DELIVERABLE 6 – INDIVIDUAL CONTRIBUTION FORM

Group Number:	**MEng 6**
Name of Group Coordinator:	**Harry Deed**

Student Name	**Student ID**	**Individual Contribution (out of 100%)**
Andrew Tay	[redacted]	100%
Harry Deed	[redacted]	100%
Kin Leung	[redacted]	100%
Muhammad Arish Bin Ismail	[redacted]	100%
Muhammad Ramli	[redacted]	100%
Shuchen Zuo	[redacted]	100%
Tom Hooper	[redacted]	100%

Table of Contents

Deliverable 6: Group Design Report Part B

1 Introduction

1.1 Background and Context to the Project

Nowadays, it is crucial to have sustainable energy supplies to minimise carbon footprint and make the world a more sustainable place to live for future generations. There are many ways to extract sustainable energy from the environment, such as wind, tide, and even nuclear fission. Solar energy only contributes a small portion of renewable energy supply. When compared to other ways of generating clean energy, as can be seen in Figure 1, it can be considered by far the most convenient way to derive clean and pure energy, directly from the sun.

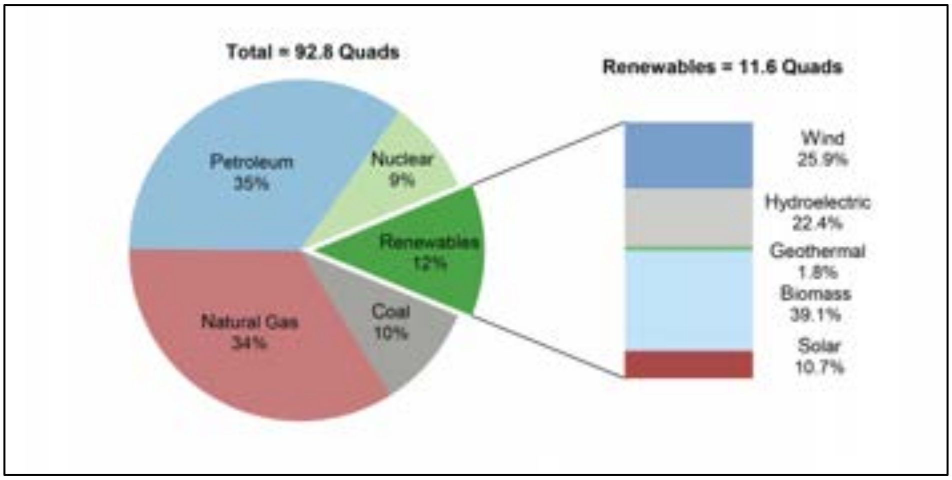


Figure 1: Total and Renewable Energy Consumption by Source in 2020 (Center for Sustainable Systems, 2021)

There are different types of solar farms, and they can be distinguished by their surroundings. There are typically two types of solar farm, land-based and water-based. If the solar farm is land-based, the accessibility is going to be much higher than the water-based facilities, hence it will be much easier for maintenance to take place. The way to clean a solar farm can be further subdivided into two categories, manual and automated cleaning, shown in Figures 2.1 and 2.2.

Solar panels are very delicate and fragile, when trying to manually clean a solar panel, the operator needs to be specially trained. For example, human error can occur if the operator does not align the cleaning tool correctly with the solar panel. The tip of the brush could easily scratch the surface of the panel, therefore decreasing the panel efficiency. The labour cost of the human cleaning operation is also very large because cleaning is often required to maintain the desired efficiency of the solar farm. Therefore, using automated machines to conduct the cleaning operation is essential. There are two predominant methods of cleaning solar panels, namely the rover-based cleaner and the rail-based cleaner, shown in Figures 3.1 and 3.2.


Figures 2.1 (Left) and 2.2 (Right): 2 Different Ways of Cleaning a Solar Panel

Both cleaning methods have their advantages and disadvantages. For instance, the rail-based method can clean up to two or three panels at a time, but its degree of freedom is limited, hence the efficiency is lower at the edge of the panel (Antonelli, M., 2020). A more dynamic solution has then been presented: the rover-based cleaner. The rover-based cleaner is similar to the commercial house floor cleaning robot. The downside of these rovers is their efficiency and the scale of operation.


Figures 3.1 (Left) and 3.2 (Right): Predominant methods of solar panel cleaning (SolarCleano, 2021; Wash Panel, 2021)

So far, the cleaning of offshore or floating photovoltaic systems has not been systematically considered and is mainly done by human labour, as shown in Figure 4. This is because the offshore solar farms have very poor accessibility. For example, it will not be economically viable to install a rail-based cleaning system because the weight of the system needs to be considered in the design stage. It is also not practical to use a rover-based method, this is because the rover operates on the surface of the panel. When floating on water, there could be movement of the panel, causing the rover to slip and damage the surface of the solar panel. From the controller's point of view, guiding a rover from distance might also cause trouble in a sense of visualising its location and manoeuvring the rover. Therefore, the design can be concluded as a potentially fully automated cleaning robot that has a cleaning arm attached to the top and drives along the maintenance pathway to tackle the lack of innovation in the field of cleaning mechanisms on a floating solar farm.

Figure 4: Floating Photovoltaic System with White Maintenance Walkway (Cision, 2017)

1.2 Summary of Design Requirements

1. Rover based designs can be heavy (the hyCLEANER Solar Facelift weighs > 80kg). However, the floaters that the solar panels rest on may not be capable of generating sufficient buoyancy for their use. Furthermore, the large weight acting on the solar panel may lead to faster degradation and cause damage to the panel surface (e.g., scratches). By using a cleaning arm the design avoids these issues since the weight of the rover is exerted on maintenance walkways that are designed to take the weight of an adult. The weight of the rover, however, should still be as light as possible.

2. The hybrid design does not require pre-existing infrastructure in the form of rails, potentially making the design a more economical alternative. To fulfil this requirement, the rover is going to be made and designed based on the dimensions of a given platform.

3. While typical cleaning rovers require human input to move the rover from one row of panels to the next, the rover uses the maintenance walkway to autonomously move between rows. Therefore, high mobility from the rover is required. This means that the rover should not only be able to move back and forward in one direction, but also be able to turn tight corners.

4. As the rover is operating in an environment surrounded by water, a certain degree of waterproofing of the outer case and the circuits within the rover will be required. Therefore, design considerations have been taken regarding the choice of casing material and its design. The standard for the prototype aligns with IP55, whereas the final product should have better water resistance and will align with IP67.

5. Lastly, one of the most important requirements for the design is the rate at which the arm can clean the solar panel. This is mainly down to two factors, the first is how quickly the rover moves along the platform and the second is how quickly the brush rotates in the cleaning arm. For the actual product, the cleaning arm will have 180 RPM, 20 RPM higher than the Cleansolar Solution.

1.3 Outline of Existing Design Solutions that Meet the Requirements

In the case of existing design solutions that partially meet the requirements that are stated in both the Appendix and briefly in section 1.2, different robots engineered by different companies were benchmarked for the design specifications:

1. The final product weighs roughly 25kg including the cleaning arm. When compared to the mass of robotic solar cleaners developed by hyCleaner and Serbot, these designs can weigh in excess of 30kg. Therefore, the robots developed by the above-mentioned companies act as a mass limit to the final product.
2. To clean the solar panel surface efficiently, a certain amount of pressure needs to be applied to the panel. A robot developed by Zedfactory can pressure the surface to a maximum of 200kg/sq.m, which would be sufficient for the final product's cleaning arm, hence the robot has been benchmarked.
3. The Hycleaner developed robot can reach a maximum cleaning speed of 1.5km/h, which is sufficient for a small or medium-scale solar farm. The final design will be able to clean with a speed of 2.5km/h, to demonstrate the increase in cleaning speed as part of the innovation.
4. The rotational speed of the cleaning brush is a crucial factor in the result of how clean the solar panel is. Cleansolar's robot has a rotational speed of 160 RPM, and it meets basic requirement set. As developed cleaning efficiency and speed have been characterized as one of the innovations, a final average rotational speed of 180 RPM is required for the final product.

1.4 What Worked Well and Could be Improved During the Design Process

Before the group meetings begin, there was a clear agenda set. This has allowed the group to begin work immediately upon meeting and helped the team have a clear sense of direction. For instance, a week before the deliverable 3 deadline submission, it was agreed the exact points of connection between all the subsystems so that dimensions could be finalized. However, in this regard, one way that the group has fallen short of the team action plan is in consistently adhering to the 3-day period. Often, the agenda of the group meeting was only established a day or two before the actual date of the meeting. In the future, the group plans to be more disciplined in following this guideline so that everyone will have more time to complete work before the meeting begins.

In some ways, the group has been proactive in exchanging information and providing advice. As part of the action plan, it was agreed to upload all the Solidworks files onto the shared google drive upon their completion. This is something that the group has managed to consistently do. As a result, it has been easy for the group to download the various subassemblies of the Solar Panel cleaner to verify interdependent dimensions.

However, the group still has many ways of improving in this regard. Some components in the Solar Panel Cleaner involve simultaneously designing multiple subassemblies. For instance, the winch that pulls in the cable that lifts the cleaning arm needs to be connected to the cleaning arm, the T-structure, and the chassis. For such components, the group has not been very consistent in communicating the constraints in attachment points for each subassembly. As such, problems that arise from the connection of such components are only surfaced later and this can result in last-minute changes. In the future, the group could improve by taking time out to voice concerns to each other. There needs to be a systematic way of managing the various dependencies of the project.

1.5 Main Assumptions and Limitations

Because the rover design operates on an open water reservoir and the surrounding environment cannot be perfectly controlled, assumptions have been made concerning both the rover and its operating conditions:

1. The dimensions of the pathway that the rover operates on have been clarified, the rover can only operate efficiently on this specific pathway. The functionality of the rover can therefore not be guaranteed on a solar farm with different pathway dimensions. Figure 5 demonstrates the dimensional constraints of the pathway.

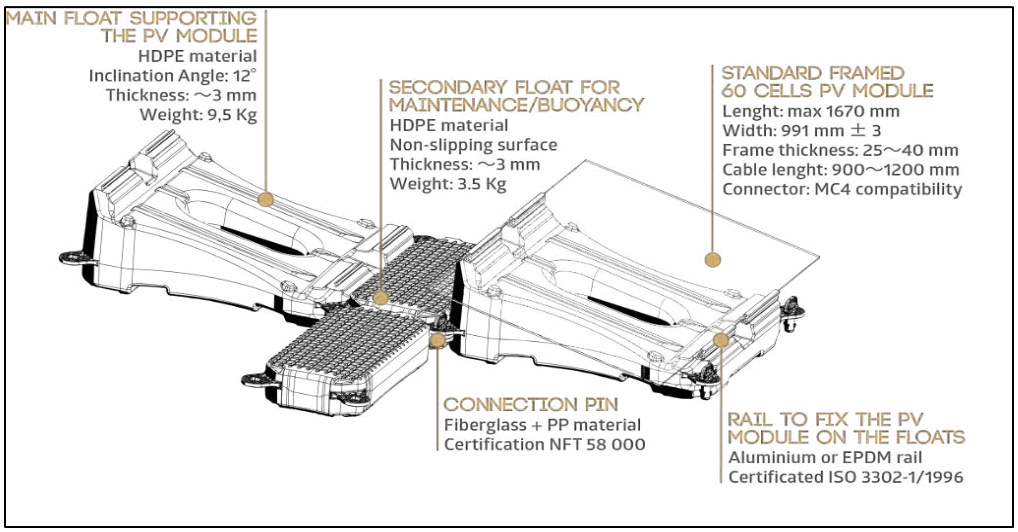


Figure 5: Pathway dimensions (Floating Solar UK, 2021)

2. With regards to the surrounding environment of the rover, assumptions have been made to reduce variabilities. For example, the rover and the pathway have been considered as a whole body. No matter how choppy the water is, it is assumed that the rover will always be stable on the pathway. There will therefore be no sliding in any direction and the prototype can be examined under a firm-ground condition.

In contrast to the main assumptions, the limitations can be drawn accordingly:

1. No measures have taken place to mitigate the effect caused by either wind or waves in an open reservoir. Hence at the initial stage of the development of the rover, it has very low adjustability and resilience to medium or extreme environmental conditions.
2. As the cleaning rover design includes the import of water into the cleaning system, the water source supply has been assumed to be stationary and constant, which means at the initial design stage, it is beyond the scope of research. However, the idealised

solution would be that the rover either carries a water tank or is connected to a pump that directly draws water from the reservoir.

2 Outline of Prototype A

2.1. Main Features of Prototype A

2.1.1 Rover Chassis

The Solar Panel Cleaner (SPC) is a rover with an extended cleaning arm that can clean the entire solar farm independent of its position or angle changes. The solar panel cleaner has a total weight of 9kg which is about 1/7 the average weight of an adult person (Walpole et al., 2012).

The rover (Figure 6.1) eliminates the need for physical labour to clean the floating solar farm. The rover has an ingress protection grade of IP55 and can travel at a rate of 0.2 ms^{-1} along the path of the solar farm. The chassis is well enclosed to ensure the electronics components are protected against water splashes from the lake or sea. Moreover, the chassis is designed to be easily accessed for electronics maintenance and replacement (Figure 6.2).

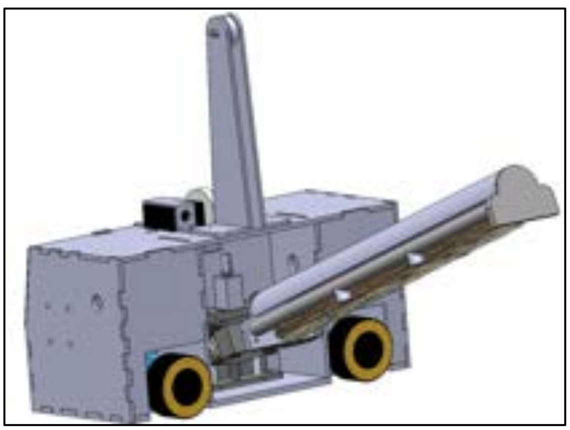
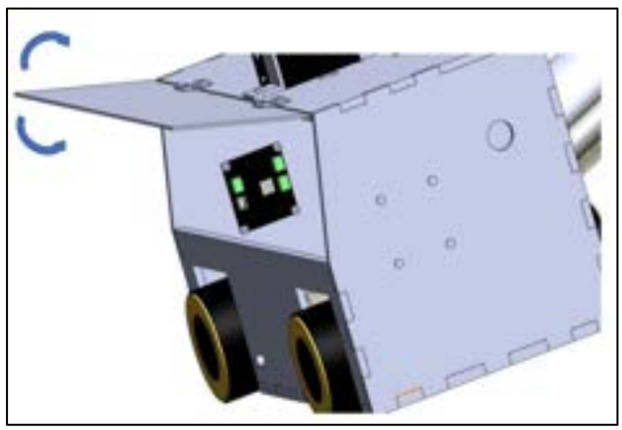



Figure 6.1: Prototype A Overall Design (Left)
Figure 6.2: Enclosure for rover chassis (Right)

2.1.2 Cleaning Arm

The cleaning arm consists of a brush mechanism and water distribution system that work in tandem to clean the solar panel. The brush has a width of 0.5m and a diameter of 35mm which can rotate at 300 RPM. The brush is supported by the lower arm and the winch attached to the rover. The angle of the cleaning arm can be adjusted from 2° to 22°, depending on the inclined plane of the solar panel. The cleaning arm weighs only 1.2kg which is light enough for its position to be controlled, other than minimising the weight distributed onto the solar panels (see Figure 7). With the help of the lower arm, the cleaning arm can be adjusted vertically within a 7.0mm range, which is enough to compensate for the vertical distance that may deviate due to the buoyancy of the solar panels on the lake (see Figure 7). The winch uses nylon as cables connecting the winch to the cleaning arm (see Figure 9.2). The strong material enables the adjustment of the angle of inclination without the risk of cable failure due to the weight of the cleaning arm. The winch is powered by a 5V servomotor as seen in Figure 9.2 and it can lift a load up to 12.8N at a 1 metre distance.

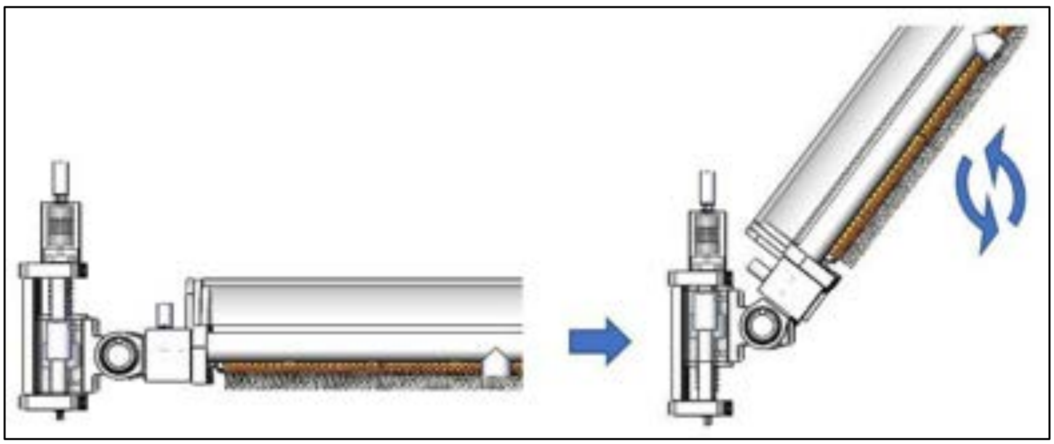


Figure 7: Overall Cleaning Arm Configuration

2.2 Function of Prototype A

As maintenance pathways of offshore farms tend to be narrow, the rover was designed to be capable of completing tight corner turns. By equipping the rover with Mecanum wheels, the rover can turn on the spot (see Figure 8). This enables it to traverse from one row of walkways to the next, allowing it to move through the entire solar farm.

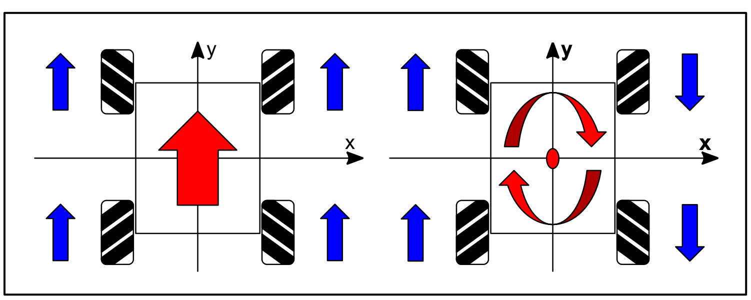


Figure 8: Possible Movements of Prototype A (Wikipedia, 2022)

The cleaning arm, on the other hand, needs to be adjusted so that it is always touches the solar panels, independent of the height or angle of the solar panels owing to buoyancy. This is achieved by integrating a linear driving mechanism (leadscrew, nut and limit switch) to move the short arm vertically up and down (see Figure 9.1), thus adjusting the height of the cleaning arm attached to it. Next, the angle of inclination of the cleaning arm is controlled by the winch, which is powered by a servo motor. It works as a pulley to either raise or lower the cleaning arm (see Figure 9.2). These adjustments require monitoring from the operator to ensure that the cleaning arm sits perfectly on the solar panel before operating the device.

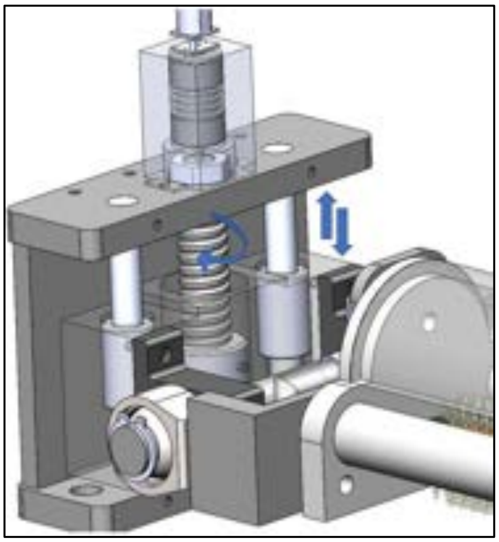
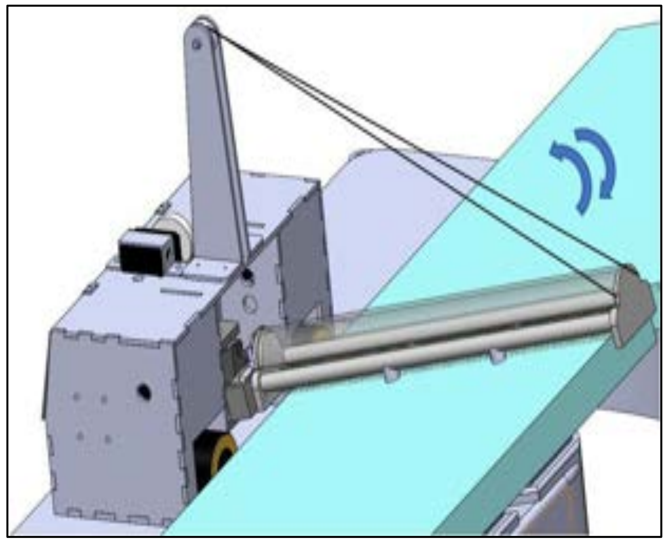



Figure 9.1: Overview of Lower Arm Functionality (Left)
Figure 9.2: Application of the Winch Mechanism (Right)

The cleaning of the solar panels is done with the flow from water outlets and the rotary motion of the brush. The outlets are linked to a tap located higher than the cleaning arm, allowing water to flow out of the cleaning arm via gravity. This assists the motor-powered brush in sweeping any debris from the solar panels (see Figure 9.2). A tube that also serves as a structure to cover the cleaning brush distributes water side to side and throughout the length of the brush for the cleaning arm. There are holes drilled in this tube that allow water to flow out and onto the solar panel. The water that flows through the tube is supplied by a hosepipe connected to the tubes (see Figure 10).

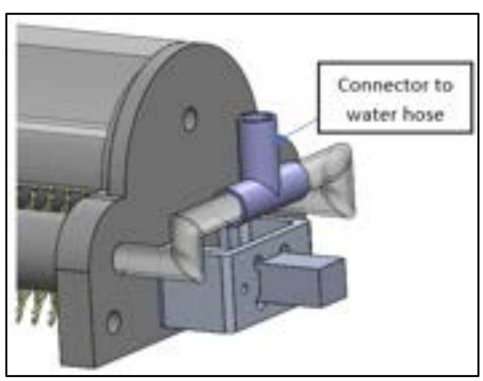


Figure 10: Overview Connection for Water Distribution System

As shown in Figure 11, the brush lies within the structure of the upper arm which is made from PVC. At either end of the brush, there are bearings that are push-fit into the endplates of the structure to allow for free rotation (see Figure 12.1). The brush is then rotated by a motor that is situated next to the lower arm (see Figure 12.2). The brush necessitates the use of a custom bolt that can pass through the centre and is threaded on both ends so that nuts can be screwed on to ensure that the bolt, not the brush, rotates. To allow for free rotation, both ends of the bolt are inserted into the bearings on the endplate.

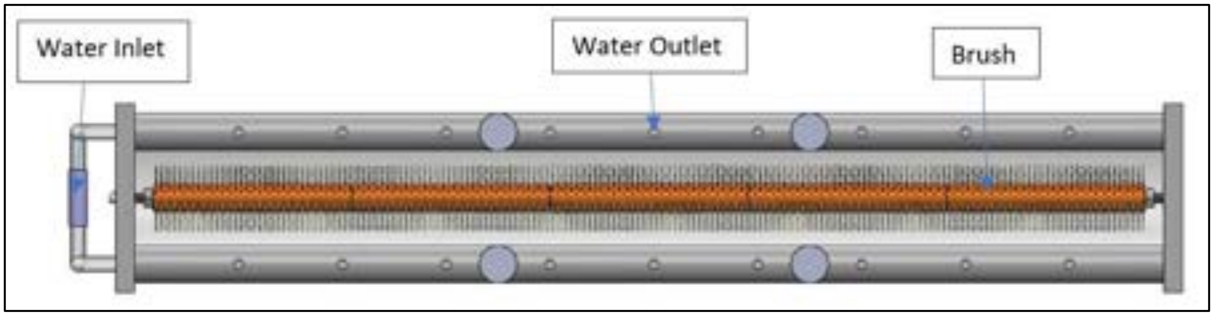


Figure 11: Bottom View of the Upper Arm

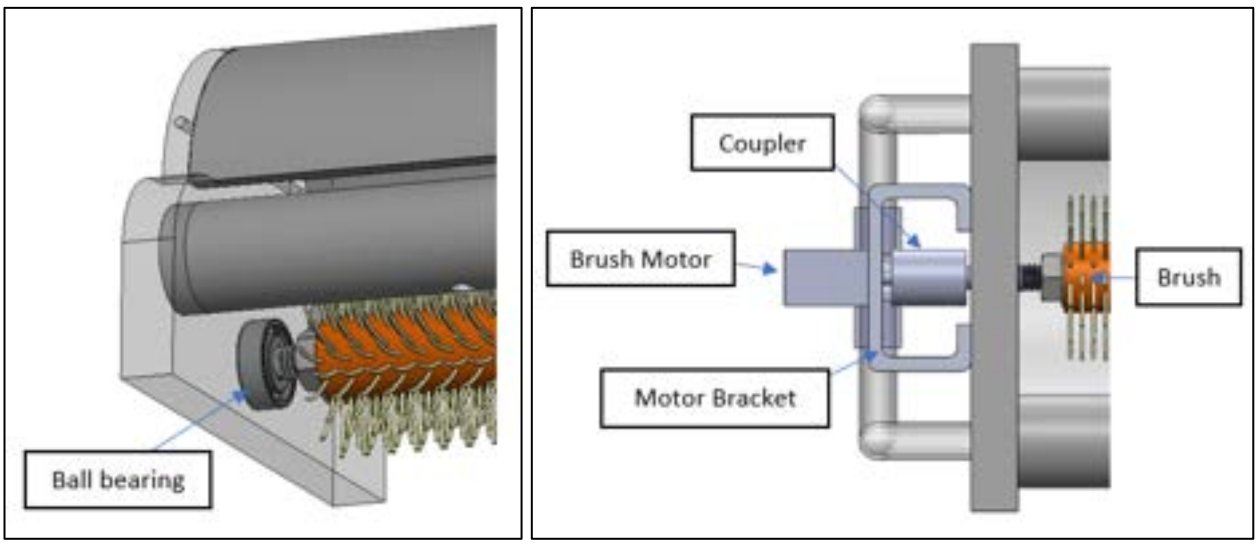


Figure 12.1: Ball Bearing Embedded Inside the End Plate (Left)
Figure 12.2: Main Connection on One End of the Upper Arm (Right)

2.3 Literature Review of Analysis/Optimisation Methods Applied

Given that prototype A was the first prototype, there were many design aspects to consider. To give structure to the process of (1) Deciding on the General Design Concept and (2) Discerning the Effect of Design Improvements, Multi-Criteria Decision Making (MCDM) methods were employed. Specifically, a Pugh's Matrix Analysis (PMA) was applied in the selection process of the General Design Concept and a Failure Modes Effects Criticality Analysis (FMECA) was employed in the process of making incremental improvements to Prototype A.

2.3.1 Pugh's Matrix Analysis

PMA is an MCDM method that uses pairwise comparisons to qualitatively evaluate alternate designs (Burge, 2009). As such, it has been applied as a tool for selecting between different design options. For instance, Thakker et al. (2008) utilised PMA for selecting and optimising the hub of impulse turbines and Renzi et al. (2013) proposed the application of PMA for the optimisation of product development. Furthermore, in the design of an electromagnetic servo brake, Villanueva et al. (2016) applied PMA extensively in determining product specifications, conceptual design and detailed design.

According to Burge (2009), PMA is comprised of five steps which are summarised in Table 1. By completing the pairwise comparison using identified selection criteria, all design options may be compared with the baseline option. This provides a more objective framework for the evaluation of design options and enables the selection of an optimal design concept.

Table 1: PMA Process (Burge, 2009)

Step 1:	Identify and Define Selection Criteria
Step 2:	Select Baseline Design Option
Step 3:	Compare Conceptualised Design Options Against Baseline Design Option
Step 4:	Generate Total Score
Step 5:	Decide and Justify Design Option

In selecting criteria, Frey et al. (2007) affirm the importance of ensuring that selected criteria are useful in discriminating superior options from poorer ones. In other words, if all design options fulfil a criterion to an equivalent extent, that specific criterion should be excluded from the analysis. Additionally, Frey et al. (2007) also suggest that criteria should not be difficult to evaluate precisely. Lastly, Burge (2009) emphasises the importance of ensuring that selected criteria are important to key stakeholders to ensure the analysis conducted is meaningful.

In the selection of criteria weight, several approaches can be taken. They include the use of (1) an Absolute Scale, (2) a Sales Driven Scale or, (3) the Analytic Hierarchy Process (Burge, 2009). The absolute scale considers the subjective importance key stakeholders place on each criterion. Followingly, criteria that stakeholders view as being more critical will be weighted higher and vice versa. The sales driven scale considers the effect that the fulfilment of the criteria would have on sales. Such an approach assigns a high weight to a criterion if its fulfilment leads to an improvement in sales or if its lack of fulfilment results in a large loss of sales (e.g., losing sales due to a lack of safety). Lastly, Analytic Hierarchy Process (AHP) can be used to weigh criteria based on their relative importance (to each other) through a series of pairwise comparisons. However, it is worth noting that such an approach may be time consuming if there are many criteria.

Lastly, the selected baseline concept should be a market leader (Frey et al., 2007). Doing so ensures that the baseline concept is successful in fulfilling market needs. Furthermore, given its prominence as a market leader, it tends to be well understood, which eases the process of pairwise comparison in PMA.

2.3.2 Failure Modes Effects Criticality Analysis

As its name suggests, FMECA involves two steps of analysis. The first is the performance of a Failure Modes Effects Analysis (FMEA) and the second is the completion of a Criticality Analysis (CA). This two-step process is well established as an effective means of identifying the cause and effect of failure modes. It was first conceptualised in the Aerospace Industry in the 1950s and has since been applied across a multitude of engineering subspecialties (Chen et al., 2012). Notably, it has been applied in the design process to improve conceptual reliability. For instance, Goo et al. (2019) applied FMECA to the shipbuilding design process and Catelani et al. (2011) proposed its use in the assessment of Photovoltaic Modules to eliminate failure modes in the design process.

In conducting an FMEA, Failure Modes first need to be identified. Examples of common failure modes include cracks, deformation and incorrect hole dimensions. Failure effects are then defined based on their effect on system performance. The analysis that follows should then examine the cause of the identified failure modes to create control measures to either (1) prevent the failure mode from occurring or (2) enable early detection of the failure mode (Lipol & Haq, 2011).

After completing the FMEA, a criticality analysis needs to be conducted. To that end, an RPN needs to be calculated. To accomplish this, each failure mode needs to be assigned a score for its Severity (S), Occurrence (O) and Detection (D). Typically, the scores assigned range from 1 to 10. After S, O and D have been assigned a score, the scores are multiplied together to generate an RPN for the specific failure mode (Carpitella et al., 2018). In Design FMECA, the aim is to introduce a series of control measures to reduce the RPN of each failure mode to improve the reliability of the design. Table 2 below illustrates how the RPN may be generated for a fault.

Table 2: Example FMECA

Failure Mode	Effect	S	O	D	RPN (S´O´D)
Mode A	Effect B	9	5	1	9´5´1 = 45

However, the FMECA has limitations in its application. Lipol and Haq (2011) note that the scores assigned for severity, occurrence and detection are ordinal numbers. However, the process of calculating the RPN involves multiplication. Given that multiplication is not a valid operation for numbers on an ordinal scale, rank reversal may occur. In such a scenario, less important failure modes may mistakenly receive greater attention than more important failure modes.

2.4 Outline of Applied Analysis/Optimisation Methods

In determining the general design, a PMA was conducted. The four designs under consideration were (1) Fixed Brush Arm - Mounted to Rover, (2) Fixed Brush Arm - Mounted to Rails, (3) Moving Brush Arm - Jointed Extending Arm and (4) Moving Brush Arm - Tensile Cable. These designs are illustrated in Figures 13.1-13.4 below. A blow-up of the joint of the Moving Brush Arm - Jointed Extending Arm can be found in Appendix B.



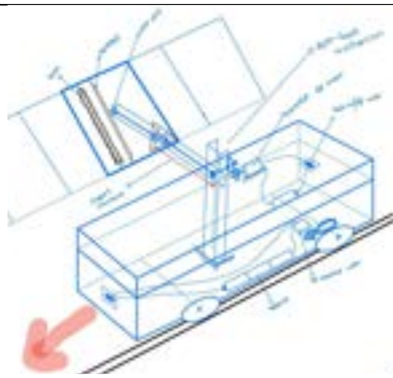
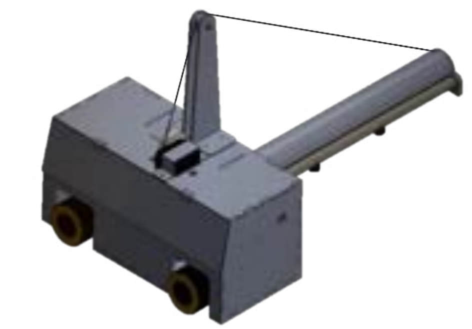



Figure 13.1: Fixed Brush Arm - Mounted to Rover (hyCleaner, 2022) (Top Left)
Figure 13.2: Fixed Brush Arm - Mounted to Rails (Grando et al., 2017) (Top Right)
Figure 13.3: Moving Brush Arm - Jointed Extending Arm (Bottom Left)
Figure 13.4: Moving Brush Arm - Tensile Cable and Lower Platform (Bottom Right)

2.4.1 Pugh's Analysis of Solar Panel Cleaner Designs

Regarding the selection of criteria, existing literature emphasises the importance of ensuring that the criteria are relevant to stakeholders and that it is discriminating. Taking this into consideration, the criteria applied include (1) Dynamic Response, (2) Cost, (3) Weight, (4) Ease of Maintenance and (5) Ease of Implementing Automation. To ensure that the selected criteria are relevant to stakeholders, they were adapted from the design specifications that were established in Deliverable 3 (using market research). Furthermore, through trial and error, it was determined that these criteria were sufficiently discriminating.

For the selection of the baseline design, given that existing literature endorses the use of market leaders, the hyCleaner Black Solar was chosen as it has achieved commercial adoption globally. As illustrated in Table 3, it makes use of a fixed brush arm system that is mounted to a rover to clean solar panels. Additionally, for the selection of weights, the AHP method as proposed by Saaty (2004) was applied. The application of the AHP method can be found in Appendix A.

Table 3: PMA of Solar Panel Cleaner Designs

Evaluation Criteria	Weight Factor	Alternative Cleaning Designs							
		Baseline: Fixed Brush Arm (Mounted to Rover)		Fixed Brush Arm (Mounted to Rails)		Movable Brush Arm (Jointed Extending Arm)		Movable Brush Arm (Tensile Cable and Lower Platform)	
		Rating	Weight	Rating	Weight	Rating	Weight	Rating	Weight
Dynamic Response	0.489	0	0	-1	-0.489	1	0.489	1	0.489
Cost	0.178	0	0	-1	-0.178	0	0.000	0	0.000
Weight	0.178	0	0	-1	-0.178	1	0.178	1	0.178
Ease of Maintenance	0.098	0	0	-1	-0.098	-1	-0.098	0	0.000
Ease of Implementing Automation	0.059	0	0	1	0.059	1	0.059	1	0.059
Score					**-0.882**		**0.627**		**0.725**

From conducting PMA, the movable arm designs compare favourably to the baseline design. While ease of maintenance may suffer due to the increased stress placed on the moving components, the improvements in dynamic response and greater ease of implementing automation more than make up for it. Examining both movable brush designs, the design that makes use of the tensile cable and lower platform performs better. By splitting the load between a cable and lower platform, the stresses are less concentrated, allowing for the cleaning arm to move into the position faster. Consequently, the Movable Brush Arm (Tensile Cable and Lower Platform) design was adopted for Prototype A.

2.4.2 Failure Modes Effects Criticality Analysis (FMECA)

With the general design identified, incremental improvements to the reliability of the Solar Panel Cleaner need to be made to further optimise the design. To facilitate this process, a FMECA was conducted. Through the analysis, it was found that the failure modes either stemmed from the electrical system of the cleaner or were a result of structural shortcomings. An example of an identified failure mode was the possibility of the lower arm cracking the base plate. The effect of such a failure mode would be the reduction of the lifespan of the Solar Panel Cleaner and an increase in maintenance. While such a failure mode would reduce the cleaner’s ability to operate in the long term, in the short term, the cleaner would still be able to function. As such, severity is given a moderate score of five. Detection is assigned a moderate score of three as while the cracks can be observed on the external surface of the cleaner, they cannot be observed unless the rover is turned over. Lastly, the occurrence is given a low score of two as the cable linked to the T-Structure removes a significant amount of the load. The other failure modes and their corresponding RPN are detailed in Table 4.

Table 4: FMECA of Initial Solar Panel Cleaner Design

System	No.	Failure Mode	Effects	S	O	D	RPN
Electrical	E1	Battery Overheats or Battery Receives Water Damage	Rover has no power and is unable to function.	10	2	4	80
	E2	ESC receives Water Damage	Motors are unable to receive the signal to actuate and rover is unable to function.	10	2	4	80
	E3	Motor Overload	Motor is unable to actuate, and rover is unable to function.	10	3	4	120
Structural	S1	Rover Falls Over	Rover has no self-righting capability and hence is unable to function without human intervention.	8	3	1	24
	S2	Lower Arm Cracks Base Plate	Lifespan of the rover is reduced, and more frequent maintenance will be required.	5	3	3	45
	S3	Lower Arm Breaks Base Plate	Lower arm detaches from the rover and hence the cleaning arm is no longer in contact with the solar panel.	10	2	1	20
	S4	Upper Arm Detaches from Lower Arm	Upper arm can no longer clean solar panel.	10	3	1	30

To improve the reliability of the cleaner, the following measures (see Table 5) were employed to reduce the occurrence of failure modes and improve their detectability.

Table 5: Implemented Improvements and its Effect on Failure Modes

Failure Mode	Implemented Improvement	Effect on Occurrence and Detection
E1, E2, E3	Addition of maintenance opening (covered by a lid) by the Side of the Cleaner.	Electrical components can be accessed and examined without having to disassembly the entire rover. This improves detection.
E1, E2	Battery and ESC is mounted on the wall.	In the event of water pooling in the rover, the battery and ESC would have minimal contact with the water.
E3	Use of Mecanum wheels driven by four motors.	The increase of motors used (from two to four) reduces the average motor load.
S1, S4	Cleaning arm weight is reduced by changing steel rod for an aluminium one. Cleaning arm PVC case is reduced in thickness. Electrical components are shifted to the side of the chassis opposite to the cleaning arm.	The reduction in weight places less stress on the connection between the lower and upper arm. This also brings the centre of gravity closer to the centre of the rover. The shift of position of electrical components further improves the centre of gravity.
S2, S3	Base plate thickness is increased from 6mm to 8mm.	The thicker base plate reduces the formation of cracks by reducing the stress experience by the base plate.

With the implementation of improvements in Table 5, the FMECA now yields a lower RPN as demonstrated in Table 6 below. This demonstrates an improvement in the design and reliability of the Solar Panel Cleaner.

