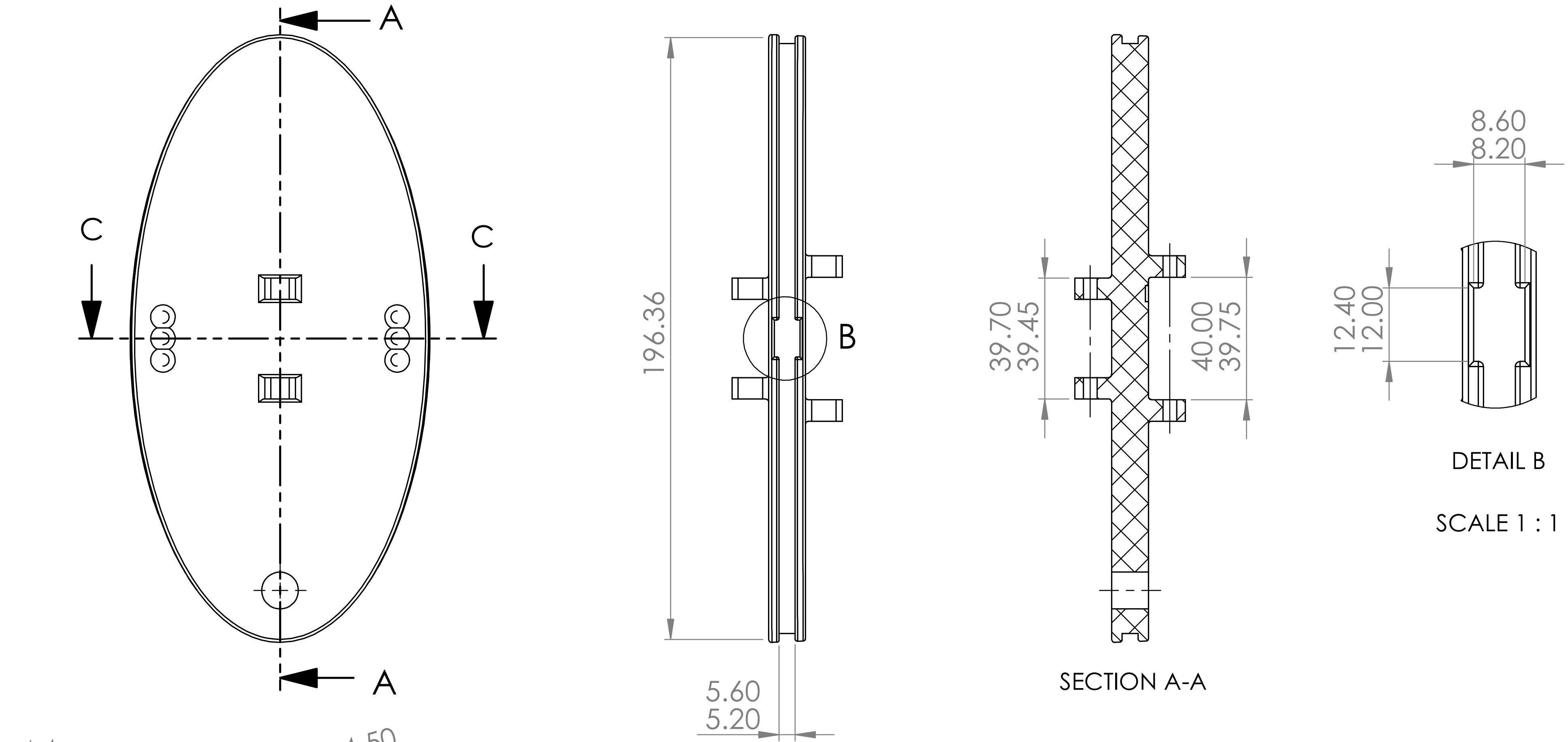
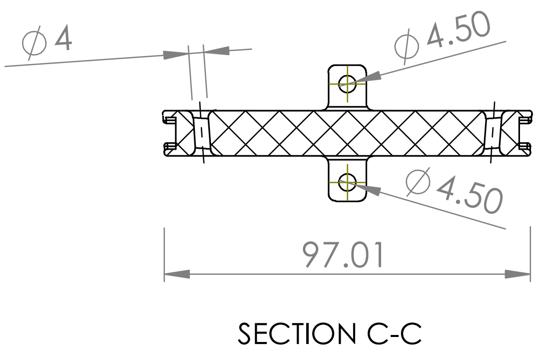
TOLERANCE
LINEAR: ± 0.5
ANGULAR: ± 1°

Vertebrae Assembly

ALL DIMENSIONS ARE IN MILLIMETRES	ISSUE DATE 24/02/19	REVISION 5	DRAWN BY FK	DRAWING NO. BPS.02.00
DRAFTING STANDARD BS 8888	MODULE MM4GDM	SCALE 1:2	SIZE A3	SHEET 1 of 1

DO NOT SCALE





Note: Only where specified are strict tollerances required, elsewhere the accuracy obtained using 3D Printing is accepable

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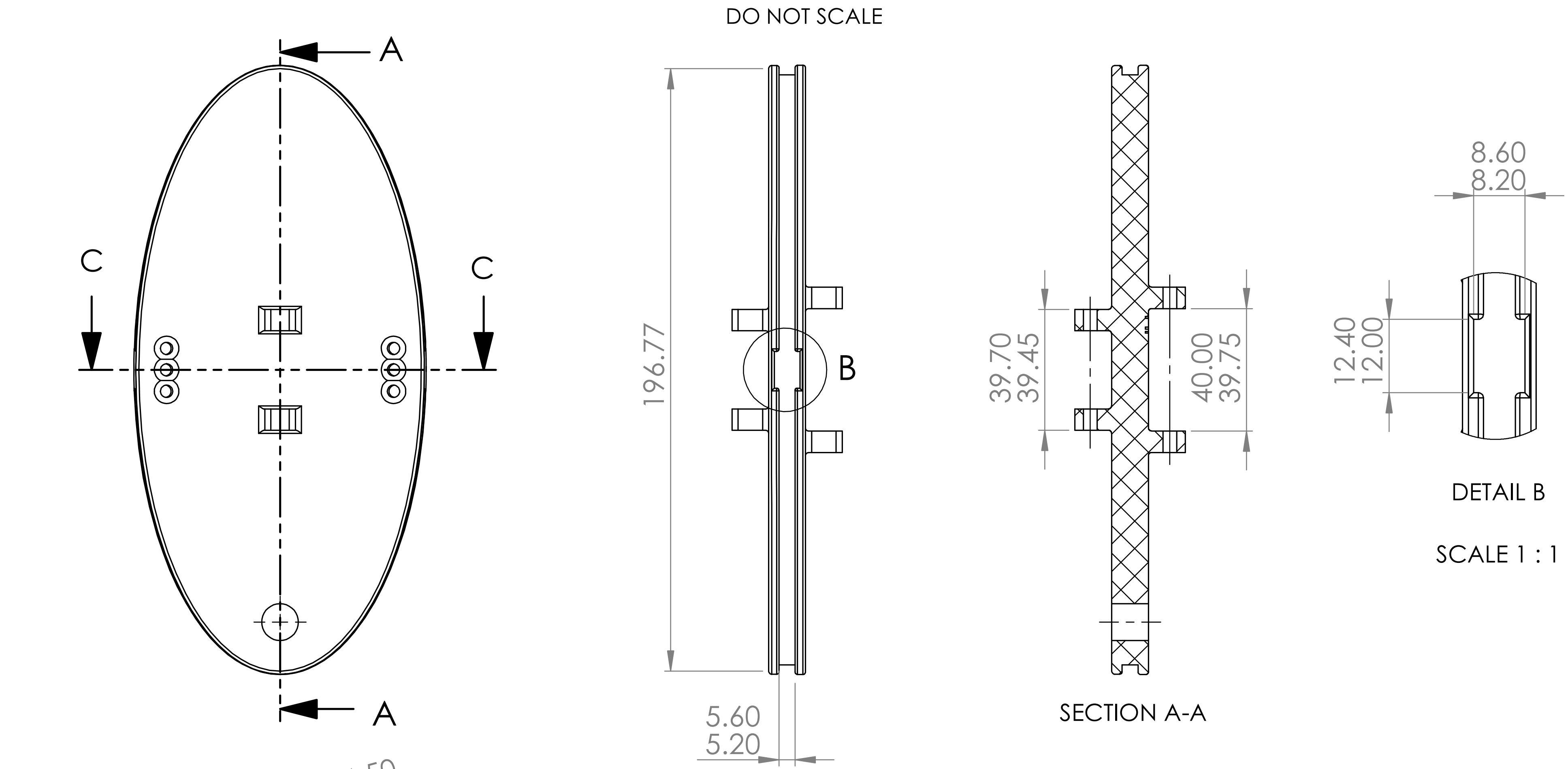
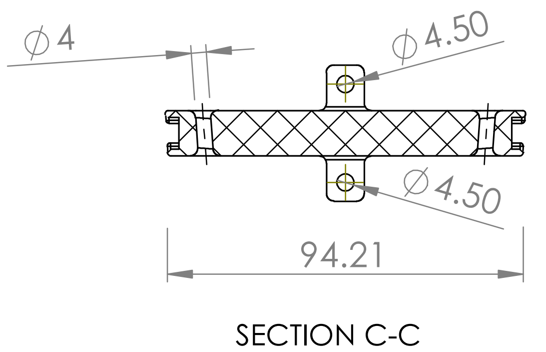
Vertebrae Link 1						
ALL DIMENSIONS IN MILLIMETRES	MATERIAL CODE -	PROCESS 3D Print	ISSUE DATE 28/02/2019	REV 7	DRAWN BY FK	DRAWING NO. BPS.02.01
DRAFTING STANDARD 8888	MATERIAL PLA		MODULE MM4GDM	SCALE 1:2	SIZE A4	SHEET 1 of 1





Note: Only where specified are strict tollerances required, elsewhere the accuracy obtained using 3D Printing is accepable

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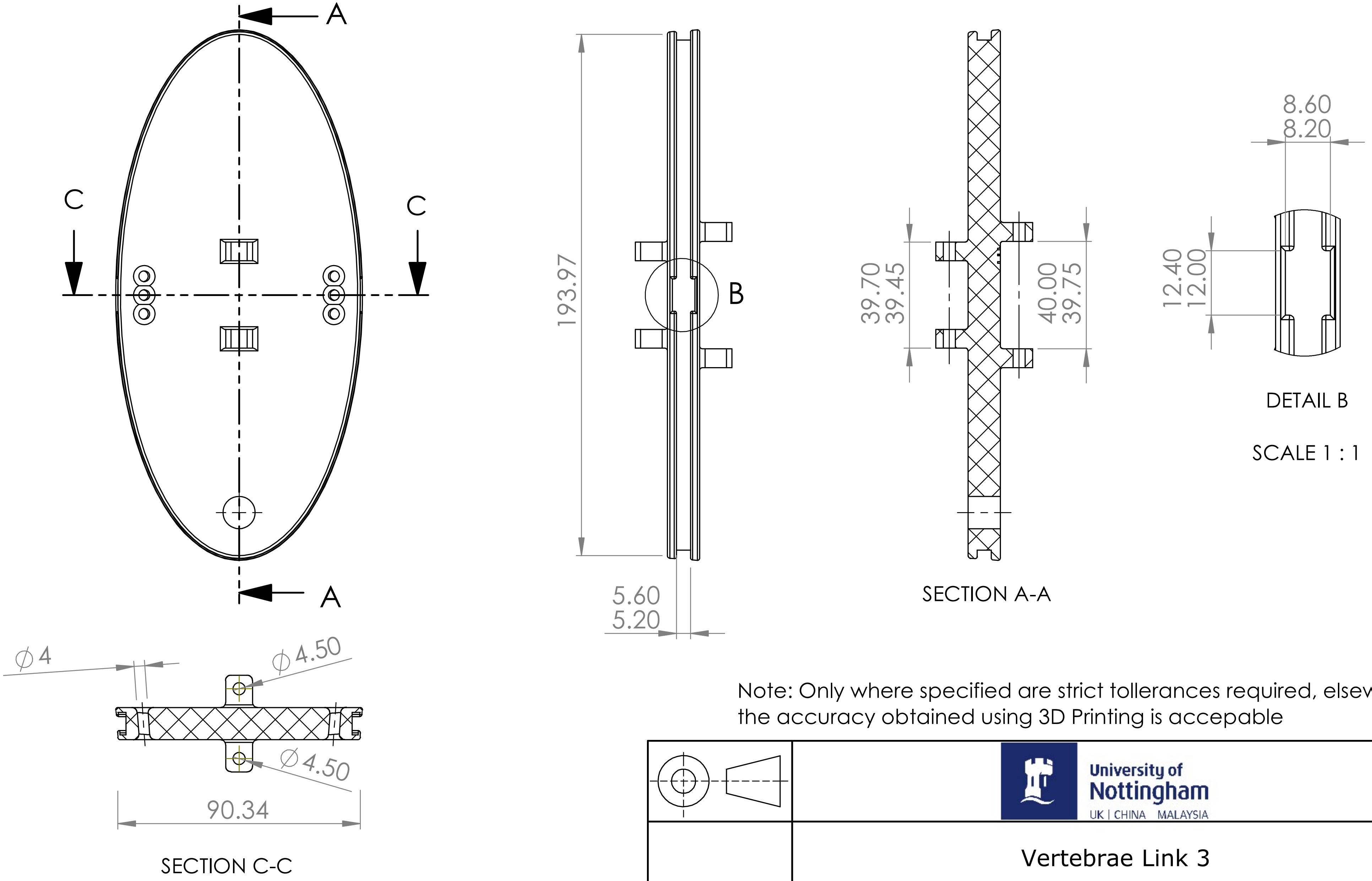
Vertebrae Link 2

ALL DIMENSIONS IN MILLIMETRES	MATERIAL CODE -	PROCESS 3D Print	ISSUE DATE 28/02/2019	REV 7	DRAWN BY FK	DRAWING NO. BPS.02.02
DRAFTING STANDARD 8888	MATERIAL PLA		MODULE MM4GDM	SCALE 1:2	SIZE A4	SHEET 1 of 1

DO NOT SCALE



Note: Only where specified are strict tollerances required, elsewhere the accuracy obtained using 3D Printing is accepable

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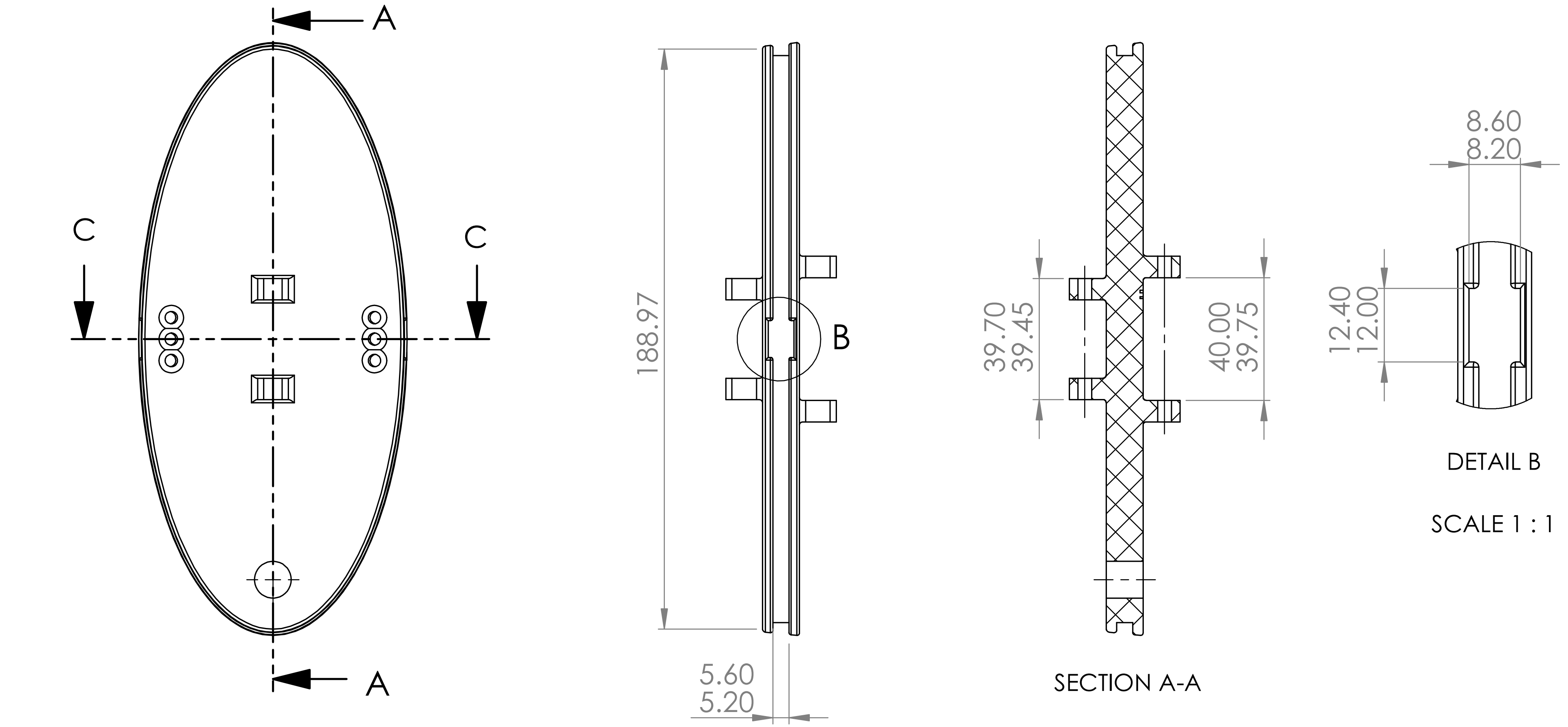
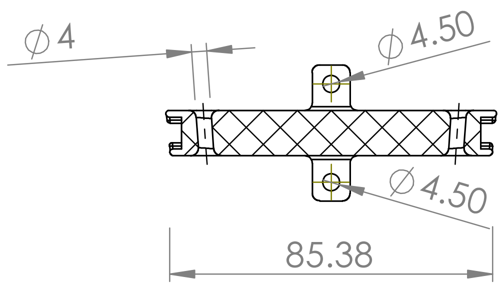
Vertebrae Link 3						
ALL DIMENSIONS IN MILLIMETRES	MATERIAL CODE -	PROCESS 3D Print	ISSUE DATE 28/02/2019	REV 7	DRAWN BY FK	DRAWING NO. BPS.02.03
DRAFTING STANDARD 8888	MATERIAL PLA		MODULE MM4GDM	SCALE 1:2	SIZE A4	SHEET 1 of 1

DO NOT SCALE





SECTION C-C

Note: Only where specified are strict tollerances required, elsewhere the accuracy obtained using 3D Printing is accepable