Table 6: FMECA of Final Solar Panel Cleaner Design

System	No.	Failure Mode	Effects	S	O	D	RPN
Electrical	E1	Battery Overheats or Battery Receives Water Damage	Rover has no power and is unable to function.	10	2	2	40
	E2	ESC receives Water Damage	Motors are unable to receive the signal to actuate and rover is unable to function.	10	2	2	40
	E3	Motor Overload	Motor is unable to actuate, and rover is unable to function.	10	1	2	20
Structural	S1	Rover Falls Over	Rover has no self-righting capability and hence is unable to function without human intervention.	8	2	1	16
	S2	Lower Arm Cracks Base Plate	Lifespan of the rover is reduced, and more frequent maintenance will be required.	5	2	3	30
	S3	Lower Arm Breaks Base Plate	Lower arm detaches from the rover and hence the cleaning arm is no longer in contact with the solar panel.	10	1	1	10
	S4	Upper Arm Detaches from Lower Arm	Upper arm can no longer clean solar panel.	10	2	1	20

2.5 Main Innovations of Prototype A

For prototype A there are 2 main innovations. The first innovation is that there is no longer any need to have any human interaction when the solar panel is being cleaned on a floating solar farm. As the prototype will be operating on floating solar panels, eliminating the need for a human to stand on the walkways in between the solar panels would mean that the solar farm does not become unsteady with the weight of a human. The walkway only must support the weight of the solar panel cleaner which is 1/7 of the average human weight.

The second innovation is eliminating the need for any pre-existing infrastructure to be built on the solar panels. This reduces the overall capital investment that the design requires.

Figure 3.1 shows an example of a cleaner that requires rails to be installed on both sides of the solar panel along the entire length. In comparison, prototype A (see Figure 14) moves independently along the walkways in between the solar panels and does not require any such infrastructure.

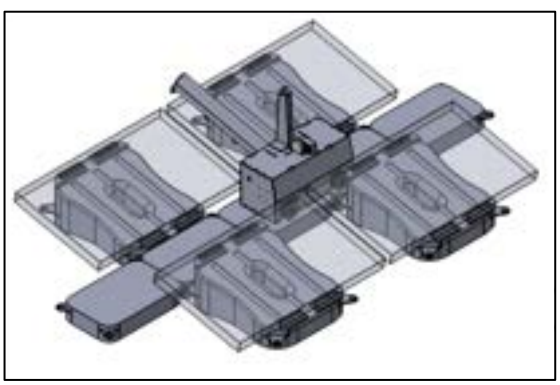


Figure 14: Prototype A Modelled onto the Solar Farm Walkway

2.6 Suitability of the Design for Manufacture and Assembly

The section discusses the suitability of SPC design in the manufacturing and assembly session as well as concluded the positive actions that have been done and further improvisation steps that could be taken. The discussion done for every sub-assembly was based on the observation when assembling the device in the workshop.

1) Rover Chassis

Relevance Issue	What worked well?	What can be improved?
1. Changed chassis' material from PVC due to the difficulty in the manufacturing process. 2. One of the parts broke and required reattachment.	1. The dimensions of the parts manufactured perfectly fit one another. 2. The spacing created was sufficient to mount the other sub-system to the chassis.	1. Use a better material that has high specific strength and stiffness (FRP). 2. Improved the attachment methods by using a more reliable alternative (welding)

2) Lower Arm

Relevance Issue	What worked well?	What can be improved?
1. Changed the entire lower arm parts' material from steel to aluminium to reduce the weight. 2. Lead screw sizing problem that led to remodification of other manufactured parts and hindered the assembly steps. 3. Remanufactured the moving short arm to provide compartments for lead screw nut, linear bearings, and limit switches. 4. Insufficient motor power to power the lead screw.	1. The tolerances in the manufactured parts are well-annotated, leading to smooth assembly steps. 2. The ball bearing from the supplier fits tightly in the designated shoulder to allow for smooth leadscrew rotational motion. 3. The attachment points are sufficient to mount the entire lower arm to the rover chassis.	1. Remove any sharp features in the manufactured parts to prevent unwanted injuries in the assembly session. 2. Use a higher motor power and take into consideration the total weight of components that will be moved.

4) Upper Arm

Relevance Issue	What worked well?	What can be improved?
1. The brush bolt was not compatible with the motor and needed to be remanufactured. 2. Presence of exposed slit on the upper arm that required part remanufacturing. 3. Problem in the attachment points to the upper arm holder on the lower arm. Needed to enlarge the hole and drills new holes.	1. The tube for water inlets fits well in the allocated spaces. 2. The spacing of the entire upper arm was measured accurately and prevent it from hitting the lower arm and chassis frame. 3. Good selection of motors to power the brush bolt and provide the preferred spinning speed. 4. The brush is well attached to the brush bolt.	1. Select a better candidate material than PVC, which is lighter and stronger. 2. Use an attachment method than may work well in wet conditions. 3. Choose a higher quality brush for a more effective cleaning section.

5) Winch mechanism

Relevance Issue	What worked well?	What can be improved?
1. Using of water jet cutting process hinders the assembly process since it took a long time to manufacture the parts.	1. The overall winch mechanism is light in weight (easy for assembly) as it needs to be mounted on top of the rover.	1. Replace the fishing string with a proper alternative to lift the upper arm. 2. Propose a more suitable machining process for the manufactured parts.

2.7 Device Performance During Testing

To ensure that the risk of a failed prototype A was minimised, multiple stages of testing were conducted. The first stage involved the testing of individual electronic components to root out any electronics that failed. In this stage, none of the components failed. Afterwards, the subsystems mentioned in section 2.6 were assembled to a point where they were functional and were tested separately; the chassis was able to travel and rotate with ease, the lower arm was easily able to travel up and down, and the upper arm brush was able to rotate at a high rate and also dispense water.

Once the assembly of the SPC was complete, two tests were performed: once without water, and once with water. In the test without water, it was confirmed that the servo winch was able to withstand the full weight of the upper arm and would automatically perform corrections. The uneven weight distribution did occasionally cause the left wheels to slip although when the upper arm was fully brought up by the winch this did not happen.

Additionally, the lower arm could move the upper arm up with ease, but the lower arm struggled to move the upper arm down.

In the test with water, a wooden frame with a thin sheet of Perspex was used to simulate a solar panel. A problem arose whereby depending on the angle of contact between the Perspex and the brush, the upper arm motor would sometimes struggle to spin, resulting in a failure to clean. Another problem that arose was the Perspex itself; the Perspex was too thin and would bend whenever the upper arm was positioned on top, so the brush occasionally lost contact with the panel, which led to a poorer clean. Finally, the water being pumped into the upper arm had insufficient pressure. As such, water was not able to reach the top of the brush arm.

Despite these problems, the SPC was able to conduct all the necessary operations remotely to clean the Perspex with little to no assistance. The before and after images of the SPC cleaning the Perspex are shown in Figures 15.1 and 15.2.

Figure 15.1: The Perspex "Solar Panel" Before Cleaning (Left)
Figure 15.2: The Perspex "Solar Panel" After Cleaning (Right)

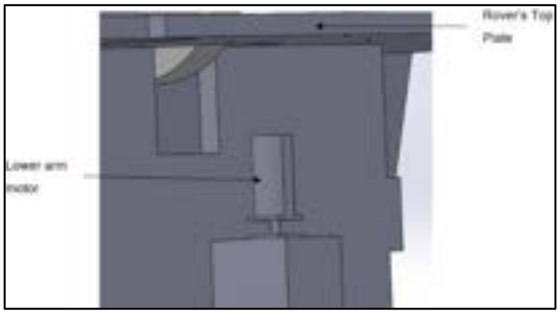
3 Outline of Prototype B

3.1 Outline of Opportunities for Design Improvements

Prototype A has proved its ability to clean solar panels. However, the solar panel cleaner may require some modifications to meet the demand from consumers. With the evolving technologies, the consumers may expect an autonomous SPC with high cleaning qualities and speed. There are a few areas of improvement to achieve these expectations.

3.1.1 Bigger Space for More Powerful Electronic Components

Due to the small size of prototype A, there is limited space for the installation of motors as shown in Figure 16.1 and Figure 16.2. As such, smaller-sized motors with less torque were selected. However, with an increase in space, larger motors that generate greater torque can be used. This would result in faster movement of the rover and faster cleaning speeds.



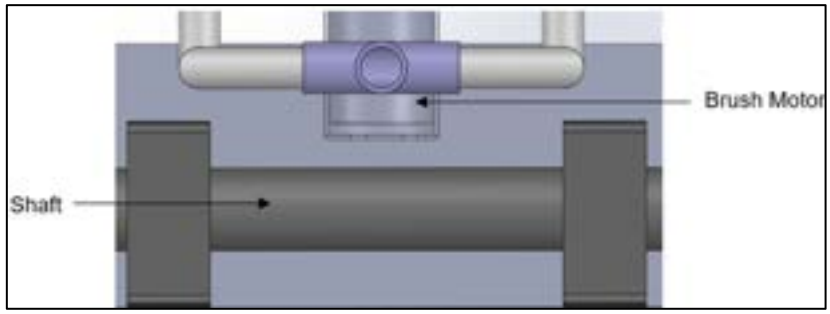


Figure 16.1: Space between Lower Arm Motor and Rover's Top Plate
Figure 16.2: Space between Brush Motor and Shaft in the Lower Arm

3.1.2 Brush with Bristles

Prototype A uses a paint roller as the brush in the cleaning arm which is limited in its effectiveness. A brush with bristles can instead be used to remove more unwanted residues from the surface of the solar panel.

3.1.3 Automation

Prototype A lacks sensors and actuators which would enable it to respond to changes in the environment. With these components installed, the rover will gain the ability to autonomously navigate the entire solar farm. Moreover, sensors and actuators may also be used in the lower arm and in the winch, to enable the adjustment of the position of the cleaning arm based on the tilt of the solar panel. The modified lower arm and winch will be very helpful as it would not require an operator to observe the surroundings of the solar panel cleaner to manually adjust the position of the cleaning arm, leading to a smoother operation of the SPC. Another electronic subsystem can be added to the cleaning arm to switch between power and idle mode, resulting in a more efficient cleaning process.

3.1.4 Water Distribution System

The flow rate and pressure of the water distribution system can also be optimised. By using nozzles, the cleaning performance will be enhanced as the flow rate and pressure of the water may improve the cleaning capabilities of the rover.

In this report, the optimisation of the rover for automation and optimising the water distribution system will be explored in greater detail.

3.2 Literature review of analysis / optimisation methods applied to Prototype B

3.2.1 Automated Brush Cleaning Methods

There are three main types of SPC mechanical brushing systems: wiper blade, rolling brush, and dry cleaning (using silicon rubber foam brush). It is important to evaluate all mechanisms to see if there is value in changing the cleaning method of Prototype A (rolling brush).

The wiper blade system acts similarly to the window wiper of a car; a wiping blade connected to a servo motor with an electrostatic cloth to help remove small particles. Librandi et al. (2012) designed an SPC which utilised this technology whilst also implementing a dust detection system that would allow the SPC to save energy by determining the optimal time to activate the cleaning system. This method is autonomous, easy to manufacture, and cheap to produce however applying this stationary system to the current robot design which will be traversing along an offshore solar panel farm will prove difficult and the design of the rest of the robot would most likely change with its implementation. Additionally, there are issues with the top corners of the solar panel not getting cleaned effectively.

The rolling brush system has currently been adopted in Prototype A, due to its compatibility with the rover, whereas a wiper system would need near perfect contact with the solar panel surface. Figure 17.1 shows an example of a rolling brush mechanism used for cleaning solar panels, an advantage of this system is the ease of combining the brushing mechanics with pressurised water outlets to improve the cleaning efficiency, as they can be placed along the brush support. However, this system requires more energy than other methods such as the wiper blade, hence there is a lower overall efficiency increase of the solar panel.

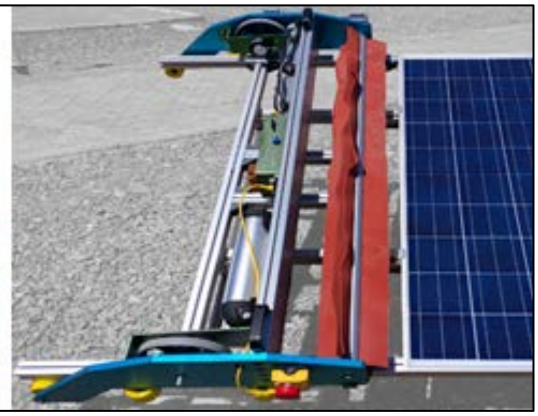



Figure 17.1: Mounted rolling brush solar panel cleaner (Parrott et al., 2018) (Left)
Figure 17.2: Silicone rubber foam brushing device (Manju et al., 2018) (Right)

The third and final automated cleaning method which was reviewed uses silicone rubber foam flaps attached to an aluminium core, as seen in Figure 17.2. This device excels in dry situations (i.e., no water nozzles). It helps with the cleaning process as the removal of the debris relies on the friction generated between the silicone rubber and the solar panel surface. This is a great option for dry conditions, especially from a sustainability standpoint as it tackles the issue of using a water pump. However, as the solar panel farm considered for this design is specifically located on water, it is expected that waves will splash on the solar panels which would reduce the cleaning efficiency of the silicone rubber brush.

3.2.2 Pressurised Water Nozzles

There are many advantages to using water nozzles to clean solar panels, firstly the water helps remove debris through water runaway but also softens harder objects such as animal waste and crystalised salt which will be expected on offshore solar panel farms. Furthermore, when the water evaporates, it removes energy from the solar panel surface hence cooling the system down. This cell temperature reduction increases the efficiency of the solar panel as there is a power output loss of about 0.4%/°C -0.5%/°C for monocrystalline and multi-crystalline silicon PV cells (Abdolzadeh and Ameri, 2009). It has been shown that water is the most effective cooling technology when it comes to increasing the efficiency of solar panels by Alami, A (2014), who conducted experiments on solar panels which resulted in a 19.4% power increase when allowing a thin film of water to evaporate during a 2-hour test period.

Prototype A includes a water outlet; however, this is a very simple system where holes

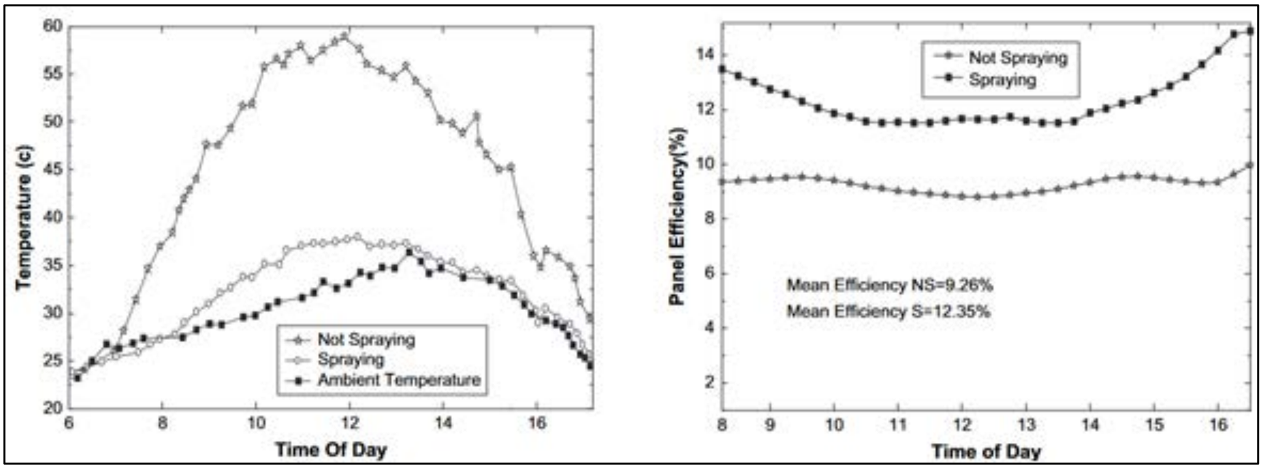


Figure 18: Comparison of cell temperature and efficiency with and without water spraying (Abdolzadeh and Ameri, 2009)

are drilled into the side structures of the brush support. Hence, water will trickle out onto the surface of the solar panel and aid the cleaning process. There is a big issue here as effective temperature reduction of the solar panel requires a thin water layer across the whole surface, which may be difficult to achieve through a system of a low-pressure water outlet alone. Another experiment was conducted by Abdolzadeh and Ameri (2009), where they collected data on the effect of water spraying on the temperature of the PV cell along with its efficiency, shown in Figure 18. There is a mean efficiency increase of around 3% when water spraying, on a large-scale solar panel farm, which is what the project focuses on, this is a significant difference. Therefore, not only should cleaning efficiency be the aim of the SPC, but also temperature reduction through water cooling means and Prototype B should include an improved method of water distribution.

There are multiple research papers that investigate the removal of soil layers (e.g., animal waste on a solar panel) which give great insight into the effectiveness of high-pressure jet spraying. Fernandes and Wilson (2022) compared various computational models including a fully coupled CFD model which predicts the motion of the fluid and soil interaction of three soil layers of differing thickness. With comparison to experimental data, a conclusion was made that, although some models were able to accurately simulate certain aspects of the soil-liquid interaction, no researched model could accurately describe the cleaning experiments. Hence, it is not feasible to simulate the effect of implementing Prototype B with high pressure nozzles.

El Zohbi et al. (2022) investigated (using CFD) the effects of different jet nozzle geometries and locations on fluid ejectors, which are used in industrial water heating. Figure 19 shows the configurable nozzle setup which they used in their computational experiment. Through analysing flow data, they were able to configure a nozzle geometry with optimal performance through the identification of unfavourable flow characteristics, such as the formation of circulation regions located in the throat which led to flow blockages. Similar simulations could be conducted on the nozzles which will be implemented in Prototype B to obtain a geometry with ideal pressure output.

3.2.3 Using CFD to Simulate Different Nozzle Scenarios

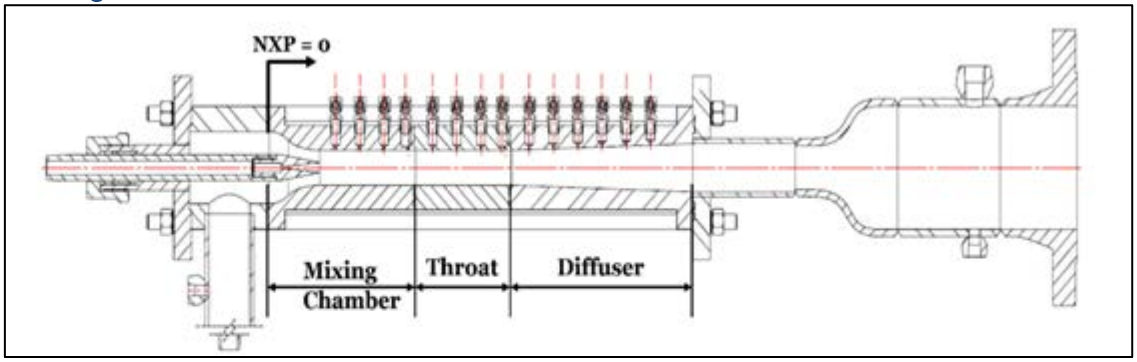


Figure 19: Schematic of configurable nozzle setup (El Zohbi et al., 2022)

CFD can be utilised to obtain flow data of different nozzle arrangement scenarios on the solar panel cleaner without the need to carry out experimental testing, hence saving time and money. Even if experimental testing was to be used, simulation results provide a good indication on what scenarios to focus on. The motion of viscous fluid (in this situation; water) can be described by solving partial differential transport equations known as 'Navier-Stokes equations', seen in Equations 1 and 2. The conservation of mass and momentum is expressed in these equations; however, it is not possible to analytically solve these problems in most situations. Hence, Computational Fluid Dynamics was created to obtain approximate, computer-based solutions to the Navier-Stokes equations.

Continuity:

$$\frac{\partial \rho}{\partial t} + \frac{\partial \rho U_i}{\partial x_i} = 0 \qquad \text{---- (1)}$$

Momentum:

$$\frac{\partial \rho U_i}{\partial t} + \frac{\partial \rho U_i U_j}{\partial x_j} = \frac{\partial P}{\partial x_i} + \frac{\partial}{\partial x_j}\left(\mu \frac{\partial U_i}{\partial x_j}\right) \qquad \text{---- (2)}$$

CFD works by changing the continuous domain of a fluid problem with a discretised domain through the generation of a grid. From this, flow data is calculated at grid points and those values are then interpolated over the cells through different schemes to solve the flow behaviour. Using CFD could help optimise the solar panel cleaner via modelling the flow of nozzles with different geometries or flow rates and analysing the data. However, it is important to ensure that the created model is accurate. Firstly, the flow boundary conditions must be adequately described for the inlet conditions as well as describing the contact between the flow and the pipes carrying the fluid. Furthermore, the mesh needs to be suitably chosen as the finer the mesh the more accurate the results, however too fine a mesh becomes computationally expensive and simulation time would exceed what is necessary. A mesh sensitivity study may be adopted which compares the increase in data accuracy with mesh refinement and simulation time. The selected grid would show that the increased accuracy through any further mesh refinement is negligible.

3.2.4 Need for Integrating Automation

There is a great need to reduce the need for human contact with offshore solar panel farms, firstly a reduction in labour needs (no SPC operator on site) reduces the cost of employing this type of cleaning technology. Furthermore, the more human interaction is needed on an offshore solar farm, the larger the risk of injury (drowning, electric shock, injury to moving objects). This is a serious matter as workers may work in solitude with no nearby medical points. To remove the need for a human operator for the SPC which has been described in this report, the robot must have a means of navigating the offshore solar farm by itself.

'Line following robots' are often used in medical and inventory management systems, which utilise a light dependent resistor sensor to follow a predetermined line on the ground (Punetha et al., 2013). The sensor detects the level of reflection of whatever it is pointing at and adjusts the resistance accordingly. Hence, a contrast of colour must be used for the line and the surrounding floor. For example, if the robot is traversing over a white terrain with a black line in the centre, the sensor would decrease the resistance to a minimum whilst over the black line (which reflects the least light) and increase to a maximum when sensing the white colours (which reflects the most amount of light). This signal is then sent to a microcontroller which determines the course of action, as shown in Figure 20.

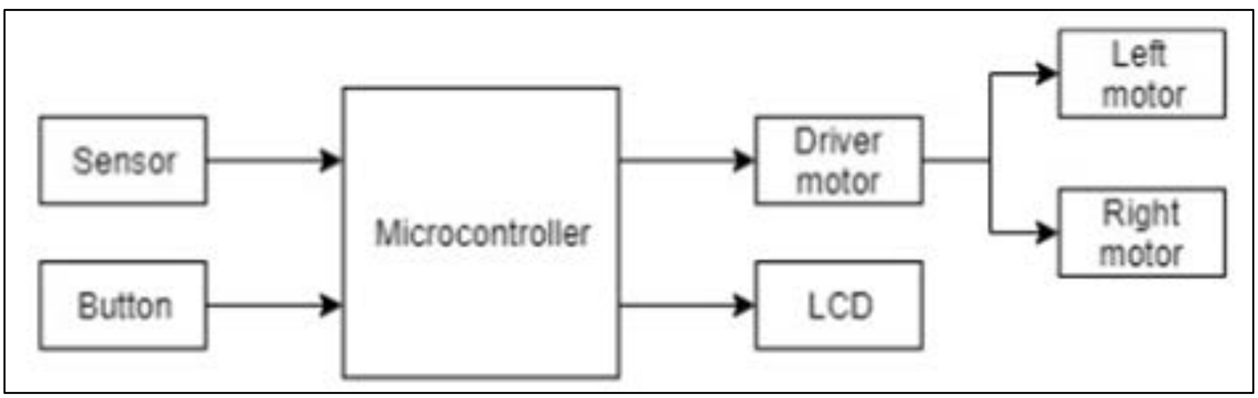


Figure 20: Line following robot block diagram (Gorla et al., 2012)

Due to the length of the SPC described in this report, it would be necessary to have multiple light-dependent resistor sensors on the robot to ensure that both the rear and front halves are simultaneously following the prescribed line.

3.3 Optimisation analysis

3.3.1 - CFD Nozzle Analysis

3.3.1.1 Setup

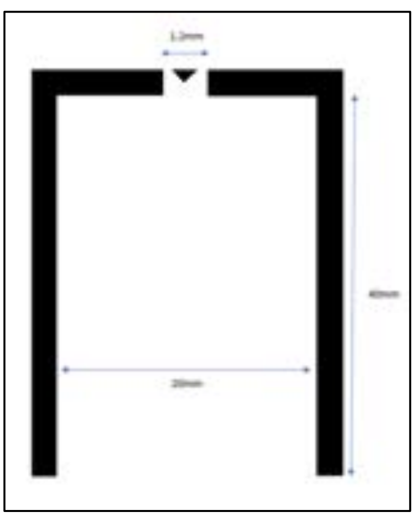
From the literature review, it is clear to see that adding nozzles to the design could greatly increase the cleaning capacity of the rover. To show that this would be an improvement, a nozzle was chosen to be analysed using CFD. CFD was used to decide how many nozzles would be required and what the ideal flow rate for cleaning would be. By changing the inlet velocity of the nozzle on CFD, the flow rate would also change, and it would indicate a varying number of nozzles. A smaller inlet velocity would indicate a greater number of nozzles because the overall flow rate would be split over more nozzles, a larger inlet velocity would therefore indicate a smaller number of nozzles.

When doing the CFD analysis, several assumptions were taken:

1. The overall flow rate of the inlet was split equally over all the nozzles independent of where they are on the upper arm.
2. Although a typical nozzle incorporates air into the system, the domain that the nozzle was part of was assumed to be entirely water
3. A 2D slice of the nozzle was taken instead of a full 3D model

As a control, an analysis of the pipe with no nozzle was done. This allows for a comparison of any results that are collected. Varying flow rates were used for this, shown in Table 7.

The nozzle that was chosen to be analysed was an adjustable brass misting nozzle shown in Figure 21.1. Each nozzle has a flow rate between 0.2 and 0.7 Litres per minute, the length of the nozzle is 4cm and the width is 2cm with a nozzle diameter of 1.2mm. This was modelled using Ansys. The shape of the flow directors was changed to see if there was any difference. Figure 21.2 shows the different shapes that were analysed. The first shape was a standard right-angle triangle from the brass nozzle, the second was an isosceles and the last shape was a flat rectangle.



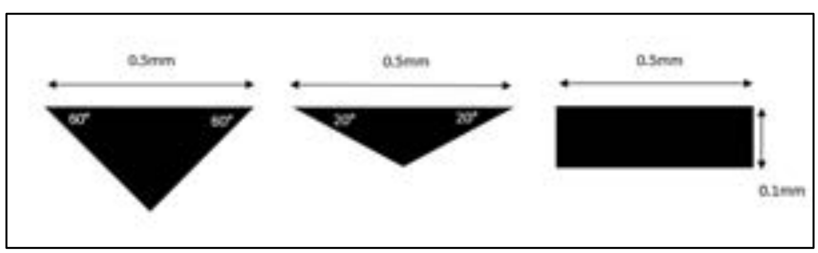


Figure 21.1: Diagram of the Misting Nozzle (Left)
Figure 21.2: Diagrams of the Different Nozzles (Right)

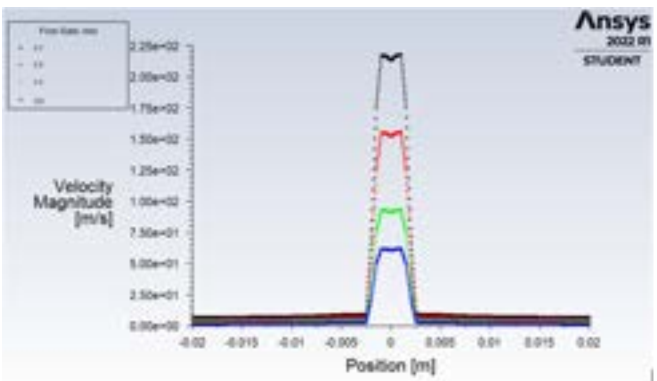
Flow rates of 0.2, 0.3, 0.5 and 0.7 Litres/ minute were used and then converted into the required inlet velocity for this nozzle. The flow rates and velocities are shown in Table 7.

Table 7: Various Flow Rates and Velocities

Flow rate/min	Flow rate/s	velocity m/s
0.2	0.003333333	10.61032954
0.3	0.005	15.91549431
0.5	0.008333333	26.52582385
0.7	0.011666667	37.13615339

3.3.1.2 Results

No Nozzle:



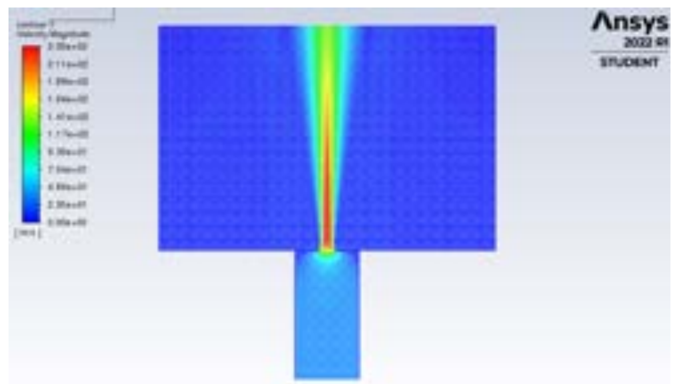
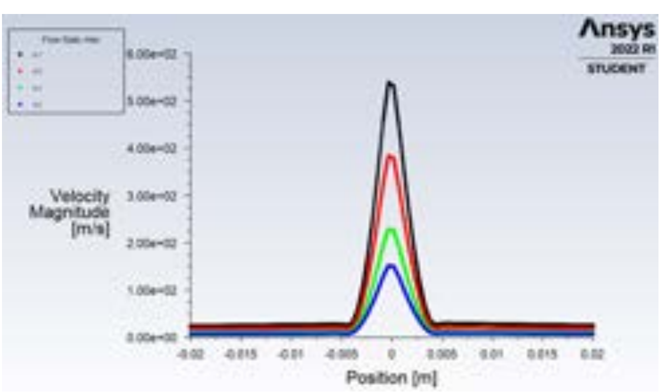


Figure 22.1: Velocity Magnitude and Position Plot with No Nozzle (Left)
Figure 22.2: Graphical Representation of the Velocity Plot with No Nozzle (Right)

These are the results for the setup on prototype A. Figure 22.1 shows a plot of the velocity magnitude at 2cm from the exit. This is the distance between the solar panel and the nozzle should be when it is being tested. The graph shows that the higher the inlet flow rate, the higher the velocity at 2cm away from the exit. From a hole that has a diameter of 5mm, the peak width of the flow is approximately 3mm. This peak diameter does not change depending on the flow rate, the width is constant.

Nozzle 1:



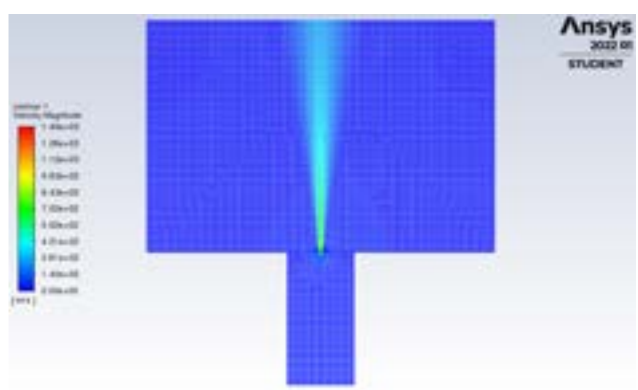
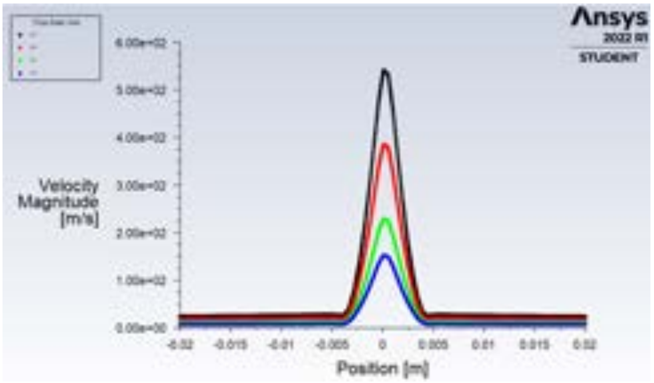


Figure 23.1: Velocity Magnitude and Position Plot with Nozzle 1 (Left)
Figure 23.2: Graphical Representation of the Velocity Plot with Nozzle 1 (Right)

These are the results for the first nozzle that was simulated. Figure 23.1 shows the velocity magnitude 2cm from the nozzle. It is clear to see that at a higher flow rate, the velocity is larger. Each of the flow rates follow the same profile across the line. The width of the flow is also constant with the largest width being 10mm. This is independent of the flow rate.

Nozzle 2:



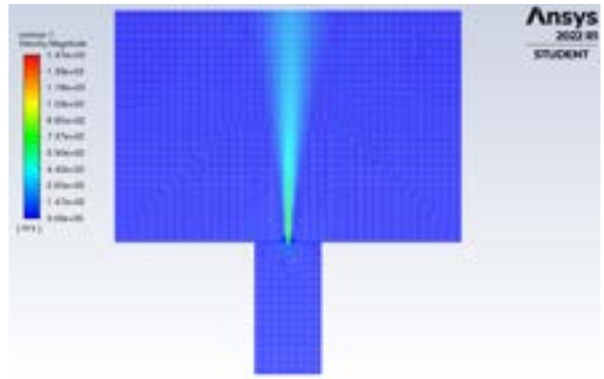
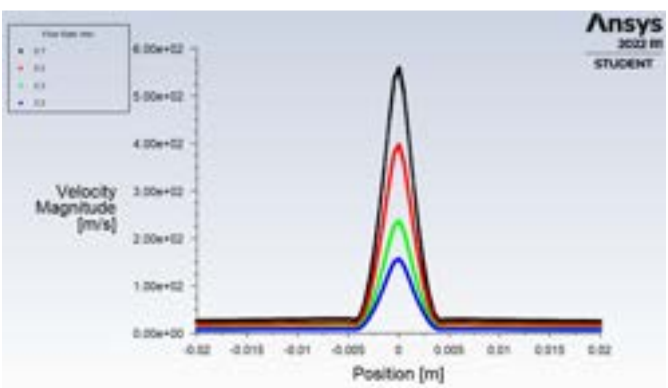


Figure 24.1: Velocity Magnitude and Position Plot with Nozzle 2 (Left)
Figure 24.2: Graphical Representation of the Velocity Plot with Nozzle 2 (Right)

Nozzle 2 follows the same profile as Nozzle 1, the velocity across the line is the same and the peak velocities are also equal. The maximum width of the flow is also the same at 10mm**.**

Nozzle 3:



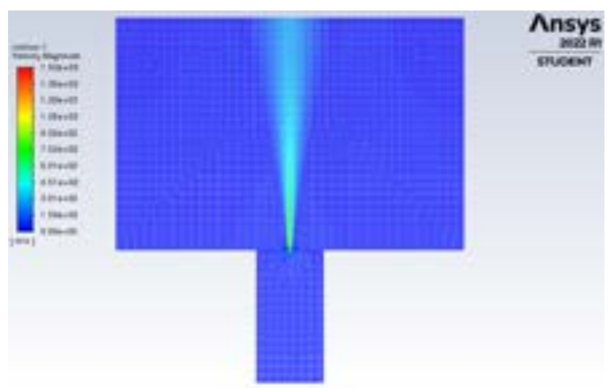


Figure 25.1: Velocity Magnitude and Position Plot with Nozzle 3 (Left)
Figure 25.2: Graphical Representation of the Velocity Plot with Nozzle 3 (Right)

Nozzle 3 follows the same profile as nozzles 1 and 2. The maximum velocities are the same and the width of the flow remains at 10mm.

3.3.1.3 Discussion

These results are given some important findings, some of the findings were expected but others were not. As expected, the flow rate for each of the scenarios changed the velocity of the flow after the nozzle. The higher the flow rate, the higher the peak velocity. The peak velocity was also in line with the nozzle which was also expected. For each of the graphs, a smooth curve was created each with different maximum values.

There were also unexpected results. The width of the flow remains constant for each of the flow rates; this means the width of any spray that comes from the nozzle is independent of the inlet flow rate. This means that the water is still distributed to the same areas and a high flow rate is not required. The nozzles are clearly better than the flow with no nozzle in this respect. With no nozzle, the width of the flow narrows slightly from a hole of 5mm to a flow of 3mm. Compared to the nozzles that have a flow width of 10mm from a nozzle width of 1.2mm.

These results show that although there is a definite need for nozzles to be attached to aid with water distribution, there is no need to design and manufacture a complex nozzle when the geometry makes negligible differences between the flows. A standard off-the-shelf nozzle will do a suitable job, and these are preferable as standard nozzles do not require further testing on their functionality. The job of the nozzles is to distribute the water onto the solar panels, they are not required to be so powerful that they clean the solar panels alone, the lowest flow rate of 0.2 L/min is sufficient to spray and coat the whole solar panel. Assuming a typical tap has a flow rate of 4 L/min, using the nozzle flow rate of 0.2 L/min, it indicates that 18 nozzles should be used in total for prototype B.

3.3.1.4 Potential Inaccuracies in the Simulations

CFD simulations can never be completely accurate because it is only a simulation of what happens in real life. Depending on the model used and the mesh used the results can vary slightly. It is used to provide a quicker and cheaper way of understanding what is happening.

In real life in a nozzle, air and water combine to create a mist. To simulate this using CFD, a much more complex simulation must be done by using two phase flow. This uses a lot of computing power which is not possible to get access to. The student edition of ANSYS fluent also has a limit of 512,000 mesh elements and using two phase flow meant this limit was far exceeded. The compromise of using water as the only fluid was therefore used.

3.3.2 Applied Automation Analysis

To determine a design to implement automation into the SPC, a PMA was conducted which consists of 3 separate designs including the baseline model (Prototype A). The main difference between the three designs is the degree of automation.

1. **Baseline model:** Completely remote controlled and always requires an operator to function.
2. **Line Following SPC:** Builds off the baseline model by adding in 4 light-dependent resistor sensors, 2 at the front and 2 at the back, in addition to Arduino programming which will allow set conditions. The SPC will traverse along a predetermined line at a fixed angle, water outlet, and rotational brushing speed. When the SPC reaches the end of one row of solar panels and registers a turning point, the upper arm will be pulled up to a 90-degree angle and the water inlet will be turned off whilst it gets to the next row of solar panels. From this point, the process is repeated until all solar panels are cleaned and the SPC follows the line back to its recharge point.
3. **Line Following SPC with Automated Mechanisms:** This design builds off the Line following SPC, however, has various proximity sensors integrated inside the upper

arms. This allows the SPC to automatically adjust to different solar panel inclination angles by detecting the solar panel surface and sending a signal to the various motors to further adjust the upper and lower arm before the cleaning process begins.

Table 8: PMA of Solar Panel Cleaner Designs

Evaluation Criteria	Weight Factor	Alternative Cleaning Designs					
		Baseline: Remote controlled SPC		Line Following SPC (using Light Dependent Resistors)		Line Following SPC with Automated Mechanisms	
		Rating	Weight	Rating	Weight	Rating	Weight
Degree of Automation	0.55	0	0	+1	+0.4	+1	+0.4
Maintenance Requirement	0.2	0	0	0	0	-1	-0.2
Risk of Damaging SPC	0.15	0	0	-1	-0.15	0	0.0
Operational hours	0.05	0	0	-1	-0.05	-1	-0.05
Cost	0.05	0	0	-1	-0.05	-1	-0.05
Score			**0.0**		**+0.15**		**+0.1**

From the PMA shown in Table 8, both proposed models are an improvement from the baseline model, regardless of their drawbacks. It can be seen that there are various drawbacks to making the SPC autonomous, including:

- **Higher need for maintenance:** Due to the lack of interaction with any moving parts, the light-dependent resistor sensors for the line following SPC do not require any extra need for maintenance/repair. However, as the proximity sensors on the upper arm of the third design may accidentally make contact with objects on the solar farm, occasional maintenance would be required to replace/repair them.
- **Increased risk of damaging SPC (or solar panel):** As the line following SPC is completely autonomous and only uses 2 different modes (cleaning and traversing), there is an additional risk of damaging the solar panels if an error occurs; this is because there is no safety system implemented. However, the third design uses proximity sensors which can tell the SPC to move away from detected surfaces if it is too close; thus, not suffering from this issue.
- **Reduced operational hours:** Both proposed designs will be unable to effectively work at night. This is because they both use light-dependent sensors which detect the amount of light reflected, even with an integrated light it is not recommended to carry out cleaning overnight.
- **Increased cost:** Both proposed designs require expensive sensors which need to be very accurate; this is because the potential failure could lead to a large cost e.g. the SPC falls off the solar farm. This leads to more expensive design costs. However, it should be noted that these costs will be made up for as time goes on due to the autonomous design.