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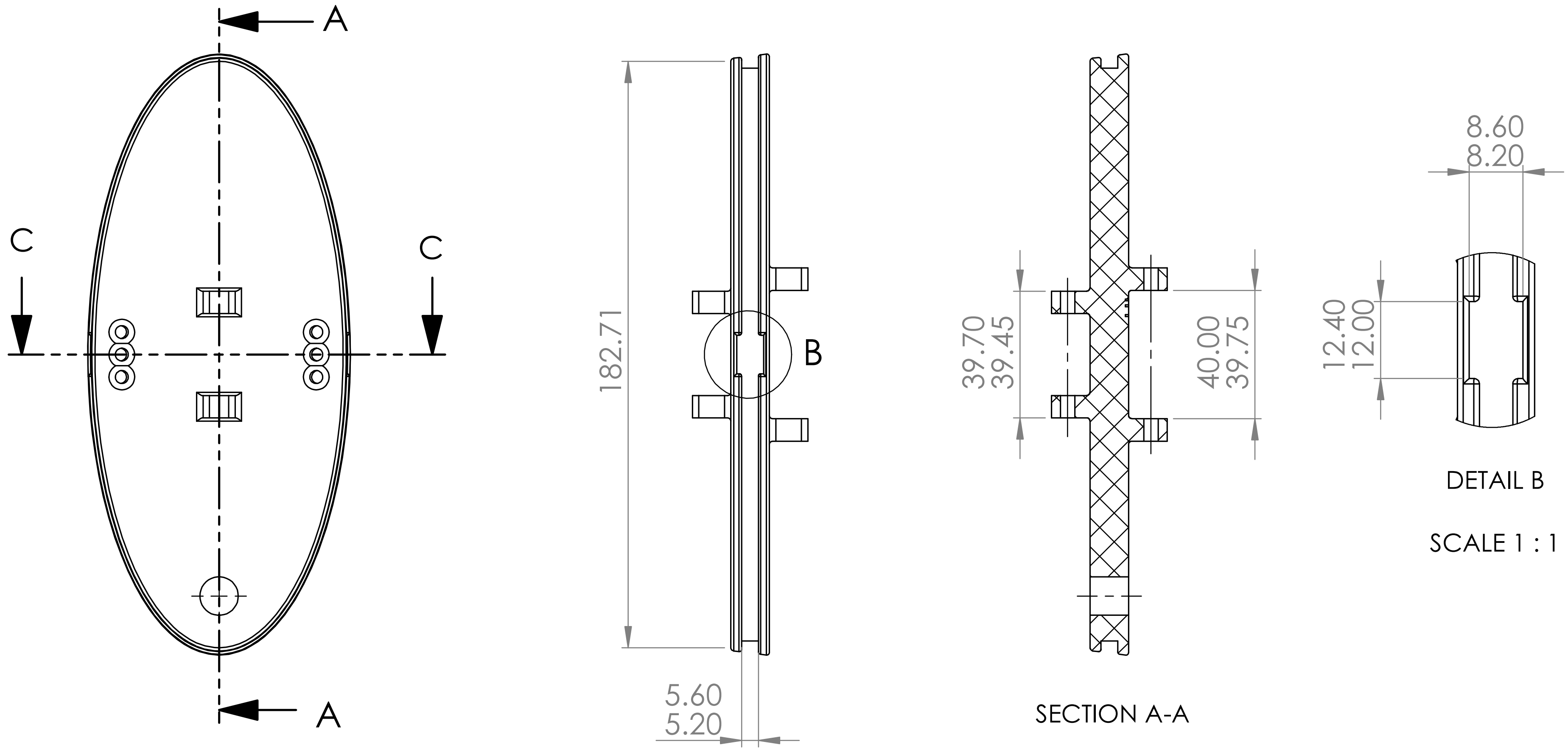
Vertebrae Link 4

ALL DIMENSIONS IN MILLIMETRES	MATERIAL CODE: -	PROCESS: 3D Print	ISSUE DATE: 28/02/2019	REV: 7	DRAWN BY: FK	DRAWING NO.: BPS.02.04
DRAFTING STANDARD: 8888	MATERIAL: PLA		MODULE: MM4GDM	SCALE: 1:2	SIZE: A4	SHEET: 1 of 1

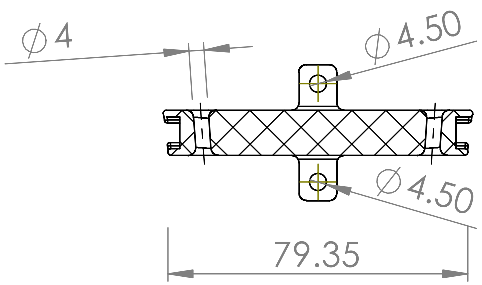
DO NOT SCALE



SECTION A-A

DETAIL B

SCALE 1 : 1



SECTION C-C

Note: Only where specified are strict tollerances required, elsewhere the accuracy obtained using 3D Printing is accepable

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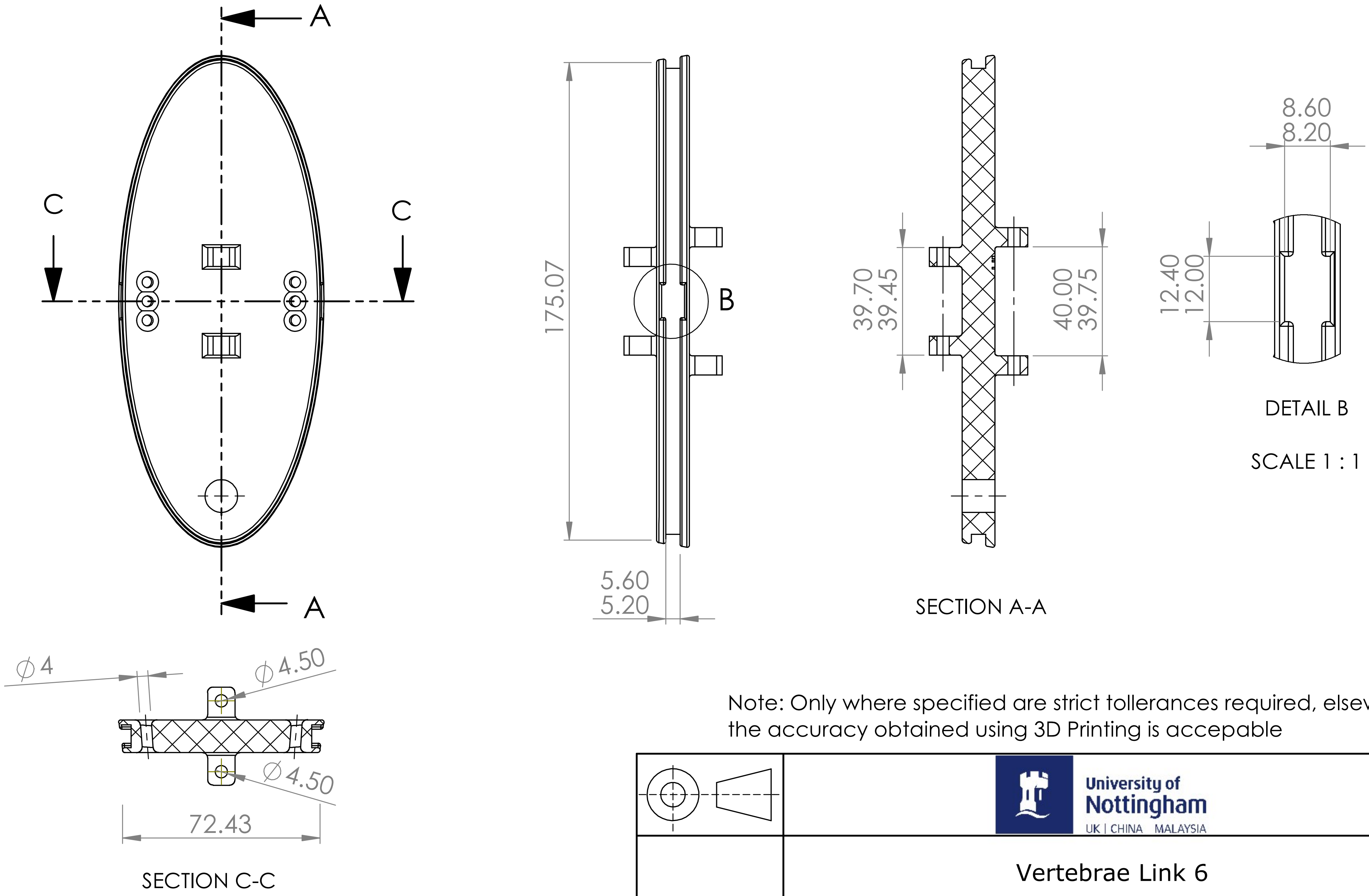
Vertebrae Link 5

ALL DIMENSIONS IN MILLIMETRES	MATERIAL CODE -	PROCESS 3D Print	ISSUE DATE 28/02/2019	REV 7	DRAWN BY FK	DRAWING NO. BPS.02.05
DRAFTING STANDARD 8888	MATERIAL PLA		MODULE MM4GDM	SCALE 1:2	SIZE A4	SHEET 1 of 1

DO NOT SCALE



Note: Only where specified are strict tollerances required, elsewhere the accuracy obtained using 3D Printing is accepable

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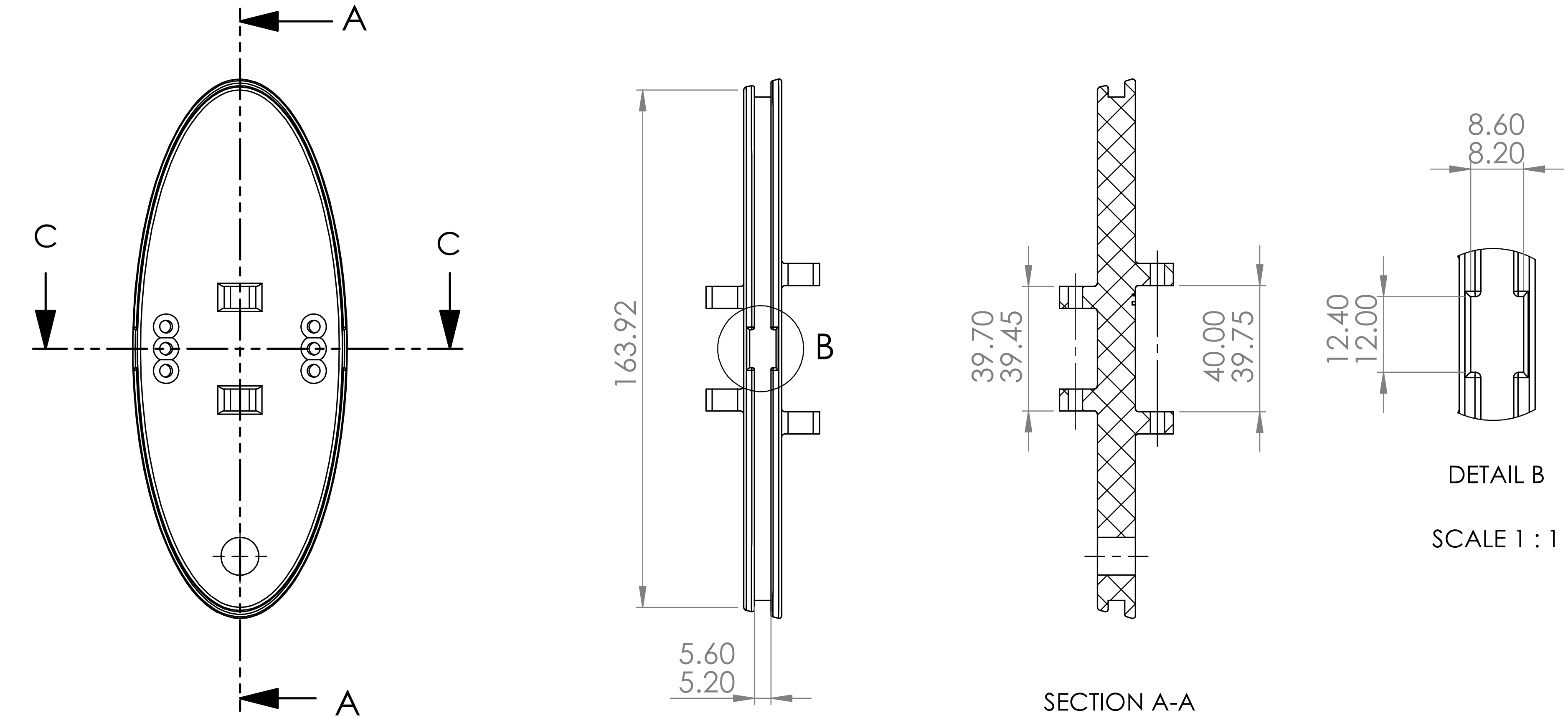
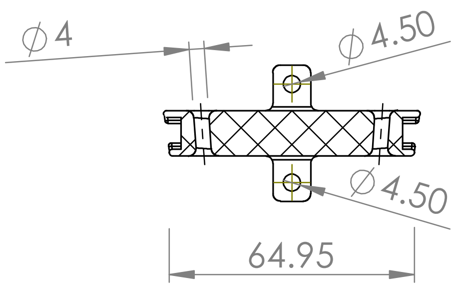
Vertebrae Link 6

ALL DIMENSIONS IN MILLIMETRES	MATERIAL CODE -	PROCESS 3D Print	ISSUE DATE 28/02/2019	REV 7	DRAWN BY FK	DRAWING NO. BPS.02.06
DRAFTING STANDARD 8888	MATERIAL PLA		MODULE MM4GDM	SCALE 1:2	SIZE A4	SHEET 1 of 1

DO NOT SCALE





SECTION C-C

Note: Only where specified are strict tollerances required, elsewhere the accuracy obtained using 3D Printing is accepable

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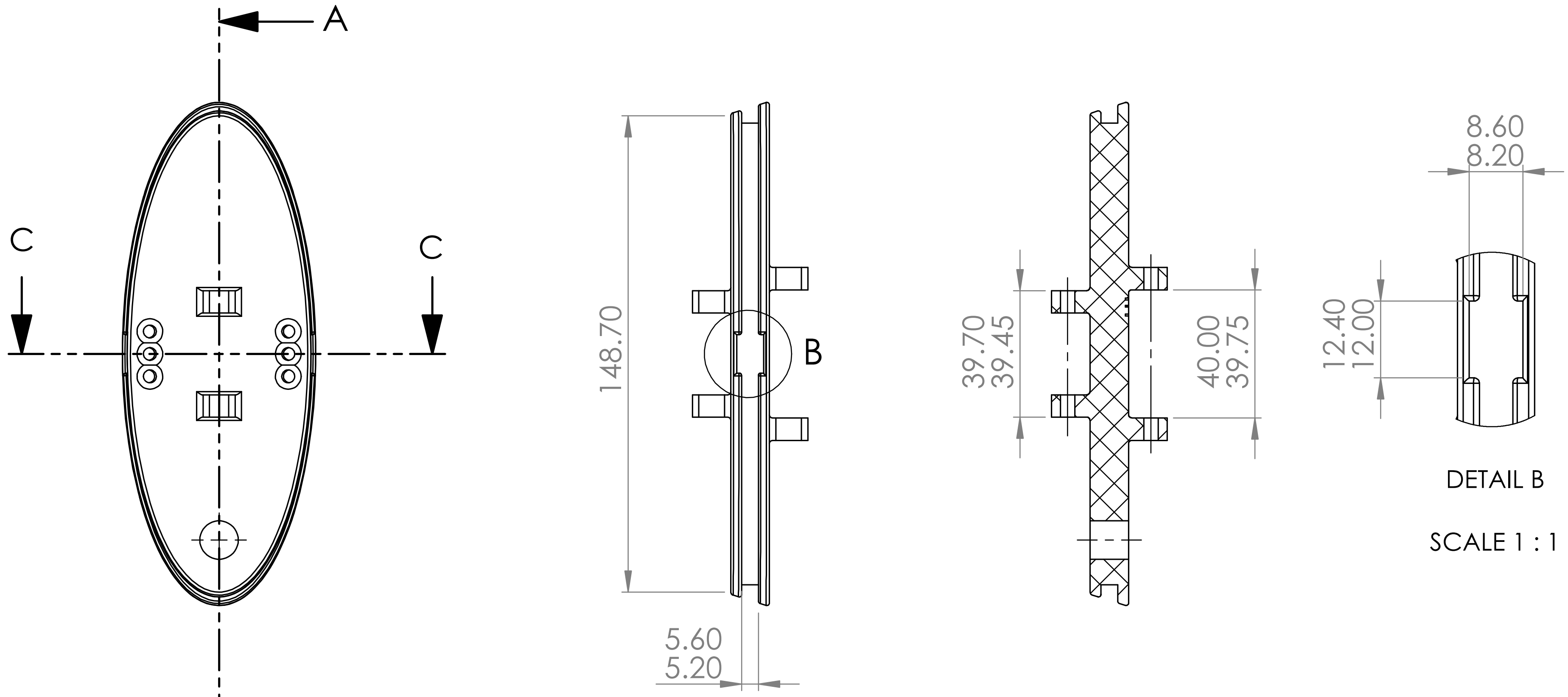
Vertebrae Link 7

ALL DIMENSIONS IN MILLIMETRES	MATERIAL CODE -	PROCESS 3D Print	ISSUE DATE 28/02/2019	REV 7	DRAWN BY FK	DRAWING NO. BPS.02.07
DRAFTING STANDARD 8888	MATERIAL PLA		MODULE MM4GDM	SCALE 1:2	SIZE A4	SHEET 1 of 1

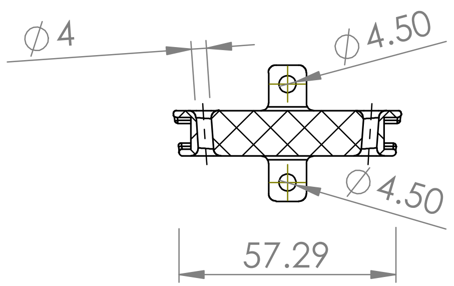
DO NOT SCALE



SECTION A-A

DETAIL B

SCALE 1 : 1



SECTION C-C

Note: Only where specified are strict tollerances required, elsewhere the accuracy obtained using 3D Printing is accepable

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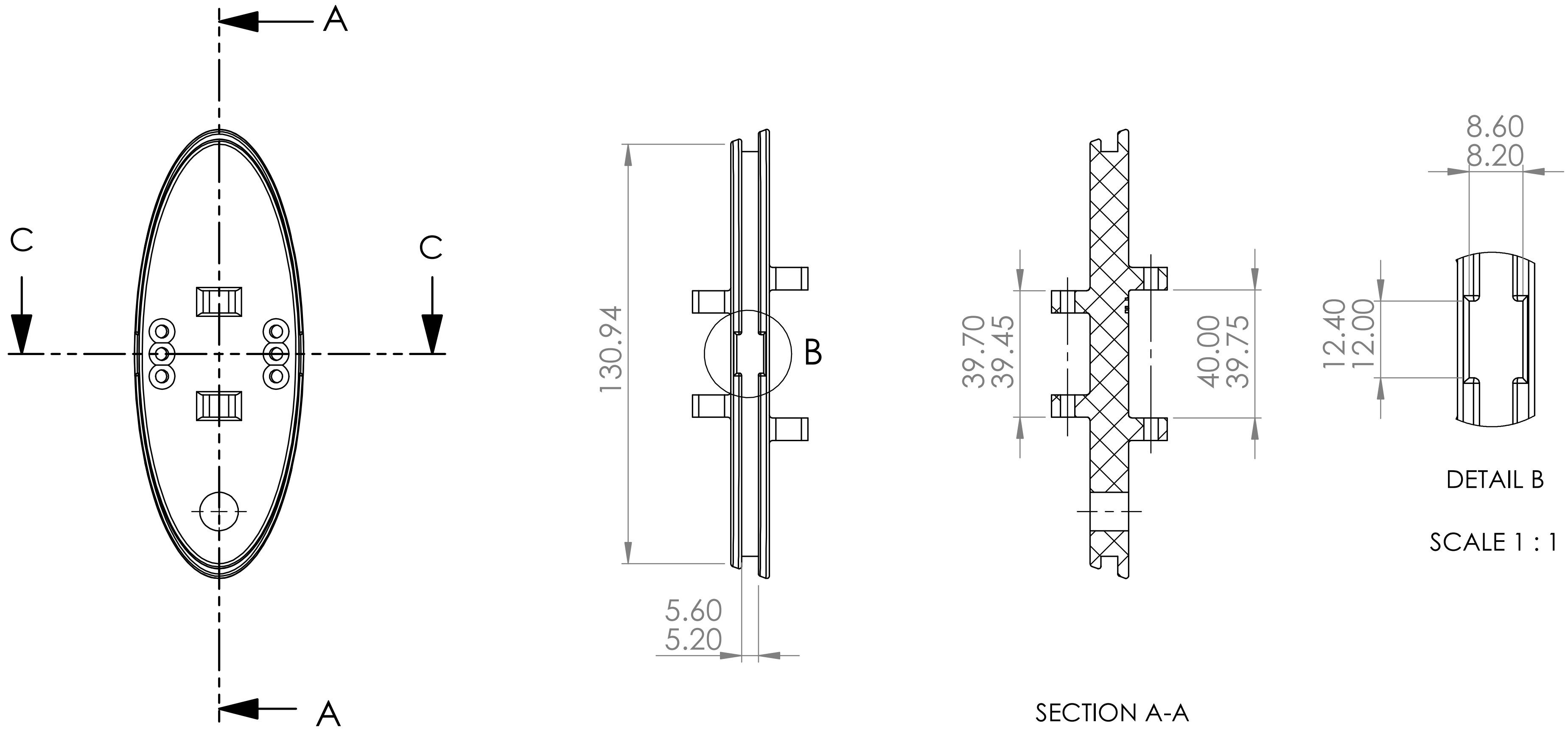
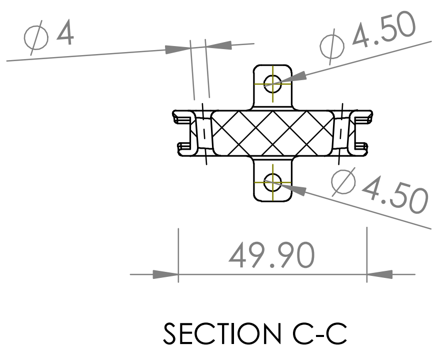
Vertebrae Link 8