After analysing the PMA results, it was decided that design 2 would be used in response to the proposed optimisation method: making the SPC autonomous. Figure 26 shows the CAD design of the implemented optimisation method.

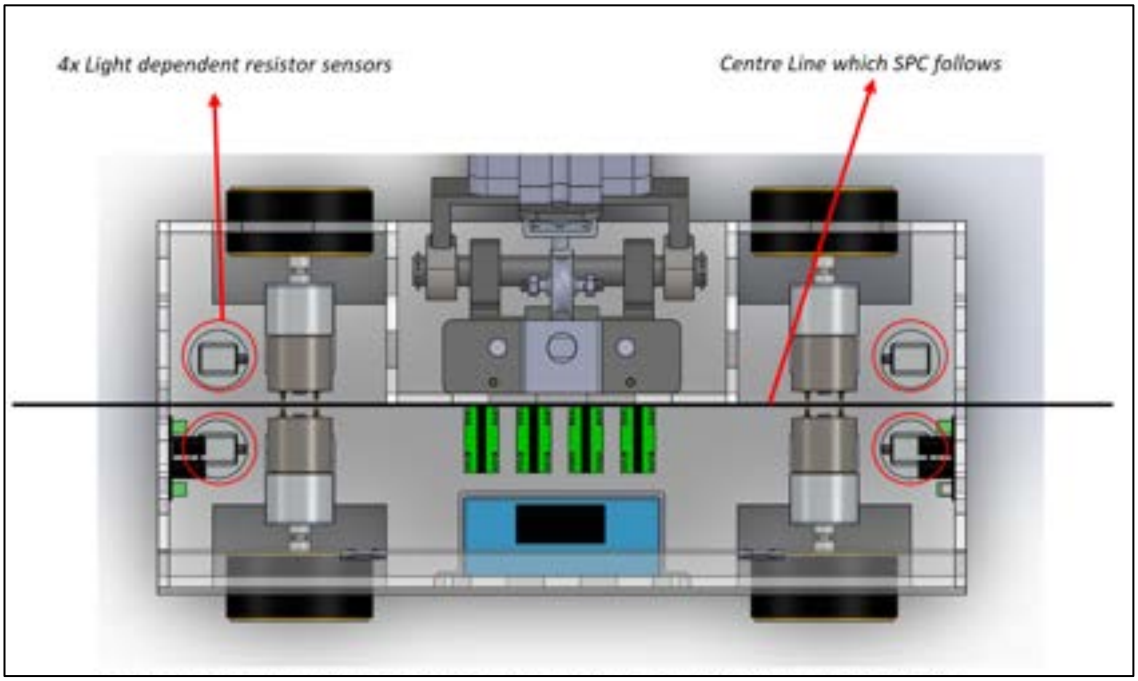


Figure 26: Updated SPC Design Based off Optimisation Method 2 (Autonomous SPC)

3.4 Prototype B Design

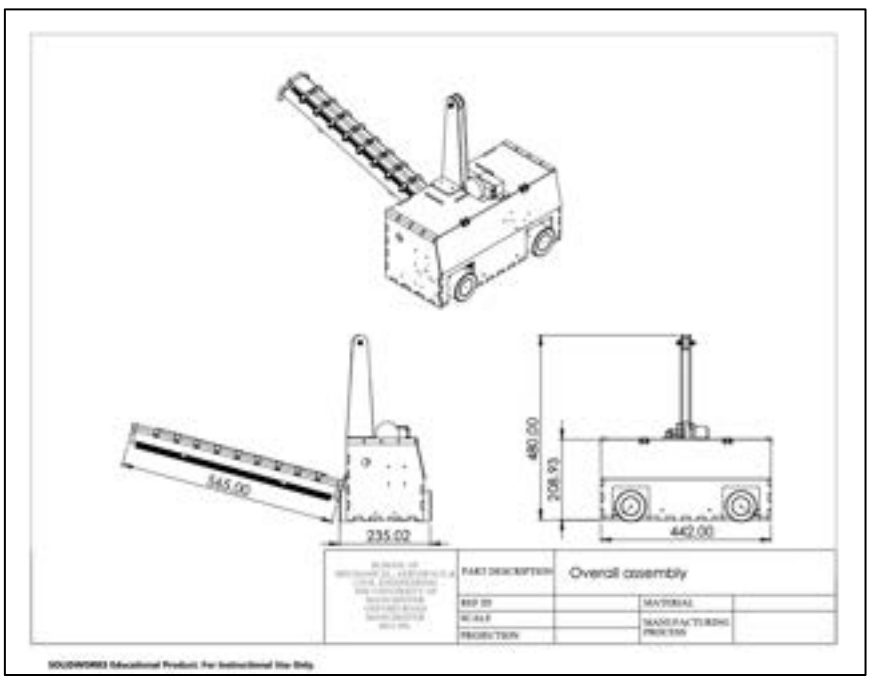


Figure 27: General Assembly Drawing for Prototype B

A full-sized view of the General Assembly Drawing is given in Appendix D along with the detailed drawings of prototype B. The CAD drawing of the updated upper arm is shown in Appendix B.

3.5 Summary of Design Improvements

3.5.1 Automation

Sensors are added to the bottom of SPC level of automation. For a line following SPC, the rover can move along the walkway and switch lanes without human interference. The water inlet will be turned off when switching lanes. On the other hand, a line following SPC with an integrated automated mechanism has proximity sensors in the cleaning arm which will help inclination adjustment depending on the angle of solar panel surface. These additional modifications enhance the degree of automation in SPC, making it more responsive to its surroundings.

3.5.2 Use of Nozzles in Water Distribution System

With nozzles in Prototype B, the water is spread out in larger area compared to when it only leaks out from holes in Prototype A. Therefore, more surface area of the solar panels is covered with water as the cleaning arm moves along the solar farm. From the CFD results mentioned earlier, the number of nozzles is determined c considering the water distribution system is connected to a 4L/m tap. 18 nozzles of 0.2L/m nozzles are spaced equally along the length of the cleaning arm. The improved water distribution system helps the brush to remove all the debris and unwanted residue on the solar farm because the water will act as a universal solvent, dissolving most residues formed on the solar panels. These dissolved residues will be washed away with the rotating brush.

3.6 Proposed Future Work

It is important to point out what would be required prior to full-scale commercialization. If the product was looked at from an economic point of view, commercialization requires a carefully developed three-tiered product roll-out and marketing strategy. The three-tiered phases include the ideation phase, the business process, and the stakeholder stage. As prototype A has already been manufactured and it has been pointed out what could be improved in the previous sections, the last two phases are required to proceed in sequential order to fulfil full scale commercialization.

Some improvements can be done following the testing of Prototype A and these areas of improvement are as stated in Section 3.1. The real product should consider bigger space for electronic components within the SPC to install higher power components. A brush with bristle is also needed to sweep any debris present on the solar farm.

From the technical point of view, there are a few things that need to be done prior to full-scale commercialization too. As the rover is designed to work and operate in a wet environment, it is necessary for the rover to be waterproof. By waterproofing the rover, the electronics inside the rover will be protected. Waterproofing also will increase the service life of the rover, which will make it becomes a more competitive product within the market. Although in the design specifications, it was pointed out that prototype A should be “shower proof” because the outer casing is not rigid and the plastic used to make the casing is hydrophobic. However, a way has not yet been found to test this assumption. Hence before full-scale commercialization, the ability of waterproofing needs to be strengthened. Upon that, a specific testing standard should be identified and recognized by the relevant testing organization or institution.

A water tank with a pump is a crucial component of a fully autonomous SPC. Water is important in cleaning because it can act as a universal solvent, thus aiding in removing any unwanted residues on the solar farm. The water tank shall be installed to deliver water to the cleaning arm without acquiring it from water mains. The size of the water tank should be considered carefully so that it does not affect the mobility and speed of the rover. Together with a high volt battery, SPC could operate on its own for a longer time and clean a significantly bigger area of the solar farm.

Lastly, a stable supply chain is needed because most of the parts are bought in. Accurate information about what is going to be manufactured and what is going to be contracted by supply companies needs to be established. This information should then be fed back to both the management and the supply chain because it helps manufacturers and retailers produce and transport only what is needed. This will decrease the cost of the product and increase its competitiveness. From the company’s point of view, a stable relationship between manufacturers and suppliers can reduce the unnecessary expenses associated with producing, insuring, and shipping inventory, in other words, maximizing the profit made from the rover.

4 Team Professional Practice Statement

<table>
<tr><td colspan="2">Team Needs Analysis</td></tr>
<tr><td colspan="2">TEAM MEMBER NAMES & STUDENT ID NUMBERS:
HARRY DEED – [redacted]
KIN LEUNG – [redacted]
MUHAMMAD ARISH BIN ISMAIL – [redacted]
MUHAMMAD RAMLI – [redacted]
SHUCHEN ZUO – [redacted]
TAY WEN JIE ANDREW - [redacted]
TOM HOOPER – [redacted]</td></tr>
<tr><td>Where is the team starting from?</td><td>What evidence have you used to make these judgements?</td></tr>
<tr><td>Personal and Social Skills
The team is generally agreeable and team members often make an effort to understand the needs and concerns of each other (P2). When two group members reach an impasse in the discussion of an issue, other group members make an effort to</td><td>EPIC
Meeting Minutes
Meeting Reflection
WhatsApp Chat</td></tr>
</table>

intervene and offer additional perspectives. This has been helpful in resolving conflict (P5).

Leading and Developing Teams
While the group may schedule meetings, not all meetings are productive as there is often no clear agenda set for the meeting. Consequently, improving coordination activities and establishing collective goals (T1) is an area of improvement. Ensuring that there is collective involvement in determining team objectives may also ameliorate this issue (T2).

Communication
Between Andrew and Derek, the group consistently keeps records of meetings and discussions (C1). However, given that our group's design concept is made up of three distinct subsystems, there is a tendency to work within our individual subgroups. Consequently, in providing advice and exchanging information (C3) between subgroups, our group has room for improvement.

TEAM GOALS:

T1: Project Coordination. We aim to be more deliberate in the coordination of activities and in setting goals.

T2: Team Work Planning. We plan to be more proactive in contributing to discussions to better establish team objectives and work plans.

C3: Providing Advice. We aspire to be more proactive in exchanging information and providing advice.

Team Action planning

What do you need to do to achieve these goals?	*Who?*	*When?*
Set meeting agenda prior to the start of the meeting and summarise work to be completed by the following week at the end of the meeting (T1).	All Members	Three days before the weekly meeting takes place.
Be more proactive in voicing opinions regarding team objectives and work plans. If necessary, team members should prompt each other to ensure no one remains unheard (T2).	All Members	During weekly meetings.
Team members will give regular updates on work progress through the WhatsApp chat, Google Sheet work tracker and during team meetings. Completed work should also be uploaded into the Google drive.	All Members	During weekly meetings and upon completion of tasks.

During weekly meetings, more details about the completed work can be shared (C3).		

TEAM ROLES: *What are the roles of different members in the team? What will each be responsible for?*

Goal 1: Improving Coordination of Activities and Setting Goals (T1)

- Set meeting agenda – Harry and Andrew
- Summarise work to be completed by the following week – Kin Leung
- Provide feedback on meeting agenda and work to be completed – All members

Goal 2: Increasing Proactivity in Contributing to Discussions to Establish Team Plans (T2)

- Ensuring that everyone has had a chance to voice their opinions through gathering feedback – All members

Goal 3: Improving Proactivity in Exchanging Information and Providing Advice (C3)

- Updating WhatsApp Chat, Google work tracker and Google Drive – All members
- Giving updates on subgroup progress – All Subgroups
- Keeping each other accountable for giving regular updates – All members

EVIDENCING TEAM ACTIVITY & IMPACT: *How will you evidence your activity and impact?*

- Use of EPIC to illuminate the needs of the team.
- Use of meeting minutes to show meeting outcomes.
- Use of meeting reflection to demonstrate growth
- Use of WhatsApp messages to highlight events that occurred.

Team Reflection on impact

How did you make progress towards your goal? Make reference to evidence in your Individual and Team portfolios to justify your comments. (750 words)

Defining the Team's Needs

By using the Team Epic Review (Figure A1), we determined that our teamwork planning and coordination was lacking. This was corroborated by our Team Reflections on 12-Oct-2021 (Figure A2). In this reflection, we note that our lack of planning had led to an unproductive meeting with the teaching assistants, highlighting the need for setting goals (Goal 1) and establishing team plans as a group (Goal 2).

To ensure we fulfilled Goal 1 and Goal 2, we also found it necessary to improve our proactivity in exchanging information and providing advice (Goal 3). Additionally, as illustrated by our Team Reflections on 16-Nov-2021 (Figure A3), our lack of proactivity in sharing information (in this case sharing of subsystem dimensions), had led to wasted time in the meeting.

Method of Achieving Goals

Fostering proactive communication (Goal 3) is a condition that needs to be fulfilled for coordination and collaborative planning (Goal 1 & Goal 2) to take place. To achieve Goal 3, we made use of a WhatsApp Chat, Google Tracker Sheet and Google Drive Folder. They each served the following functions (Figure 1). As WhatsApp and the Google Suite are collaborative tools that the group was accustomed to using, we proactively shared information. Resultingly, it was easy for group members to reference information and track progress.

Figure 27: Collaborative Tools Promoting Proactive Communication

To fulfil Goal 1 and Goal 2, we set meeting agendas (Figure A5) prior to our meeting and made time every meeting to go round the group to gather feedback before summarising key points of the meeting (Figure 2). However, gathering feedback was not consistently done as it was often neglected when we were running short on time. Additionally, such a process flow did not work well when we transitioned to having meetings in the workshop as there was a stronger focus on working on the assembly rather than on having a discussion.

Figure 28: Meeting Process Flow

Impact of Team Development Goals

The methods employed in fulfilling our goals solve the problems initially identified and this has translated to improvements in group performance (Figure 3). Notably, team productivity, team engagement and team collaboration have been enhanced.

Figure 29: Group Problem Statement

Impact of Structured Meetings and Gathering Feedback (Goal 1 & 2)

Initially, group members attended meetings without a clear direction or purpose. While there was a vague understanding of the problems we needed to address, the issues tended to be poorly articulated. However, implementing a structured approach to conducting meetings addressed this issue by ensuring that problems that required attention were systematically defined. Initially, sticking to a fixed structure felt tedious, however, the process soon yielded results. For example, by setting a meeting agenda in advance and gathering feedback from all members, we had a productive meeting whereby all the issues surrounding the submission of Prototype B were defined (Figure A6). Instances such as this helped our group to internalise the importance of defining the problem statement motivated us to stick with our plan.

Impact of Fostering Proactive Communication (Goal 3)

Fostering proactive communication enabled our group to plan and coordinate better. For example, when it came to assembling our prototype, we extensively used WhatsApp to give live updates on the manufacturing and delivery process (Figure A7). As the full assembly first required the assembly of three separate sub-assemblies, this was helpful in allowing the group to gauge the progress of each subgroup and better manage interdependencies. Moreover, this proactivity allowed us to troubleshoot better. As significant changes were made to the lower-arm between deliverable three and four, there were issues with its assembly (Figure A8). However, with proactive communication, the group responded in a timely manner and drilled additional holes in the chassis to support its installation.

Additionally, proactive communication improved solidarity and allowed the group to better harness the potential of all members. For instance, for our prototype optimisation in deliverable six, despite not being a part of the upper-arm subgroup, Shuchen shared useful research that the subgroup could use for finite element analysis (Figure A9). Despite tasks being delegated to an individual subgroup, the subgroup did not feel like they were alone in completing the assignment. While the importance of having good communication within a team is an often-quoted platitude, these experiences helped us to internalise its significance.

The Path Ahead

As mentioned earlier, our meeting structure does not work as effectively in a workshop setting. This made us realise that the structure of a meeting ought to change with setting. Although having structure is important, we must also learn to be flexible. An approach to consider would be to utilise a mix of online, hybrid and in-person meetings. If a task is complex and personal (e.g. conflict mediation) in person meetings will be made. However, if the task is simple and impersonal (e.g. giving updates) online meetings can be considered. This could make better use of everyone’s time and improve efficiency.

5 Conclusions and Recommendations

5.1 Summary of Team Professional Practice Performance

As a group, we have developed our soft skills. Through our efforts to create an environment that was conducive for improving group engagement, we fostered proactive communication. This enabled us to give feedback to each other which played a key role in enabling us to structure our meetings in an organised and effective manner. Looking ahead, we will continue to develop our team building skills to become professional engineers.

5.2 Summary of main achievements

The main achievement of this design project is that prototype A of the SPC is successfully built within the design constraints shown in Appendix B. Prototype A weighs 10 kg, the whole assembly is within $1m^3$ control volume, and it took less than 100 hours to be manufactured. Other than that, the total cost of building prototype A is £743.16.

Moreover, Figure 15.1 and Figure 15.2 proves the ability of prototype A to clean solar panels. As it is controlled from a remote control, Prototype A can clean solar panels without an operator being near the solar panels. Thus, Prototype A built in this design project has served the main purpose of SPC which is to eliminate the requirement of human labour to clean solar panels.

The SPC is redesigned as in Figure 3.4 and Appendix D to install more sensors to allow the SPC to move and operate on its own. The CFD results from Section 3.3 concludes that nozzles spread water better on the solar farm and 20 standard 0.2L/min nozzles. Although Prototype B is not physically built, constant virtual analysis done on the SPC has provided the guidelines for further assembly to enhance the performance of the SPC.

5.3 Summary of Main Innovations

The present design project aims to create a hybrid solar panel cleaner (rover type device with a cleaning arm) by combining commercially available designs of rover-type and rail-type solar panel cleaners. There are two innovative approaches considered to be implemented in the project.

The first innovation criterion is to eliminate or minimise human interaction on the floating solar farm when cleaning solar panels. This criterion is concerned with preventing any unintended accidents from occurring to the operator while cleaning the floating solar panel. This is due to the solar farm's slippery and wobbly pathways, which could cause instability and jeopardise the operator's safety. The second innovative action is to remove the need for pre-existing infrastructure mounted on the solar panel. The installation of infrastructure such as rail may result in additional weight to the solar farm, which is undesirable in a floating environment. Moreover, when installing such infrastructure, some areas on the solar panel may be covered, reducing the efficiency to generate more electricity.

As a result, the proposed design solution will include an autonomous system guided rover and a self-adjusting cleaning arm. Ideally, the operator should be able to operate and control the device from a safe distance, without having to step on the solar farm walkways to adjust the rover's position.

5.4 Summary of Main Lessons Learned

Indeed, there are numerous lessons learned both directly and indirectly while completing the present design project. The previous semester 1 lecture series of the academic year covered some beneficial design processes that are applicable for the project to be a success. After identifying the problem, further research/reading on the chosen field is required to gain a better understanding of what criteria and constraints should be considered. Following that, when creating the design specifications, the method of benchmarking with some of the commercial designs (hyCLEANER, Zedfactory, Cleansolar) was used to outline all the characteristics that could be improved, such as cleaning speed, cleaning efficiency, material selection, maintainability, weight, and cost.

Aside from that, the lecture series covers a wide range of technical risk assessment methods and the importance of this aspect in any design-related project. The Pugh's Matrix Analysis (PMA) and Failure Modes Effects Criticality Analysis (FMECA) were used in the current study for concept design process selection and improvisation on the design aspects of prototype A. Furthermore, the Design for Standardisation theory is applied to the current project, where all bought-in components and materials are obtained from standard suppliers. In terms of project management, the team's professional practice performance has significantly improved and been critically evidenced in the selected aspects from the beginning to the end of the semester (see Section 4.0). Finally, some of the indirect lessons learned are in the aspect of technical experience when assembling prototype A in the workshop session, where the students are exposed to activities such as drilling, soldering, 3D-printing, and troubleshooting problems in the manufactured parts.

5.5 Recommendations for Future Design Improvements

To conclude, there are many aspects for us as a team to improve on, with regards to the rover-based cleaning device’s design. For example, as stated in section 3.3, there are many challenges lying ahead of us prior to full scale commercialization, in terms of finding a stable supply chain and creating a hierarchy of business management. Afterwards, conformity testing with regards to the ability of waterproofing needs to meet industry standards, to prove its reliability and establish extreme weather compliance.

Other than that, for further design improvements, a larger rover will allow larger and more powerful motors to be installed. A high-quality brush is needed to improve the sweeping of debris on solar farms without damaging the solar panels. For the SPC to operate by itself, a water tank with a pump shall be installed inside the rover to supply water to the cleaning arm.

6 References

Abdolzadeh, M. and Ameri, M., 2009. Improving the effectiveness of a photovoltaic water pumping system by spraying water over the front of photovoltaic cells. Renewable Energy, 34(1), pp.91-96.

Alami, A., 2014. Effects of evaporative cooling on efficiency of photovoltaic modules. Energy Conversion and Management, 77, pp.668-679.

Antonelli, M., Beomonte Zobel, P., De Marcellis, A. and Palange, E., 2020. Autonomous robot for cleaning photovoltaic panels in desert zones. Mechatronics, 68, p.102372.

Burge, S., 2009. The Systems Engineering Tool Box.

Carpitella, S., Certa, A., Izquierdo, J. and La Fata, C., 2018. A combined multi-criteria approach to support FMECA analyses: A real-world case. Reliability Engineering & System Safety, 169, pp.394-402.

Catelani, M., Ciani, L., Cristaldi, L., Faifer, M., Lazzaroni, M. and Rinaldi, P., 2011. FMECA technique on photovoltaic module. 2011 IEEE International Instrumentation and Measurement Technology Conference,

Center for Sustainable Systems, University of Michigan. 2021. “U.S. Renewable Energy Factsheet.” Pub. No. CSS03-12.

Chen, Y., Cui Ye, Bingdong Liu and Rui Kang, 2012. Status of FMECA research and engineering application. Proceedings of the IEEE 2012 Prognostics and System Health Management Conference (PHM-2012 Beijing),

Cision, 2017. World’s largest floating photovoltaic power plant test-bed features ABB technology. Available at: https://news.cision.com/abb-electrification-products/r/world-s-largest-floating-photovoltaic-power-plant-test-bed-features-abb-technology,c2277103 [Accessed: 25 November 2021].

El Zohbi, B., Bukharin, N., Assoum, H., Abed-Meraim, K., Sakout, A. and El Hassan, M., 2022. Investigation of the effects of the jet nozzle geometry and location on the performance of supersonic fluid ejectors. Energy Reports, 8, pp.228-233.

Farrokhi Derakhshandeh, J., AlLuqman, R., Mohammad, S., AlHussain, H., AlHendi, G., AlEid, D. and Ahmad, Z., 2021. A comprehensive review of automatic cleaning systems of solar panels. Sustainable Energy Technologies and Assessments, 47, p.101518.

Fernandes, R., Tsai, J. and Wilson, D., 2022. Comparison of models for predicting cleaning of viscoplastic soil layers by impinging coherent turbulent water jets. Chemical Engineering Science, 248, p.117060.

Floating Solar UK, (2021). Floating Solar UK | Ciel et Terre | Hydrelio. [online] Floating Solar Panels. Available at: <http://www.floatingsolarpanels.co.uk/hydrelio-floating-solar-system/> [Accessed: 25 November 2021].

Frey, D., Herder, P., Wijnia, Y., Subrahmanian, E., Katsikopoulos, K. and Clausing, D., 2008. The Pugh Controlled Convergence method: model-based evaluation and implications for design theory. Research in Engineering Design, 20(1), pp.41-58.

Goo, B., Lee, J., Seo, S., Chang, D. and Chung, H., 2019. Design of reliability critical system using axiomatic design with FMECA. International Journal of Naval Architecture and Ocean Engineering, 11(1), pp.11-21.

Gorla, C., Concli, F., Stahl, K., Höhn, B., Klaus, M., Schultheiß, H. and Stemplinger, J., 2012. CFD Simulations of Splash Losses of a Gearbox. Advances in Tribology, 2012, pp.1-10.

Grando, M., Maletz, E., Martins, D., Simas, H. and Simoni, R., 2017. Robots for Cleaning Photovoltaic Panels: State of the Art and Future Prospects. Revista Tecnología y Ciencia, (35), pp.137-150.

hyCleaner, 2022. hyCLEANER SOLAR facelift. [online] Hycleaner.eu. Available at: <https://hycleaner.eu/en/produkte/hycleaner-black-solar/> [Accessed 10 May 2022].

Librandi, G., Narain, J. and Yu, H., 2012. Autonomous Photovoltaic Panels Cleaning System.

Lipol, L. and Haq, J., 2011. Risk analysis method: FMEA/FMECA in the organizations. International Journal of Basic & Applied Sciences, [online] 11(05), pp.74-82. Available at: <https://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.419.7912&rep=rep1&type=pdf> [Accessed 10 May 2022].

Manju, B., Abdul B. and Pavan C M., 2018. Automatic Solar Panel Cleaning System. International Journal of Advances in Scientific Research and Engineering, 4.

Parrott, B., Carrasco Zanini, P., Shehri, A., Kotsovos, K. and Gereige, I., 2018. Automated, robotic dry-cleaning of solar panels in Thuwal, Saudi Arabia using a silicone rubber brush. Solar Energy, 171, pp.526-533.

Punetha, D., Kumar, N., Mehta, V., 2013. Development and Applications of Line Following Robot Based Health Care Management System. International Journal of Advanced Research in Computer Engineering & Technology, 2.

Renzi, C., Leali, F., Pellicciari, M., Andrisano, A. and Berselli, G., 2013. Selecting alternatives in the conceptual design phase: an application of Fuzzy-AHP and Pugh's

Controlled Convergence. International Journal on Interactive Design and Manufacturing (IJIDeM), 9(1), pp.1-17.

Saaty, T., 2004. Decision making — the Analytic Hierarchy and Network Processes (AHP/ANP). Journal of Systems Science and Systems Engineering, 13(1), pp.1-35.

SolarCleano, 2021. SolarCleano. [online] SolarCleano. Available at: <https://www.solarcleano.com/> [Accessed 20 October 2021].

Thakker, A., Jarvis, J., Buggy, M. and Sahed, A., 2009. 3DCAD conceptual design of the next-generation impulse turbine using the Pugh decision-matrix. Materials & Design, 30(7), pp.2676-2684.

Villanueva, P., Lostado Lorza, R. and Corral Bobadilla, M., 2016. Pugh's Total Design: The design of an electromagnetic servo brake with ABS function – a case study. Concurrent Engineering, 24(3), pp.227-239.

Wash Panel, 2021. Washpanel - Washpanel systems. [online] Washpanel.com. Available at: <http://www.washpanel.com/en/documenti.php> [Accessed 20 October 2021].

7 Appendix A: Application of AHP

The methodology applied draws from the process laid out Saaty (2014).

Pairwise Comparison

The scoring for the pairwise comparison draws from the definition proposed by Saaty (2014) in Figure 31 below. The pairwise comparison is completed in Table 9.

Table 9: Pairwise Comparison of Design Criteria

	Dynamic Response	Cost	Weight	Ease of Maintenance	Ease of Implementing Automation
Dynamic Response	1	3	3	5	7
Cost	1/3	1	1	2	3
Weight	1/3	1	1	2	3
Ease of Maintenance	1/5	1/2	1/2	1	2
Ease of Implementing Automation	1/7	1/3	1/3	1/2	1

Intensity of Importance	*Definition*	*Explanation*
1	Equal importance	Two activities contribute equally to the objective
2	Weak or slight	
3	Moderate importance	Experience and judgment slightly favor one activity over another
4	Moderate plus	
5	Strong importance	Experience and judgment strongly favor one activity over another
6	Strong plus	
7	Very strong or demonstrated importance	An activity is favored very strongly over another; its dominance demonstrated in practice
8	Very, very strong	
9	Extreme importance	The evidence favoring one activity over another is of the highest possible order of affirmation
Reciprocals of above	If activity *i* has one of the above nonzero numbers assigned to it when compared with activity *j*, then *j* has the reciprocal value when compared with *i*	A reasonable assumption
Rationals	Ratios arising from the scale	If consistency were to be forced by obtaining *n* numerical values to span the matrix

Figure 30: Scoring for Pairwise Comparison (Saaty, 2004)

Calculation of Weights

The calculation of weights and normalised weights are completed using the following formula and the results are shown in Table 10.

$$Weight_i = (a_{i1} \times a_{i2} \times \ldots \times a_{in} \times)^n$$

$$Normalised\ Weight = Weight \div \sum_{i=1}^{n} Weight_i$$

Table 10: Calculation of Weights and Normalised Weights

	Weight	Normalised Weight
Dynamic Response	3.159818	0.488509
Cost	1.148698	0.177589
Weight	1.148698	0.177589
Ease of Maintenance	0.630957	0.097546
Ease of Implementing Automation	0.380125	0.058767
Sum	6.468297	1

8 Appendix B: Supporting Content

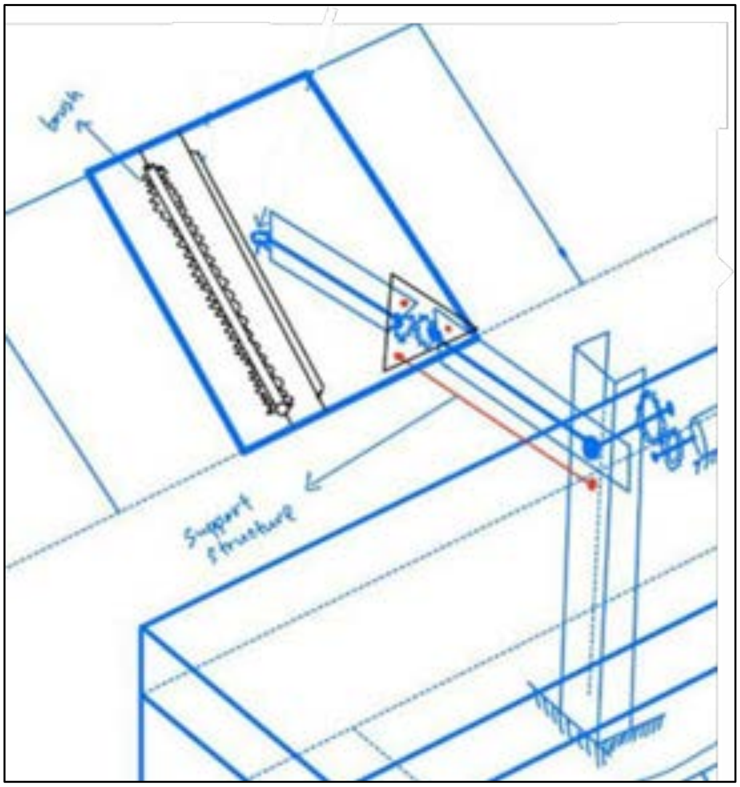


Figure 31: Blow Up of Cleaning Arm Joint

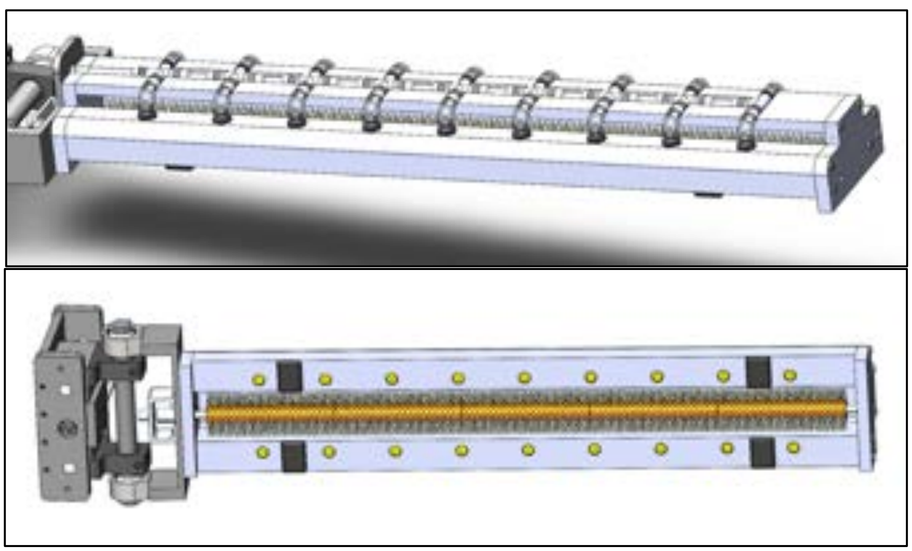


Figure 32.1: 3D Model of the Prototype B Upper Arm (Top)
Figure 32.2: Bottom of the Prototype B Upper Arm (Bottom)

Figure 33: Team EPIC Review

Group Reflection

Goal 1. Improve on coordinating project activities by identifying, and agreeing collective goals (T1) 2. As a group, contribute to establishing individual and team objectives and work plans (T2) 2. Become more proactive in exchanging information and providing advice (C3)		
What went well?	What can be improved?	What was surprising?
The presentation done by the group was good such that the TAs understood what the project entailed and what the key areas of our design was.	We need to <u>have an agenda for the meeting so that we can discuss all the important points before the meeting with the TAs</u>.	There was a lot of emphasis on the pump by the TAs, which means that we will need to have an in-depth look at what pumping system we are going to use.

Figure 34: Group Reflection on 12 October 2021

Group Reflection

Goal		
1. Improve on coordinating project activities by identifying, and agreeing collective goals (T1) 2. As a group, contribute to establishing individual and team objectives and work plans (T2) 2. Become more proactive in exchanging information and providing advice (C3)		
What went well?	What can be improved?	What was surprising?
There was progress on the CAD drawings and all the components were assembled together.	The dimensions of the connection points of the various subsystems could have been specified on the shared spreadsheet before the meeting.	The design flaws of the lower arm.