ALL DIMENSIONS IN MILLIMETRES	MATERIAL CODE: -	PROCESS: 3D Print	ISSUE DATE: 28/02/2019	REV: 7	DRAWN BY: FK	DRAWING NO.: BPS.02.08
DRAFTING STANDARD: 8888	MATERIAL: PLA		MODULE: MM4GDM	SCALE: 1:2	SIZE: A4	SHEET: 1 of 1

DO NOT SCALE





Note: Only where specified are strict tollerances required, elsewhere the accuracy obtained using 3D Printing is accepable

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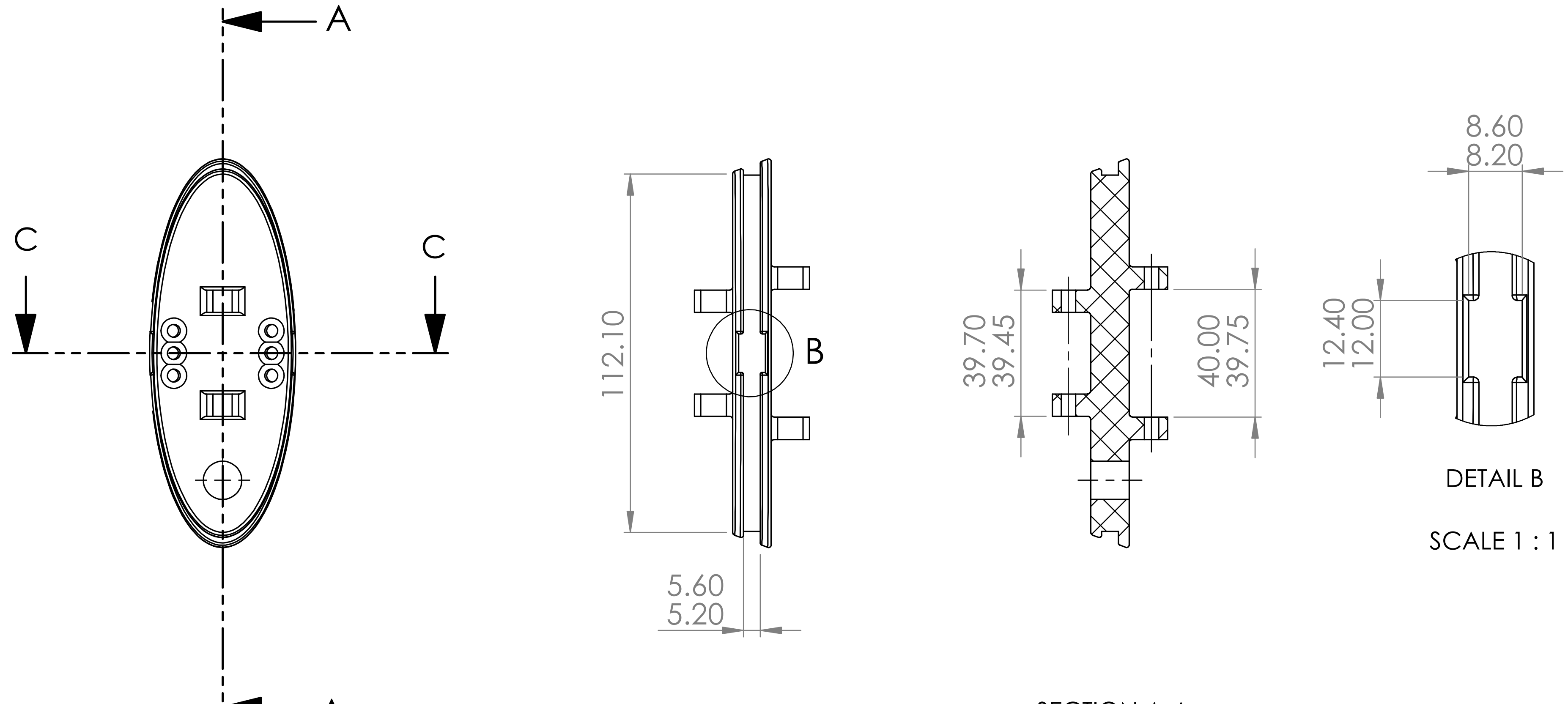
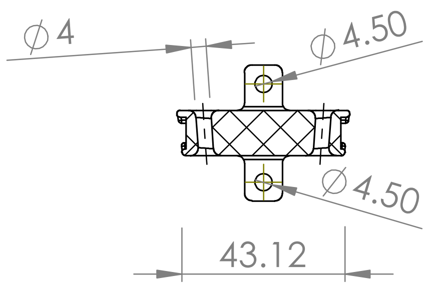
Vertebrae Link 9

ALL DIMENSIONS IN MILLIMETRES	MATERIAL CODE	PROCESS	ISSUE DATE	REV	DRAWN BY	DRAWING NO.
	-	3D Print	28/02/2019	7	FK	BPS.02.09
DRAFTING STANDARD	MATERIAL		MODULE	SCALE	SIZE	SHEET
8888	PLA		MM4GDM	1:2	A4	1 of 1

DO NOT SCALE



SECTION A-A



SECTION C-C

Note: Only where specified are strict tollerances required, elsewhere the accuracy obtained using 3D Printing is accepable

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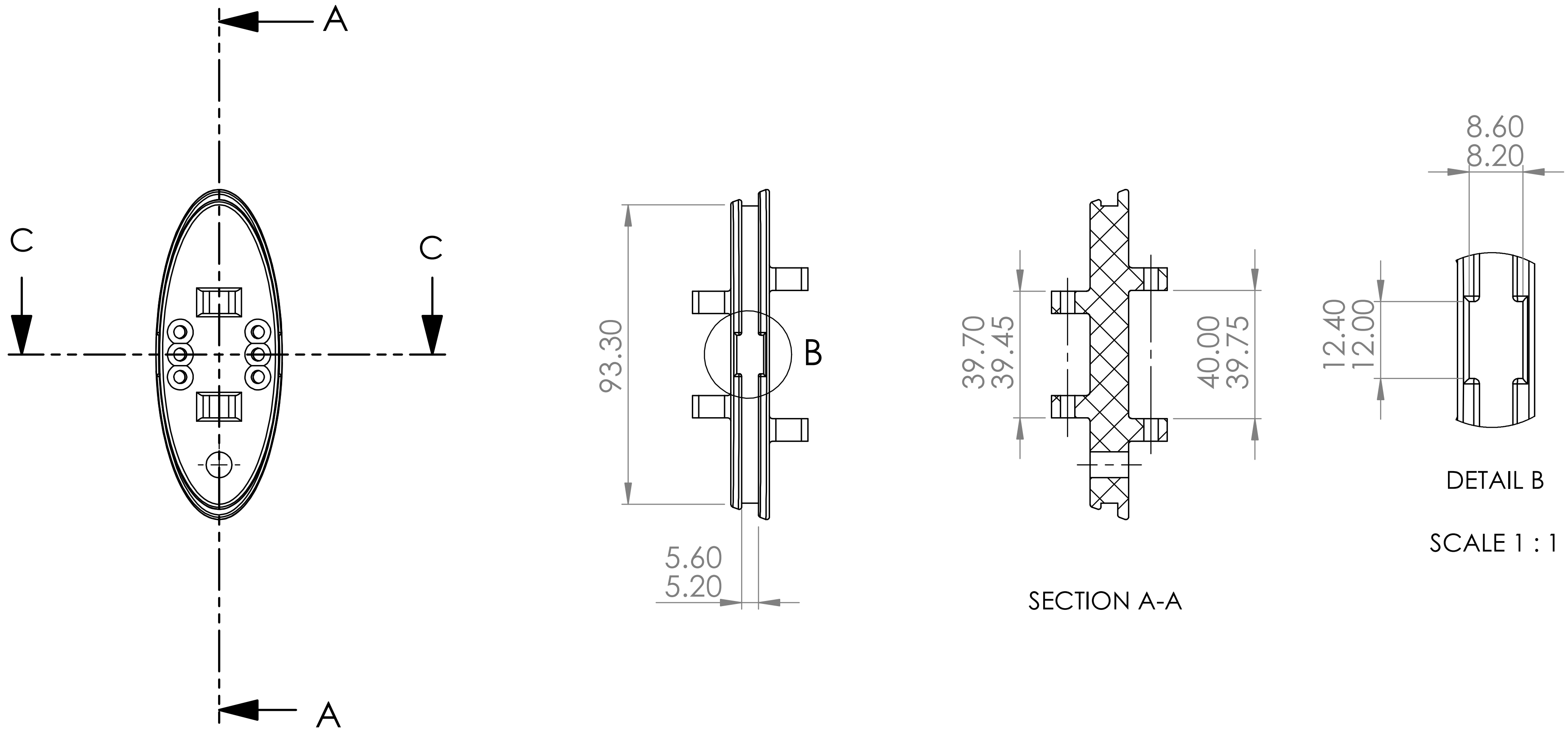
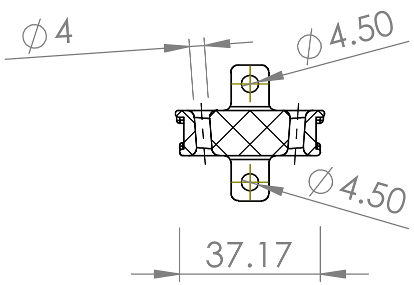
	Vertebrae Link 10					
ALL DIMENSIONS IN MILLIMETRES	MATERIAL CODE -	PROCESS 3D Print	ISSUE DATE 28/02/2019	REV 7	DRAWN BY FK	DRAWING NO. BPS.02.10
DRAFTING STANDARD 8888	MATERIAL PLA		MODULE MM4GDM	SCALE 1:2	SIZE A4	SHEET 1 of 1

DO NOT SCALE





SECTION C-C

Note: Only where specified are strict tollerances required, elsewhere the accuracy obtained using 3D Printing is accepable

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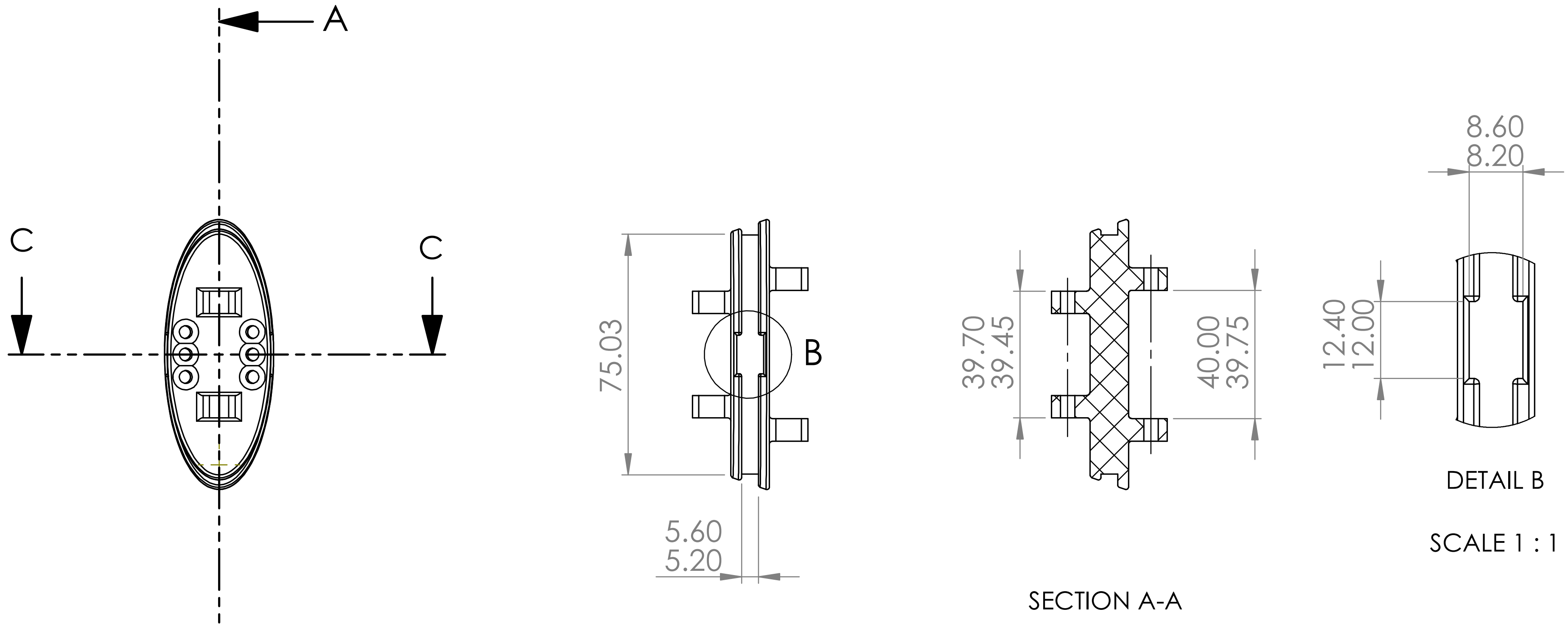
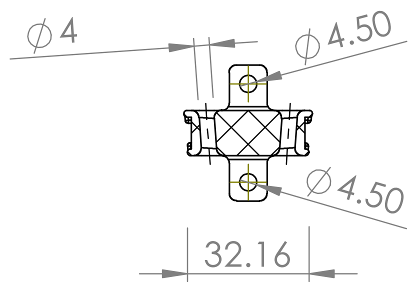
Vertebrae Link 11

ALL DIMENSIONS IN MILLIMETRES	MATERIAL CODE -	PROCESS 3D Print	ISSUE DATE 28/02/2019	REV 7	DRAWN BY FK	DRAWING NO. BPS.02.11
DRAFTING STANDARD 8888	MATERIAL PLA		MODULE MM4GDM	SCALE 1:2	SIZE A4	SHEET 1 of 1

DO NOT SCALE





SECTION C-C

Note: Only where specified are strict tollerances required, elsewhere the accuracy obtained using 3D Printing is accepable

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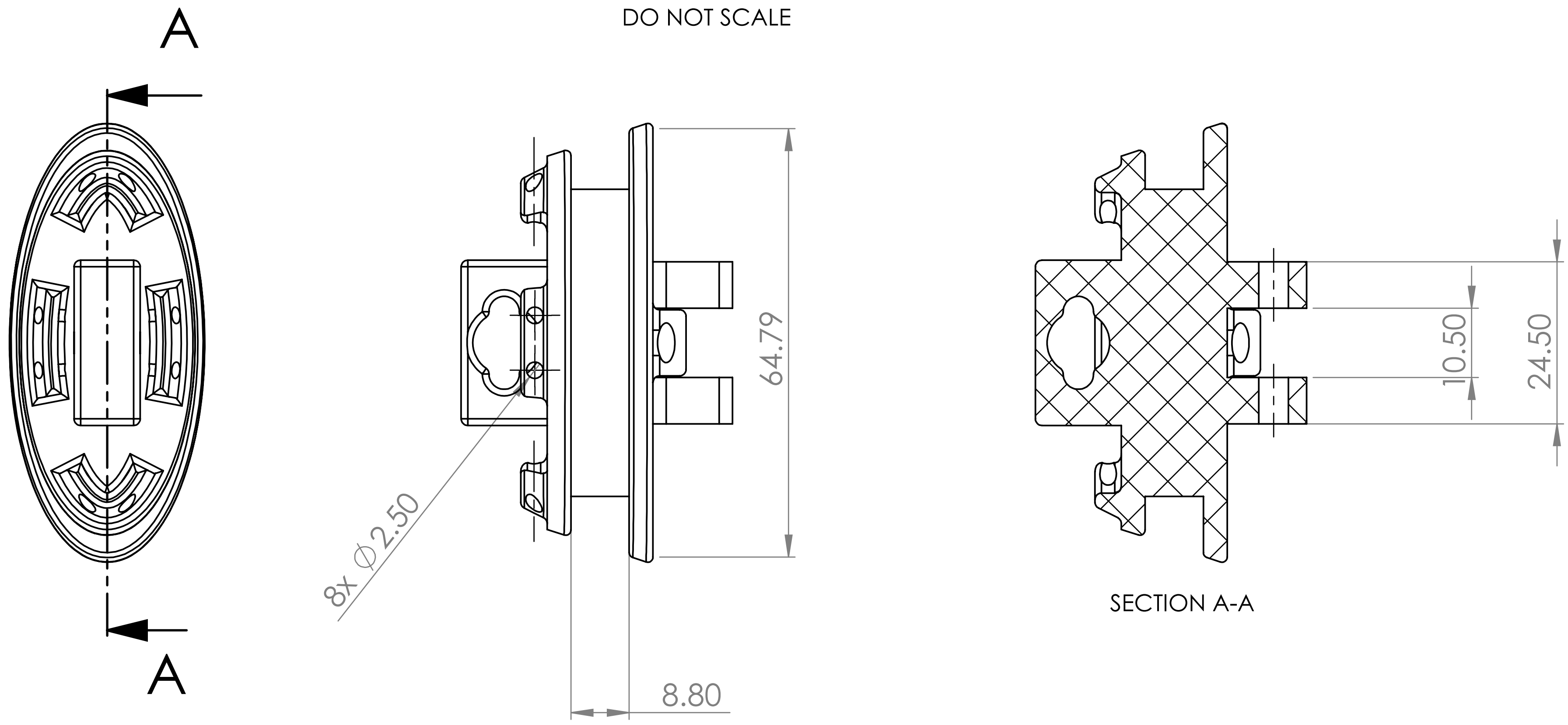
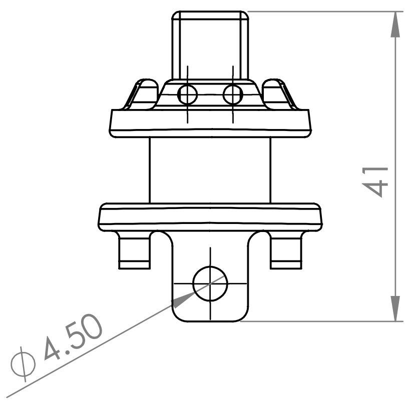
	Vertebrae Link 12					
ALL DIMENSIONS IN MILLIMETRES	MATERIAL CODE -	PROCESS 3D Print	ISSUE DATE 28/02/2019	REV 7	DRAWN BY FK	DRAWING NO. BPS.02.12
DRAFTING STANDARD 8888	MATERIAL PLA		MODULE MM4GDM	SCALE 1:2	SIZE A4	SHEET 1 of 1

DO NOT SCALE





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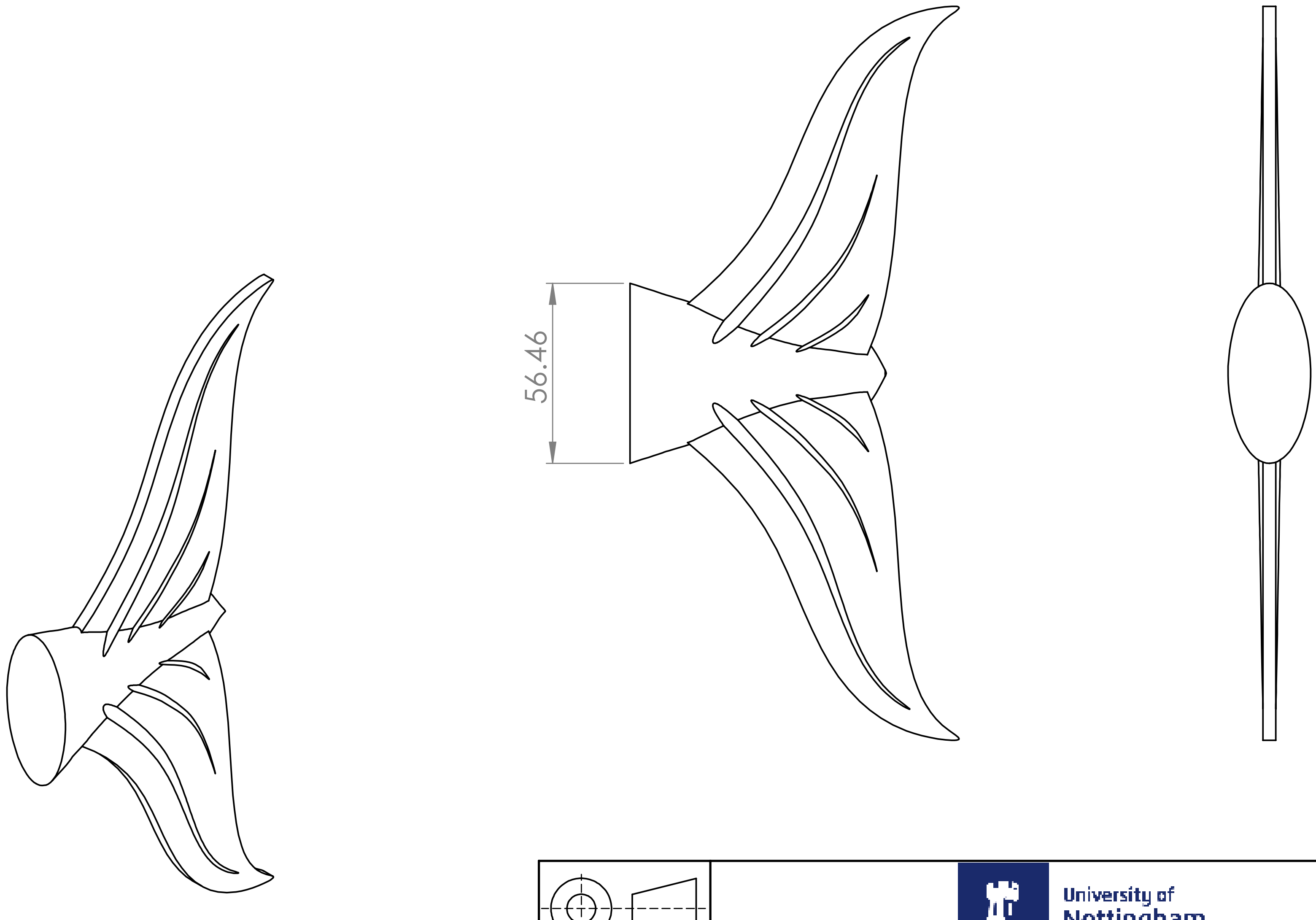
TOLERANCE LINEAR: ±0.5 ANGULAR: ±1	Tail Link					
ALL DIMENSIONS IN MILLIMETRES	MATERIAL CODE -	PROCESS 3D Print	ISSUE DATE 28/02/2019	REV 4	DRAWN BY AS	DRAWING NO. BPS.03.01
DRAFTING STANDARD 8888	MATERIAL PLA		MODULE MM4GDM	SCALE 1:1	SIZE A4	SHEET 1 of 1

DO NOT SCALE



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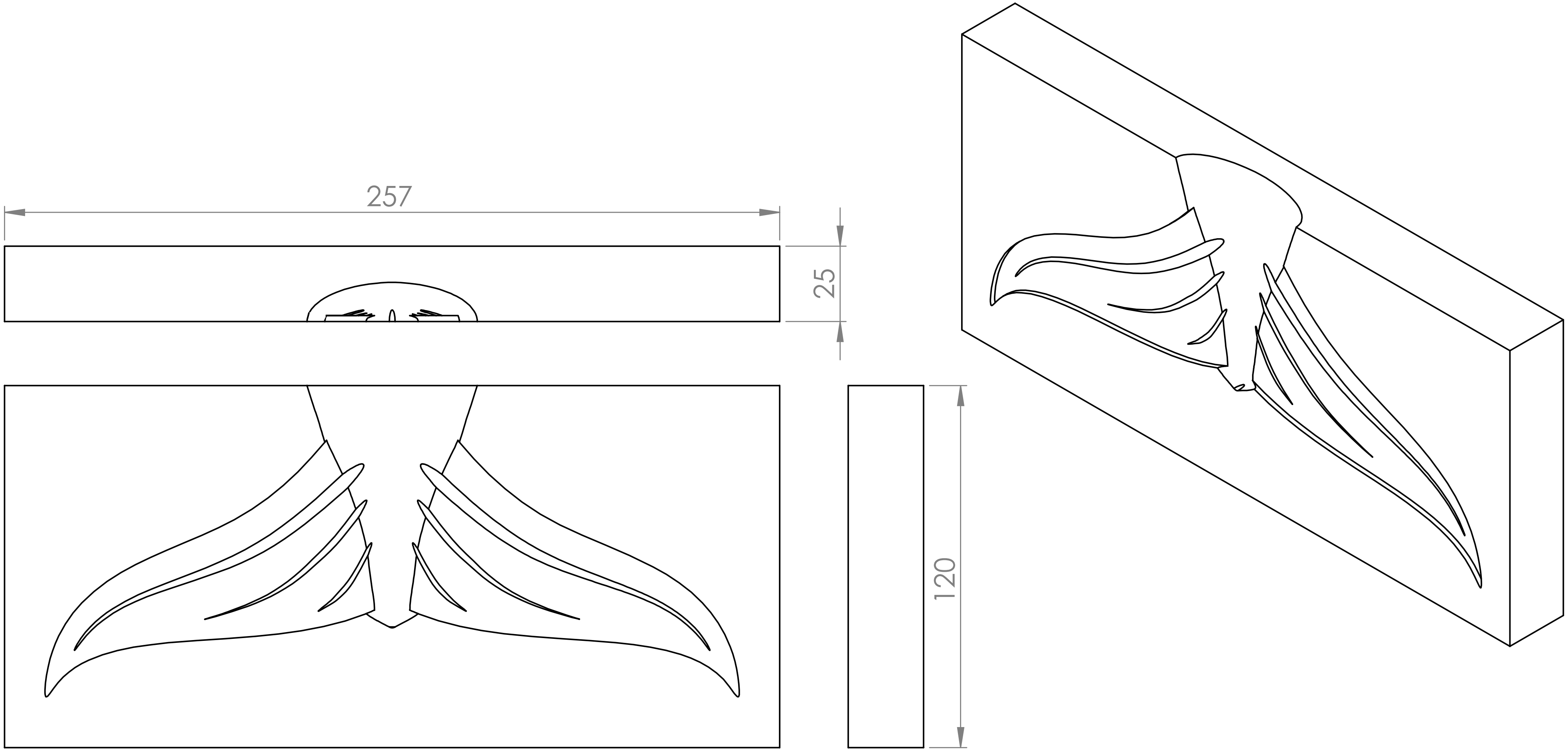
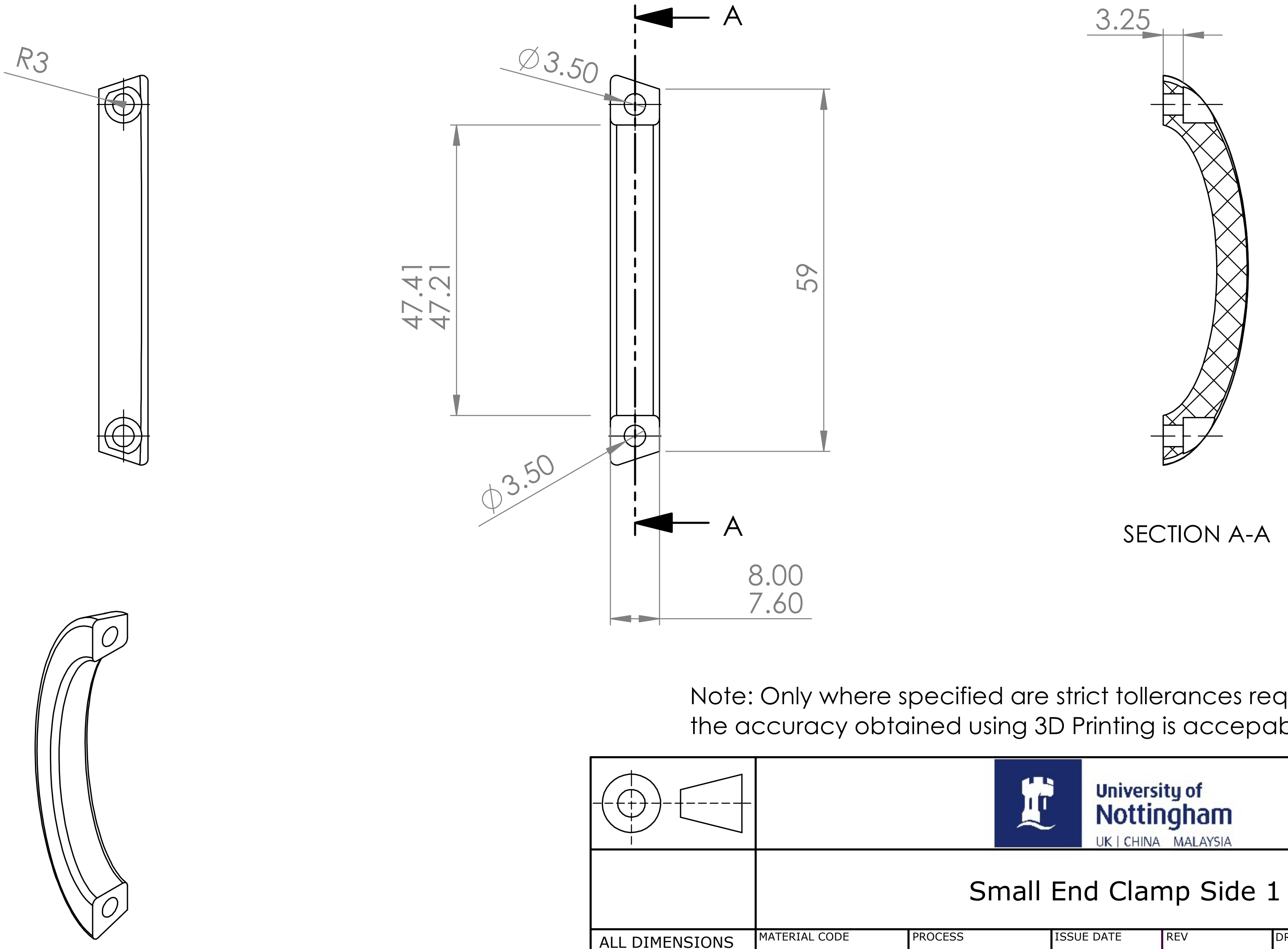
TOLERANCE LINEAR: ±0.5 ANGULAR: ±1	Tail						
ALL DIMENSIONS IN MILLIMETRES	MATERIAL CODE -	PROCESS Cast	ISSUE DATE 28/02/2019	REV 1	DRAWN BY JZ	DRAWING NO. BPS.03.02	
DRAFTING STANDARD 8888	MATERIAL POLYURETHANE (11671)		MODULE MM4GDM	SCALE 1:2	SIZE A4	SHEET 1 of 1	

DO NOT SCALE



TOLERANCE LINEAR: ±0.5 ANGULAR: ±1	Tail Mould					
ALL DIMENSIONS IN MILLIMETRES	MATERIAL CODE -	PROCESS CNC	ISSUE DATE 28/02/2019	REV 1	DRAWN BY JZ	DRAWING NO. BPS.03.03
DRAFTING STANDARD 8888	MATERIAL 6063-T83		MODULE MM4GDM	SCALE 1:2	SIZE A4	SHEET 1 of 1

DO NOT SCALE



Note: Only where specified are strict tollerances required, elsewhere the accuracy obtained using 3D Printing is accepable

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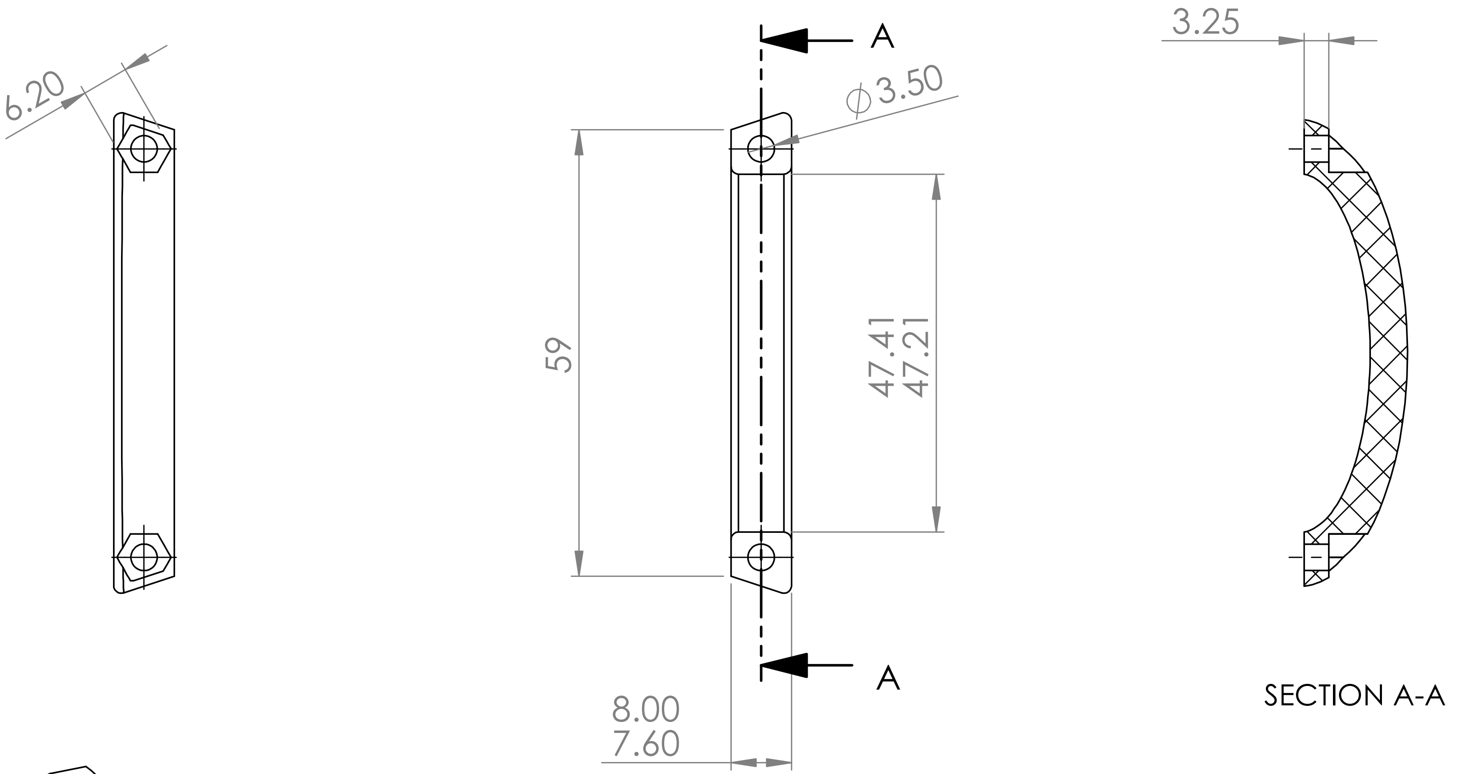
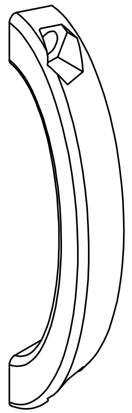
Small End Clamp Side 1

ALL DIMENSIONS IN MILLIMETRES	MATERIAL CODE -	PROCESS 3D Print	ISSUE DATE 28/02/2019	REV 1	DRAWN BY FK	DRAWING NO. BPS.00.01
DRAFTING STANDARD 8888	MATERIAL PLA		MODULE MM4GDM	SCALE 1:1	SIZE A4	SHEET 1 of 1

DO NOT SCALE





Note: Only where specified are strict tollerances required, elsewhere the accuracy obtained using 3D Printing is accepable