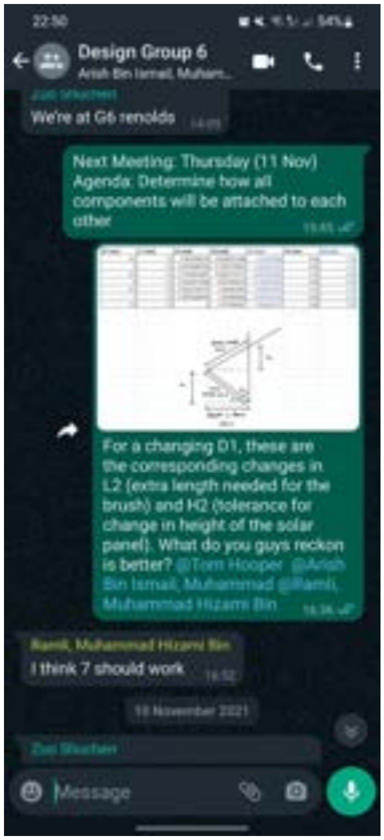
Figure 35: Group Reflection on 16 November 2021

Deliverable 6

Name	No.	Content	To Do	%	Arising Issues
Shu Chen	1	Introduction	uploaded	10	
Arish & Mui	2.1	Description of Main Design Features	uploaded		winch power, winch material
Arish & Mui	2.2	Description of How the Device Functions	uploaded		Need Derek and Andrew to explain more on the rover. (transmission, power, the advantage of mecannum wheels)
Andrew	2.3	Literature Review of Analysis/Optimisation Methods	uploaded		
Andrew	2.4	Outline of Applied Analysis/Optimisation	uploaded		
Tom	2.5	Outline of Main Innovations	uploaded	30	Figures need to be inserted but didn't want to mess up formatting
Arish	2.6	Outline Suitability of Design for Manufacture & Assembly			Had to change the upper arm due to an exposed slit. Had to change lower arm due to lead screw sizing problem. Had to change the material of the chassis from PVC due to problems with manufacturing. Had to change lower arm material from mild steel as it is too heavy. Had to change the brush bolt in order to attach the motor to it. USE THE EXCEL TABLE ON BB
Derek	2.7	Review of Device Performance During Testing			
Tom & Arish	3.1	Outline of Opportunities for Design Improvements	uploaded		Needs figures from prototype B.
Harry	3.2	Literature Review of Analysis/Optimisation Methods	uploaded		
Tom & Harry	3.3	Outline of Applied Analysis/Optimisation	uploaded	30	CFD done
Harry	3.4	General Assembly	Solidworks		
Arish & Mui	3.5	Summary of Design Improvements	uploaded		
Shu Chen	3.6	Proposed Future Work	uploaded		
Andrew	4	Professional Practice		20	
Andrew	5.1	Summary of Team Professional Practice Performance			Include anything that we learnt in sem 1 lectures
Arish	5.2	Summary of Main Achievements		10	
Arish	5.3	Summary of Main Invations			
TBC	5.4	Summary of Main Lessons Learnt			
Shu Chen	5.5	Recommendations for Future Design Improvments			

Legend	(yellow)	Attention Required/Incomplete
	(green)	Uploaded

Figure 36: Google Sheets Tracker for Deliverable 6



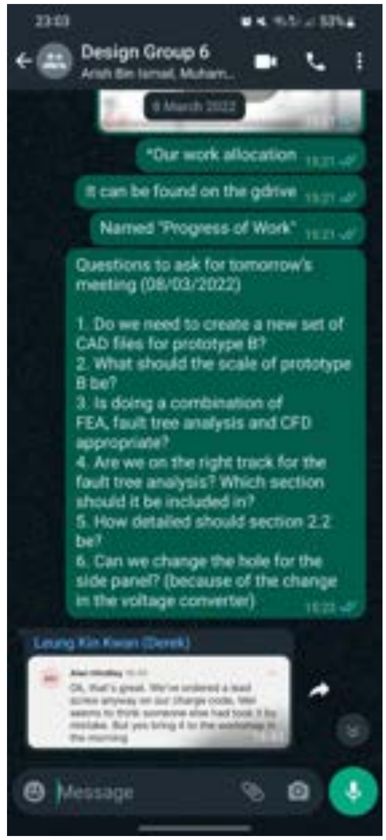
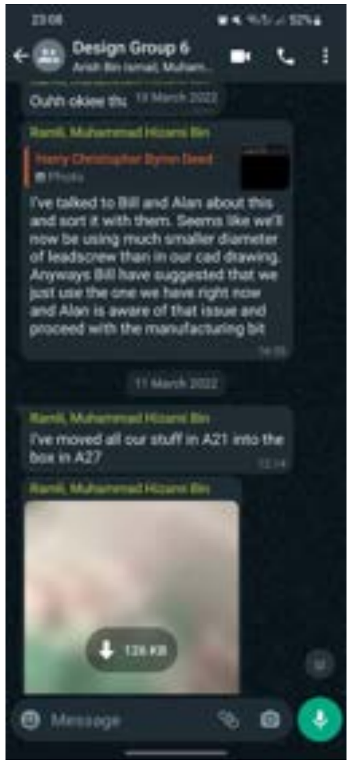


Figure 37.1: Meeting Agenda (Left)
Figure 37.2: Defining Problems Using a Structured Process (Right)



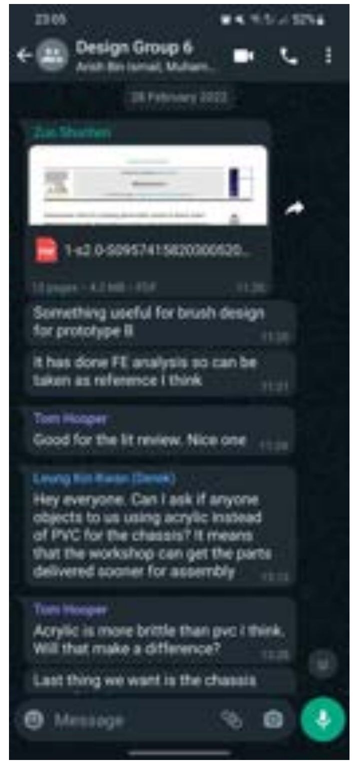


Figure 38.1: Continuous Updates (Left)
Figure 38.2: Troubleshooting (Centre)
Figure 38.3: Sharing Information for Design Optimisation (Right)

Table 11: Design Specification

Specification	Actual Product	Prototype (Half Scale)
General Aspects		
Glass Cleanliness	Testing methods • White glove test – No visible change on the white glove • Solar irradiance measurement using pyranometer – ≥ 800 W/m^2	Testing methods • White glove test – No visible change on the white glove • Solar irradiance measurement using pyranometer – ≥ 800 W/m^2
Waterproofing	• IP67	• IP55
Controls	• Fully autonomous	• Partially autonomous

	• Cleaning along solar farm is determined by the motion of the rover • The rover is able to move forward, backwards and turn left and right	• Cleaning along solar farm is determined by the motion of the rover • The rover able to move forward and do slight turnings
Cost	• ≤ £10000	• ≤ £800
Maintainability	• Able to be operated/carried by a maximum of 2 persons • Cleaning shaft can be dissembled within 30 minutes to be cleaned separately • Running time – 12 hours • Brush need changes every 4 hours of total operation time • Mean-Time-to-Repair – 4 hours with 2 skilled technicians	• Able to be operated/carried by one person • Running time – 3 hours • Brush need changes every 1 hour of total operation time • Mean-Time-to-Repair – 2 hours with 1 skilled technician •
Dimensions	• Cleaning arm: 1.70m x 1m x 1m, • Rover: 0.82m x 0.40m x 0.90 (Width of the rover follows the width of the pathway as reported by Ciel & Tierre)	• Cleaning arm: 0.10m x 0.57m x 0.072m • Rover: 0.41m x 0.24m x 0.45
Angle of Inclination	12 ± 10°	12 ± 10°
Weight	25kg including the cleaning arm (innovated to significantly reduce the weight of robotic solar cleaners by hyCleaner and Serbot)	12.5 kg including the cleaning arm

Surface Maximum Load Capacity	Cleaning arm should exert a maximum of 200kg/sq.m Benchmarked with Zedfactory	Cleaning arm should exert a maximum of 200kg/sq.m
Cleaning Speed	Determined by the rover speed which is 2.50 km/h (Innovated to be 1km/h faster than hyCLEANER which has a driving speed of 1.5km/h)	Determined by the rover speed which is 0.70 km/h
Power	42V Lithium-ion battery	11.1V Lithium-polymer battery
Brush		
Width	1m (following the width of solar panel)	0.5
Diameter	0.20m	0.035m
Rotation Speed	180 RPM (Benchmarked to Cleansolar solution which has 160 RPM)	90 RPM
Weight	3kg	1.5kg
Maximum Hardness of Bristles	• ≤6.9 GPa (Allsop,2020)	• ≤2.3 GPa
Water Injector		
Transport System	• Water injection system with sprinkler directed from water tank in the rover	• Water is supplied to two tubes from a tap, water will then drip out from the tubes through tiny holes along the tube
Pressure	0.3 bar	Adjustable with the tap

Flow rate	0.75 L/min	Adjustable with the tap
Water tank volume	3.0L	No water tank
Medium	• Distilled water	• Distilled water

Table 12: Bill of Materials

REF ID	Part Description	Quantity	Supplier & Part Reference (if applicable)	Material	Cost per unit (£)
1.	40mm diameter pulley wheel with 8mm inner diameter	1	MACE stock	PLA	1.31
2.	M4 Bolt and Nut set	20	MACE stock	Stainless Steel	0.05
3.	80mm Mecanum Wheel Kit (4x)	1	Robotshop (Product Code : RB-Dfr-906)	Plastic + Silicone Rubber	17.69
4.	Rod End Bearing 16mm inner diameter	2	Brammer Buck & Hickman (RUBIX: 103A7238 or SKF: SAKAC 16M	Combination steel/bronze	37.54
5.	RS PRO Lead Screw, 12mm Shaft Diam. , 1000mm Shaft Length	1	R.S. Components (RS Stock No.: 862-5281	Steel	14.82
6.	NSK Deep Groove Ball Bearing 6800 Series (10mm inner diameter)	1	Brammer Buck & Hickman (RUBIX: 102A4127)	Bearing Steel	6.95
7.	NSK Deep Groove Ball Bearing 6801 Series (12mm inner diameter)	1	Brammer Buck & Hickman (RUBIX: 102A4122 or NSK: 6801ZZ)	Bearing Steel	13.51
8.	Ruland Bellows Coupling Coupler 15mm Outside Diameter	1	R.S. Components (RS Stock No.: 174-7167)	Hubs: 2024-T351 Aluminium Bar Bellows: Type 321 Stainless Steel	49.14
9.	Shaft Support Block (16mm shaft diameter)	2	Brammer Buck & Hickman (RUBIX:	Aluminium Alloy	16.00

			103A1236 or INA: GWA16)		
10.	Moving Plate	1	MACE stock	Carbon Steel	17.45
11.	Sliding Rods	2	MACE stock	Stainless Steel	0.48
12.	Top plate	1	MACE stock	Carbon Steel	10.80
13.	Bottom Plate	1	MACE stock	Carbon Steel	10.86
14.	M4 Screws (20mm length)	16	MACE stock	Stainless Steel	0.03
15.	Igus Flange Bearing, A500FM-1214-15	4	RS Components (RS Stock no: 750-6912)	Rubber	4.70
16.	16mm Shaft (Lower Arm)	1	MACE stock	Carbon Steel	7.95
17.	Cleaning Arm Holder	1	MACE stock	Carbon Steel	9.72
18.	Base Plate	1	MACE stock	Carbon Steel	23.68
19.	M6 nuts	7	MACE stock	Stainless Steel	0.03
20.	T structure	2	MACE stock	Aluminium	1.00
21.	T structure connection rod	1	MACE stock	Aluminium	0.01
22.	Fishing braid 1-2m long	1	MACE stock	Nylon	2.50
23.	6V Polulu 50:1, Micro Metal Gear Motor	1	RobotShop (Product Code: RB-Pol-435)	Steel	13.85
24.	INA LINEAR BALL BEARING KH10-PP	2	Brammer Buck and Hickman (Product code:102A4025)	Steel	10.42
25.	RS PRO Steel Hex Nut, Zinc Plated, M5	1	MACE stock	Steel	0.02
26.	RS PRO Hex Nut, Plain, M10	1	MACE stock	Steel	0.08
27.	Bright Zinc Plated Steel Plain Washer,	1	MACE stock	Steel	0.02

	1mm Thickness, M5 (Form C)				
28.	Bright Zinc Plated Steel Plain Washer, 1.45mm Thickness, M10, M10 (Form B)	1	MACE stock	Steel	0.03
29.	Pololu 100:1 Metal Gearmotor 37Dx57L mm 12V (Helical Pinion)	4	RobotShop (Product Code: RB-Pol-885)	Stainless Steel	19.20
30.	12V, 90rpm, 70oz-in Spur Gear Motor	1	RobotShop (Product Code: RB-Sct-169)	Stainless Steel	10.82
31.	Hitec HS-785HB Winch Servo	1	Active Robots (Product Code: HS-785HB)	Plastic + Steel	41.58
32.	Pololu 37D mm Metal Gearmotor Bracket (Pair)	2	RobotShop (Product Code: RB-Pol-03)	Steel	5.86
33.	GensAce 5200mAh 11.1V 10/20C 3S2P Lipo Battery Pack	1	Unmanned Tech (SKU: 337-0A3-5AF)	Lithium Polymer	44.50
34.	M2 x 6mm Grub Screw	16	MACE stock	Steel	0.43
35.	FlyBird ST-i8 8CH 2.4G Transmitter Support PPM Output Compatible AFHDS 2A with Receiver for RC Drone	1	Banggood (ID: 1531754) (For costing only)	Plastic	35.12
36.	Step-down DC-DC Power Converter 25W	2	RobotShop (Product Code : RB-Dfr-222)	Plastic	7.67
37.	DFRobot 20A Bidirectional Brushed ESC Speed Controller (XT60 Connector)	4	RobotShop (Product Code : DRI0047)	Plastic	14.94
38.	Motor Bracket	1	MACE stock	Steel	1.04
39.	Brush Motor Cover	1	MACE stock	Polyvinyl Chloride (PVC)	0.03
40.	Brush Bolt	1	MACE stock	Aluminium	9.20

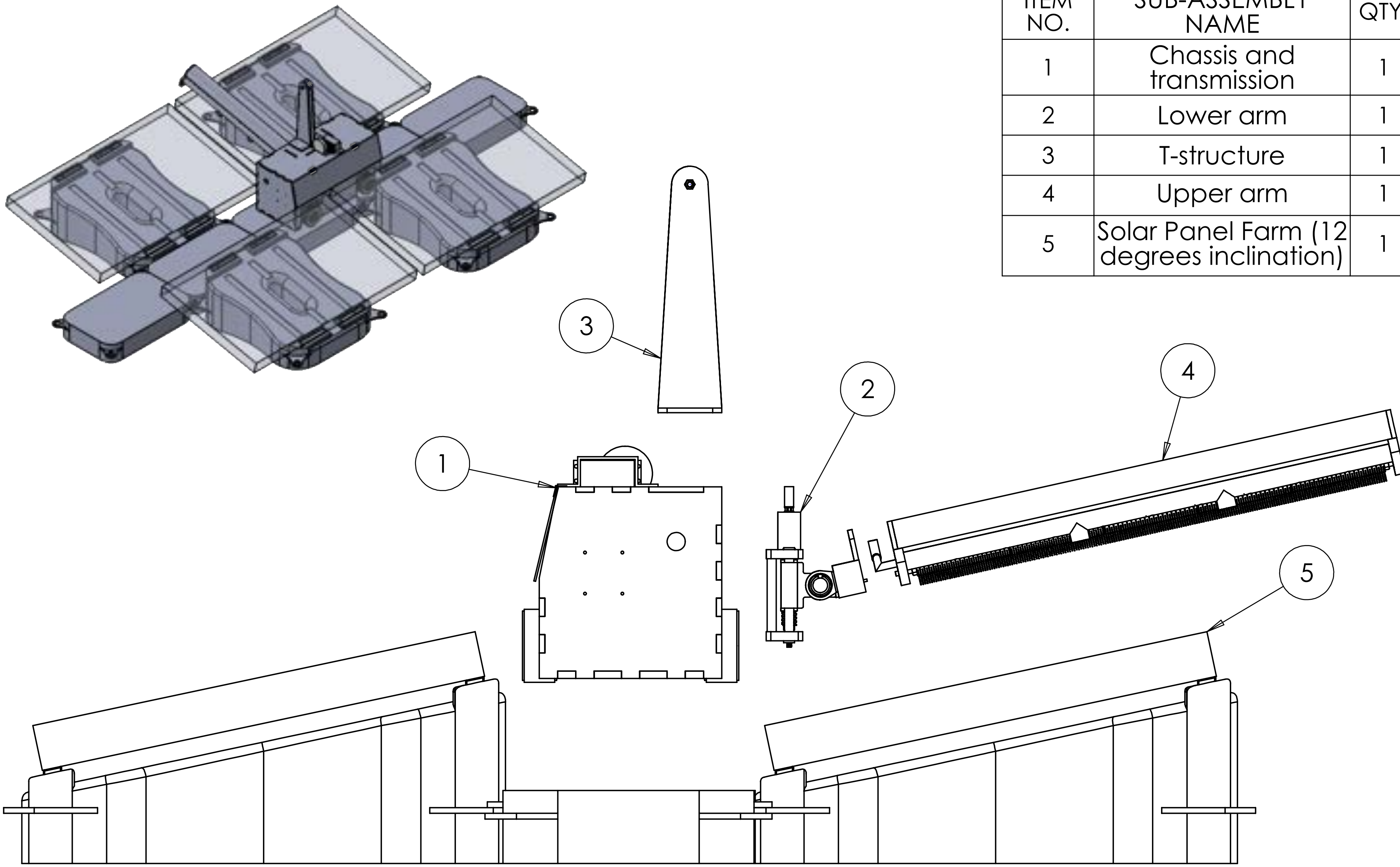
41.	Upper Arm Beginning Piece	1	MACE stock	Polyvinyl Chloride (PVC)	0.75
42.	Upper Arm End Piece	1	MACE stock	Polyvinyl Chloride (PVC)	0.78
43.	Upper Arm Top Piece	1	MACE stock	Polyvinyl Chloride (PVC)	4.35
44.	Upper Arm Side Support	2	MACE stock	Polyvinyl Chloride (PVC)	0.33
45.	Upper Arm Nylon Support Foot	4	MACE stock	Nylon 20mm diameter section	0.30
46.	Baseplate	1	MACE stock	Polyvinyl Chloride (PVC)	8.81
47.	Front/Back Plate	2	MACE stock	Polyvinyl Chloride (PVC)	3.75
48.	Side Plate	1	MACE stock	Polyvinyl Chloride (PVC)	2.93
49.	Lower Arm Left/Right Plate	2	MACE stock	Polyvinyl Chloride (PVC)	1.84
50.	Side Plate (Lower Arm Side)	2	MACE stock	Polyvinyl Chloride (PVC)	1.64
51.	Lower Arm Back Plate	1	MACE stock	Polyvinyl Chloride (PVC)	3.56
52.	Top Plate	1	MACE stock	Polyvinyl Chloride (PVC)	7.23
53.	Servo Winch Clamp	1	MACE stock	Aluminium	0.23
54.	Self-Colour Fixed Pin Butt Hinges 25 x 24.5mm 2 Pack	1	Screwfix (Product Code: 318PR)	Steel	0.59

55.	Lid	1	MACE stock	Polyvinyl Chloride (PVC)	1.56
56.	Battery Bracket	1	MACE stock	Aluminium	0.08
57.	Wheel Connector	4	MACE stock	Stainless Steel	0.42
58.	M3 Nut and Bolt Set	32	MACE stock	Stainless Steel	0.05
59.	NO NONSENSE 4" EMULSION ROLLER SLEEVES EMULSION 4" X5 PACK	1	Screwfix (Product Code: 2195V)	Polyester	3.99
60.	xiros® radial deep groove ball bearing, xirodur B180, stainless steel balls, cage made of xirodur B180, mm	2	igus (Part no: BB-625-B180-30-ES, xiros installation size: 625)	Stainless Steel	4.63
61.	3 Way Pipe Conjunction 8mm diameter	1	MACE stock	Polyvinyl Chloride (PVC)	0.20
62.	8mm Diameter Flexible PVC Tubing (1 Meter length, made to fit)	1	MACE stock	Polyvinyl Chloride (PVC)	1.50
63.	M6 Bolt 30mm Length	3	MACE stock	Stainless Steel	0.20
64.	M6 Washer	8	MACE stock	Steel	0.05
65.	RS Pro Cylindrical Nut For Lead Screw, 12mm Shaft Diameter	1	R.S. Components (R.S. Stock no: 862-5373)	Steel	5.63
66.	M3 Grub screws, 3mm	2	MACE stock	Steel	0.10
67	L Brackets	2	MACE stock	Aluminium	0.50
68	Motor Bracket	1	MACE stock	Aluminium	1.20
69	Motor Coupler	1	Mace Stock	Aluminium	0.65
Total material cost (£)					**743.14**

Table 13: Breakdown of Shipping Costs by Suppliers

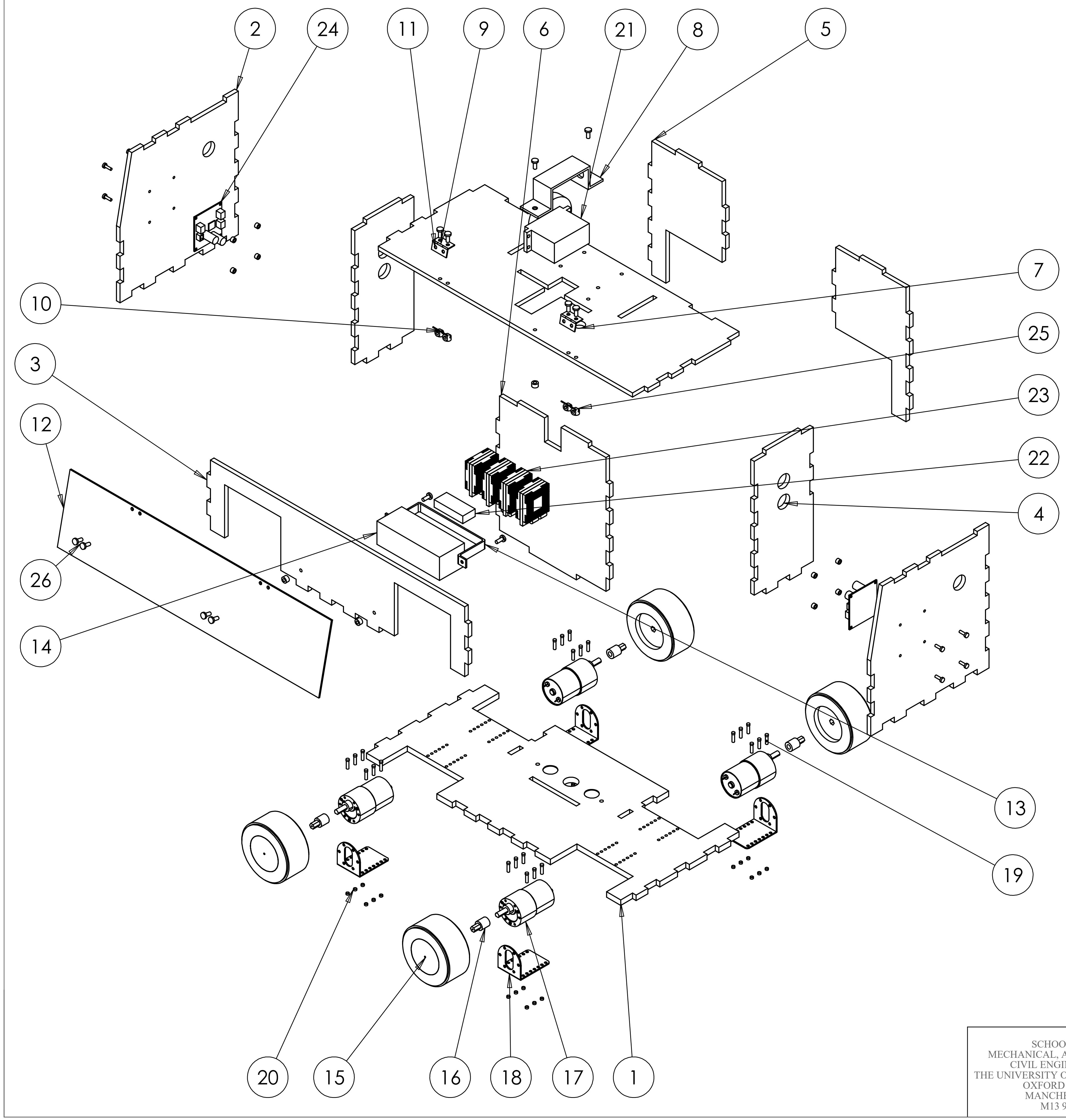
Supplier	Shipping Cost (£)
RobotShop	11.69
Screwfix	5.00
Active robots	4.70
Igus	8.50
Unmanned tech	3.50
RS Components	0.00
Brammer	0.00
Total shipping cost (£)	**33.69**

Total Cost = Material Cost + Shipping cost = £743.14 + £33.69 = **£776.53**



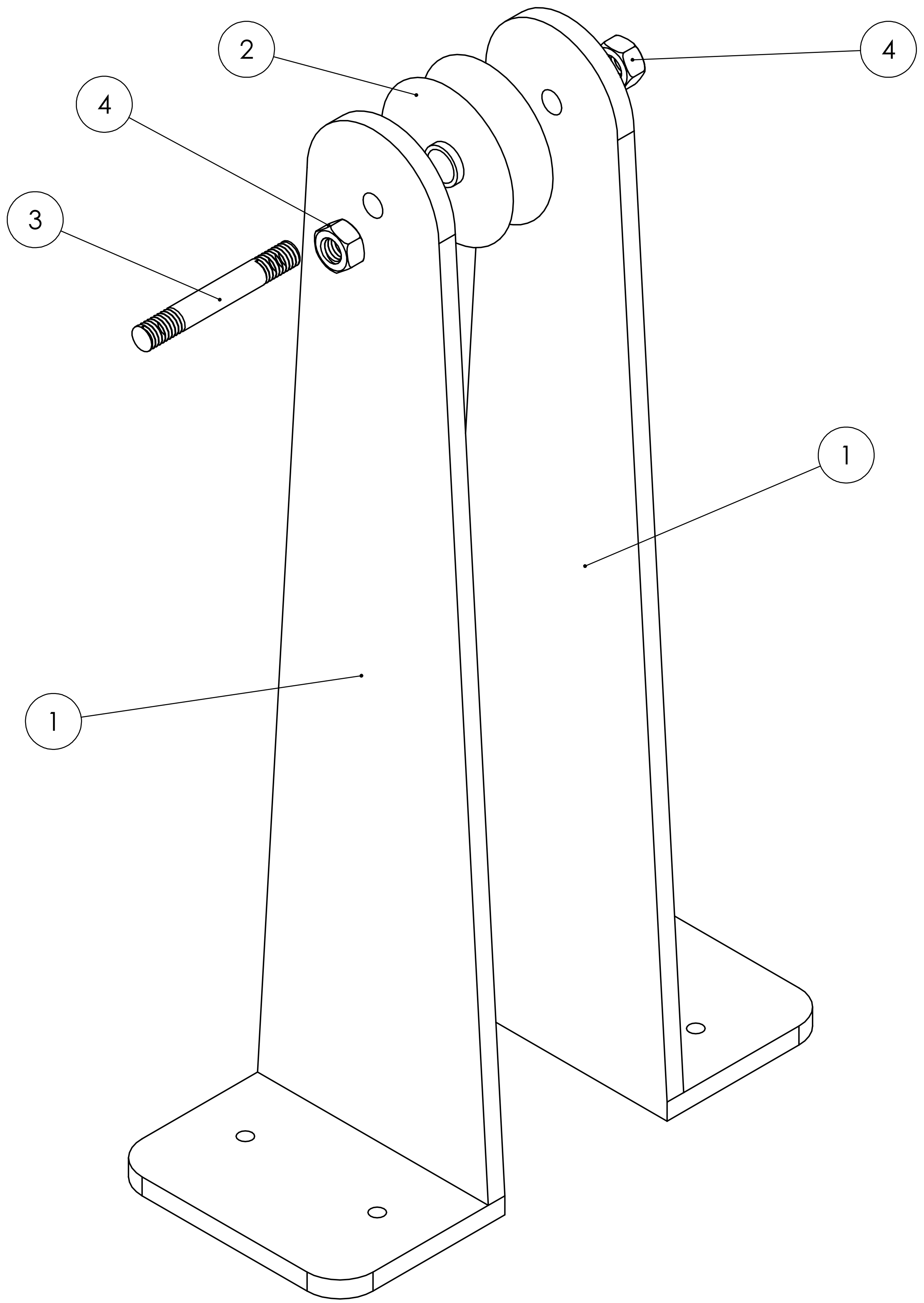
ITEM NO.	SUB-ASSEMBLY NAME	QTY.
1	Chassis and transmission	1
2	Lower arm	1
3	T-structure	1
4	Upper arm	1
5	Solar Panel Farm (12 degrees inclination)	1

SCHOOL OF MECHANICAL, AEROSPACE & CIVIL ENGINEERING THE UNIVERSITY OF MANCHESTER OXFORD ROAD MANCHESTER M13 9PL	PART DESCRIPTION	Full assembly of solar panel cleaner (SPC) with solar farm benchmark
	SCALE	1:6
	PROJECTION	First Angle



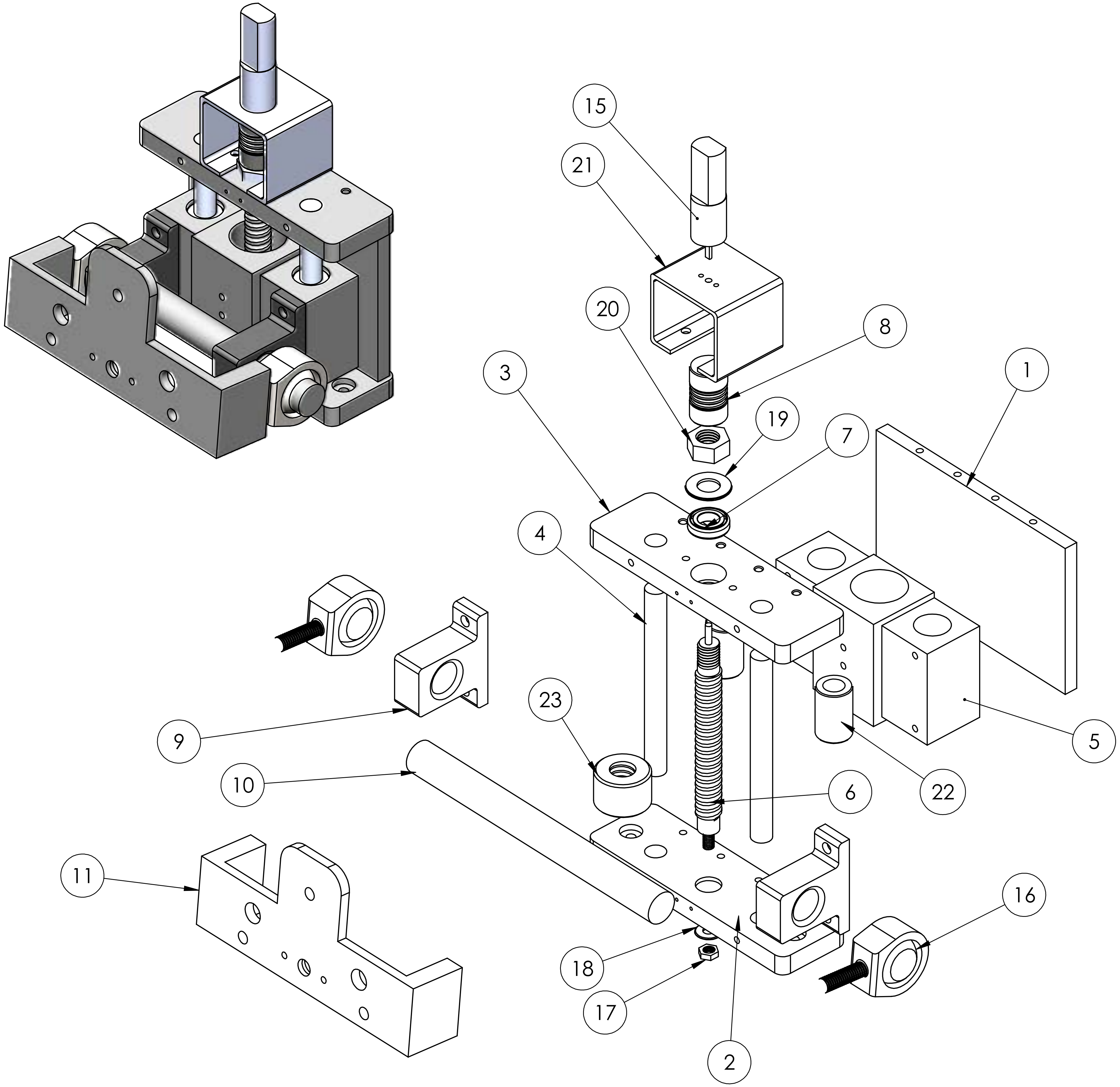
PART NUMBER	REFERENCE ID	PART NAME	QTY.
1	46	BASE PLATE	1
2	47	FRONT/BACK PLATE	2
3	48	SIDE PLATE	1
4	49	LOWER ARM LEFT/RIGHT PLATE	2
5	50	SIDE PLATE (LOWER ARM SIDE)	2
6	51	LOWER ARM BACK PLATE	1
7	52	TOP PLATE	1
8	53	SERVO WINCH CLAMP	1
9	54	HINGE LOWER	2
10	54	HINGE PIN	2
11	54	HINGE UPPER	2
12	55	LID	1
13	56	BATTERY BRACKET	1
14	33	5200mAh BATTERY	1
15	3	MECANUM WHEEL	4
16	57	WHEEL CONNECTOR	4
17	29	DRIVE MOTOR	4
18	32	DRIVE MOTOR BRACKET	4
19	58	M3 SCREW (REPRESENTATIVE)	32
20	58	M3 NUT (REPRESENTATIVE)	32
21	31	SERVO MOTOR	1
22	35	RECEIVER	1
23	37	ESC	4
24	36	DC TO DC CONVERTER	2
25	2	M4 NUT (REPRESENTATIVE)	12
26	2	M4 SCREW (REPRESENTATIVE)	12

SCHOOL OF MECHANICAL, AEROSPACE & CIVIL ENGINEERING THE UNIVERSITY OF MANCHESTER OXFORD ROAD MANCHESTER M13 9PL	PART DESCRIPTION	CHASSIS AND TRANSMISSION		
	REF ID		MATERIAL	
	SCALE	1:5	MANUFACTURING PROCESS	
	PROJECTION	EXPLODED		



Reference ID	Part Number	Part Name	Quantity
REF ID 20	1	T structure	2
REF ID 1	2	Pulley wheel	1
REF ID 21	3	Connection rod	1
REF ID 19	4	M6 Nut	2

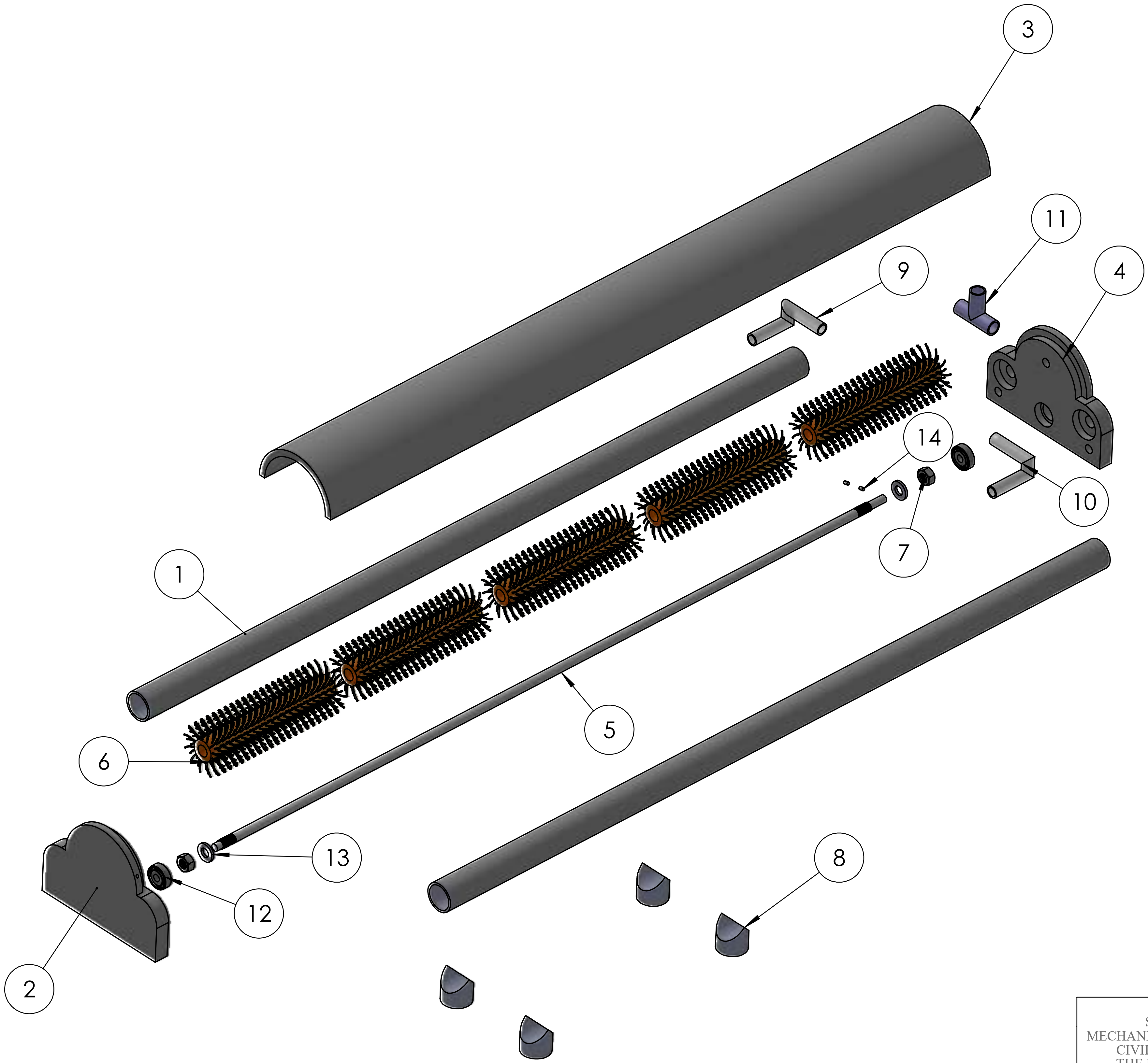
SCHOOL OF MECHANICAL, AEROSPACE & CIVIL ENGINEERING THE UNIVERSITY OF MANCHESTER OXFORD ROAD MANCHESTER M13 9PL	NAME	Shuchen Zuo	TITLE	T structure Assem
	DATE	22/11/2021	SCALE	1:1.2
	PROGRAMME	Design 4	PROJECTION	Exploded view
	EMAIL			



Reference ID	Part Number	Part Name	Quantity
REF ID 18	1	Base Plate	1
REF ID 13	2	Bottom Plate	1
REF ID 12	3	Top Plate	1
REF ID 11	4	Cylindrical Rods	2
REF ID 10	5	Moving Plate	1
REF ID 5	6	Lead Screw	1
REF ID 6	7	Ball Bearing (10mm Dia)	2
REF ID 8	8	Coupler	1
REF ID 9	9	Shaft Support	2
REF ID 16	10	Shaft	1
REF ID 17	11	Cleaning Arm Holder	1
REF ID 30	12	Brush Motor	1
REF ID 39	13	Motor Cover	1
REF ID 15	14	Flange Bearing	4
REF ID 23	15	Leadscrew Motor	1
REF ID 4	16	Rod End Bearing	2
REF ID 25	17	Hex Nut (M5)	1
REF ID 27	18	Washer (M5)	1
REF ID 28	19	Washer (M10)	1
REF ID 26	20	Hex Nut (M10)	1
REF ID 38	21	Motor Bracket	1
REF ID 24	22	Linear Bearing	2
REF ID 65	23	Leadscrew Nut	1

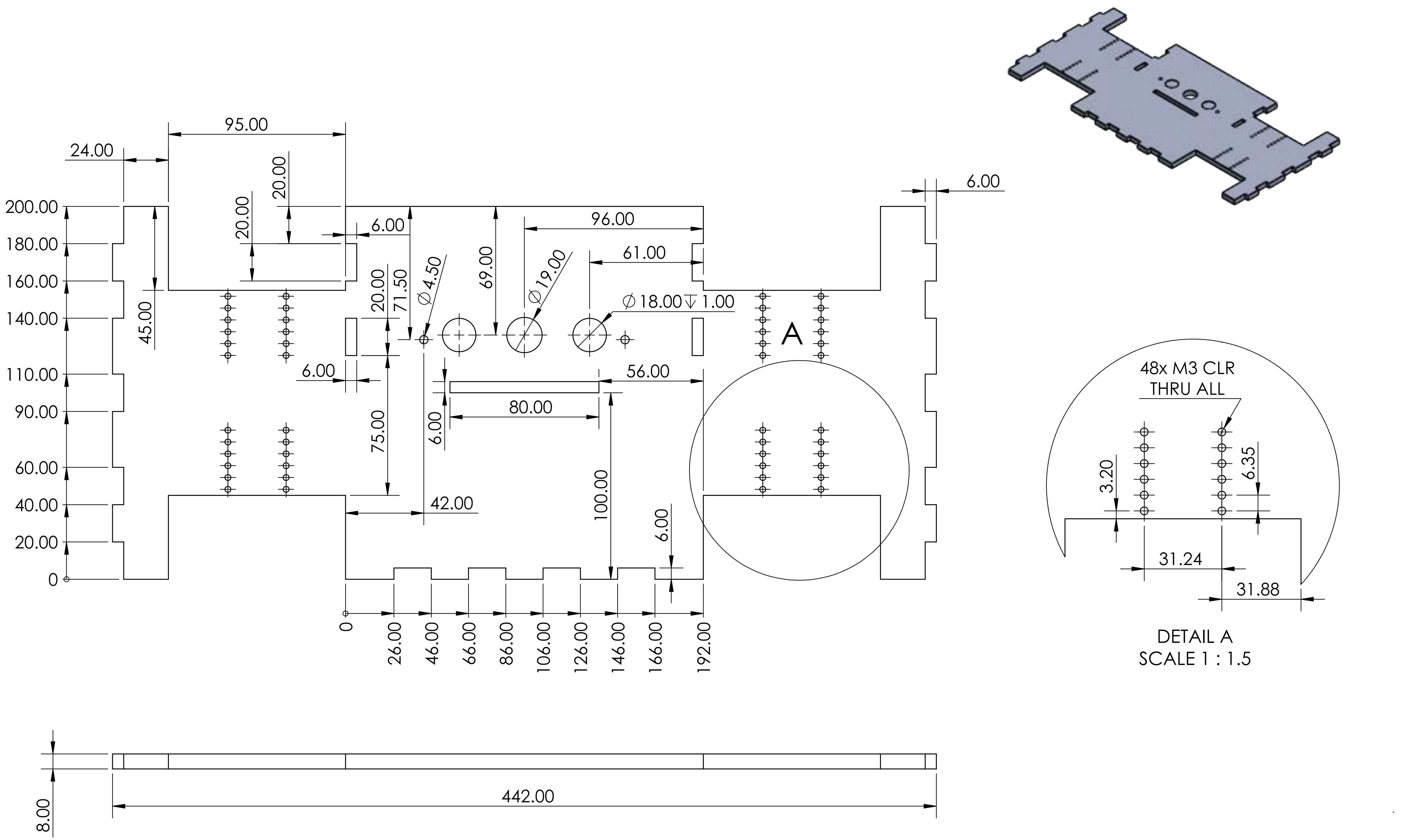
SCHOOL OF
MECHANICAL, AEROSPACE & CIVIL ENGINEERING
THE UNIVERSITY OF MANCHESTER
OXFORD ROAD
MANCHESTER
M13 9PL