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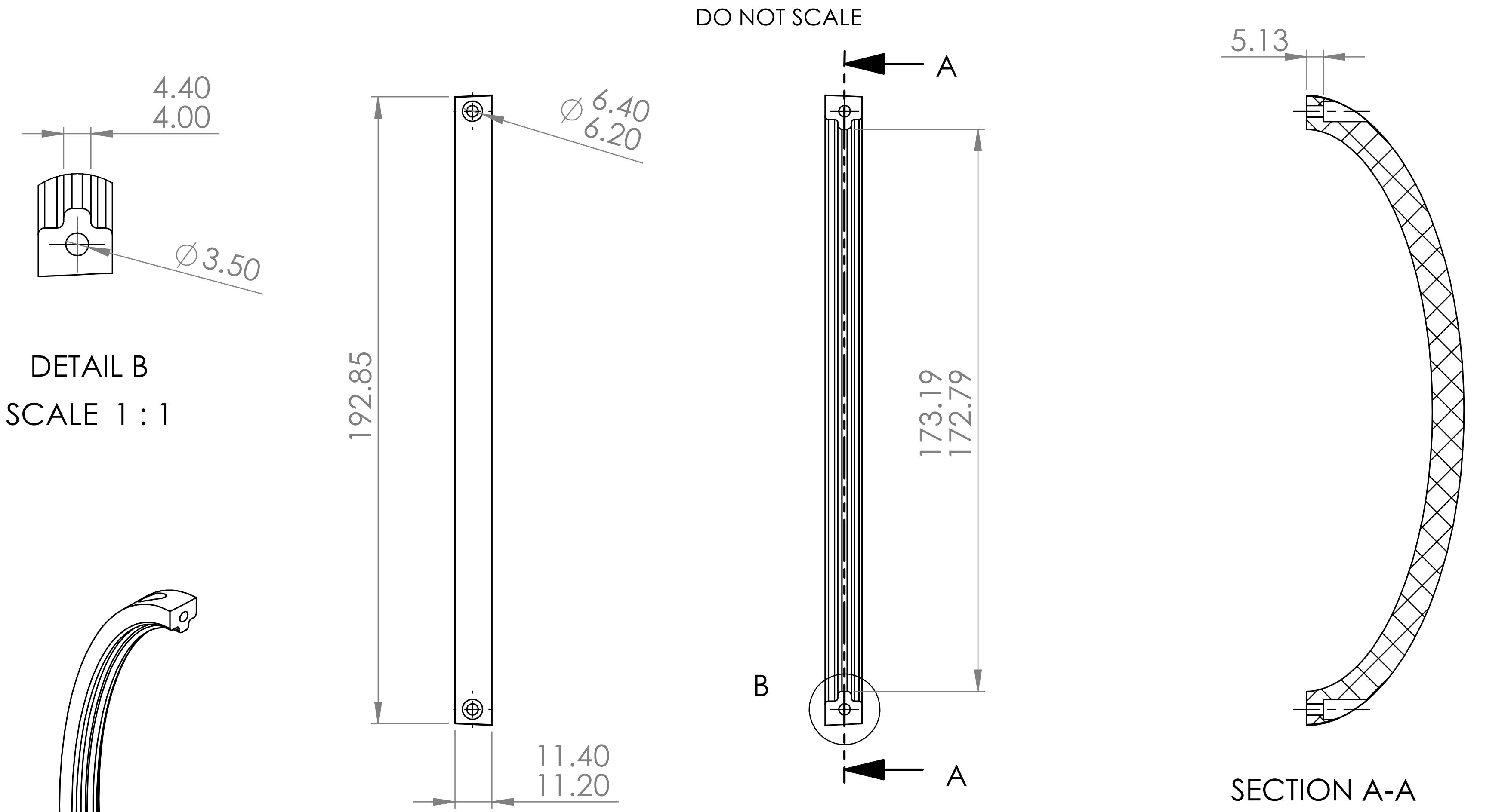
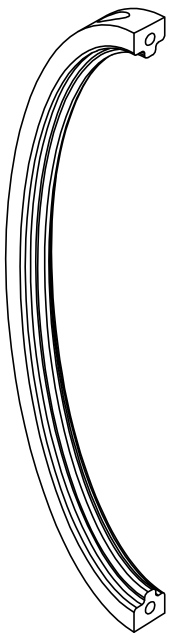
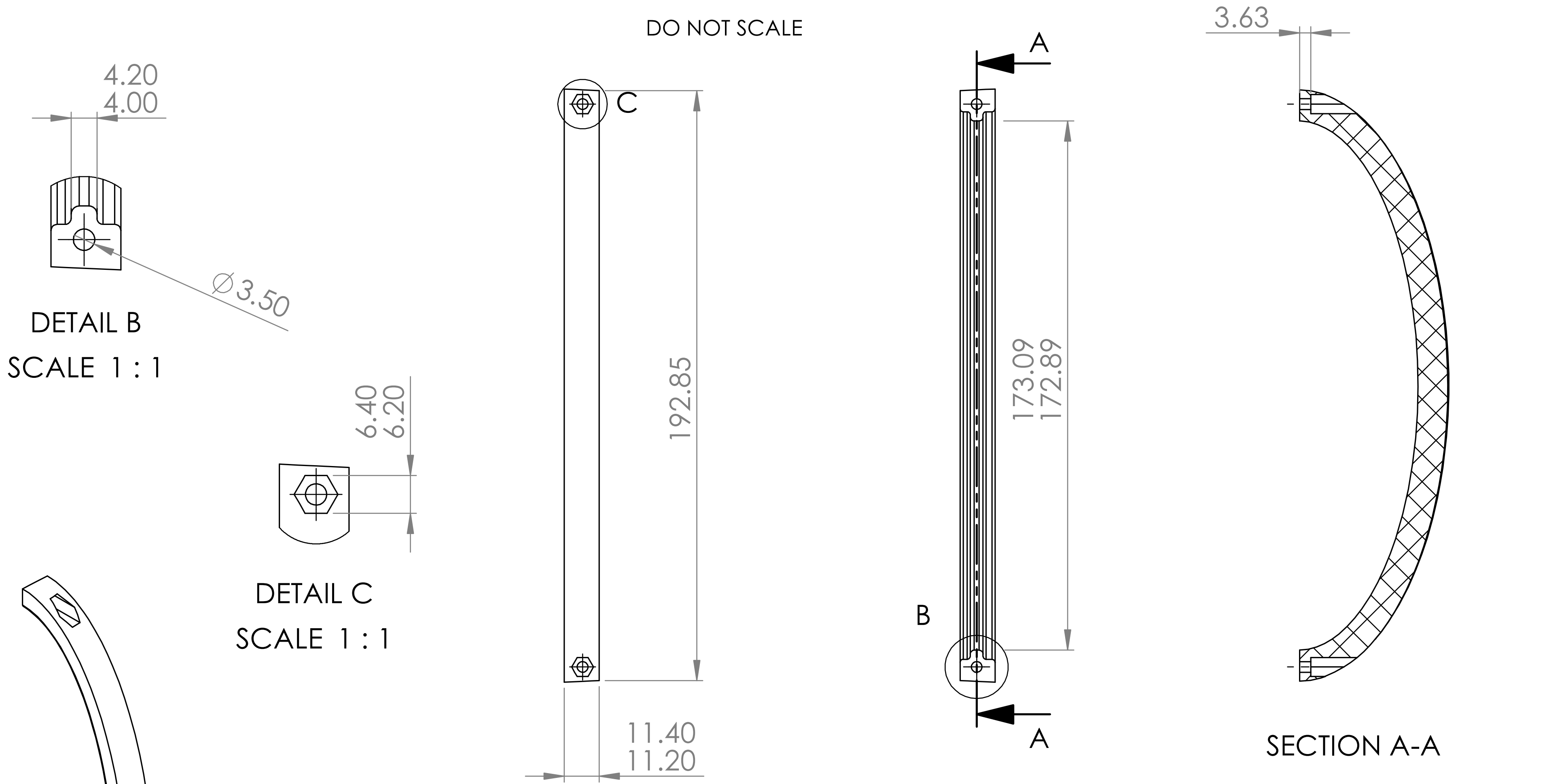
TOLERANCE LINEAR: ±0.5 ANGULAR: ±1	Small End Clamp Side 2					
ALL DIMENSIONS IN MILLIMETRES	MATERIAL CODE -	PROCESS 3D Print	ISSUE DATE 28/02/2019	REV 2	DRAWN BY FK	DRAWING NO. BPS.00.02
DRAFTING STANDARD 8888	MATERIAL PLA		MODULE MM4GDM	SCALE 1:1	SIZE A4	SHEET 1 of 1

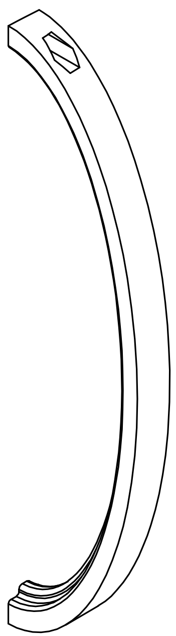




Note: Only where specified are strict tollerances required, elsewhere the accuracy obtained using 3D Printing is acceptable

	University of Nottingham UK | CHINA MALAYSIA					
	Large Skin Clamp Side 1					
ALL DIMENSIONS IN MILLIMETRES	MATERIAL CODE -	PROCESS 3D Print	ISSUE DATE 28/02/2019	REV 3	DRAWN BY FK	DRAWING NO. BSP.00.03
DRAFTING STANDARD 8888	MATERIAL PLA		MODULE MM4GDM	SCALE 1:2	SIZE A4	SHEET 1 of 1





Note: Only where specified are strict tollerances required, elsewhere the accuracy obtained using 3D Printing is acceptable

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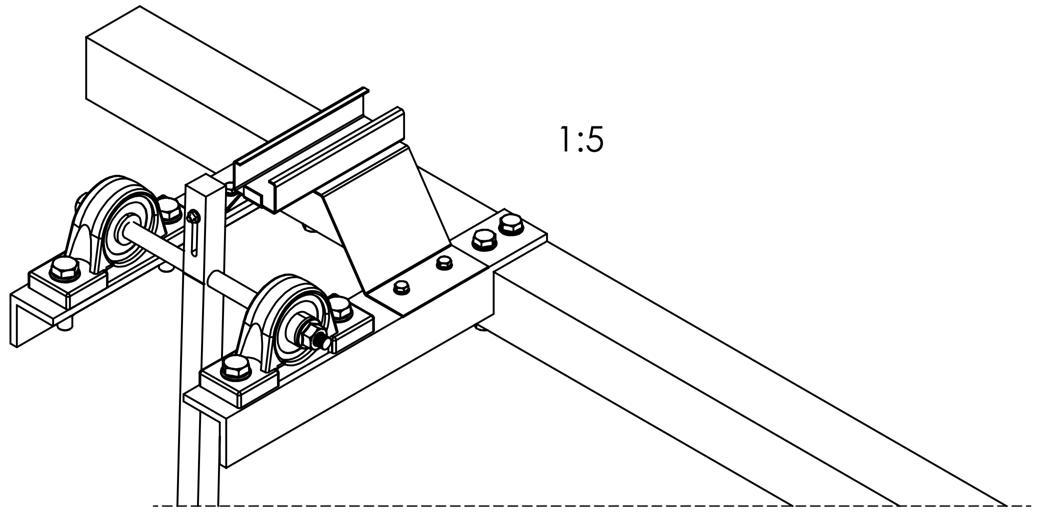
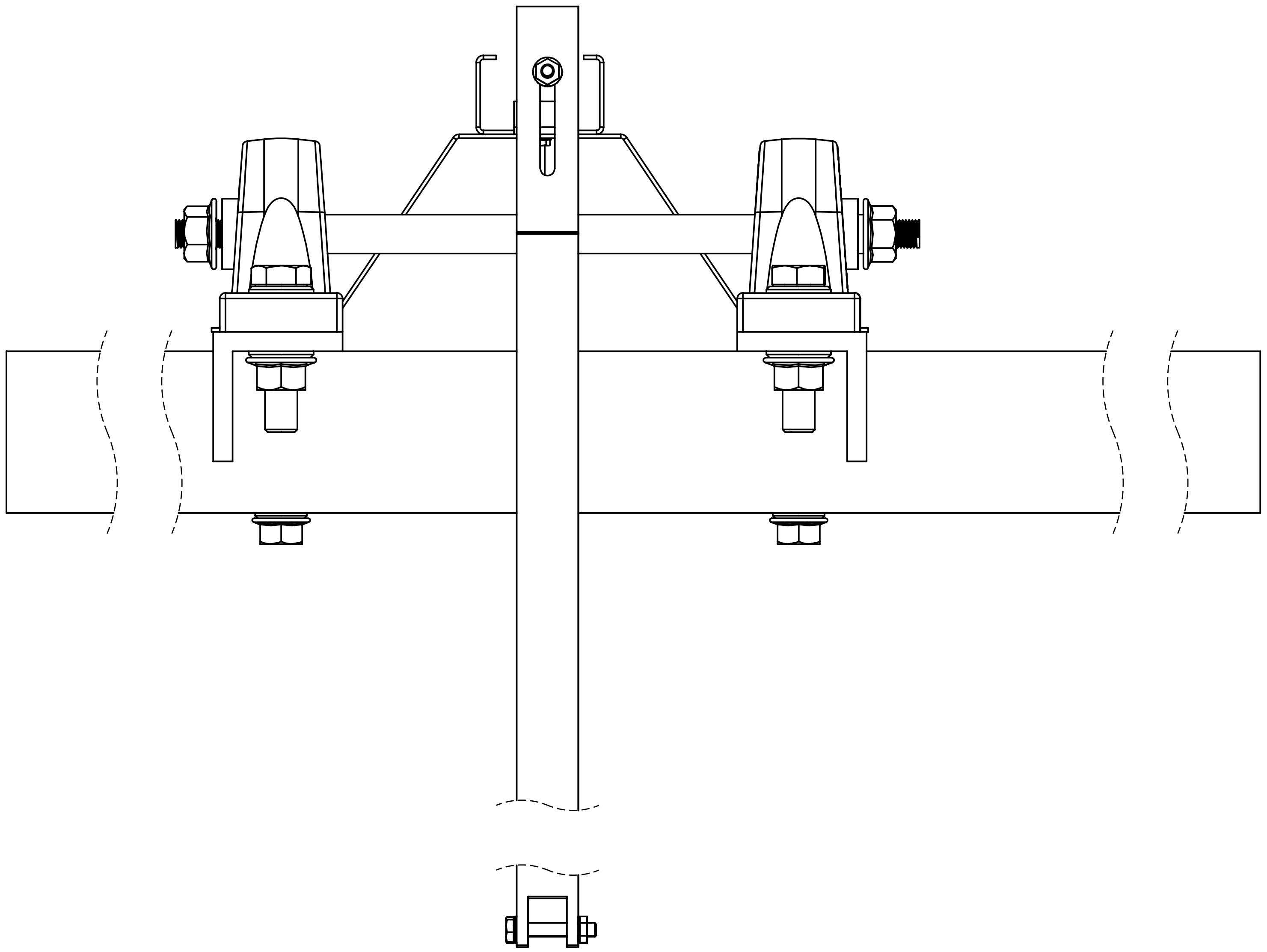
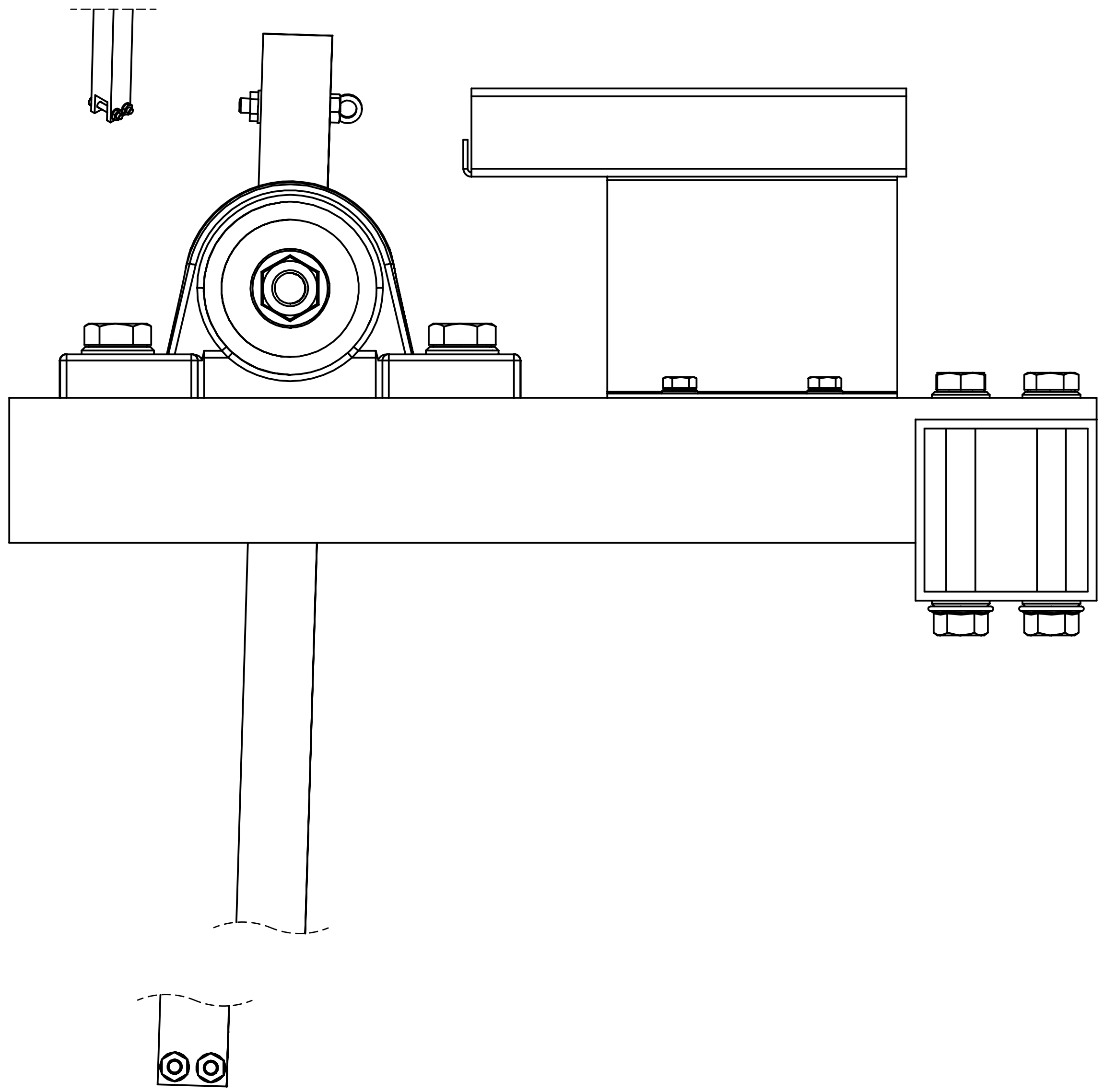
Large Clamp Side 2

ALL DIMENSIONS IN MILLIMETRES	MATERIAL CODE	PROCESS	ISSUE DATE	REV	DRAWN BY	DRAWING NO.
	-	3D Print	28/02/2019	3	FK	BPS.00.04
DRAFTING STANDARD	MATERIAL		MODULE	SCALE	SIZE	SHEET
8888	PLA		MM4GDM	1:2	A4	1 of 1

DO NOT SCALE







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TOLERANCE
LINEAR: 0.5
ANGULAR: 1

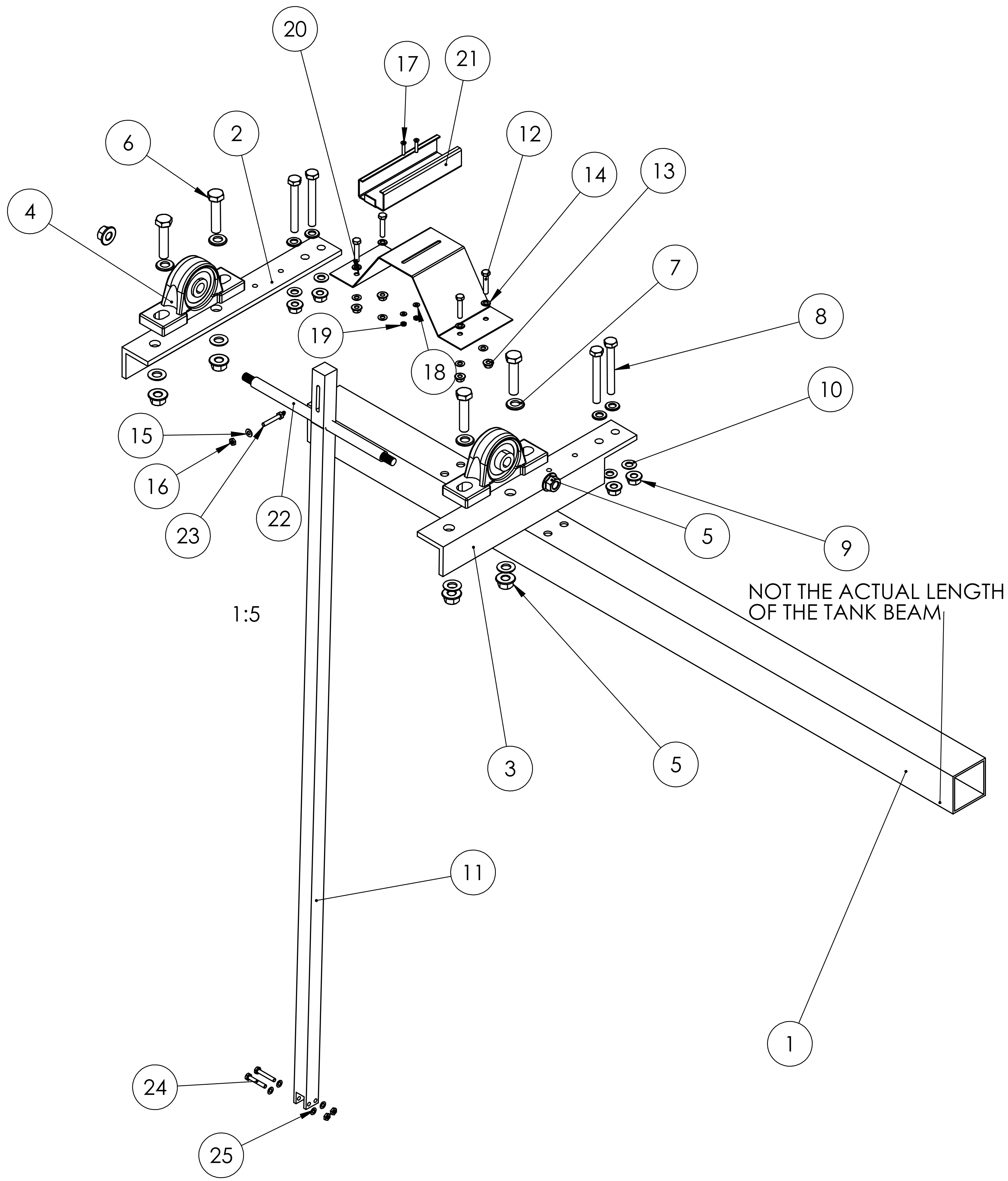
Test Rig General Assembly

ALL DIMENSIONS ARE IN MILLIMETRES

ISSUE DATE	REVISION	DRAWN BY	DRAWING NO.
20/03/2019	1	EA	RSA GA

DRAFTING STANDARD	MODULE	SCALE	SIZE	SHEET
BS 8888	MM4GDM	1:2	A3	1 of 2

DO NOT SCALE



ITEM	DRAWING NO.	Description	MATERIAL	QTY.
1	RSA 8	50 SQUARE HOLLOW TANK BEAM	Plain Carbon Steel	1
2	RSA 3	Test Rig Left Arm Mount	Plain Carbon Steel	1
3	RSA 4	Test Rig Right Arm Mount	Plain Carbon Steel	1
4	N/A	12 ID Pillow Block Bearing	Steel	2
5	N/A	M10 Nut	Steel	6
6	N/A	M10 Bolt	Steel	4
7	N/A	M10 Washer	Steel	8
8	N/A	M8 Bolt	Steel	4
9	N/A	M8 Nut	Steel	4
10	N/A	M8 Washer	Steel	8
11	RSA 6	Pivot Swing Bar	Aluminium	1
12	N/A	M5 Bolt	Steel	4
13	N/A	M5 Nut	Steel	4
14	N/A	M5 Washer	Steel	8
15	N/A	M4 Washer	Steel	1
16	N/A	M4 Nut	Stainless Steel	3
17	N/A	M3 CTSK Screw	Steel	2
18	N/A	M3 Washer	Steel	2
19	N/A	M3 Nut	Steel	2
20	RSA 2	Newton Meter Mount Lower Part	Plain Carbon Steel	1
21	RSA 1	Newton Meter Mount Upper Part	Plain Carbon Steel	1
22	RSA 5	Pivot Rod	Aluminium	1
23	N/A	Custom M4 Bolt	Steel	1
24	N/A	M4x25x14	Stainless Steel	2
25	N/A	M4 WASHER	Stainless Steel	4

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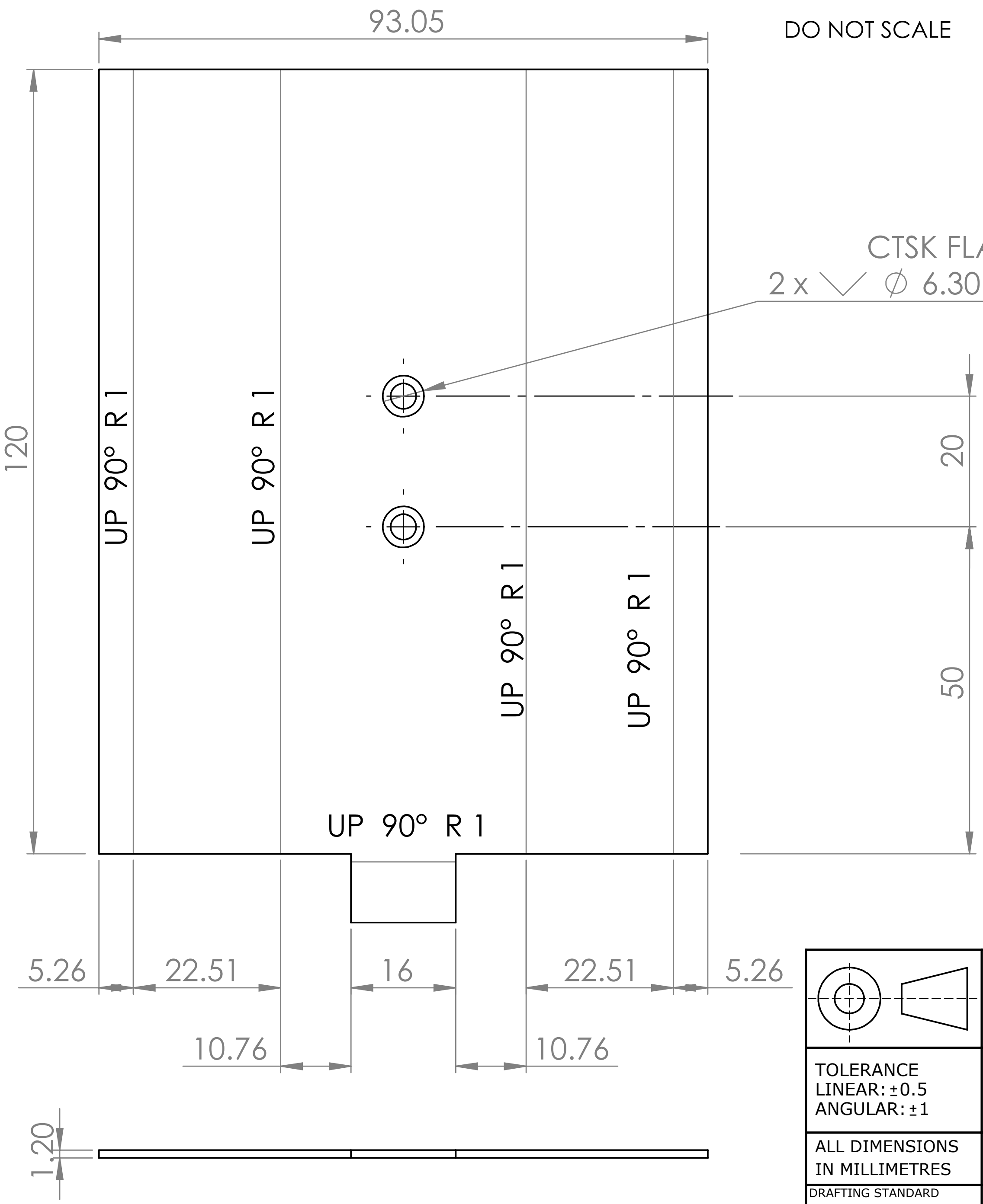
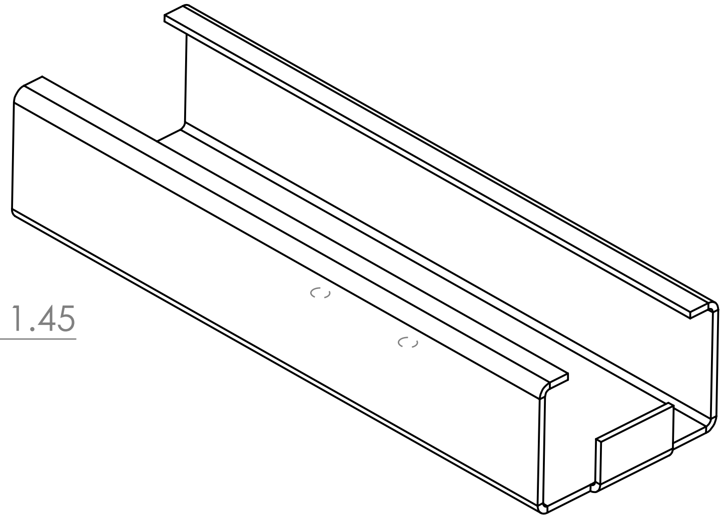
TOLERANCE
LINEAR: 0.5
ANGULAR: 1

Test Rig General Assembly

ALL DIMENSIONS ARE IN MILLIMETRES	ISSUE DATE 20/03/2019	REVISION 1	DRAWN BY EA	DRAWING NO. RSA GA
DRAFTING STANDARD BS 8888	MODULE MM4GDM	SCALE 1:2	SIZE A3	SHEET 2 of 2

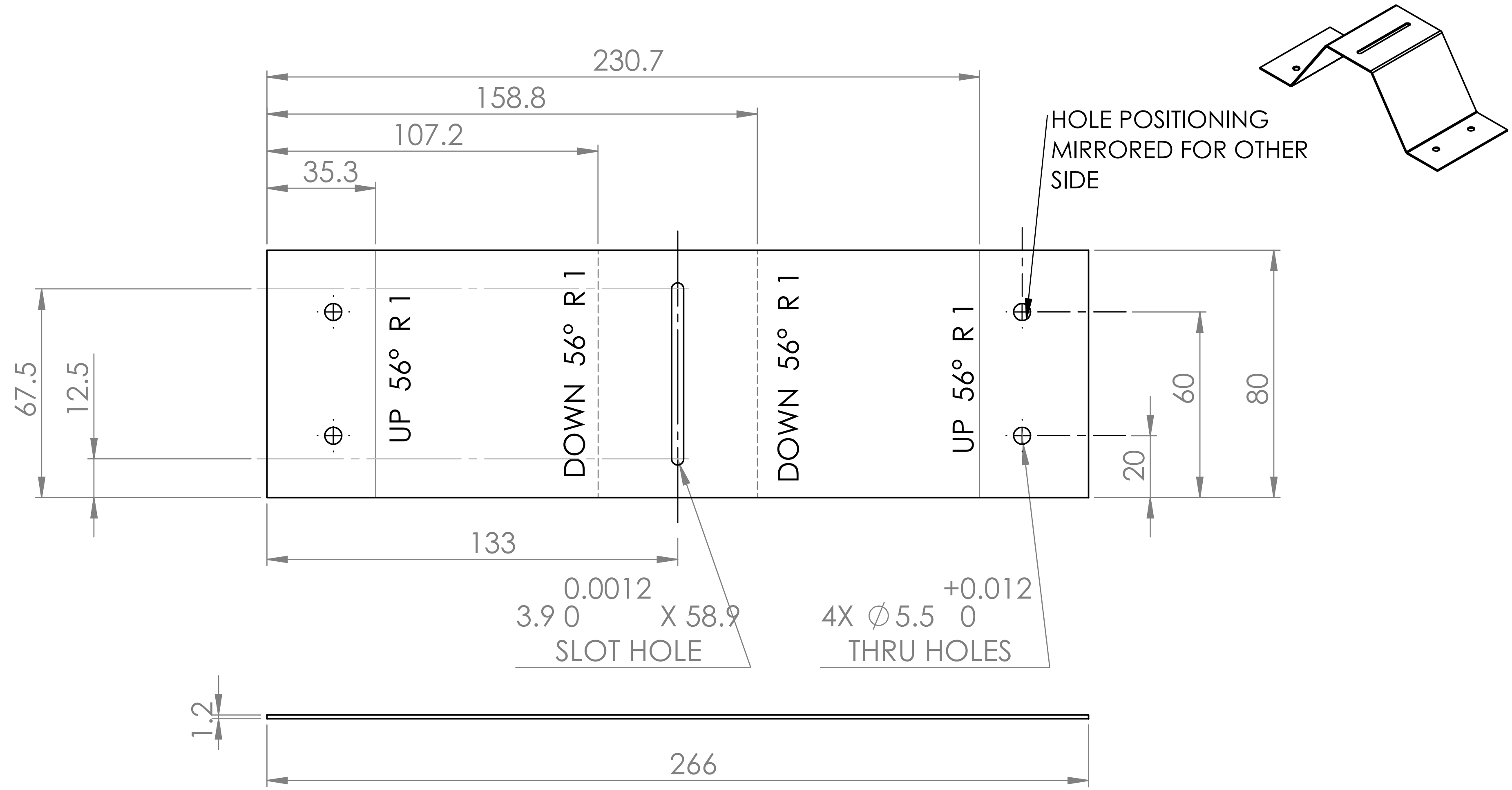
DO NOT SCALE





	University of Nottingham					
TOLERANCE LINEAR: ±0.5 ANGULAR: ±1	Newton Meter Mount Upper Part					
ALL DIMENSIONS IN MILLIMETRES	MATERIAL CODE MJ-A01006	PROCESS Sheet Folding	ISSUE DATE 21/03/2019	REV 1	DRAWN BY EA	DRAWING NO. RSA 1
DRAFTING STANDARD 8888	MATERIAL Plain Carbon Steel		MODULE MM4GDM	SCALE 1:1	SIZE A4	SHEET 1 of 1

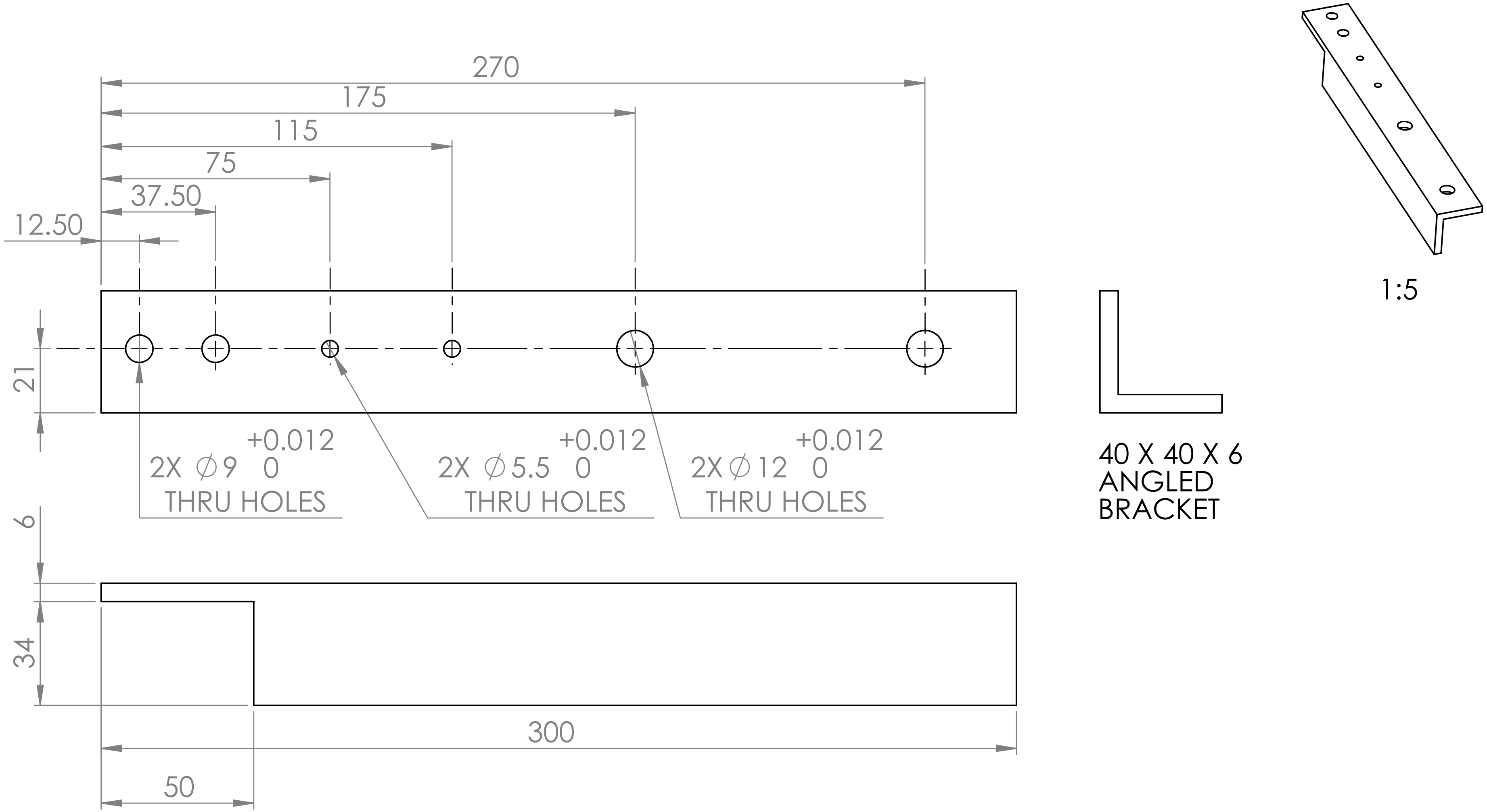
DO NOT SCALE



TOLERANCE LINEAR: ±0.5 ANGULAR: ±1	Newton Meter Mount Lower Part				
ALL DIMENSIONS IN MILLIMETRES	MATERIAL CODE MJ-A01006	PROCESS Sheet Folding	ISSUE DATE 21/03/2019	REV 1	DRAWN BY EA
DRAFTING STANDARD 8888	MATERIAL Plain Carbon Steel		MODULE MM4GDM	SCALE 1:2	SIZE A4