PART DESCRIPTION	LOWER ARM SUB-ASSEMBLY		
REF ID		MATERIAL	
SCALE	1:2	MANUFACTURING PROCESS	
PROJECTION	FIRST ANGLE		

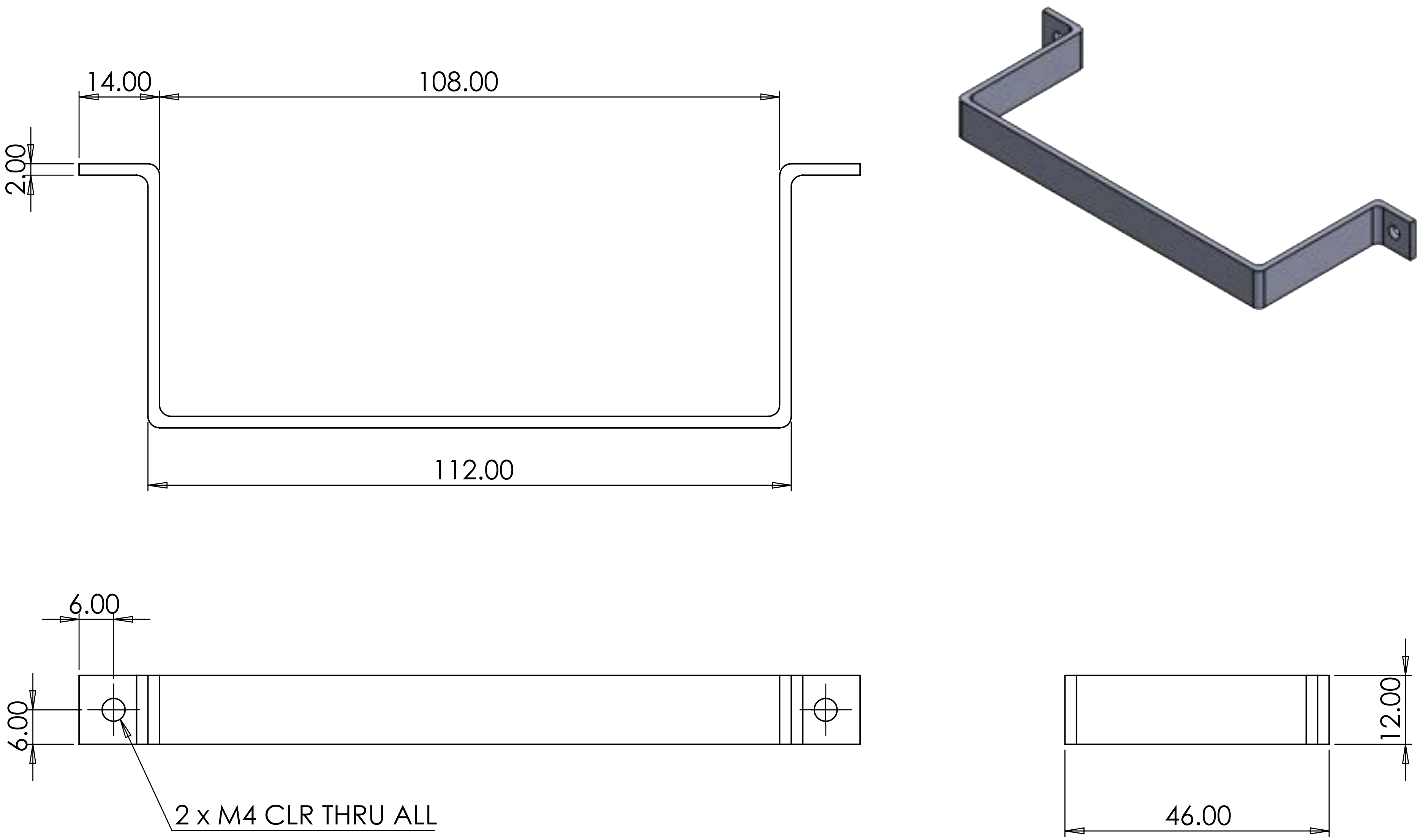


PART NUMBER	REF ID	Part Name	QTY.
1	REF ID 44	Upper Arm Side Support	2
2	REF ID 42	Upper Arm End Piece	1
3	REF ID 43	Upper Arm Top Piece	1
4	REF ID 41	Upper Arm Beginning Piece	1
5	REF ID 40	Brush Bolt	1
6	REF ID 59	Brush	5
7	REF ID 19	Nut M6 X 1	2
8	REF ID 45	Upper Arm Nylon Support Foot	4
9	REF ID 62	Water inlet tube (R)	1
10	REF ID 62	Water inlet tube (L)	1
11	REF ID 61	3 Way conjunction	1
12	REF ID 60	Bearing	2
13	REF ID 64	M6 Washer	2
14	REF ID 34	M2 Grub Screw	2

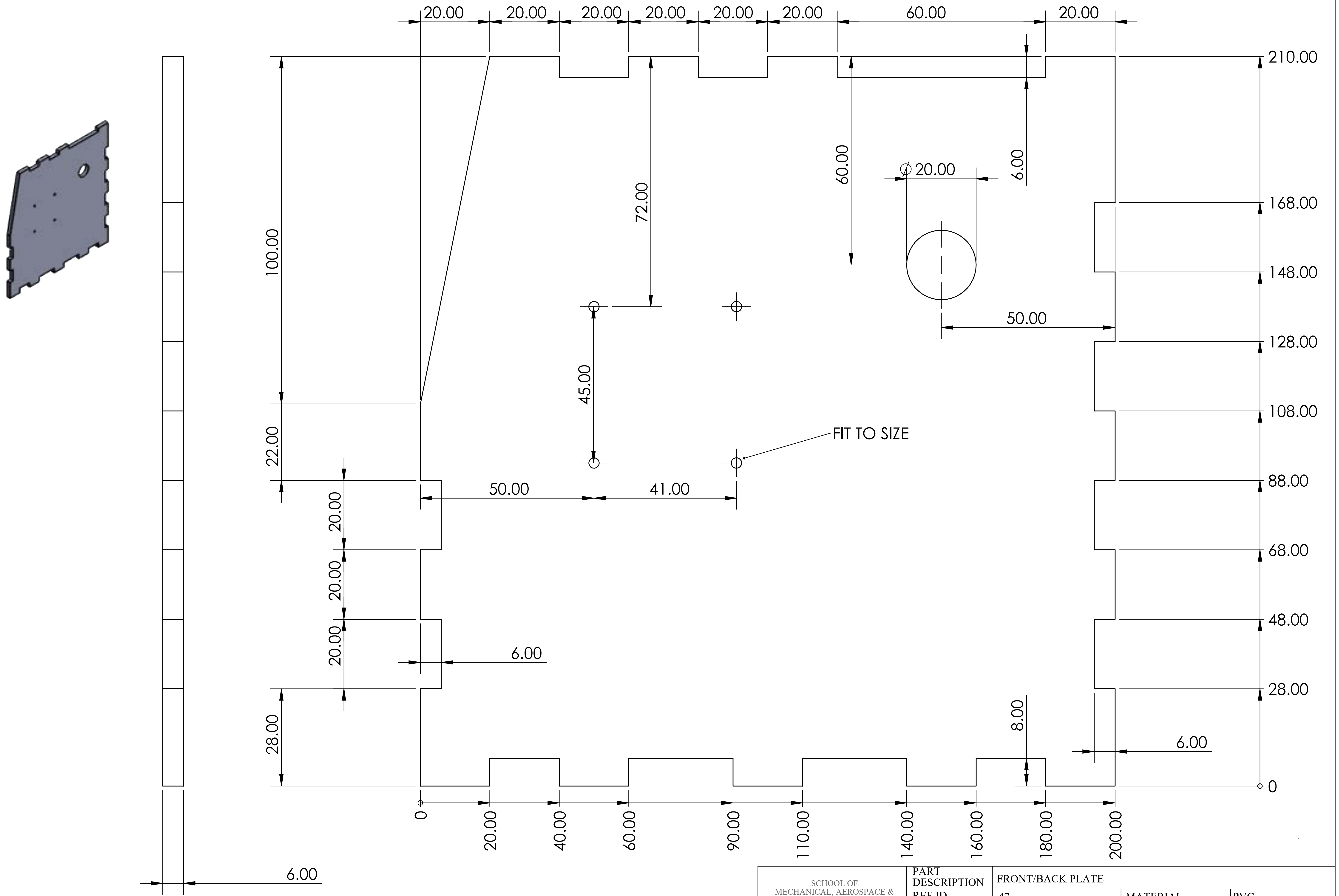
SCHOOL OF MECHANICAL, AEROSPACE & CIVIL ENGINEERING THE UNIVERSITY OF MANCHESTER OXFORD ROAD MANCHESTER M13 9PL	SUB-ASSEMBLY DESCRIPTION		Upper Arm
	SCALE	1:3	
	PROJECTION	First Angle	



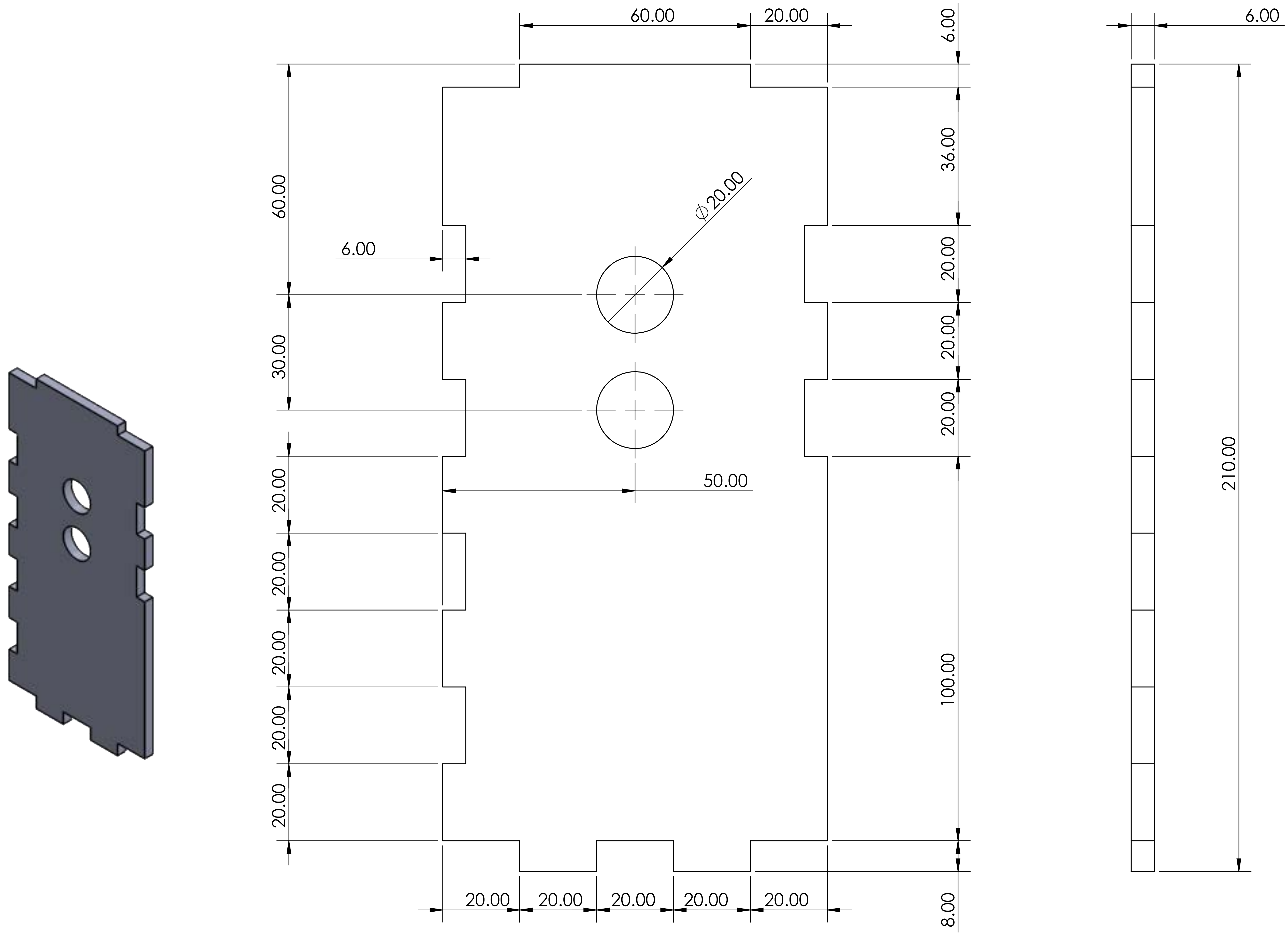
SCHOOL OF MECHANICAL, AEROSPACE & CIVIL ENGINEERING THE UNIVERSITY OF MANCHESTER OXFORD ROAD MANCHESTER M13 9PL	PART DESCRIPTION	BASE PLATE		
	REF ID	46	MATERIAL	PVC
	SCALE	1:2	MANUFACTURING PROCESS	CNC LASER CUTTING
	PROJECTION	ORTHOGRAPHIC		



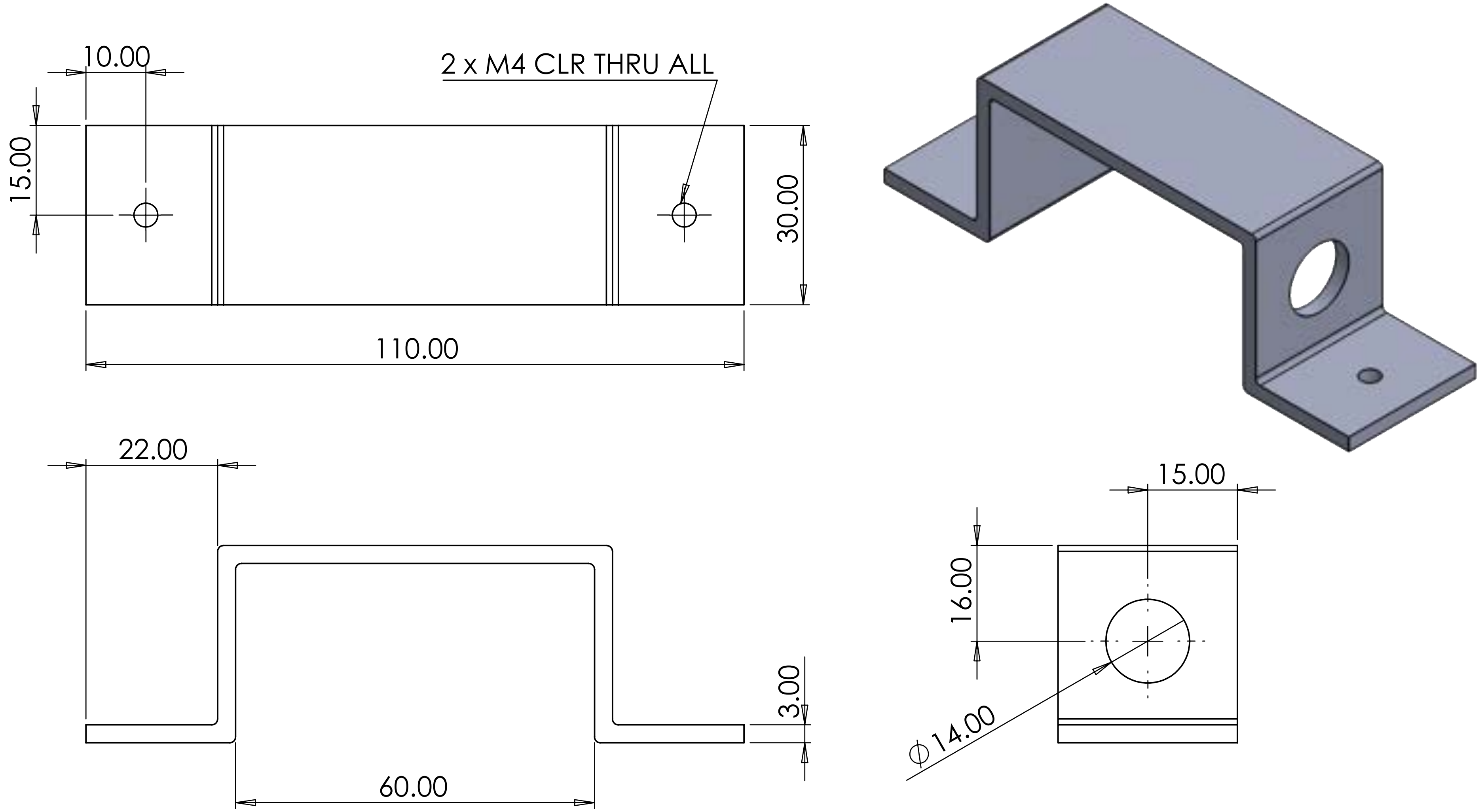
SCHOOL OF MECHANICAL, AEROSPACE & CIVIL ENGINEERING THE UNIVERSITY OF MANCHESTER OXFORD ROAD MANCHESTER M13 9PL	PART DESCRIPTION	BATTERY BRACKET		
	REF ID	56	MATERIAL	ALUMINIUM
	SCALE	1:1	MANUFACTURING PROCESS	METAL BENDING
	PROJECTION	FIRST ANGLE		



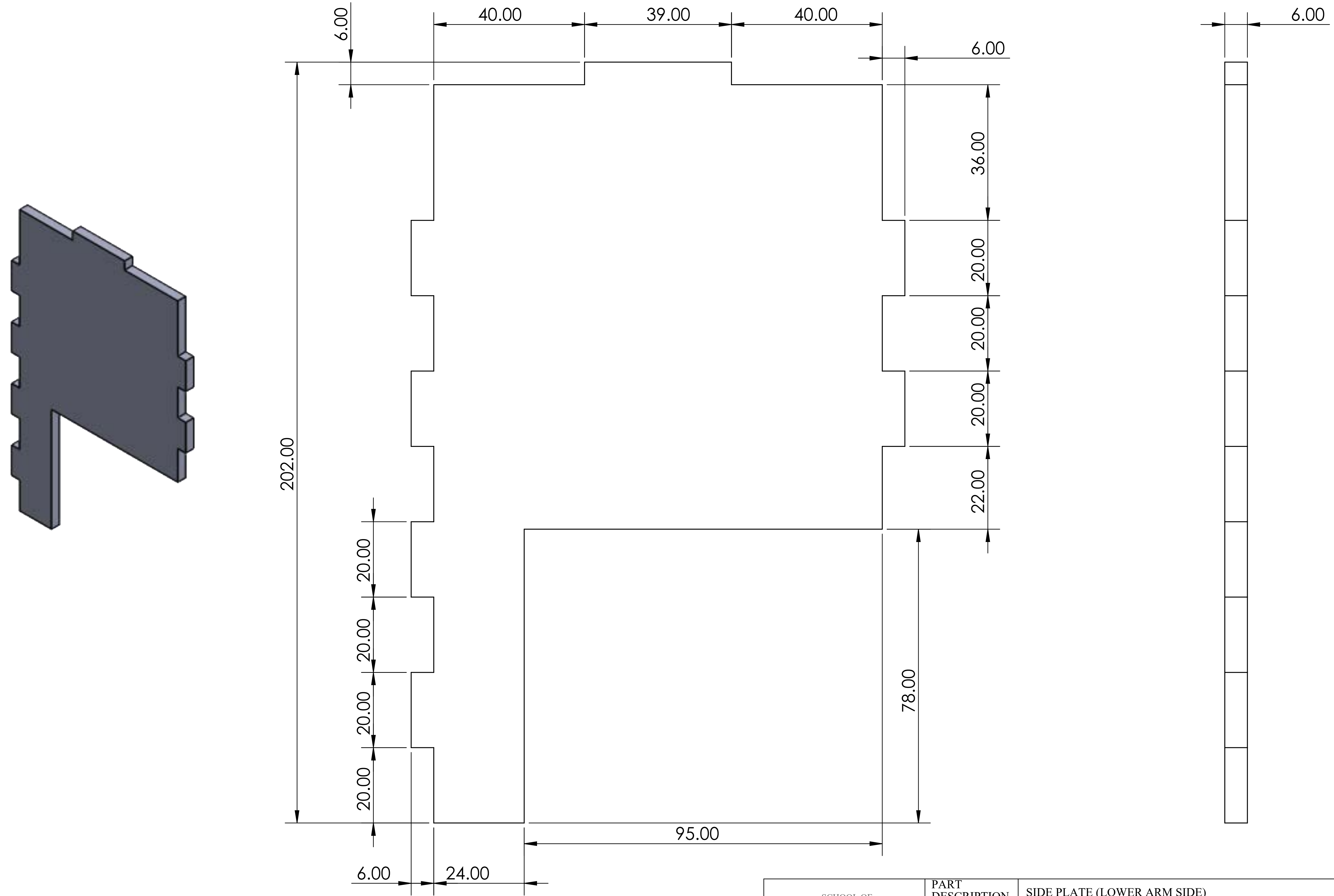
SCHOOL OF MECHANICAL, AEROSPACE & CIVIL ENGINEERING THE UNIVERSITY OF MANCHESTER OXFORD ROAD MANCHESTER M13 9PL	PART DESCRIPTION	FRONT/BACK PLATE		
	REF ID	47	MATERIAL	PVC
	SCALE	1:1	MANUFACTURING PROCESS	CNC LASER CUTTING
	PROJECTION	ORTHOGRAPHIC		



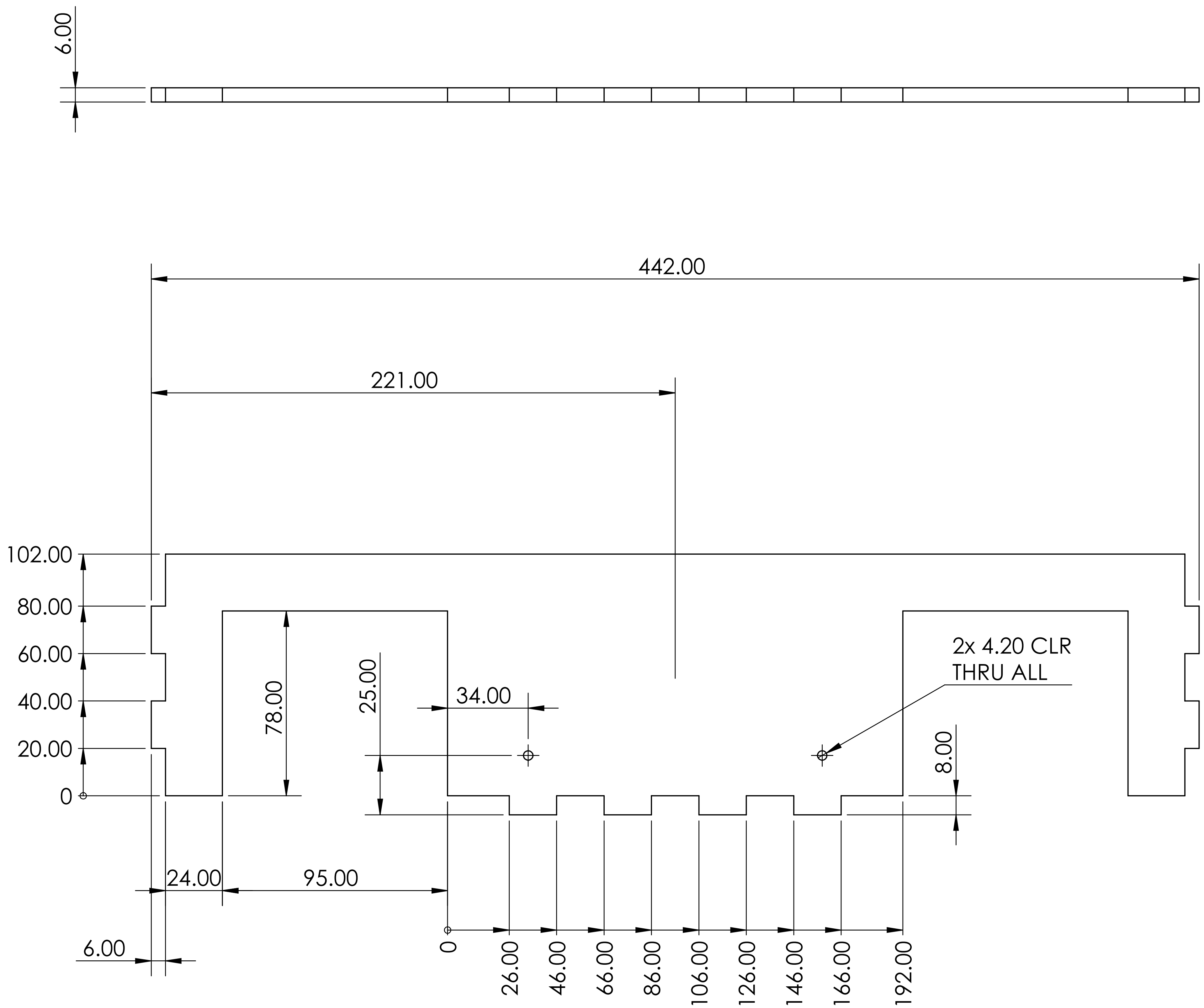
SCHOOL OF MECHANICAL, AEROSPACE & CIVIL ENGINEERING THE UNIVERSITY OF MANCHESTER OXFORD ROAD MANCHESTER M13 9PL	PART DESCRIPTION	LOWER ARM LEFT/RIGHT PLATE		
	REF ID	49	MATERIAL	PVC
	SCALE	1:1	MANUFACTURING PROCESS	CNC LASER CUTTING
	PROJECTION	ORTHOGRAPHIC		

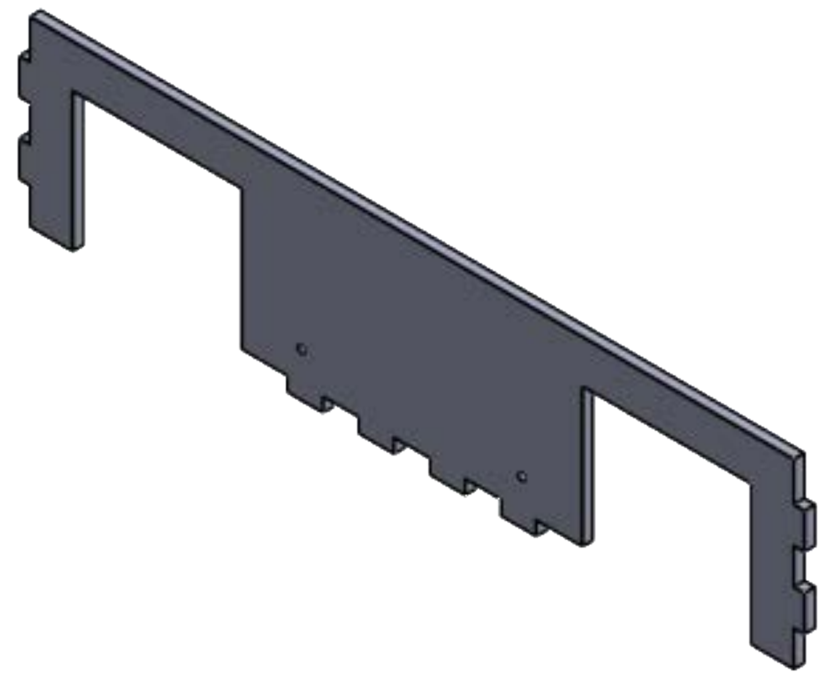


SCHOOL OF MECHANICAL, AEROSPACE & CIVIL ENGINEERING THE UNIVERSITY OF MANCHESTER OXFORD ROAD MANCHESTER M13 9PL	PART DESCRIPTION	SERVO WINCH CLAMP		
	REF ID	53	MATERIAL	ALUMINIUM
	SCALE	1:1	MANUFACTURING PROCESS	METAL BENDING
	PROJECTION	FIRST ANGLE		

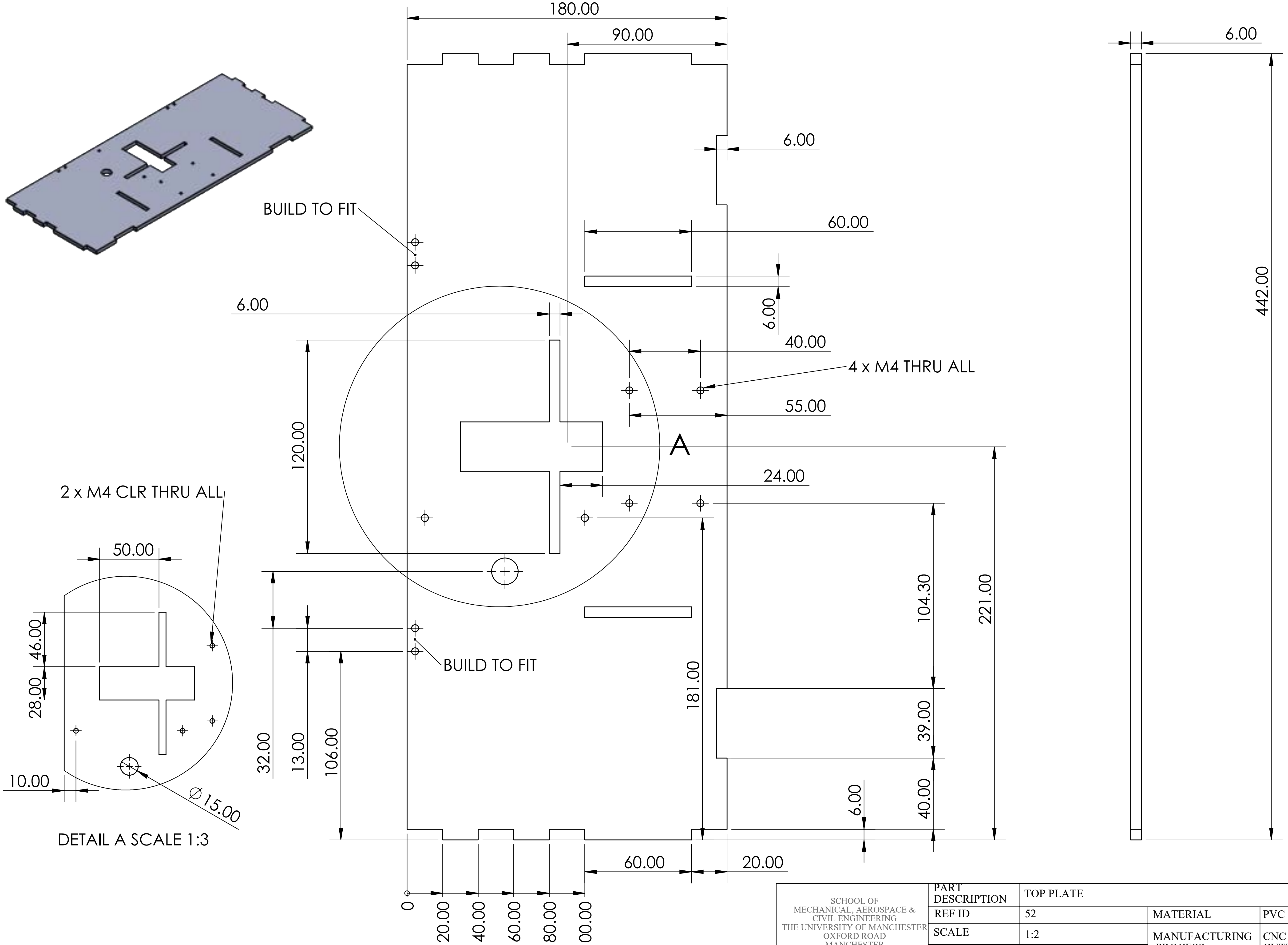


SCHOOL OF MECHANICAL, AEROSPACE & CIVIL ENGINEERING THE UNIVERSITY OF MANCHESTER OXFORD ROAD MANCHESTER M13 9PL	PART DESCRIPTION	SIDE PLATE (LOWER ARM SIDE)		
	REF ID	50	MATERIAL	PVC
	SCALE	1:1	MANUFACTURING PROCESS	CNC LASER CUTTING
	PROJECTION	ORTHOGRAPHIC		

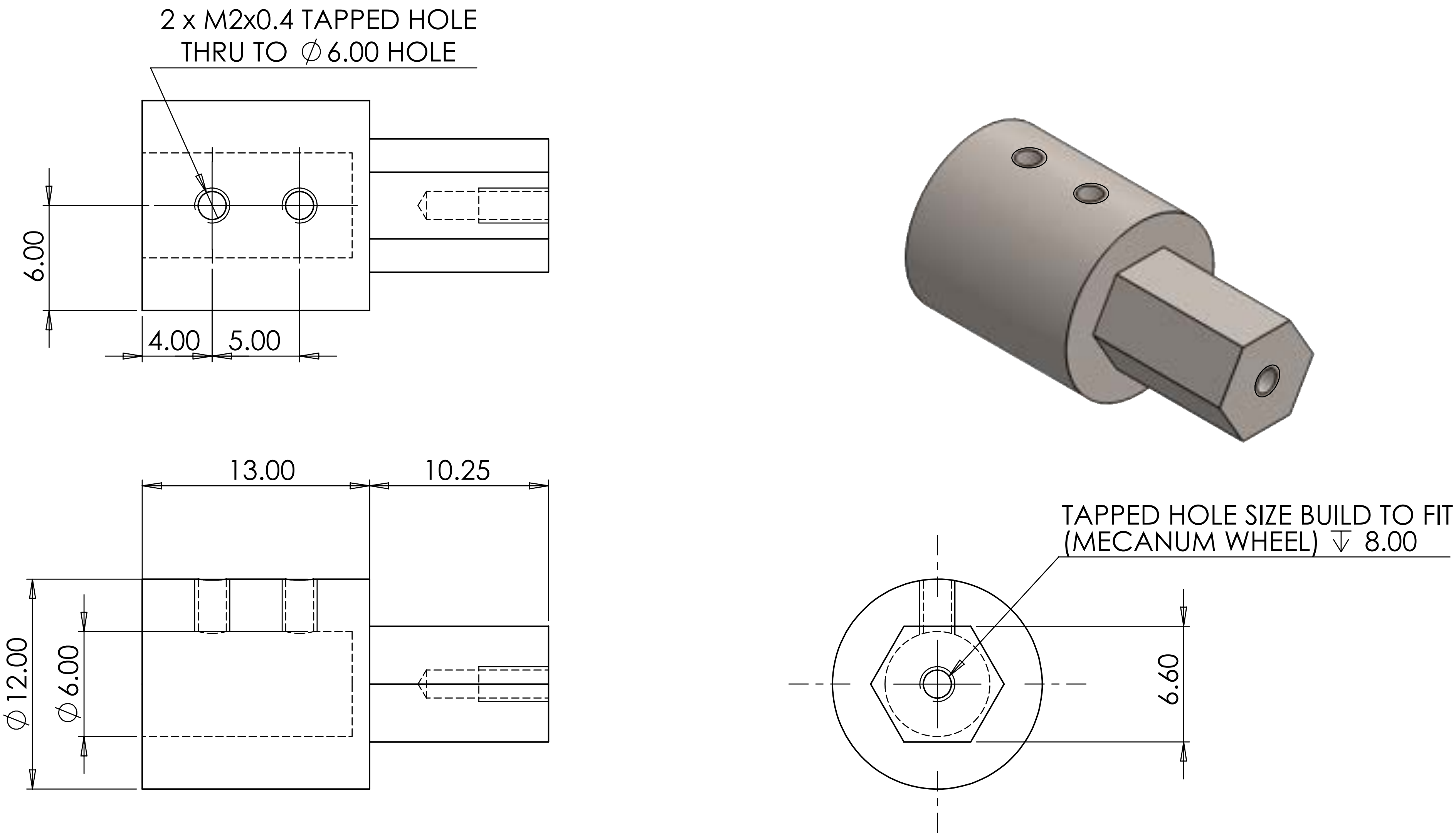




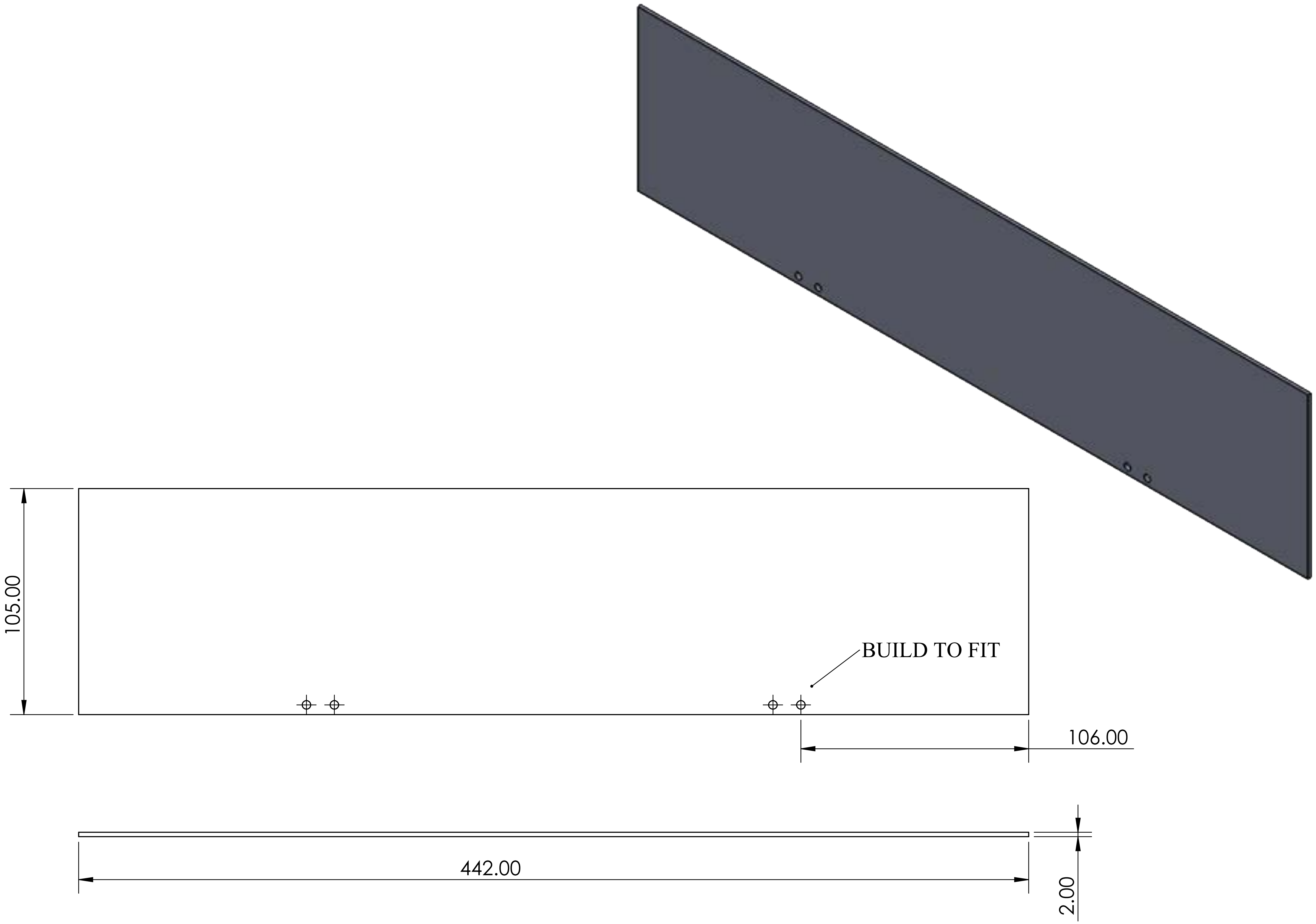
SCHOOL OF MECHANICAL, AEROSPACE & CIVIL ENGINEERING THE UNIVERSITY OF MANCHESTER OXFORD ROAD MANCHESTER M13 9PL	PART DESCRIPTION	SIDE PLATE		
	REF ID	48	MATERIAL	PVC
	SCALE	1:2	MANUFACTURING PROCESS	CNC LASER CUTTING
	PROJECTION	ORTHOGRAPHIC		