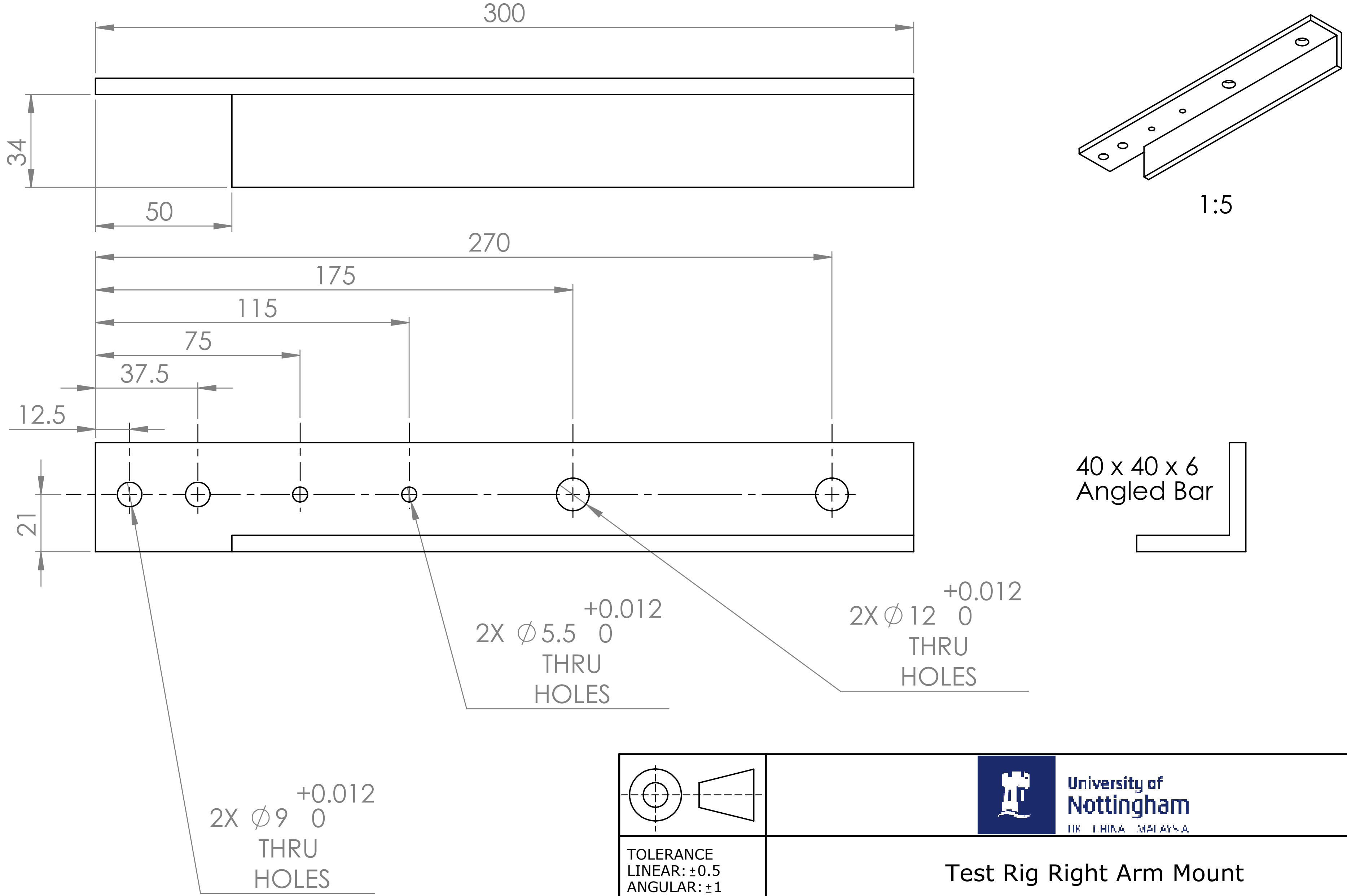
DRAWING NO.	RSA 2
SHEET	1 of 1

DO NOT SCALE



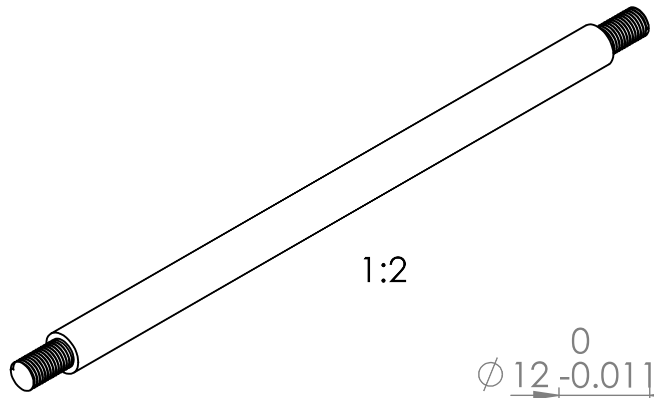
TOLERANCE LINEAR: ±0.5 ANGULAR: ±1	Test Rig Left Arm Mount					
ALL DIMENSIONS IN MILLIMETRES	MATERIAL CODE MJ-A08009	PROCESS Machining	ISSUE DATE 12/03/2019	REV 1	DRAWN BY EA	DRAWING NO. RSA 3
DRAFTING STANDARD 8888	MATERIAL Plain Carbon Steel		MODULE MM4GDM	SCALE 1:2	SIZE A4	SHEET 1 of 1

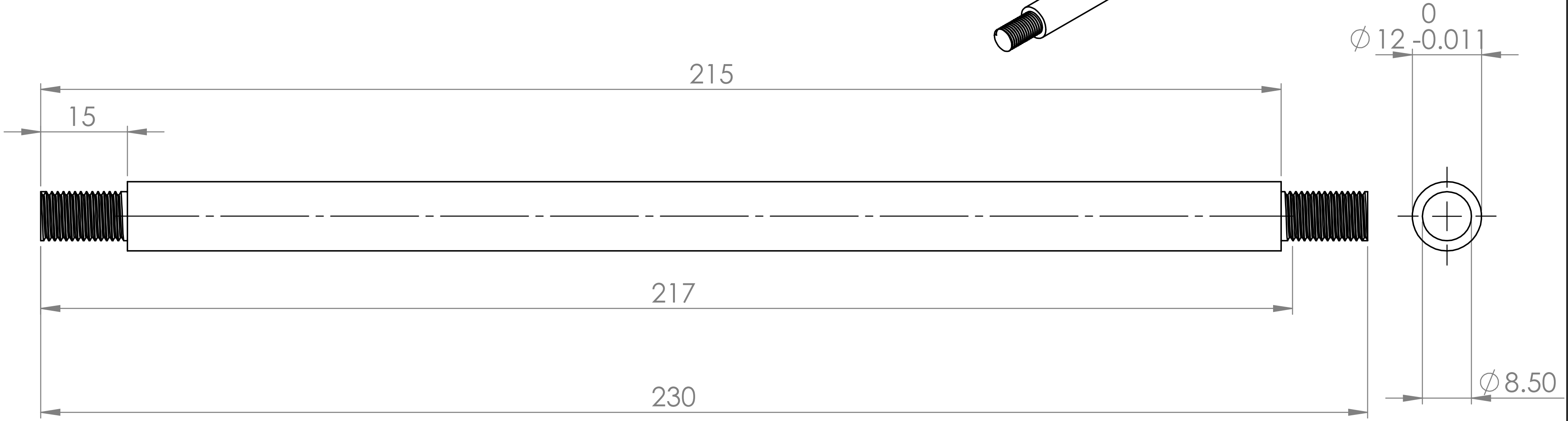
DO NOT SCALE



	University of Nottingham UK · CHINA · MALAYSIA					
TOLERANCE LINEAR: ±0.5 ANGULAR: ±1	Test Rig Right Arm Mount					
ALL DIMENSIONS IN MILLIMETRES	MATERIAL CODE MJ-A08009	PROCESS Machining	ISSUE DATE 12/03/2019	REV 1	DRAWN BY EA	DRAWING NO. RSA 4
DRAFTING STANDARD 8888	MATERIAL Plain Carbon Steel		MODULE MM4GDM	SCALE 1:2	SIZE A4	SHEET 1 of 1

DO NOT SCALE

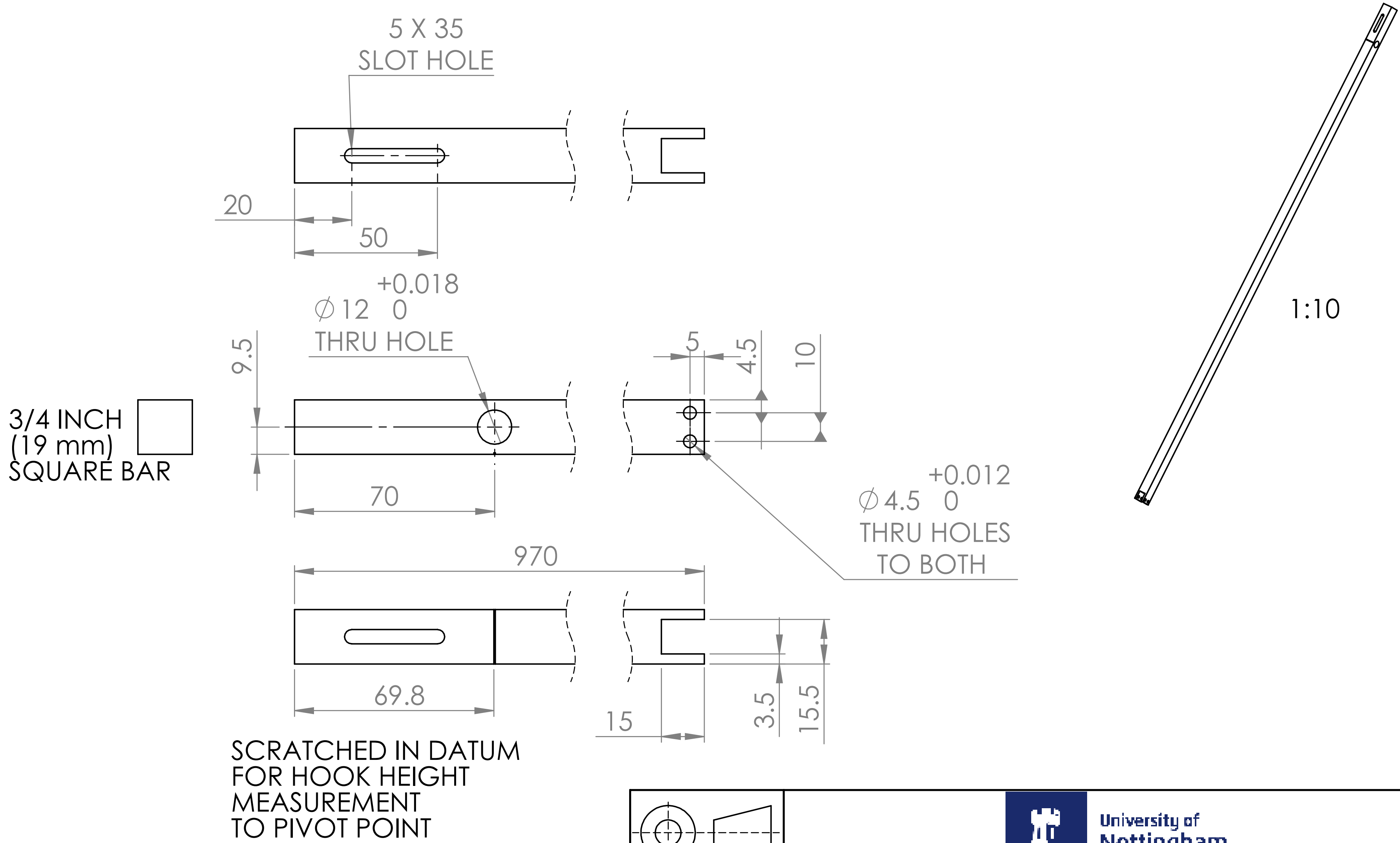




THREADED ENDS
ARE M8 x 0.1

	University of Nottingham					
TOLERANCE LINEAR: ±0.5 ANGULAR: ±1	Pivot Rod					
ALL DIMENSIONS IN MILLIMETRES	MATERIAL CODE MJ-B02010	PROCESS Lathe	ISSUE DATE 12/03/2019	REV 1	DRAWN BY EA	DRAWING NO. RSA 5
DRAFTING STANDARD 8888	MATERIAL Aluminium		MODULE MM4GDM	SCALE 1:1	SIZE A4	SHEET 1 of 1

DO NOT SCALE

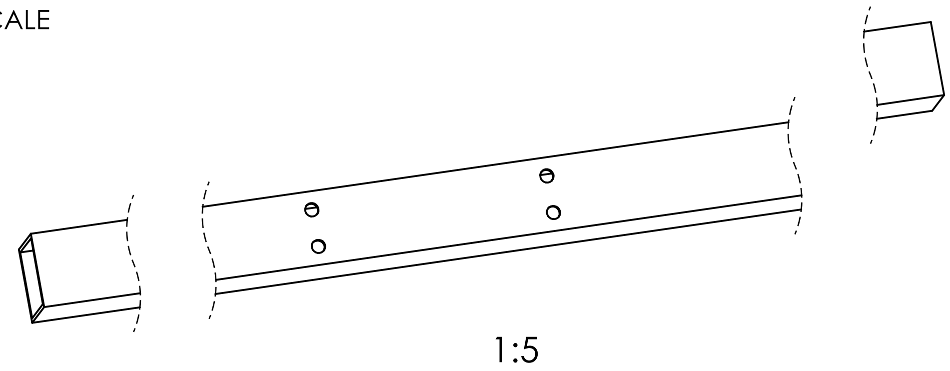


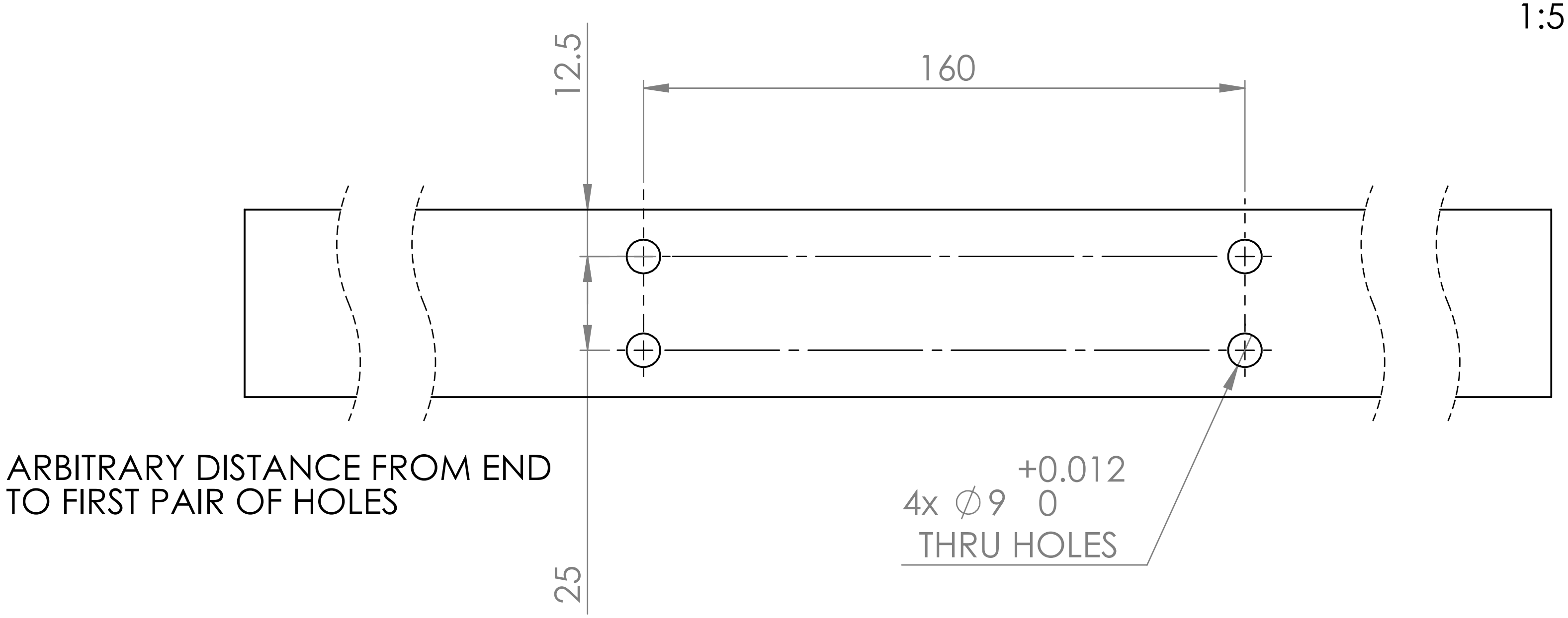
TOLERANCE
LINEAR: ±0.5
ANGULAR: ±1

Pivot Swing Bar

ALL DIMENSIONS IN MILLIMETRES	MATERIAL CODE MJ-B04010	PROCESS Machining	ISSUE DATE 12/03/2019	REV 1	DRAWN BY EA	DRAWING NO. RSA 6
DRAFTING STANDARD 8888	MATERIAL Aluminium		MODULE MM4GDM	SCALE 1:2	SIZE A4	SHEET 1 of 1

DO NOT SCALE





NOT ACTUAL
LENGTH OF 50 SQUARE
TANK BEAM

TOLERANCE LINEAR: ±0.5 ANGULAR: ±1	50 SQUARE HOLLOW TANK BEAM				
ALL DIMENSIONS IN MILLIMETRES	MATERIAL CODE N/A	PROCESS Drilling	ISSUE DATE 21/03/2019	REV 1	DRAWN BY EA	DRAWING NO. RSA 7
DRAFTING STANDARD 8888	MATERIAL Plain Carbon Steel		MODULE MM4GDM	SCALE 1:2	SIZE A4	SHEET 1 of 1

12. Appendix B - Statements of Requirements Revisions

Original

No	Customer(s)	Requirement	Method of Demonstrating Compliance	Rank
1	User	Must be operated from a 12V power supply	Inspection/Design	N/A
2	User	Must produce at least 9N of thrust at 2 m/s	Measurement	2
3	Designer	Must use no more than 3 actuators	Inspection	2
4	User	Should be able to generate motion up to the 5^{th} harmonic	Calculation	1
5	Designer	The housing for the electronic components must not leak at a water depth of 10m	Test	N/A
6	User	All materials must be corrosion resistant in a marine environment	Calculation	5
7	User	The design must provide a means to be drained	Inspection	N/A
8	User	Must fit within a size envelope of 500mm x 150mm x 150mm	Measurement	4
9	Designer	Cost must not exceed £500	Calculation	5
10	User	Design must incorporate an on/off switch	Test	N/A
11	User	Design must incorporate an emergency stop	Test	N/A
12	User	Design must eliminate risk of electric shock	Inspection/Design	N/A

Revision 1

No	Customer(s)	Requirement	Method of Demonstrating Compliance	Rank
1	User	Must be operated from a 12V power supply	Inspection/Design	N/A
2	User	Must produce at least 9N of thrust at 2 m/s	Measurement	2
3	Designer	Must use no more than 3 actuators	Inspection	2
4	User	Should be able to generate motion up to the 5th harmonic	Calculation	1
5	Designer	The housing for the electronic components must not leak at a water depth of 10m	Test	N/A
6	User	All materials must be corrosion resistant in a marine environment	Calculation	5
7	User	The design must provide a means to be drained	Inspection	N/A
8	User	Must fit within a size envelope of 500mm x 150mm x 150mm	Measurement	4
9	Designer	Cost must not exceed £500	Calculation	5
10	User	Design must incorporate an on/off switch	Test	N/A
11	User	Design must incorporate an emergency stop	Test	N/A
12	User	Design must eliminate risk of electric shock during normal handling	Inspection/Design	N/A

Revision 2

No	Customer(s)	Requirement	Method of Demonstrating Compliance	Rank
1	User	Must be operated from a 12V power supply	Inspection/Design	N/A
2	User	Must produce at least 9N of thrust at 2 m/s	Measurement	2
3	Designer	Must use no more than 3 actuators	Inspection	2
4	User	Should be able to generate motion up to the 3rd harmonic	Calculation	1
5	Designer	The housing for the electronic components must not leak at a water depth of 10m	Test	N/A
6	User	All materials must be corrosion resistant in a marine environment	Calculation	5
7	User	The design must provide a means to be drained	Inspection	N/A
8	User	Must fit within a size envelope of 500mm x 150mm x 150mm	Measurement	4
9	Designer	Cost must not exceed £500	Calculation	5
10	User	Design must incorporate an on/off switch	Test	N/A
11	User	Design must incorporate an emergency stop	Test	N/A
12	User	Design must eliminate risk of electric shock during normal handling	Inspection/Design	N/A
13	Designer	Must exhibit body – caudal fin motion	Inspection/Design	N/A
14	Designer	Must exhibit a 1st order response	Inspection/Design	N/A

Revision 3

No	Customer(s)	Requirement	Method of Demonstrating Compliance	Rank
1	User	Must be powered by a 12V power supply	Inspection/Design	N/A
2	User	Must produce at least 9N of thrust at 2 m/s	Measurement	2
3	Designer	Must use no more than 3 actuators	Inspection	2
4	User	Shall generate motion up to the 3rd harmonic	Calculation	1
5	Designer	The housing for the electronic components must not leak at a water depth of 10m	Test	N/A
6	User	All materials must be corrosion resistant in a marine environment	Calculation	5
7	User	The design must provide a means to be drained	Inspection	N/A
8	User	Must fit within a size envelope of 500mm x 150mm x 150mm	Measurement	4
9	Designer	Cost must not exceed £500	Calculation	5
10	User	Design must incorporate an on/off switch	Test	N/A
11	User	Design must incorporate an emergency stop	Test	N/A
12	User	Design must eliminate risk of electric shock during normal handling	Inspection/Design	N/A
13	Designer	Must exhibit piscine motion	Inspection/Design	N/A
14	Designer	Must exhibit a 1st order response to allow steering	Inspection/Design	N/A

Revision 4

No	Customer(s)	Requirement	Method of Demonstrating Compliance	Rank
1	User	Must be powered by a 12V power supply	Inspection/Design	N/A
2	User	Must produce at least 9N of thrust	Measurement	2
3	Designer	Must use no more than 3 actuators	Inspection	2
4	User	Shall generate motion up to the 3rd harmonic	Calculation	1
5	Designer	The housing for the electronic components must not leak at a water depth of 10m	Test	N/A
6	User	All materials must be corrosion resistant in a marine environment	Calculation	5
7	User	The design must provide a means to be drained	Inspection	N/A
8	User	Must fit within a size envelope of 500mm x 150mm x 150mm	Measurement	4
9	Designer	Cost must not exceed £500	Calculation	5
10	User	Design must incorporate an on/off switch	Test	N/A
11	User	Design must incorporate an emergency stop	Test	N/A
12	User	Design must eliminate risk of electric shock during normal handling	Inspection/Design	N/A
13	Designer	Must exhibit piscine motion	Inspection/Design	N/A
14	Designer	Must exhibit a 1st order response to allow steering	Inspection/Design	N/A

13. Appendix C

Manufacturing Process and Risk Assessment

UNIVERSITY OF NOTTINGHAM - FACULTY OF ENGINEERING
Process and Risk Assessment Record

Any Change to Processes, Location or Circumstances, Requires a Review of the Current Process and Risk Assessment.