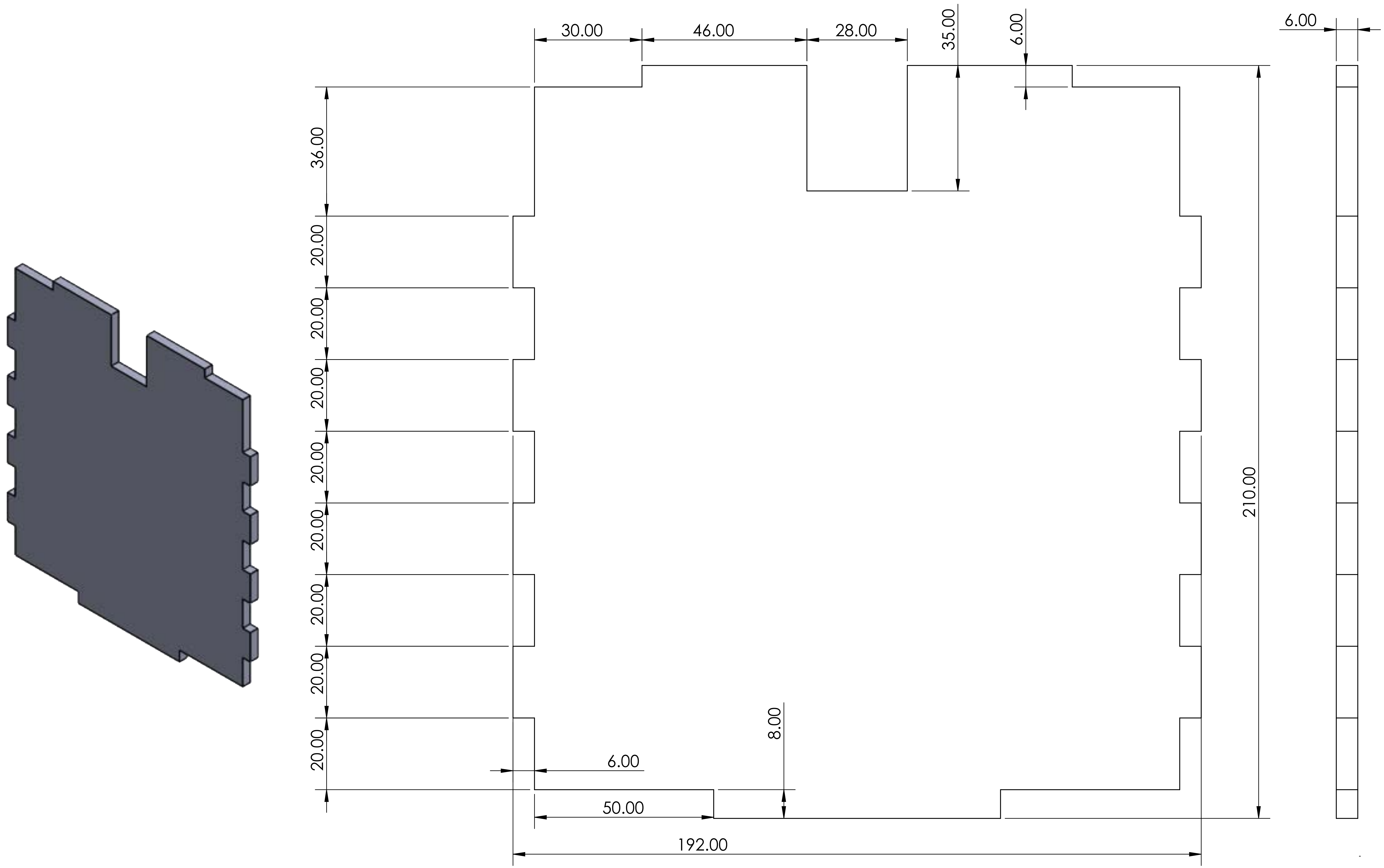
SCHOOL OF MECHANICAL, AEROSPACE & CIVIL ENGINEERING THE UNIVERSITY OF MANCHESTER OXFORD ROAD MANCHESTER M13 9PL	PART DESCRIPTION	TOP PLATE		
	REF ID	52	MATERIAL	PVC
	SCALE	1:2	MANUFACTURING PROCESS	CNC LASER CUTTING
	PROJECTION	ORTHOGRAPHIC		



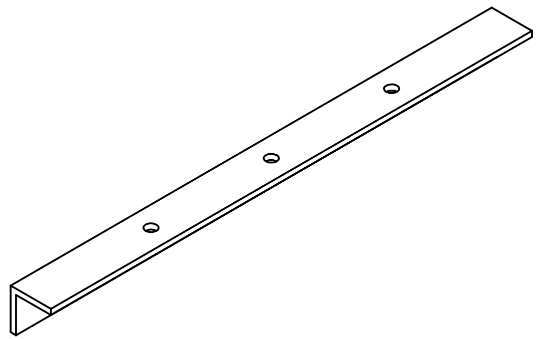
SCHOOL OF MECHANICAL, AEROSPACE & CIVIL ENGINEERING THE UNIVERSITY OF MANCHESTER OXFORD ROAD MANCHESTER M13 9PL	PART DESCRIPTION	WHEEL CONNECTOR		
	REF ID	57	MATERIAL	STAINLESS STEEL
	SCALE	3:1	MANUFACTURING PROCESS	CNC MACHINING
	PROJECTION	FIRST ANGLE		

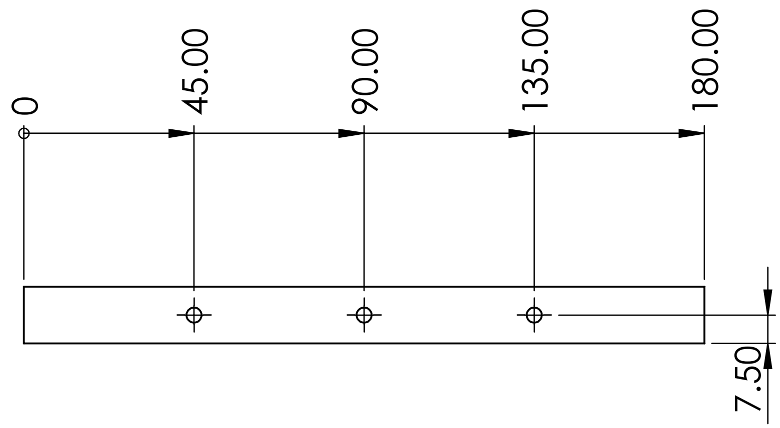


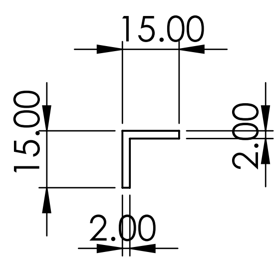
SCHOOL OF MECHANICAL, AEROSPACE & CIVIL ENGINEERING THE UNIVERSITY OF MANCHESTER OXFORD ROAD MANCHESTER M13 9PL	PART DESCRIPTION	LID		
	REF ID	55	MATERIAL	PVC
	SCALE	1:2	MANUFACTURING PROCESS	CNC LASER CUTTING
	PROJECTION	ORTHOGRAPHIC		

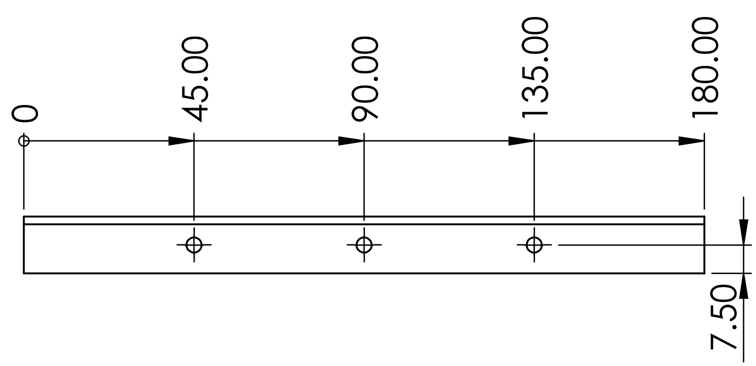


SCHOOL OF MECHANICAL, AEROSPACE & CIVIL ENGINEERING THE UNIVERSITY OF MANCHESTER OXFORD ROAD MANCHESTER M13 9PL	PART DESCRIPTION	LOWER ARM BACK PLATE		
	REF ID	51	MATERIAL	PVC
	SCALE	1:1	MANUFACTURING PROCESS	CNC LASER CUTTING
	PROJECTION	ORTHOGRAPHIC		

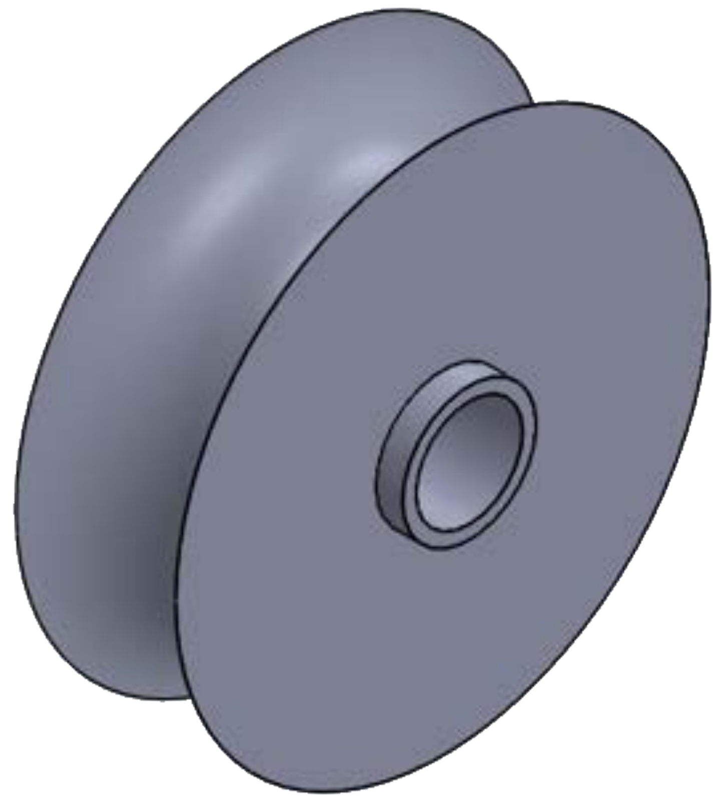


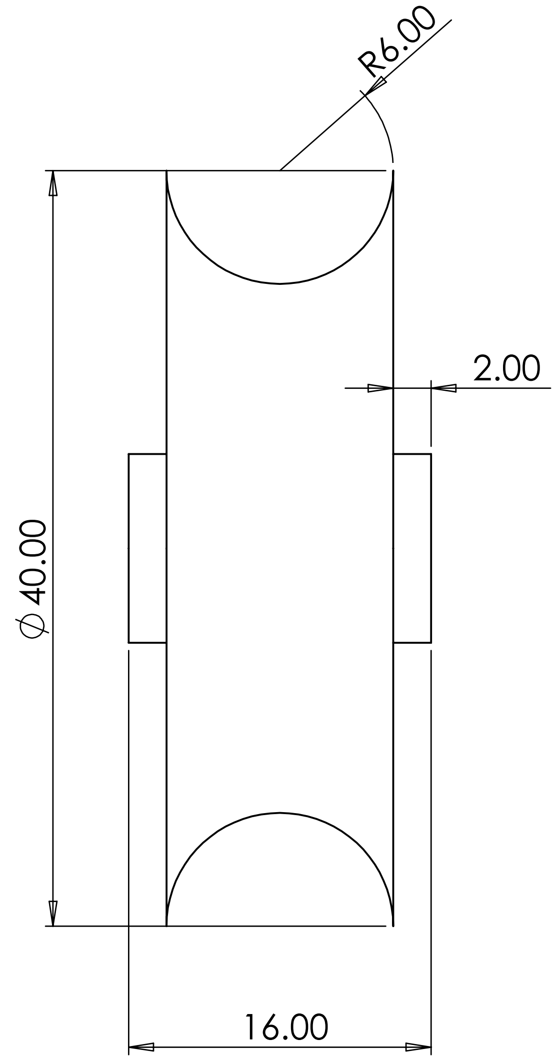


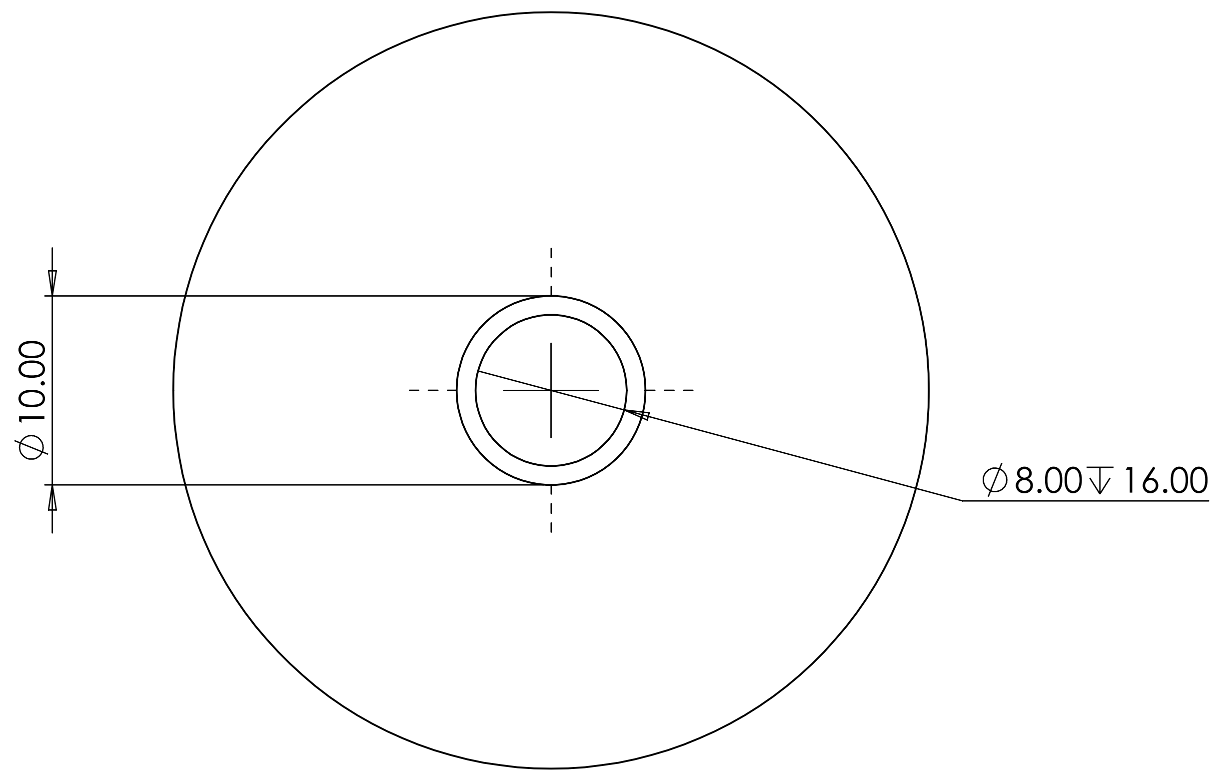




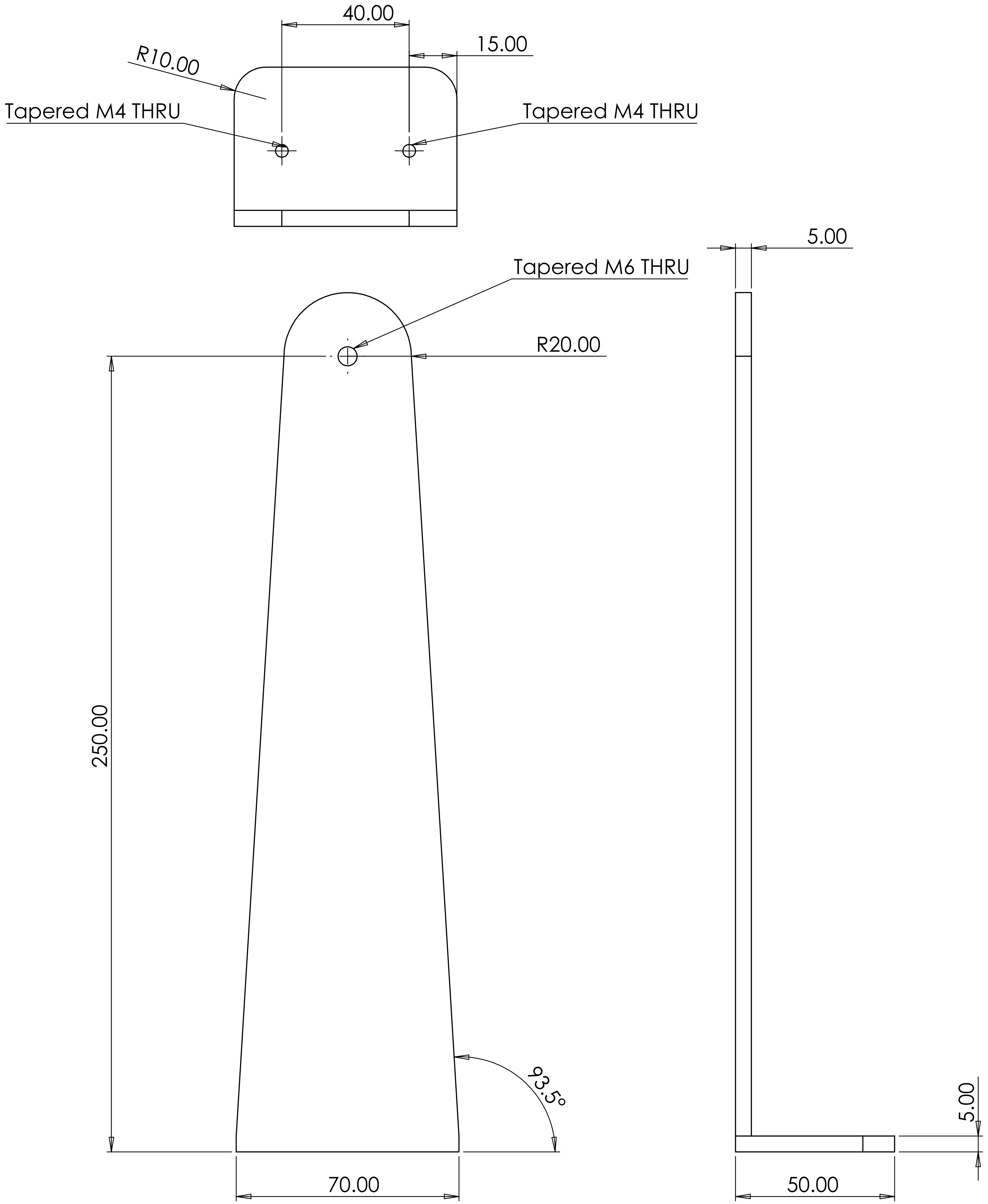
SCHOOL OF MECHANICAL, AEROSPACE & CIVIL ENGINEERING THE UNIVERSITY OF MANCHESTER OXFORD ROAD MANCHESTER M13 9PL	PART DESCRIPTION	L bracket		
	REF ID	67	MATERIAL	Aluminium
	SCALE	1:2	MANUFACTURING PROCESS	Drilling
	PROJECTION	First angle		

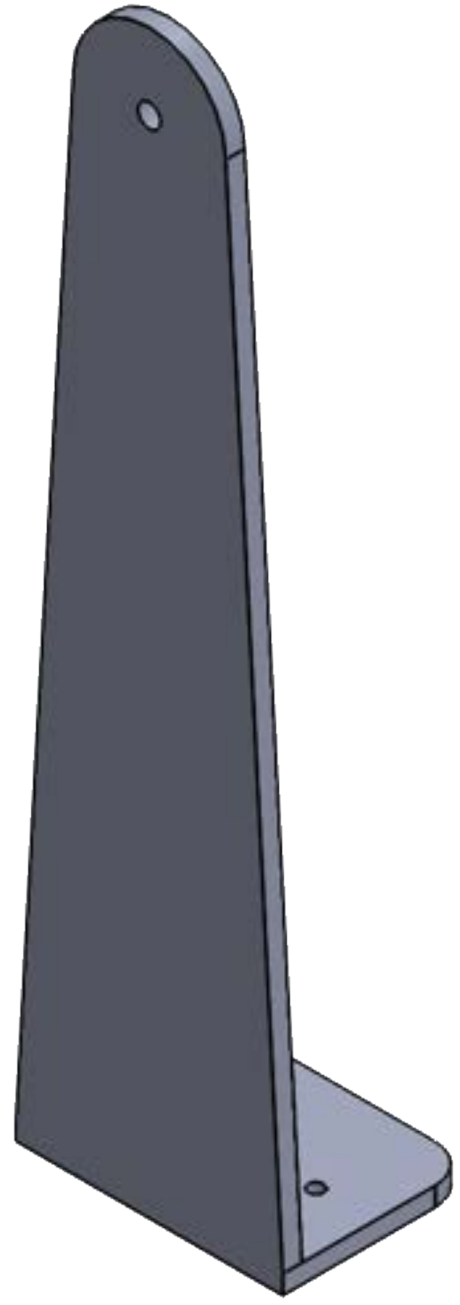




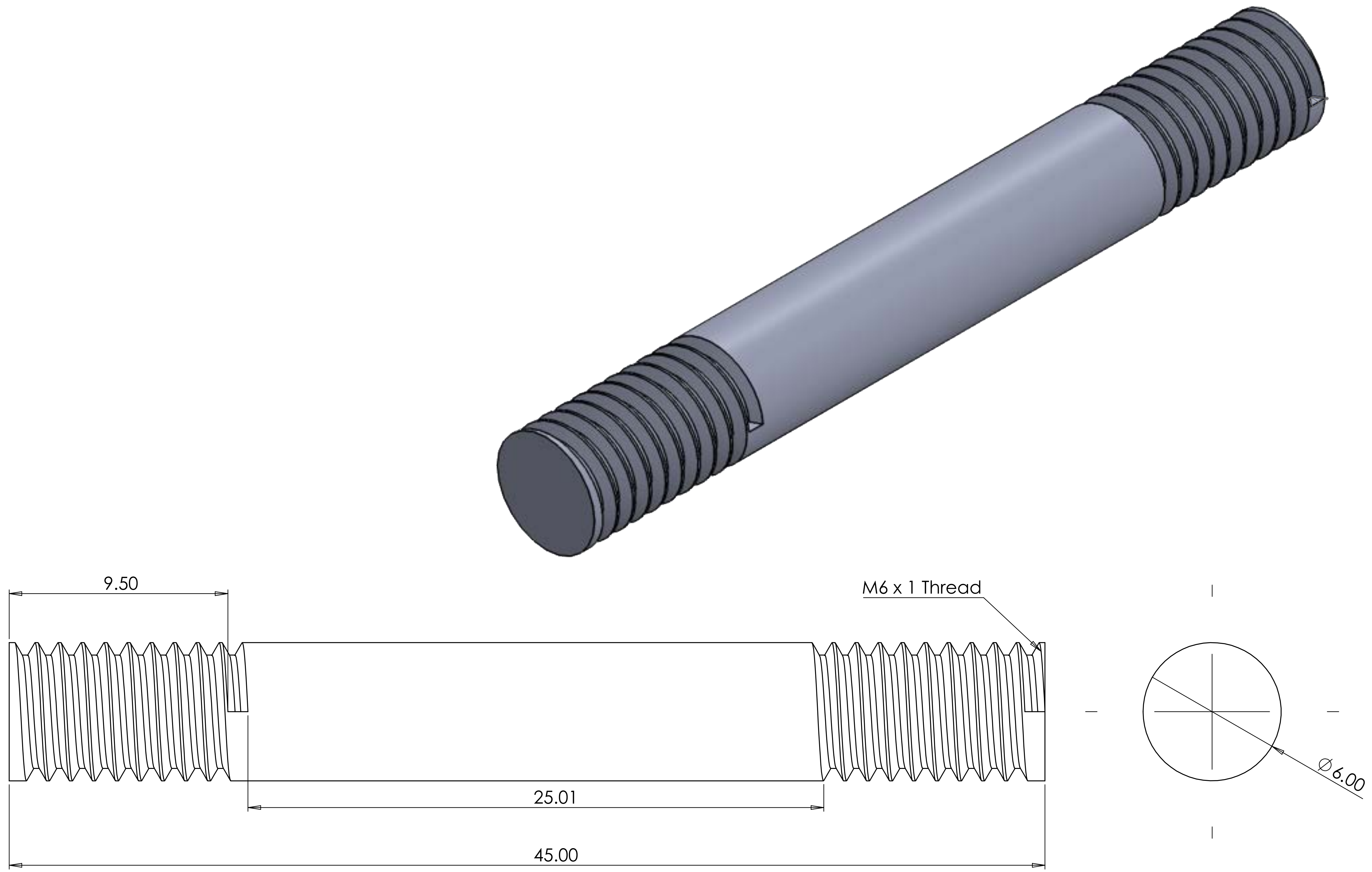


SCHOOL OF MECHANICAL, AEROSPACE & CIVIL ENGINEERING THE UNIVERSITY OF MANCHESTER OXFORD ROAD MANCHESTER M13 9PL	PART DESCRIPTION	T structure pulley wheel		
	REF ID	REF ID 1	MATERIAL	Delrin
	SCALE	2.5:1	MANUFACTURING PROCESS	Turning
	PROJECTION	First Angle		

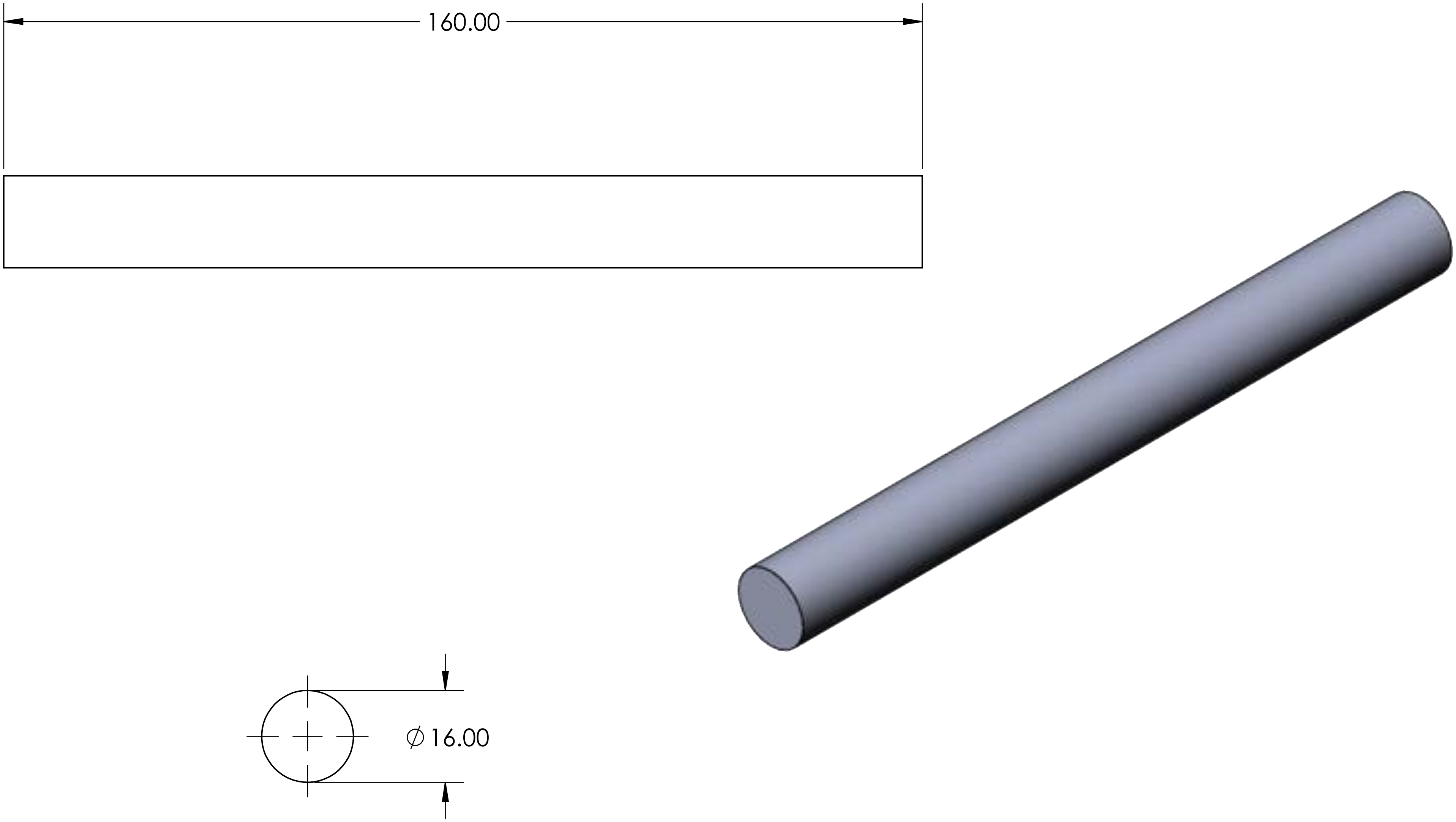




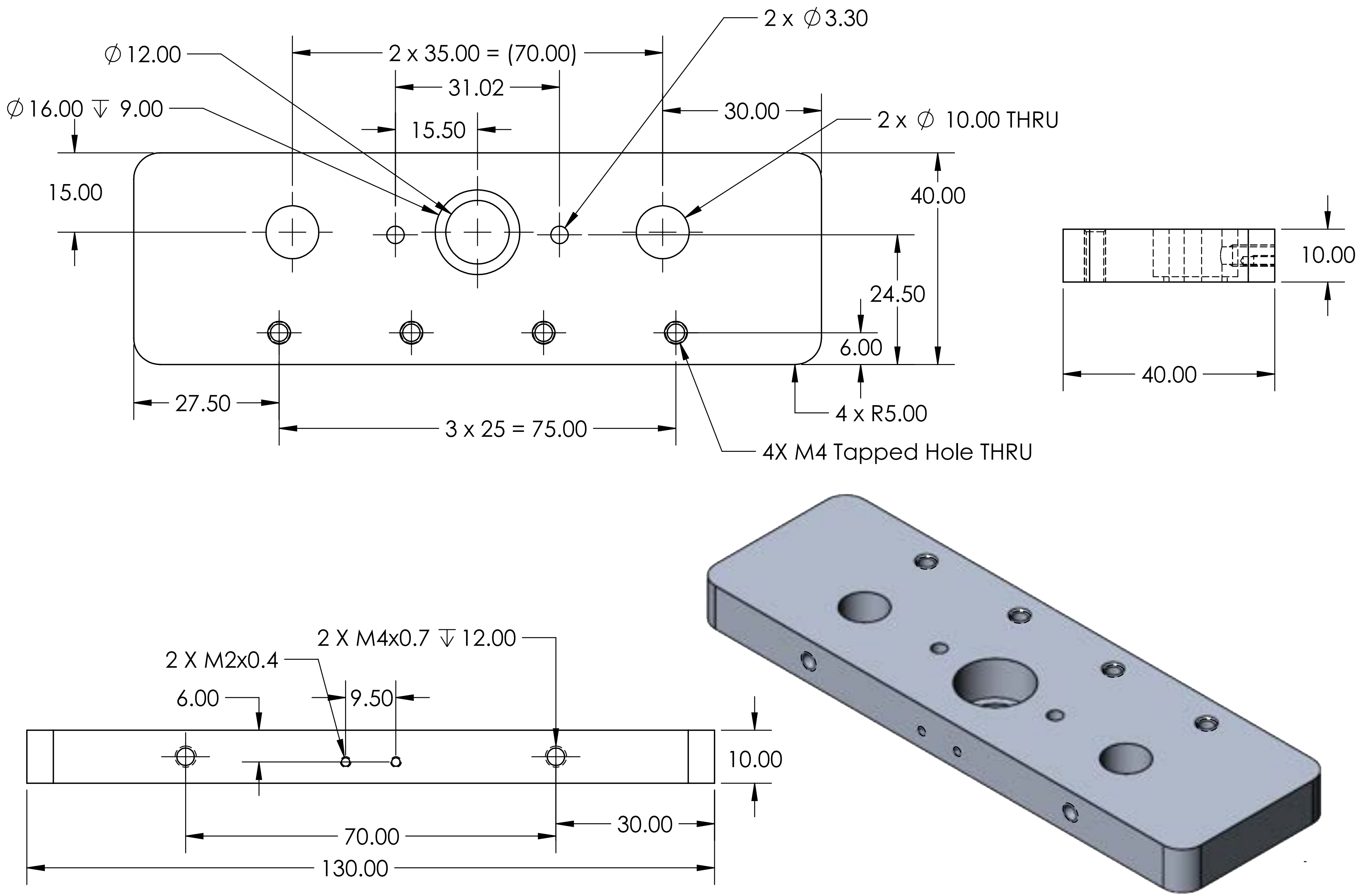
SCHOOL OF MECHANICAL, AEROSPACE & CIVIL ENGINEERING THE UNIVERSITY OF MANCHESTER OXFORD ROAD MANCHESTER M13 9PL	PART DESCRIPTION	T structure		
	REF ID	REF ID 20	MATERIAL	Aluminium
	SCALE	1:1.4	MANUFACTURING PROCESS	CNC Machining
	PROJECTION	First Angle		



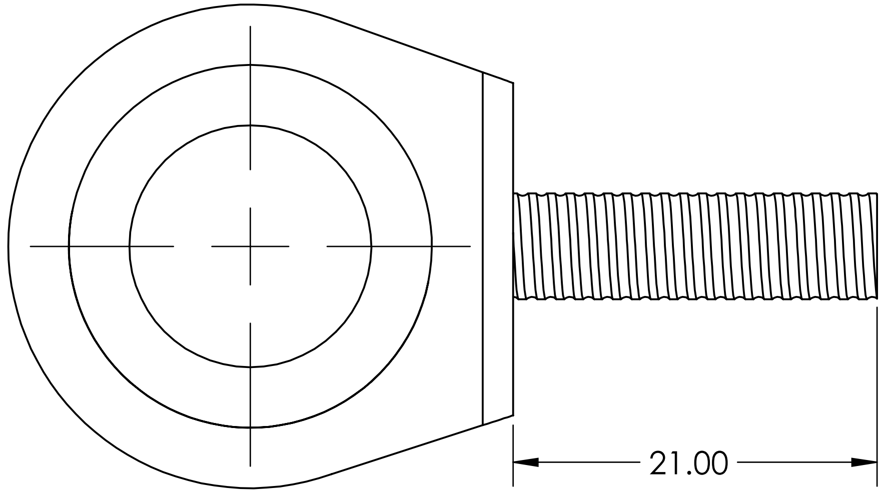
SCHOOL OF MECHANICAL, AEROSPACE & CIVIL ENGINEERING THE UNIVERSITY OF MANCHESTER OXFORD ROAD MANCHESTER M13 9PL	PART DESCRIPTION	T structure connection rod		
	REF ID	REF ID 21	MATERIAL	Aluminium
	SCALE	6:1	MANUFACTURING PROCESS	CNC machining
	PROJECTION	First Angle		

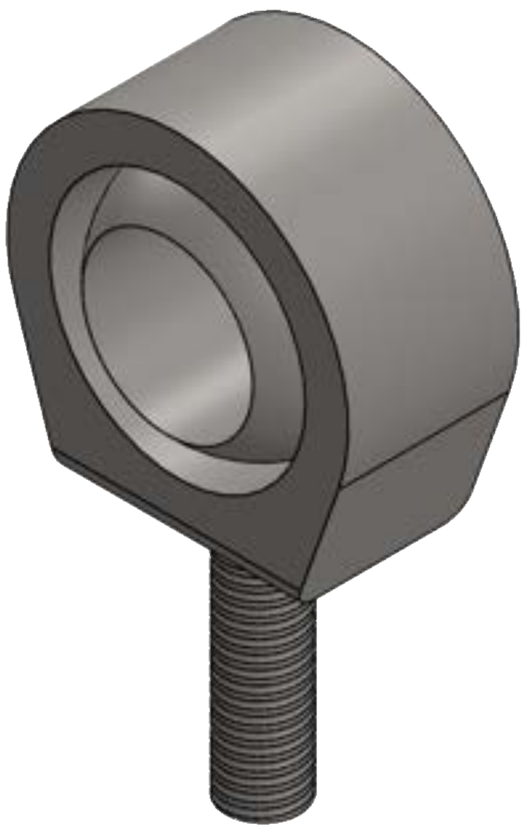


SCHOOL OF MECHANICAL, AEROSPACE & CIVIL ENGINEERING THE UNIVERSITY OF MANCHESTER OXFORD ROAD MANCHESTER M13 9PL	PART DESCRIPTION	16mm SHAFT		
	REF ID	16	MATERIAL	ALUMINIUM
	SCALE	1:1	MANUFACTURING PROCESS	TURNING
	PROJECTION	FIRST ANGLE		



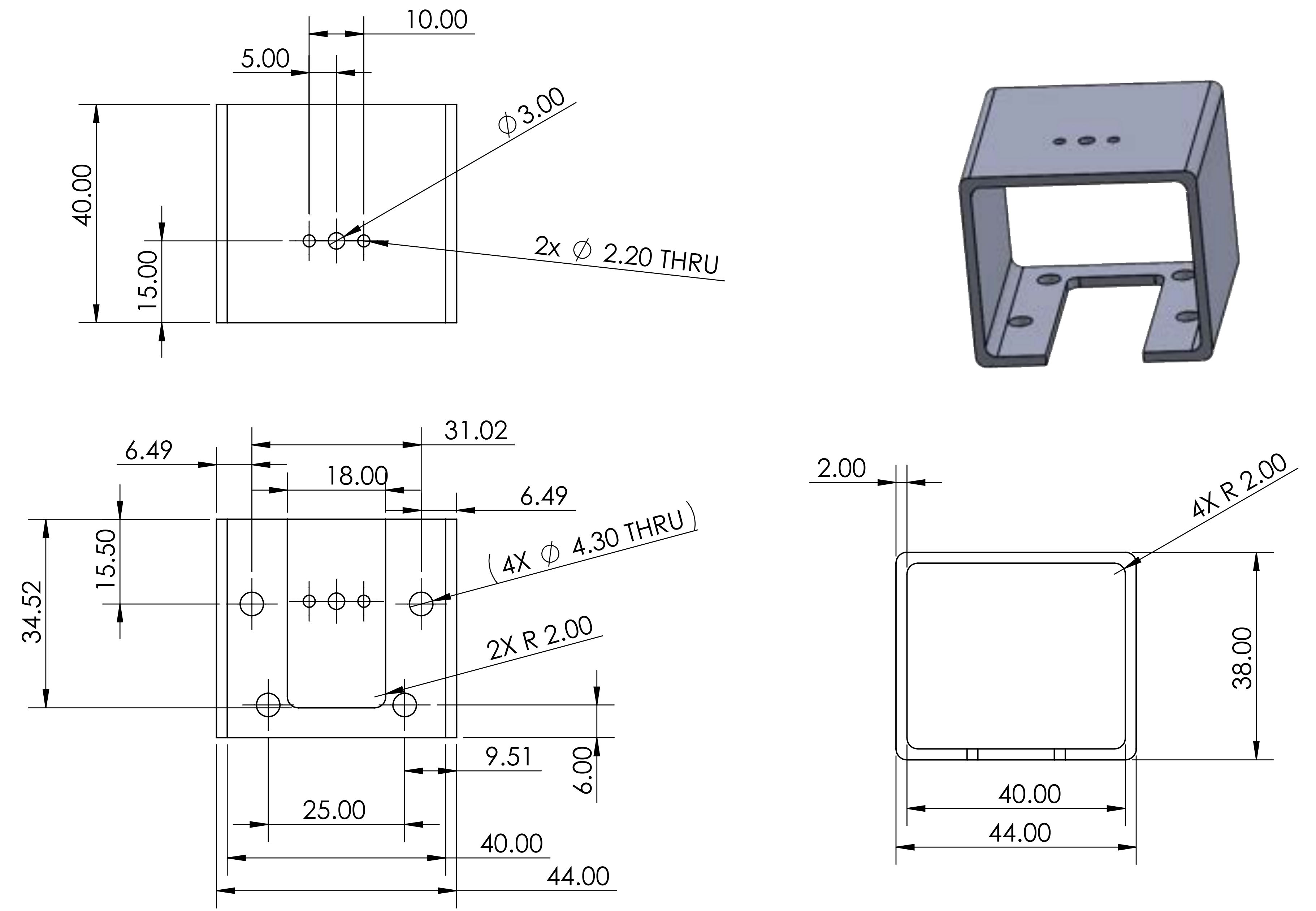
SCHOOL OF MECHANICAL, AEROSPACE & CIVIL ENGINEERING THE UNIVERSITY OF MANCHESTER OXFORD ROAD MANCHESTER M13 9PL	PART DESCRIPTION	TOP PLATE		
	REF ID		MATERIAL	ALUMINIUM
	SCALE	1:1	MANUFACTURING PROCESS	CNC MACHINING
	PROJECTION	FIRST ANGLE		



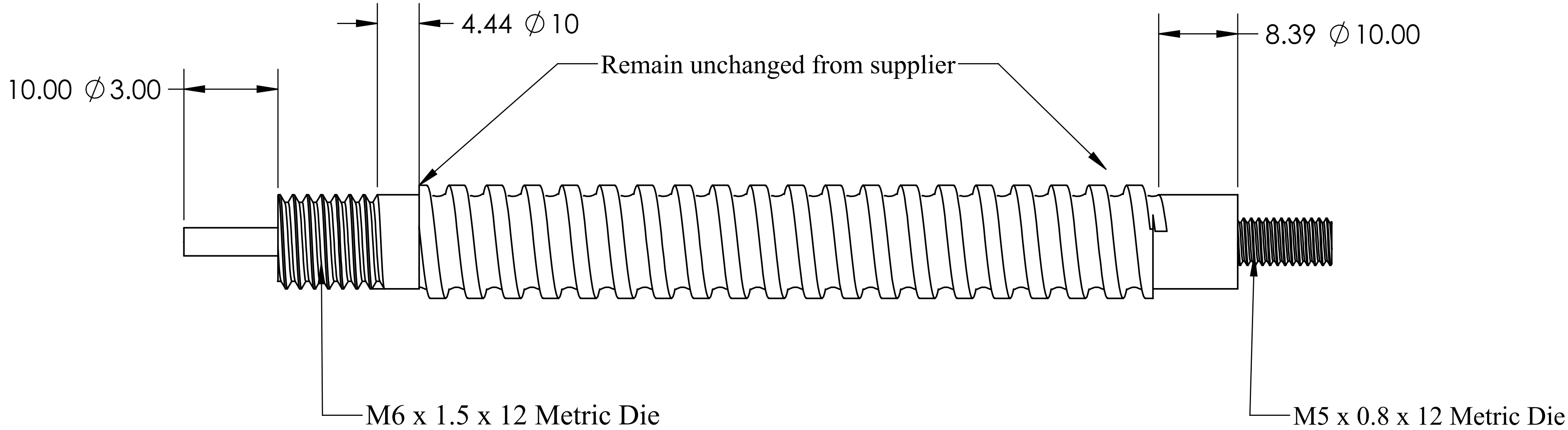


All other dimensions remain unchanged from the supplier

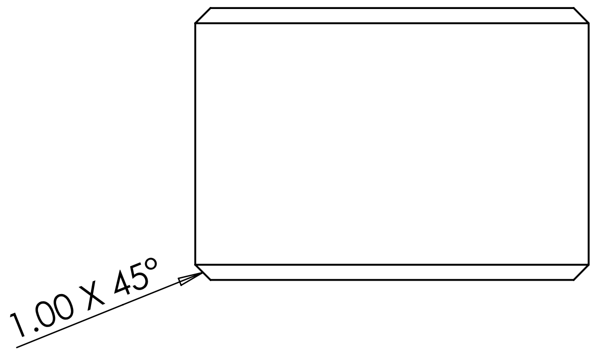
SCHOOL OF MECHANICAL, AEROSPACE & CIVIL ENGINEERING THE UNIVERSITY OF MANCHESTER OXFORD ROAD MANCHESTER M13 9PL	PART DESCRIPTION	ROD END BEARING, 16mm INNER DIAMETER		
	REF ID	4	MATERIALS	STEEL & BRONZE
	SCALE	2:1	MANUFACTURING PROCESS	Sawing
	PROJECTION	FIRST ANGLE		

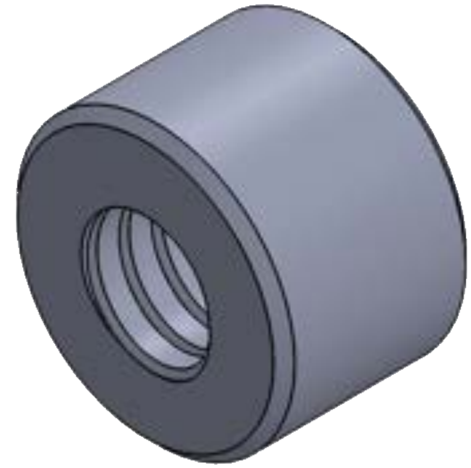


SCHOOL OF MECHANICAL, AEROSPACE & CIVIL ENGINEERING THE UNIVERSITY OF MANCHESTER OXFORD ROAD MANCHESTER M13 9PL	NAME	Motor Holder	TITLE	
	DATE		SCALE	
	GROUP	MENG 6	MATERIAL	ALUMINIUM
	EMAIL			

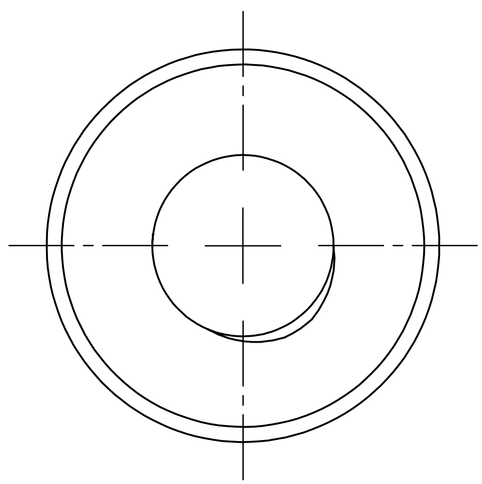


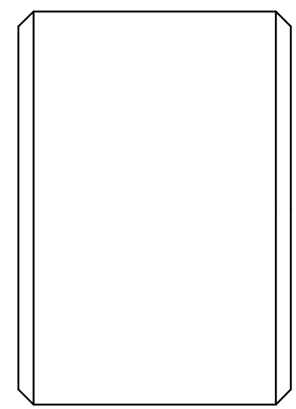
SCHOOL OF MECHANICAL, AEROSPACE & CIVIL ENGINEERING THE UNIVERSITY OF MANCHESTER OXFORD ROAD MANCHESTER M13 9PL	PART DESCRIPTION	RS PRO Lead Screw, 12mm Shaft Diameter		
	REF ID	5	MATERIAL	STEEL
	SCALE	1:1	MANUFACTURING PROCESS	TURNING, SAWING
	PROJECTION	FIRST ANGLE		



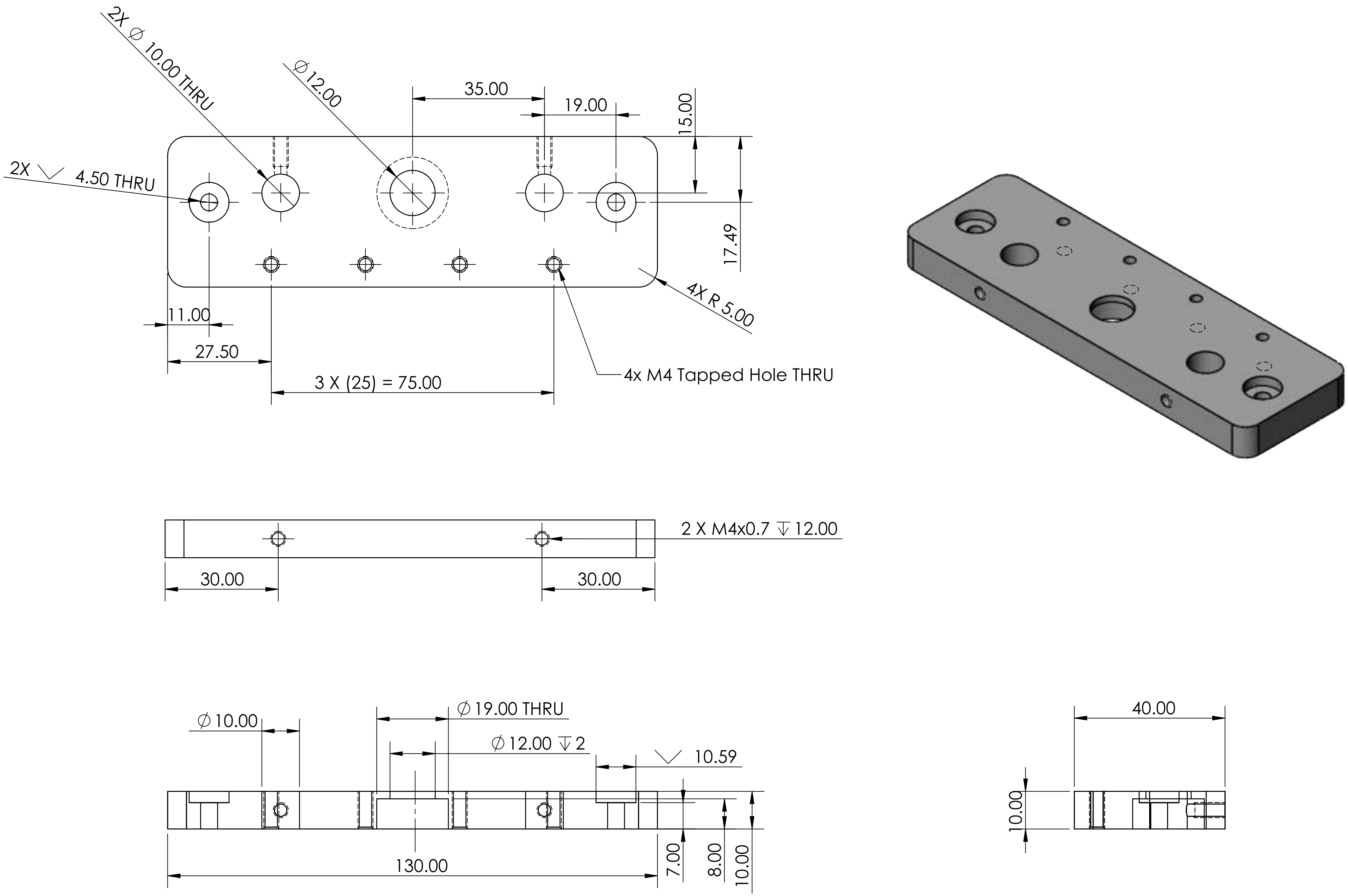


This part is obtained from the supplier.
The chamfer in the dimension above need to be removed.

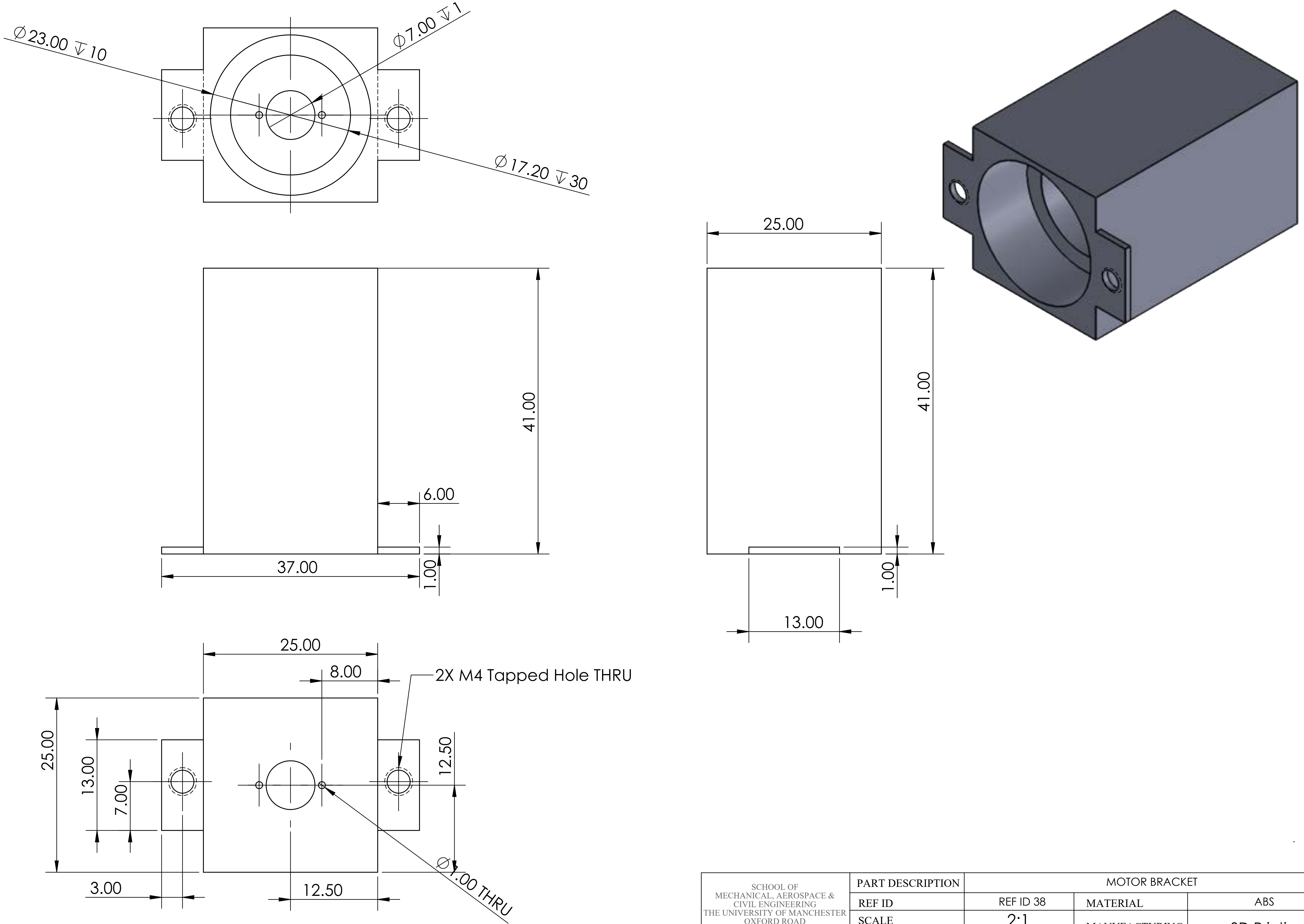




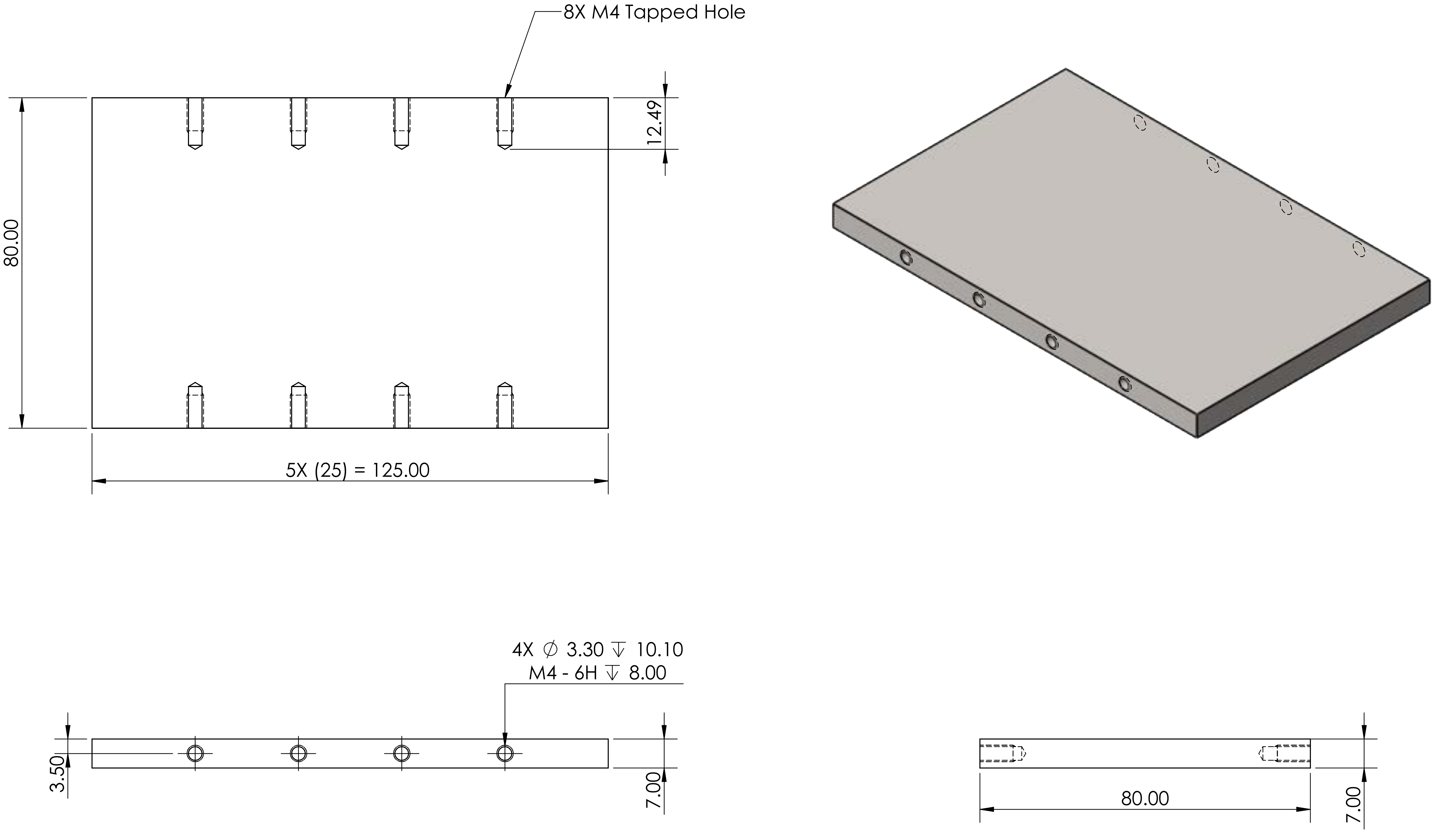
SCHOOL OF MECHANICAL, AEROSPACE & CIVIL ENGINEERING THE UNIVERSITY OF MANCHESTER OXFORD ROAD MANCHESTER M13 9PL	PART DESCRIPTION	LEADSCREW NUT		
	REF ID	REF ID 65	MATERIAL	STEEL
	SCALE	2:1	MANUFACTURING PROCESS	MILING
	PROJECTION	FIRST ANGLE		



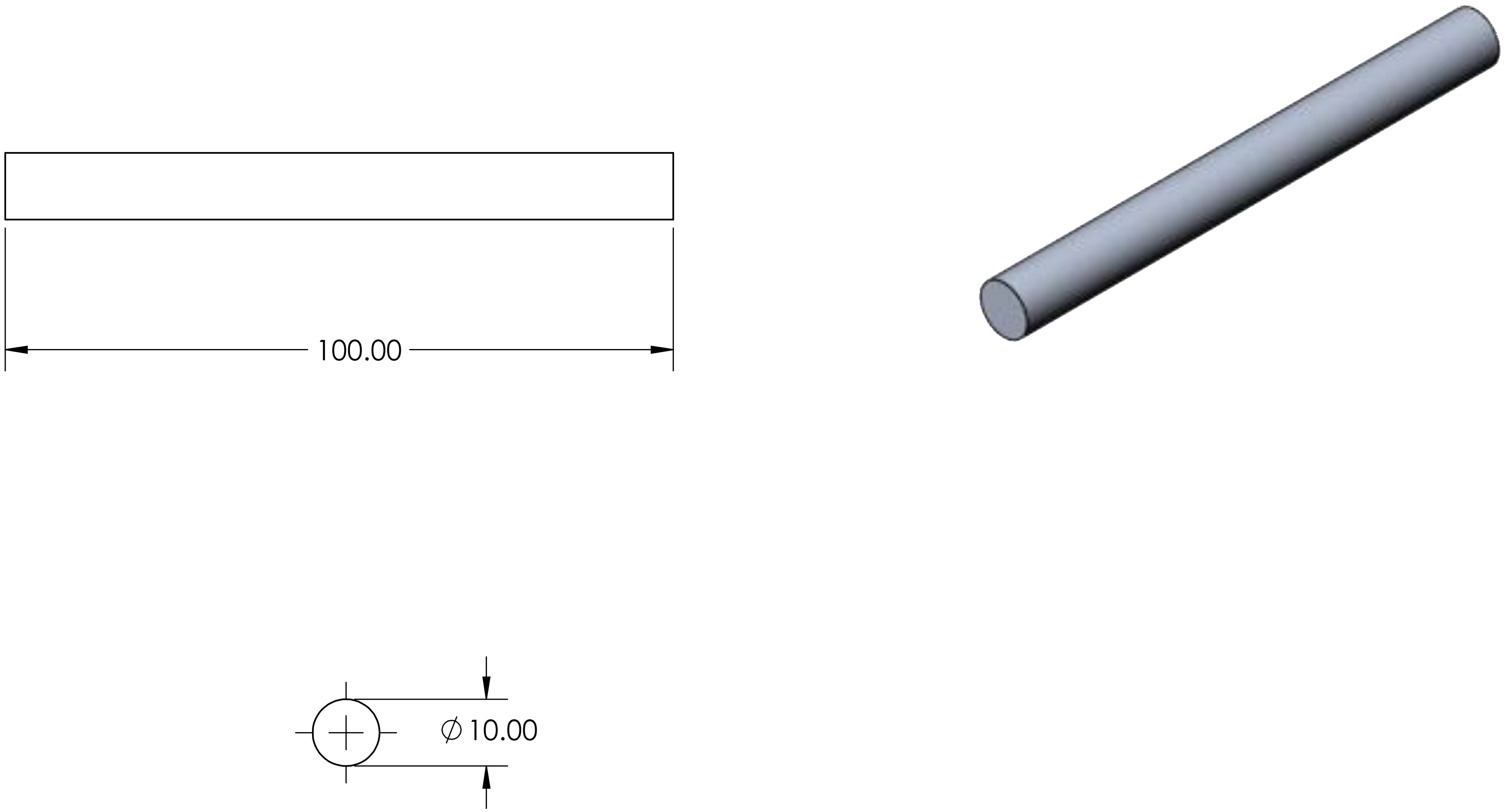
SCHOOL OF MECHANICAL, AEROSPACE & CIVIL ENGINEERING THE UNIVERSITY OF MANCHESTER OXFORD ROAD MANCHESTER M13 9PL	PART DESCRIPTION	BOTTOM PLATE		
	REF ID	REF ID 13	MATERIAL	ALUMINIUM
	SCALE	1:1	MANUFACTURING PROCESS	CNC MACHINING
	PROJECTION	FIRST ANGLE		



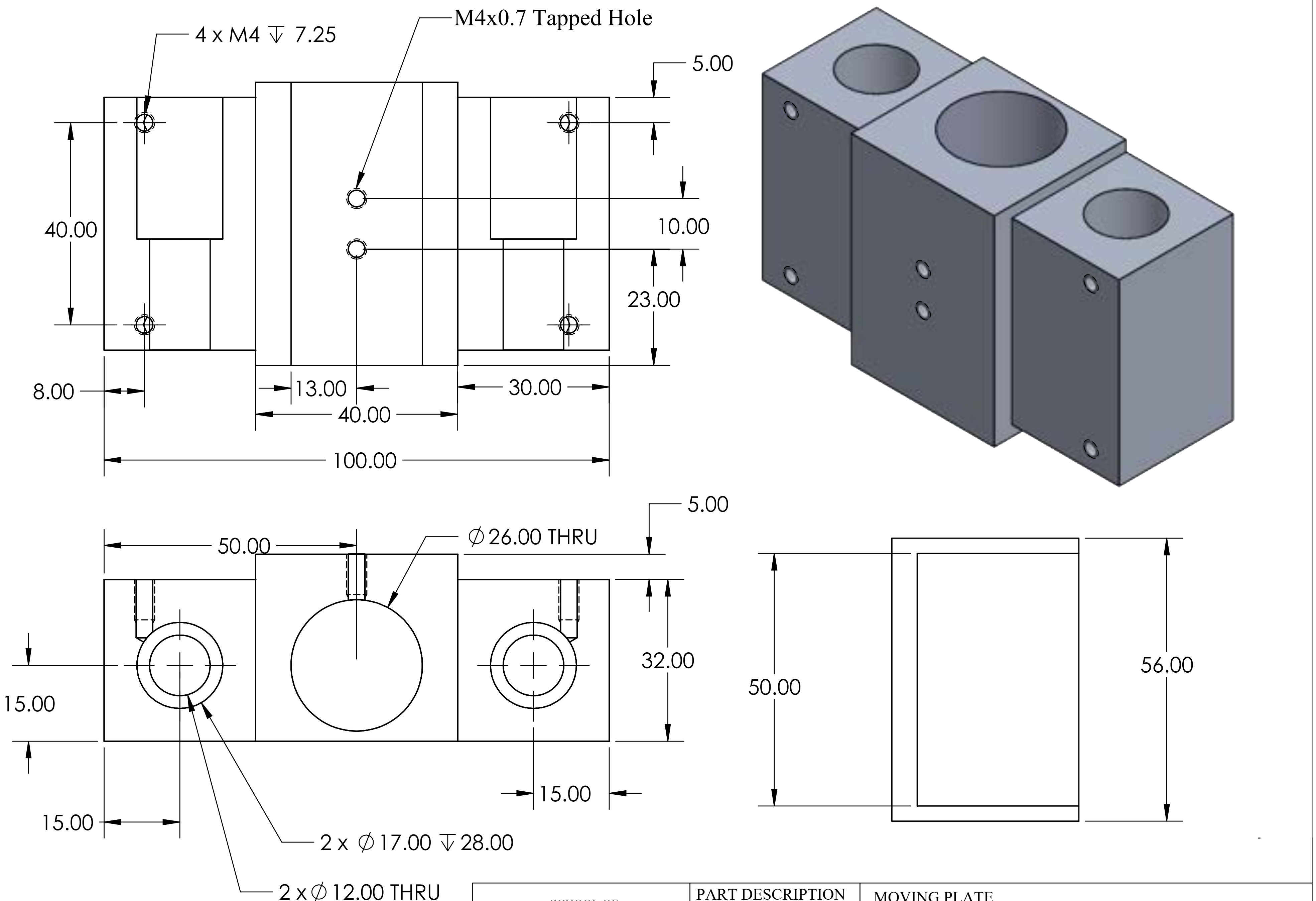
SCHOOL OF MECHANICAL, AEROSPACE & CIVIL ENGINEERING THE UNIVERSITY OF MANCHESTER OXFORD ROAD MANCHESTER M13 9PL	PART DESCRIPTION	MOTOR BRACKET		
	REF ID	REF ID 38	MATERIAL	ABS
	SCALE	2:1	MANUFACTURING PROCESS	3D Printing
	PROJECTION	FIRST ANGLE		



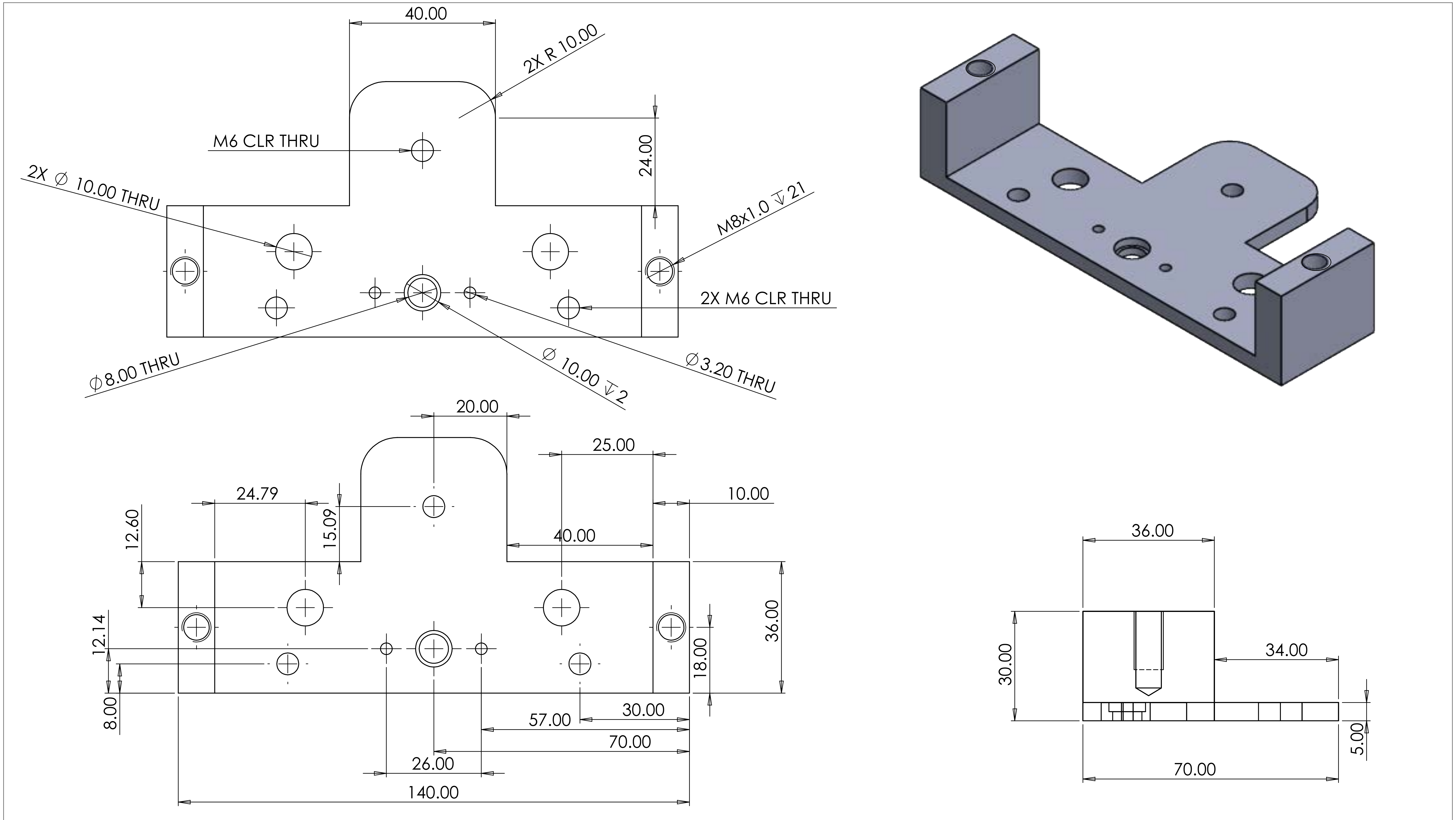
SCHOOL OF MECHANICAL, AEROSPACE & CIVIL ENGINEERING THE UNIVERSITY OF MANCHESTER OXFORD ROAD MANCHESTER M13 9PL	PART DESCRIPTION	BASE PLATE		
	REF ID	REF ID 18	MATERIAL	ALUMINIUM
	SCALE	1:1	MANUFACTURING PROCESS	CNC MACHINING
	PROJECTION	FIRST ANGLE		

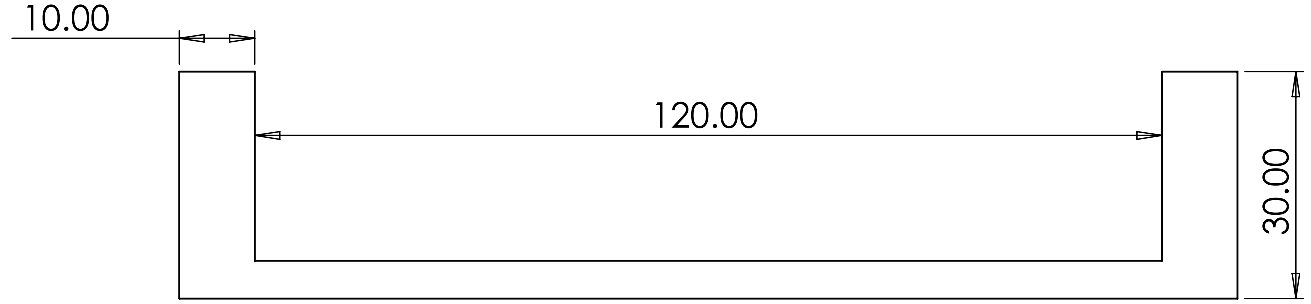


SCHOOL OF MECHANICAL, AEROSPACE & CIVIL ENGINEERING THE UNIVERSITY OF MANCHESTER OXFORD ROAD MANCHESTER M13 9PL	PART DESCRIPTION	SLIDING RODS		
	REF ID	11	MATERIAL	STAINLESS STEEL
	SCALE	1:1	MANUFACTURING PROCESS	TURNING
	PROJECTION	FIRST ANGLE		

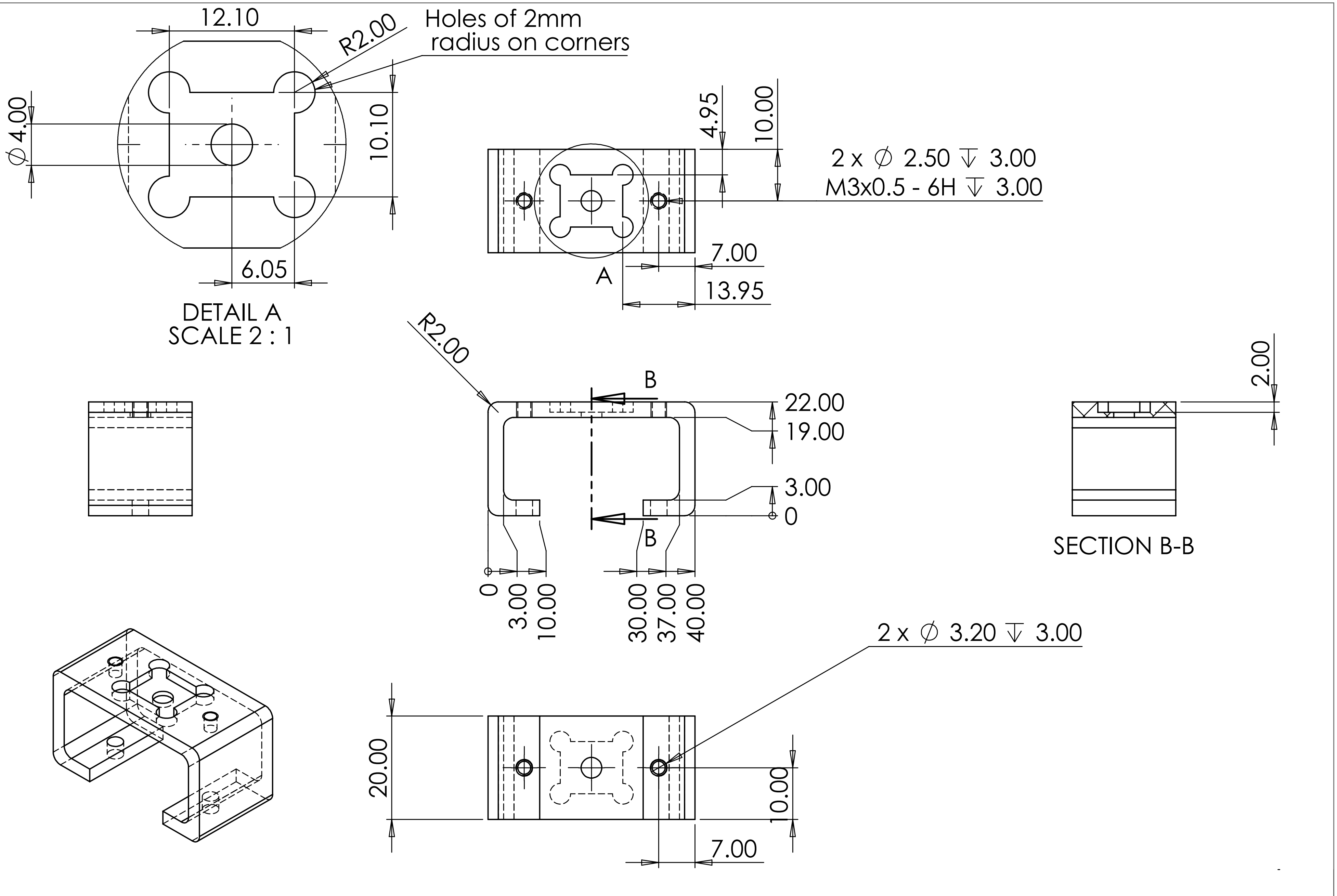


SCHOOL OF MECHANICAL, AEROSPACE & CIVIL ENGINEERING THE UNIVERSITY OF MANCHESTER OXFORD ROAD MANCHESTER M13 9PL	PART DESCRIPTION	MOVING PLATE		
	REF ID	10	MATERIAL	ALUMINIUM
	SCALE	1:1	MANUFACTURING PROCESS	CNC MACHINING
	PROJECTION	FIRST ANGLE		