Section 1: General Information

Assessment Number: *(Leave blank)* MMM-2019-3524	**Location / Building and Room Number:** *L2 Workshop*
Title of Process/Activity/Project/Experiment and/or Rig Name/Number: **GDM Group 6a Biomimetic Propulsion**	
Assessor Name: *Alexander Davies* Status: Student Signature: Date: 14/03/19	**Academic/Line Manager/Other Supervisor Name:** A. CAMPBELL RITCHIE Status: Asst. Professor Signature: Date: 19/3/2019
Laboratory Supervisor Name: I. BRENNAN Signature: Date: 15-3-19	**Area Safety Officer Name:** ALED JONES Signature: Date: 15/3/2019

Emergency Shut-Off Procedure:

All Equipment is in the L2 workshops and all Undergrads have been fully trained on the machines and where the emergency stops are.

IN CASE OF EMERGENCY CONTACT DETAILS:

Name: Contact Telephone Number(s):Ext. Mobile:

Physical conditions of rig/activity: Temperature: Room Temp Pressure: Atmospheric Machinery: Lathe, Grinder, Pillar Drill, Band Saw,3D Printer Electrics : Mains supply for 3D Printer	**Chemicals involved:** ELASTOSIL® E 41 PT Flex 70 Liquid Rubber
Environmental considerations: PT Flex classified as hazardous to the aquatic environment	**Special precautions for chemicals and experimental work:** Make sure room is well ventilated and fume hood available.
Equipment details: *Hand Tap, Welding, Casting, adhesive*	**Details of any biological effects:** N/A
Other notes:	

Date of Issue: January 2015 **Date of Printing: 13 March 2019**

Process and Risk Assessment Record

Section 2: Risk Assessment:

ACTIVITY FOR ASSESSMENT Name the activity, machine, equipment in use, etc.	**ASSOCIATED HAZARD (something with the potential to cause harm)** List the significant hazards associated with each subject e.g., electricity, moving parts, flammable liquid, hazardous materials, fumes, noise, dust, sharps, etc.	**PEOPLE INVOLVED** List the groups(s) of people who might be at risk i.e. Undergrad, Postgrad, Technicians, Cleaners, Visitors etc.	**ASSOCIATED RISK (the potential harm arising from the hazard)** Give a brief statement for each hazard e.g. electrocution, crushed limbs, cut hand, eye damage, respiratory irritation, chronic illness etc.	**EXISTING RISK-CONTROL MEASURES** List for each hazard the control procedures, equipment and devices used to control the risk e.g. Safe system of work, Local Exhaust Ventilation (extraction system), machine guarding, safety valves, fume cupboard, Portable Appliance Testing (PAT), training and specific items of PPE.
Pillar Drill	Moving parts, sharp edges from swarf created.	Undergrad	Cut hand, eye damage.	Wear all PPE (Lab coat, safety glasses and steel capped boots). Make sure to keep hands away from moving parts and use the safety guards to ensure the users safety. In the event of an emergency use the emergency stop button to stop the machine.
Grinder	Moving parts, sharp edges from swarf created.	Undergrad	Cut hand, eye damage.	Wear all PPE (Lab coat, safety glasses and steel capped boots). Make sure to keep hands away from moving parts and use the safety guards to ensure the users safety. In the event of an emergency use the emergency stop button to stop the machine.
Lathe	Moving parts, sharp edges from swarf created.	Undergrad	Cut hand, eye damage.	Wear all PPE (Lab coat, safety glasses and steel capped boots). Make sure to keep hands away from moving parts and use the safety guards to ensure the users safety. In the event of an emergency use the emergency stop button to stop the machine.
Band Saw	Moving parts, sharp edges from swarf created.	Undergrad	Cut hand, eye damage.	Wear all PPE (Lab coat, safety glasses and steel capped boots). Make sure to keep hands away from moving parts and use the safety guards to ensure the users safety. In the event of an emergency use the emergency stop button to stop the machine.
Welding	High temperature, high light intensity.	Technicians	Burns, eye damage.	Not to be undertaken by undergrads, only by technicians. The technician should wear all PPE and ensure that they wear welding masks and gloves.
FDM 3D Printer	Hot filament, electricity.	Technicians	Electrocution, burns.	Not to be undertaken by undergrads, only by technicians. The technician should wear all PPE and ensure there are no loose wires.
Moulding Tail – Liquid rubber	Fumes	Undergrad	Respiratory irritation	Wear all PPE (Lab coat, safety glasses and steel capped boots). Wear gloves to ensure if there is contact, it is not directly on the skin. Ensure that there is more than one person working so that the task is safer.
Hand Tap	Moving parts, sharp edges from swarf created.	Undergrad	Cut hand, eye damage.	Wear all PPE (Lab coat, safety glasses and steel capped boots). Make sure to keep hands away from moving parts.
Joining silicone using adhesive	Fumes	Undergrad	Respiratory irritation	Wear all PPE (Lab coat, safety glasses and steel capped boots). Ensure that the room is well ventilated and the user is not exposed to the fumes for long periods of time. Wear gloves to ensure if there is contact, it is not directly on the skin.

Section 3: Safe Operating Procedure, Process Description, Operating Instructions, Method Statement, etc.

Please refer to the process sheets for each part as available from group 6a

Section 4: Flow diagrams:

Please refer to the process sheets for each part as available from group 6a (All machines are not photographed due to being standard machines in the L2 laboratory workshop)

Section 5: Photographs.

(All machines are not photographed due to being standard machines in the L2 laboratory workshop)

Section 6: Supplier's literature.

Section 7: Any necessary working calculations.

Fully dimensioned engineering drawings are available of each part as available from group 6a.

Section 8: Other information.

Section 9: Material Safety Data Sheets (MSDS).

UNIVERSITY OF NOTTINGHAM - FACULTY OF ENGINEERING

Process and Risk Assessment Record

Section 10: Control of Substances Hazardous to Health (COSHH) Assessment:

Name of assessor:	Alexander Davies	**Date:**	**12/03/19**
Name of chemical(s)/ substance(s):	ELASTOSIL® E 41, PT Flex 70 Liquid Rubber		**Quantity: 90ml** **Quantity: 500g**
Synonyms:			
CAS No:			
Safe storage: *(MSDS section 7)* *(How will you meet the standards specified?)*	**Building and room No:**	**Cabinet/category:**	
	Other:		
Physical Properties: *(e.g. Liquid, powder, granules, fibres, gas etc.)* *(MSDS section 9)*	Liquid Liquid		
Hazard classification and category: *(MSDS section 2)*	Skin Sensitizer Category 1 Hazardous to the Aquatic Environment – Acute Hazard Category 2 Hazardous to the Aquatic Environment – Long-Term Hazard Category 2		
Pictograms: ***Delete as applicable** *(MSDS section 2)*			
Signal word and hazard statements: *(MSDS section 2)*			
Precautionary statements: *(MSDS section 2)*			

Duration of exposure to substance: ***NOT*** *the duration of the process.*	**Time:** *e.g. hrs, mins, secs.*	**Workplace Exposure Limits: (WEL)** *(MSDS section 8)*	
	5 mins	**Long-term exposure limit:**(8-hrs TWA reference period) *(ppm mg/m³)*	**Short-term exposure limit (STEL):**(15-minute reference period) *(ppm mg/m³)*
Frequency of exposure: *(e.g. times per day/week etc.)*	**4 times over a month (1 per week)**		

Is a written protocol for safe handling required? *(Are there specific requirements for handling this substance? e.g. Mercury, HF, Arsenic etc.)* Use with adequate ventilation	**Is air monitoring required?** *(Do air samples need to be taken to check airborne contamination?)* No	**Are occupational health checks required?** *(Are health checks required to monitor the health effects of exposure?)* No

Give details of engineering control measures in place:
Only use substance in a well ventilated room/fume hood

Required Personal Protective Equipment (PPE): *(MSDS section 8)* *Identify items required	Laboratory Coat	X	Howie Coat		Safety Glasses	X	Safety Boots/Shoes	X
	Disposable Gloves	X	Heavy Duty Gloves		Gauntlets		Dust Mask/Respirator	
	Protective Apron		Face Shield		Other:		Other:	

Disposal Procedures: *(MSDS section 13)*	

Date of Printing: 25 March 2019

Emergency Procedures

SPILLAGE/ACCIDENTAL RELEASE MEASURES:
Cover with an inert absorbent material and collect into an appropriate container for disposal. Avoid releases to the environment.

FIRE-FIGHTING MEASURES:
Use water fog, foam, carbon dioxide or dry chemical. Do not use solid water stream. Solid stream of water into hot product may cause violent steam generation or eruption

FIRST AID MEASURES: *(MSDS section 4)*
In case of eye contact:

Contact of unvulcanised silicone rubber with eyes and mucous membranes must be avoided as this would cause irritation. However if it does happen, rinse the affected area thoroughly.

Rinse thoroughly with water, holding the eyelids open to be sure the material is washed out. Remove contact lenses if safe and easy to do. Continue rinsing. Get medical attention if irritation persists.

In case of skin contact:

Remove contaminated clothing. Wash contact area thoroughly with soap and water. Get medical attention if irritation persists.

In case of ingestion:

Do not induce vomiting unless directed to do so by medical personnel. Get medical attention

In case of inhalation:

Remove person to fresh air. Get medical attention if symptoms persist.

UNIVERSITY OF NOTTINGHAM - FACULTY OF ENGINEERING

Process and Risk Assessment Record

Section 11: Training

Persons trained and authorised to operate the process/activity/project/experiment or equipment.

Name:	Trained/Authorised by:	Signature:	Date:
Alexander Davies	Ian Brennan	I Brennan	15-3-19
Elijah Almanzor	Ian Brennan	I Brennan	" "
Alex Sandford	Ian Brennan	I Brennan	" "
Fraser Kearsey	Ian Brennan	I Brennan	" "
Joshua Zatland	Ian Brennan	I Brennan	" "

Section 12: Declaration
To be signed by all personnel working to this Process and Risk Assessment

I confirm that I have read this Process and Risk Assessment and understand the hazards, risks and control measures associated with the process. I will not make any changes to the processes, location or circumstances, without completing and submitting a revised or new Process and Risk Assessment.

Name:	Signature:	Date:
Alexander Davies		15/03/19
Elijah Almanzor		15/03/19
Alex Sandford		15/03/19
Fraser Kearsey		15/03/19
Joshua Zatland		15/03/19

Section 13: Review
This Process and Risk Assessment must be reviewed on a regular basis, if there are any changes to the processes, location or circumstances, or, if it is deemed to be no longer suitable.

Reviewed by:	Signature:	Date:

Testing Process and Risk Assessment

UNIVERSITY OF NOTTINGHAM - FACULTY OF ENGINEERING

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Any Change to Processes, Location or Circumstances, Requires a Review of the Current Process and Risk Assessment.

Section 1: General Information

Assessment Number: *(Leave blank)* MMM-2019-3525	**Location / Building and Room Number:** *Outside L4 building in the underpass*
Title of Process/Activity/Project/Experiment and/or Rig Name/Number: GDM Group 6a Biomimetic Propulsion	
Assessor Name: *Alexander Davies* Status: Student Signature: Date: 14/03/19	**Academic/Line Manager/Other Supervisor Name:** A Campbell Ritchie Status: Asst. Professor Signature: Date: 15/3/2019.
Laboratory Supervisor Name: A. Campbell Ritchie Signature: Date: 15/3/2019.	**Area Safety Officer Name:** Aled Jones Signature: Date: 18/3/2019

Emergency Shut-Off Procedure:

The 12v power supply is connected to the mains. This will be turned off in an emergency.

IN CASE OF EMERGENCY CONTACT DETAILS:

Name:	Contact Telephone Number(s):Ext.	Mobile:

Physical conditions of rig/activity: Temperature: Outdoor temperature on the day Pressure: Atmospheric Machinery: Electrics : 12v DC power supply connected to the mains	**Chemicals involved:** N/A
Environmental considerations: N/A	**Special precautions for chemicals and experimental work:** N/A
Equipment details: *Large water tank*	**Details of any biological effects:** N/A
Other notes:	

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Section 2: Risk Assessment:

ACTIVITY FOR ASSESSMENT Name the activity, machine, equipment in use, etc.	**ASSOCIATED HAZARD (something with the potential to cause harm)** List the significant hazards associated with each subject e.g., electricity, moving parts, flammable liquid, hazardous materials, fumes, noise, dust, sharps, etc.	**PEOPLE INVOLVED** List the groups(s) of people who might be at risk i.e. Undergrad, Postgrad, Technicians, Cleaners, Visitors etc.	**ASSOCIATED RISK (the potential harm arising from the hazard)** Give a brief statement for each hazard e.g. electrocution, crushed limbs, cut hand, eye damage, respiratory irritation, chronic illness etc.	**EXISTING RISK-CONTROL MEASURES** List for each hazard the control procedures, equipment and devices used to control the risk e.g. Safe system of work, Local Exhaust Ventilation (extraction system), machine guarding, safety valves, fume cupboard, Portable Appliance Testing (PAT), training and specific items of PPE.
Water tank, attaching/detaching rig and prototype for testing. Set up using step ladder on the side of the tank	High place, large quantity of water	Undergrad	Breakage of limbs from falling, drowning	Wear all PPE (Lab coat, safety glasses and steel capped boots). Ensure that all users are able to swim unlikely event of emergency. Make sure that there is always more than one person present to hold the ladder and keep an eye on the person installing the rig. Have a throw-rope to hand to assist if anyone falls into the tank.
Running prototype	Electric power supply (12v)	Undergrad	Electric shock	Wear all PPE (Lab coat, safety glasses and steel capped boots). Ensure that there are no loose cables and that all users are far away from the water tank when the power supply is in use.
Water leak to electronics	Seal not tight enough	Undergrad	Electric Shock	IPx8 Standard followed for Product.
Running prototype	Loose Cables	Undergrad	Electric Shock	IP69k Standard Cable glands used to Pass Cables
Reading test values	Large quantity of water	Undergrad	Drowning.	Do not go above Middle rung of Ladder.
"	"	"	"	Cover top of water tank (netting) to ensure Saftey.
Installing prototype	Cables (Chords)	Undergrad	Severing Limbs	Chords are encased in a Silicon Casing.
Installing Prototype	High place	Undergrad	Impaling	Ensure area under/around ladder is kept clear.

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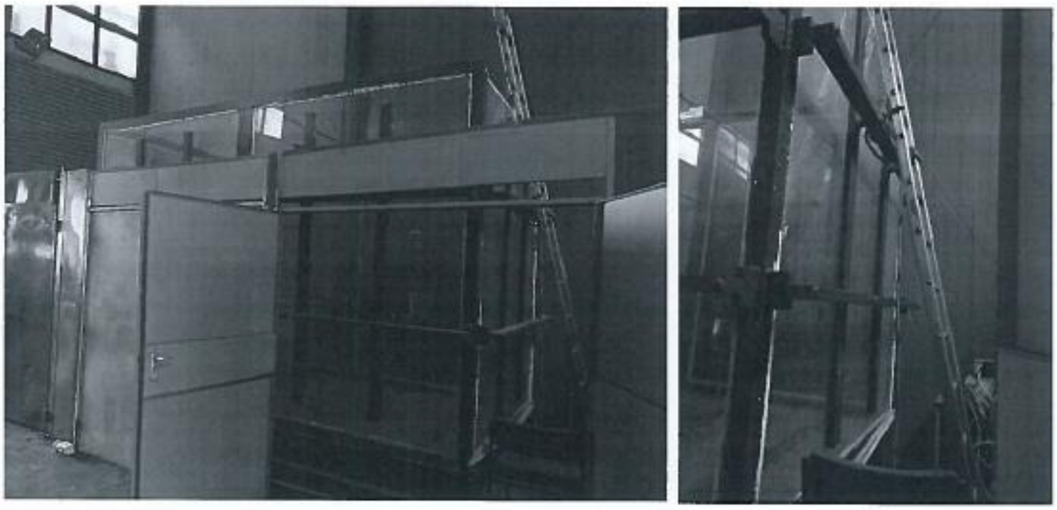
Section 3: Safe Operating Procedure, Process Description, Operating Instructions, Method Statement, etc.

All users must be wearing full PPE:
Unlock the doors to the tank. Attach the rig set up to the horizontal cross beam. Climb the ladder on the side of the water tank ensuring it is held at the bottom by another person and attach the cross beam onto the side of the tank. Lower the fish on the rod into the tank and attach to the rig set up. Ensure that all parts are secured and the user is down from the ladder before starting the power supply. Once testing is complete, turn off the power supply, take the fish out of the water and detach the cross beam. Dismantle the test rig and put all parts back in a safe location before locking up the doors to the tank.

Section 4: Flow diagrams:

All process are commenced by hand and using the equipment as shown previously. The emergency stop is the on/off switch for the 12v power supply.

Section 5: Photographs.



Photos show the water tank with dimensions 2m x 3.5m x 3m (Deep) and the ladder next to the tank used to climb to attach the product.

Section 6: Supplier's literature.

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Section 7: Any necessary working calculations.

Fully dimensioned engineering drawings are available of each part and test rig as available from group 6a.

Section 8: Other information.

Section 9: Material Safety Data Sheets (MSDS).

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Process and Risk Assessment Record

Section 11: Training

Persons trained and authorised to operate the process/activity/project/experiment or equipment.

Name:	Trained/Authorised by:	Signature:	Date:
Alexander Davies	Alastair Campbell Ritchie		15/3/19
Elijah Almanzor	Alastair Campbell Ritchie		15/3/19
Alex Sandford	Alastair Campbell Ritchie		15/3/19
Fraser Kearsey	Alastair Campbell Ritchie		15/3/19
Joshua Zatland	Alastair Campbell Ritchie		15/3/19

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Reviewed by:	Signature:	Date:

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