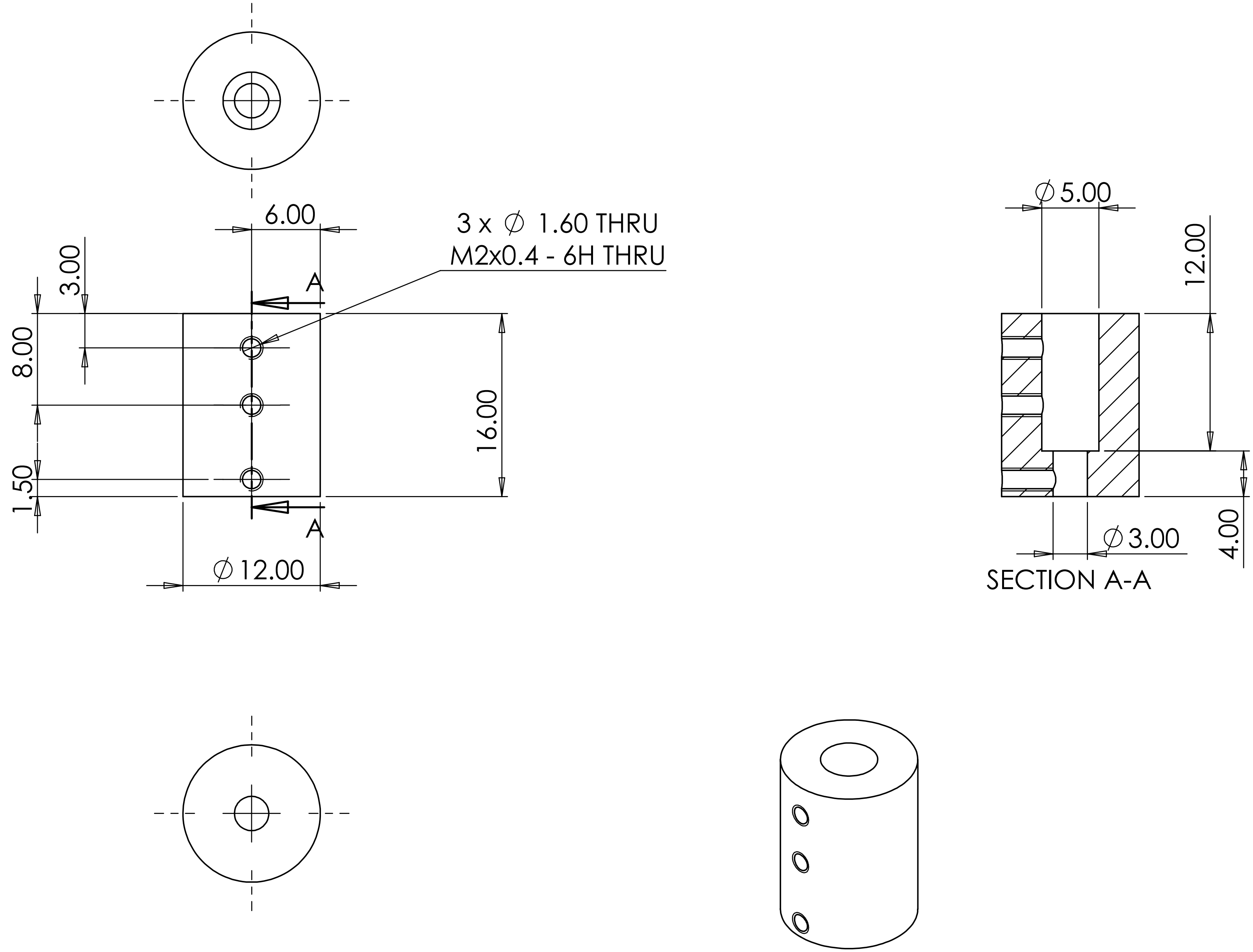




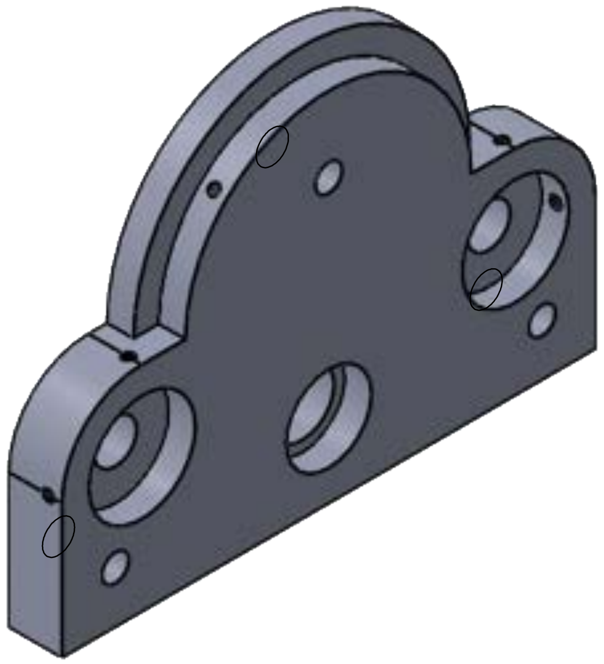
SCHOOL OF MECHANICAL, AEROSPACE & CIVIL ENGINEERING THE UNIVERSITY OF MANCHESTER OXFORD ROAD MANCHESTER M13 9PL	PART DESCRIPTION	CLEANING ARM HOLDER		
	REF ID	REF ID 17	MATERIAL	ALUMINIUM
	SCALE	1:1	PROCESS	CNC MACHINING
	PROJECTION	FIRST ANGLE		

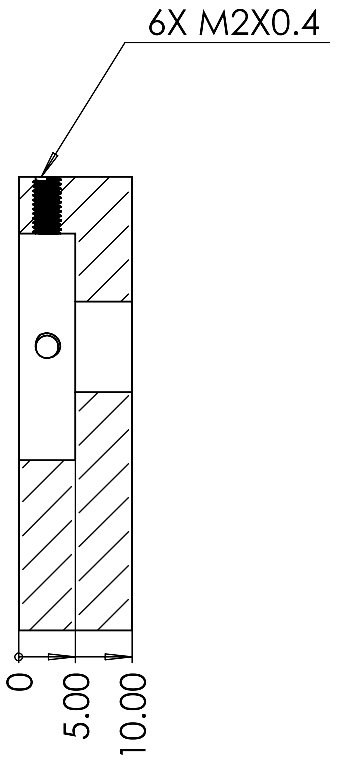


SCHOOL OF MECHANICAL, AEROSPACE & CIVIL ENGINEERING THE UNIVERSITY OF MANCHESTER OXFORD ROAD MANCHESTER M13 9PL	NAME		TITLE	
	DATE		SCALE	
	PROGRAMME		PROJECTION	
	EMAIL			



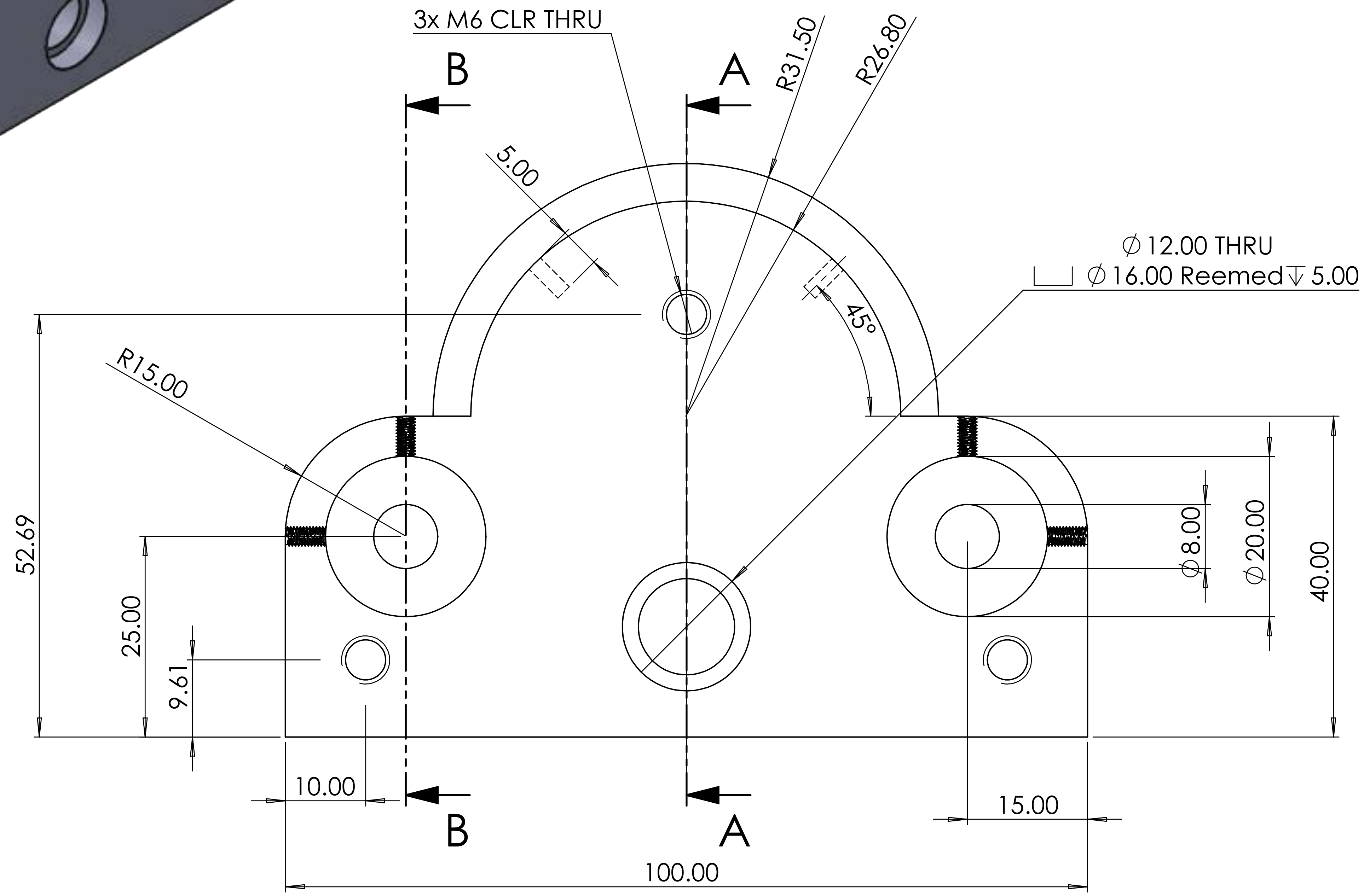
SCHOOL OF MECHANICAL, AEROSPACE & CIVIL ENGINEERING THE UNIVERSITY OF MANCHESTER OXFORD ROAD MANCHESTER M13 9PL	NAME		TITLE	
	DATE		SCALE	
	PROGRAMME		PROJECTION	
	EMAIL			

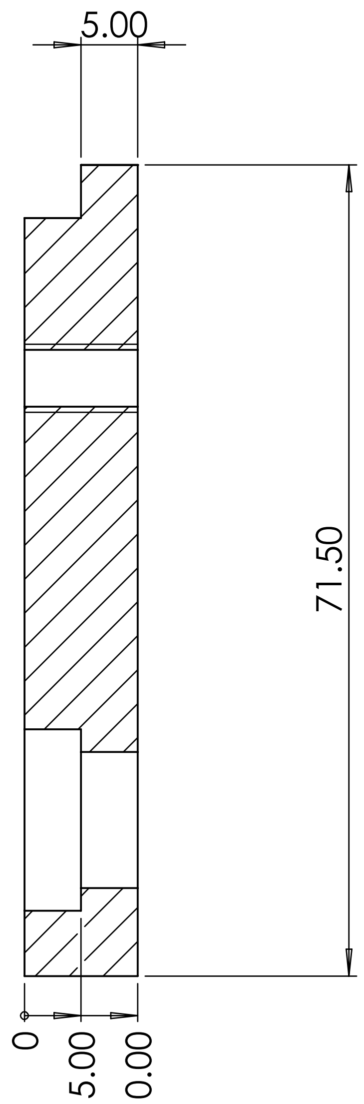




SECTION B-B

SCALE 3 : 2

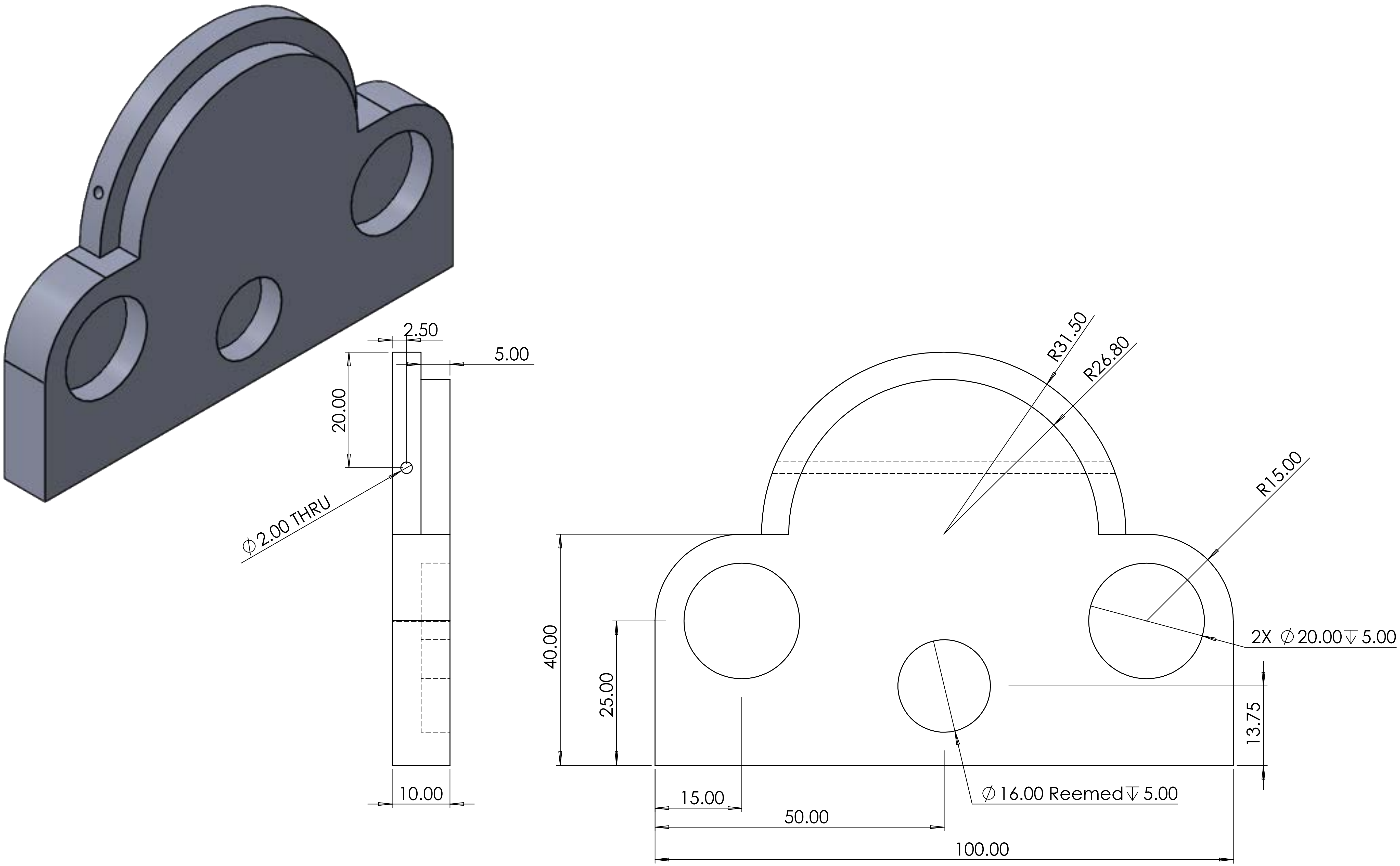




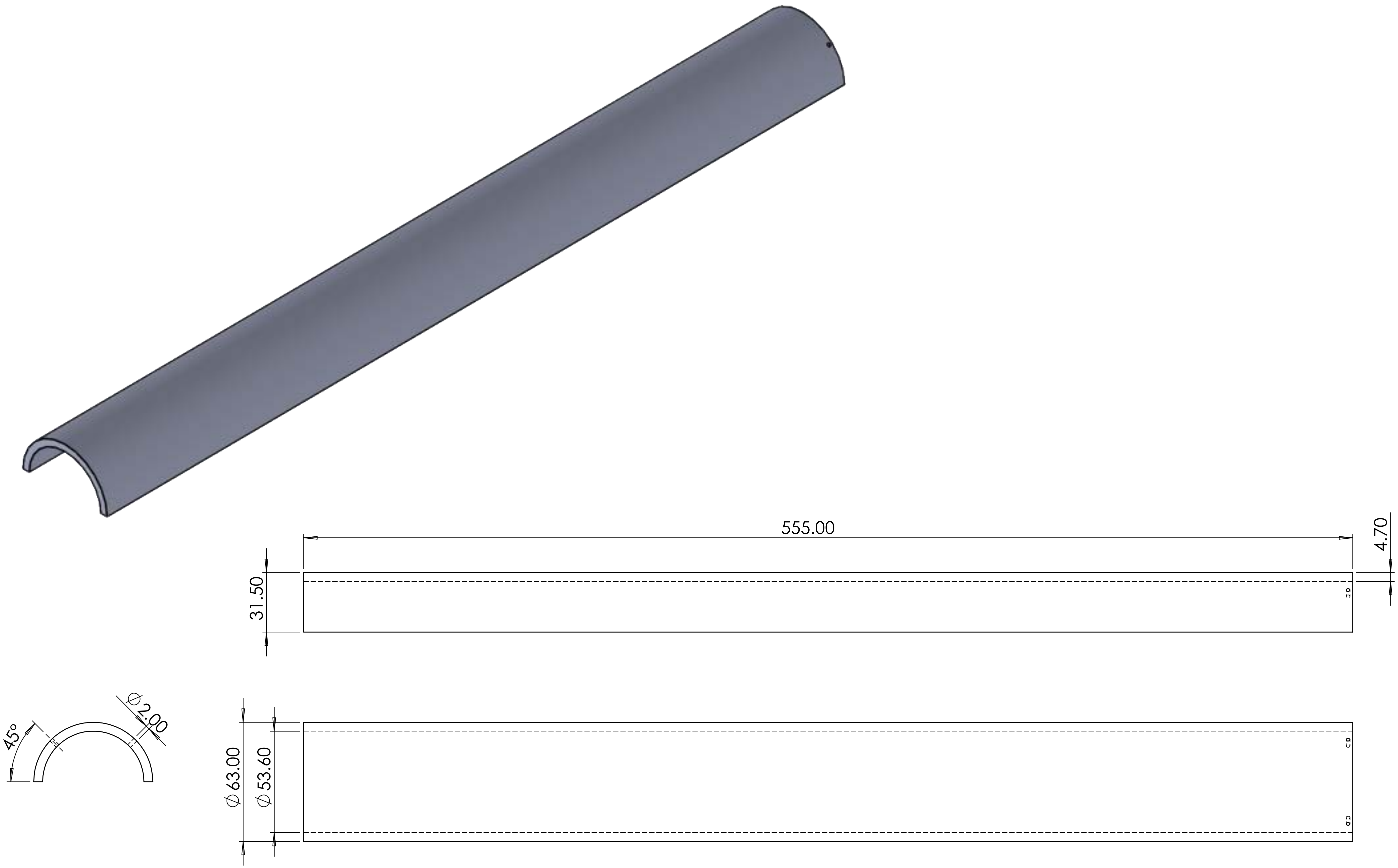
SECTION A-A

SCALE 3 : 2

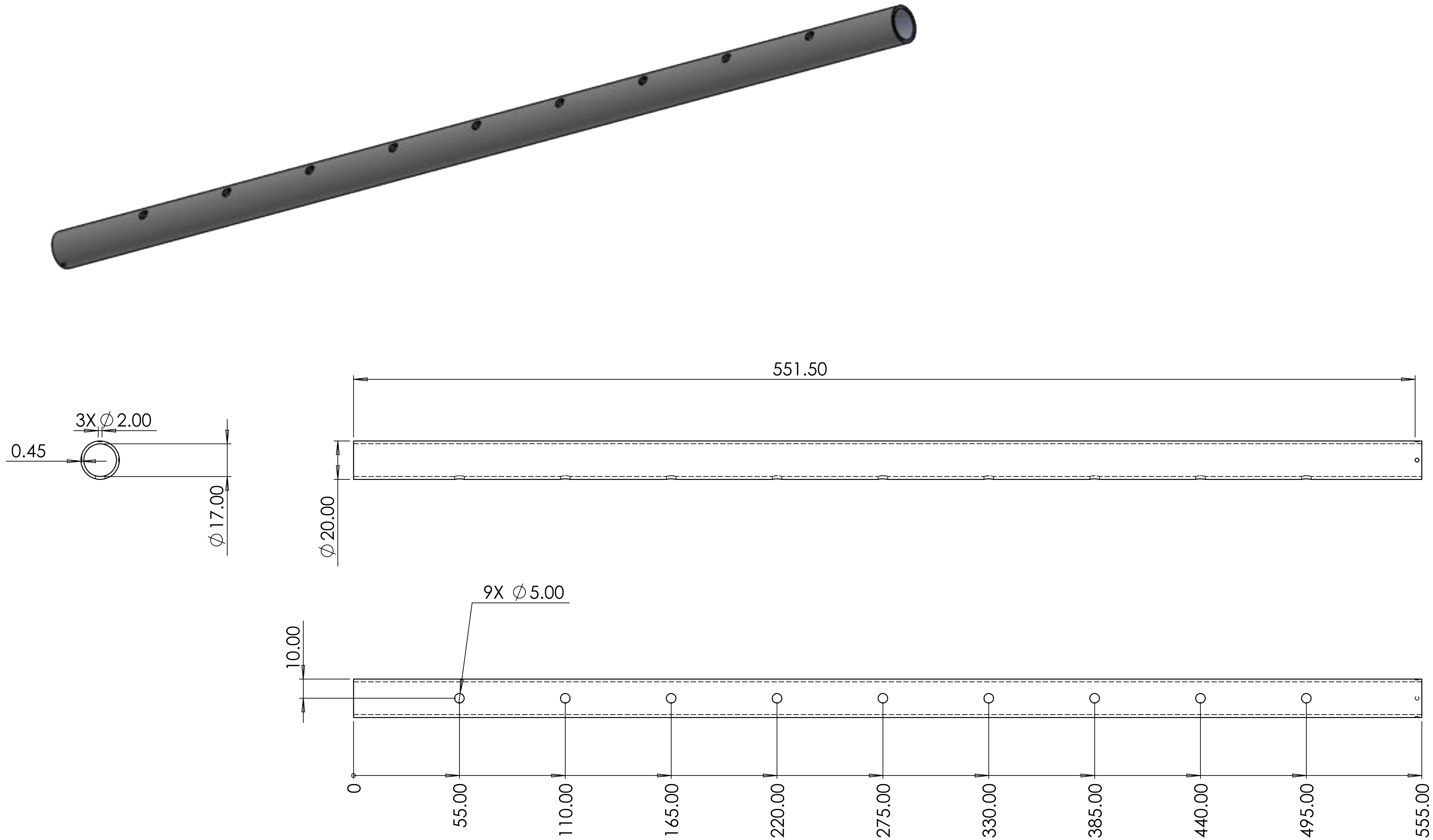
SCHOOL OF MECHANICAL, AEROSPACE & CIVIL ENGINEERING THE UNIVERSITY OF MANCHESTER OXFORD ROAD MANCHESTER M13 9PL	PART DESCRIPTION	Upper Arm Beginning Piece		
	REF ID	REF ID 41	MATERIAL	PVC
	SCALE	3:2	MANUFACTURING PROCESS	CNC Machining
	PROJECTION	Orthographic		



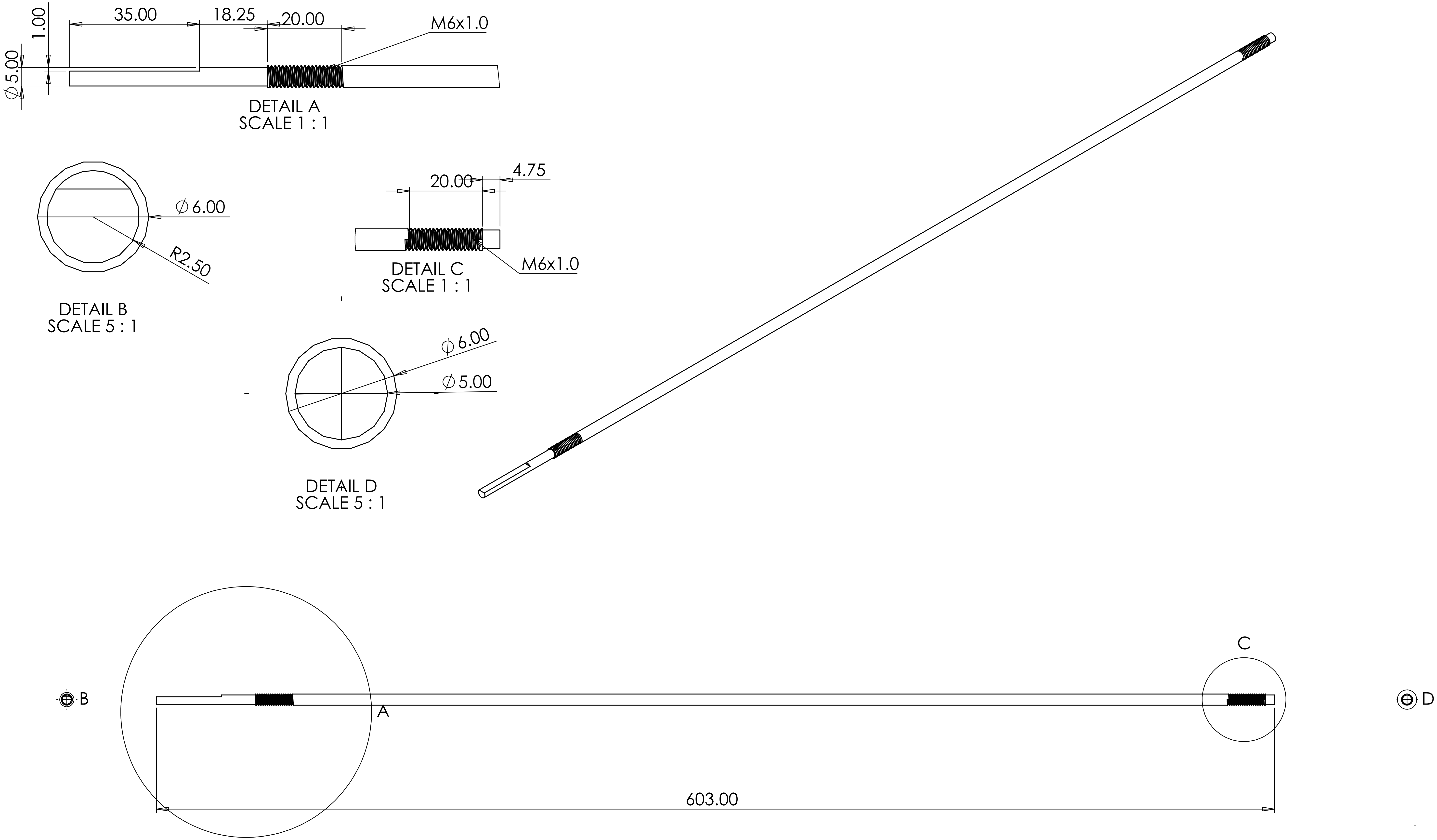
SCHOOL OF MECHANICAL, AEROSPACE & CIVIL ENGINEERING THE UNIVERSITY OF MANCHESTER OXFORD ROAD MANCHESTER M13 9PL	PART DESCRIPTION	Upper Arm End Piece		
	REF ID	REF ID 42	MATERIAL	PVC
	SCALE	3:2	MANUFACTURING PROCESS	CNC Machining
	PROJECTION			



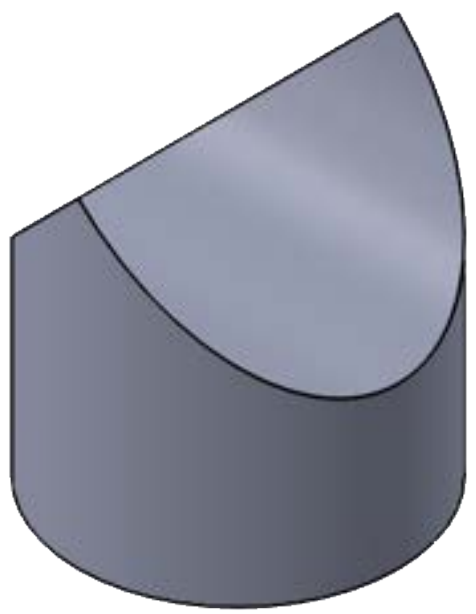
SCHOOL OF MECHANICAL, AEROSPACE & CIVIL ENGINEERING THE UNIVERSITY OF MANCHESTER OXFORD ROAD MANCHESTER M13 9PL	PART DESCRIPTION	Upper Arm Top Piece		
	REF ID	REF ID 43	MATERIAL	PVC
	SCALE	1:2	MANUFATCURING PROCESS	Circular Saw
	PROJECTION			

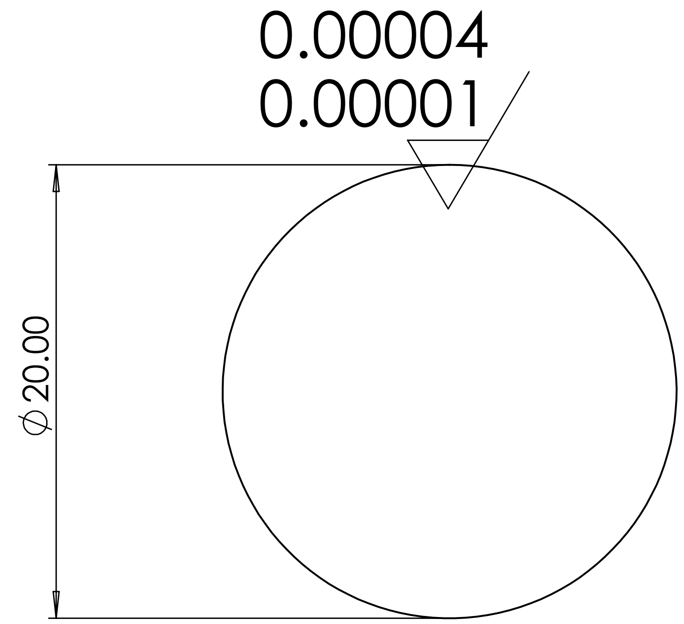


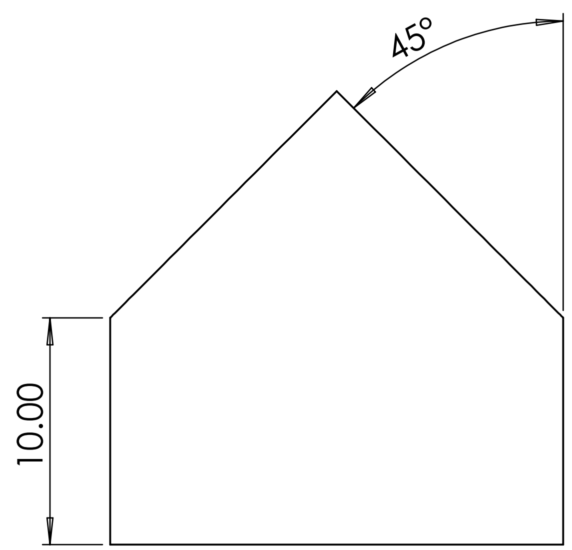
SCHOOL OF MECHANICAL, AEROSPACE & CIVIL ENGINEERING THE UNIVERSITY OF MANCHESTER OXFORD ROAD MANCHESTER M13 9PL	PART DESCRIPTION	Upper Arm Side Support		
	REF ID	REF ID 44	MATERIAL	PVC
	SCALE	1:2	MANUFACTURING PROCESS	CIRCULAR SAW/ DRILLING
	PROJECTION			

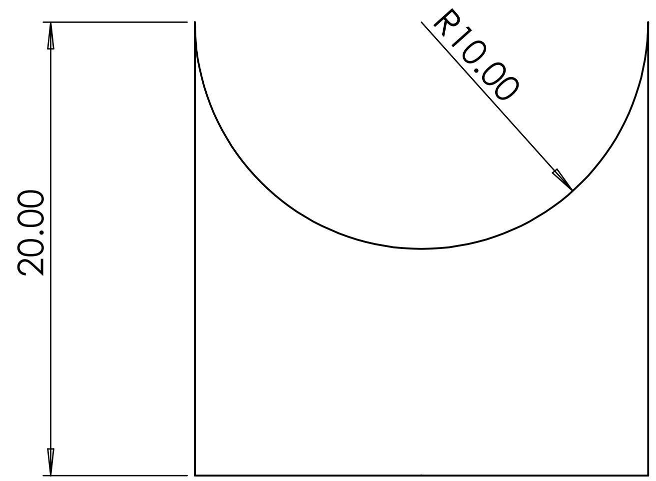


SCHOOL OF MECHANICAL, AEROSPACE & CIVIL ENGINEERING THE UNIVERSITY OF MANCHESTER OXFORD ROAD MANCHESTER M13 9PL	NAME		TITLE	
	DATE		SCALE	
	PROGRAMME		PROJECTION	
	EMAIL			



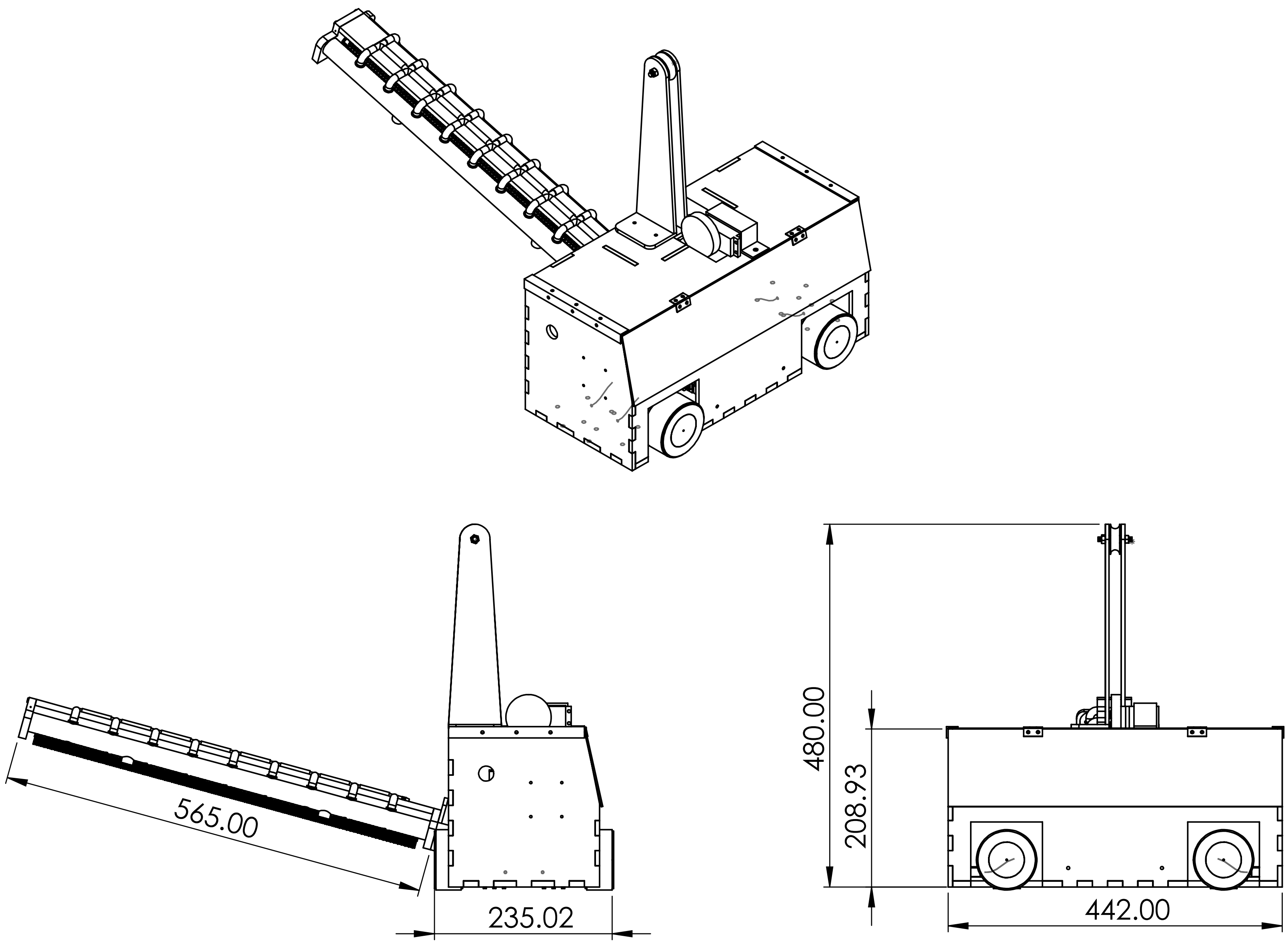






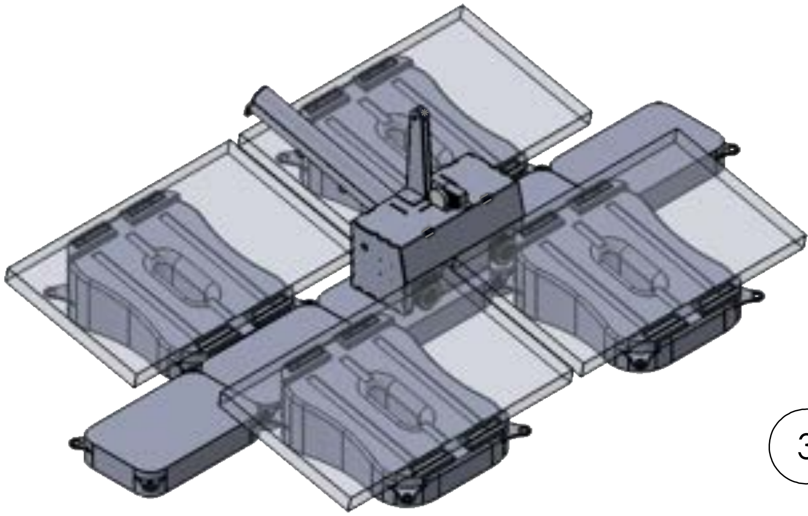
SCHOOL OF MECHANICAL, AEROSPACE & CIVIL ENGINEERING THE UNIVERSITY OF MANCHESTER OXFORD ROAD MANCHESTER M13 9PL	PART DESCRIPTION	Upper Arm Nylon Support Foot		
	REF ID	REF ID 45	MATERIAL	NYLON
	SCALE	3:1	MANUFACTURING PROCESS	Drilling
	PROJECTION	First Angle		

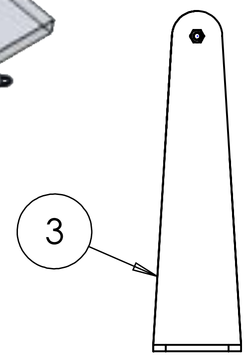
9 Appendix D:

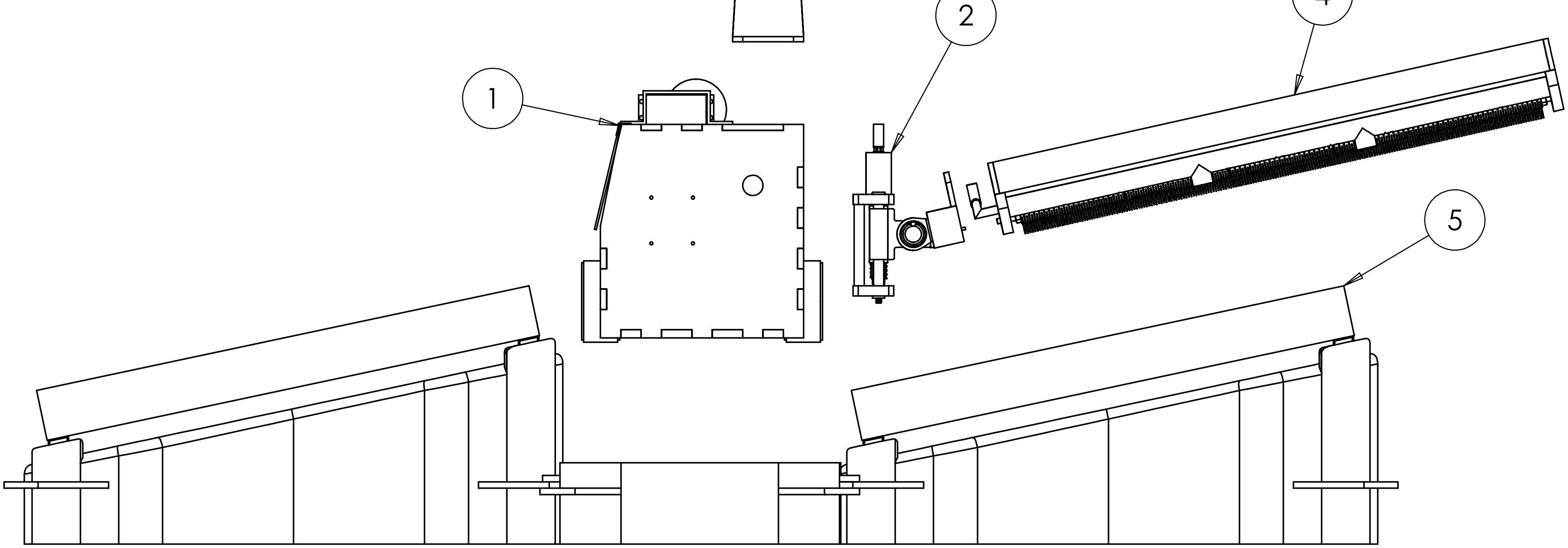


SCHOOL OF MECHANICAL, AEROSPACE & CIVIL ENGINEERING THE UNIVERSITY OF MANCHESTER OXFORD ROAD MANCHESTER M13 9PL	PART DESCRIPTION	Overall assembly	
	REF ID		MATERIAL
	SCALE		MANUFACTURING PROCESS
	PROJECTION		

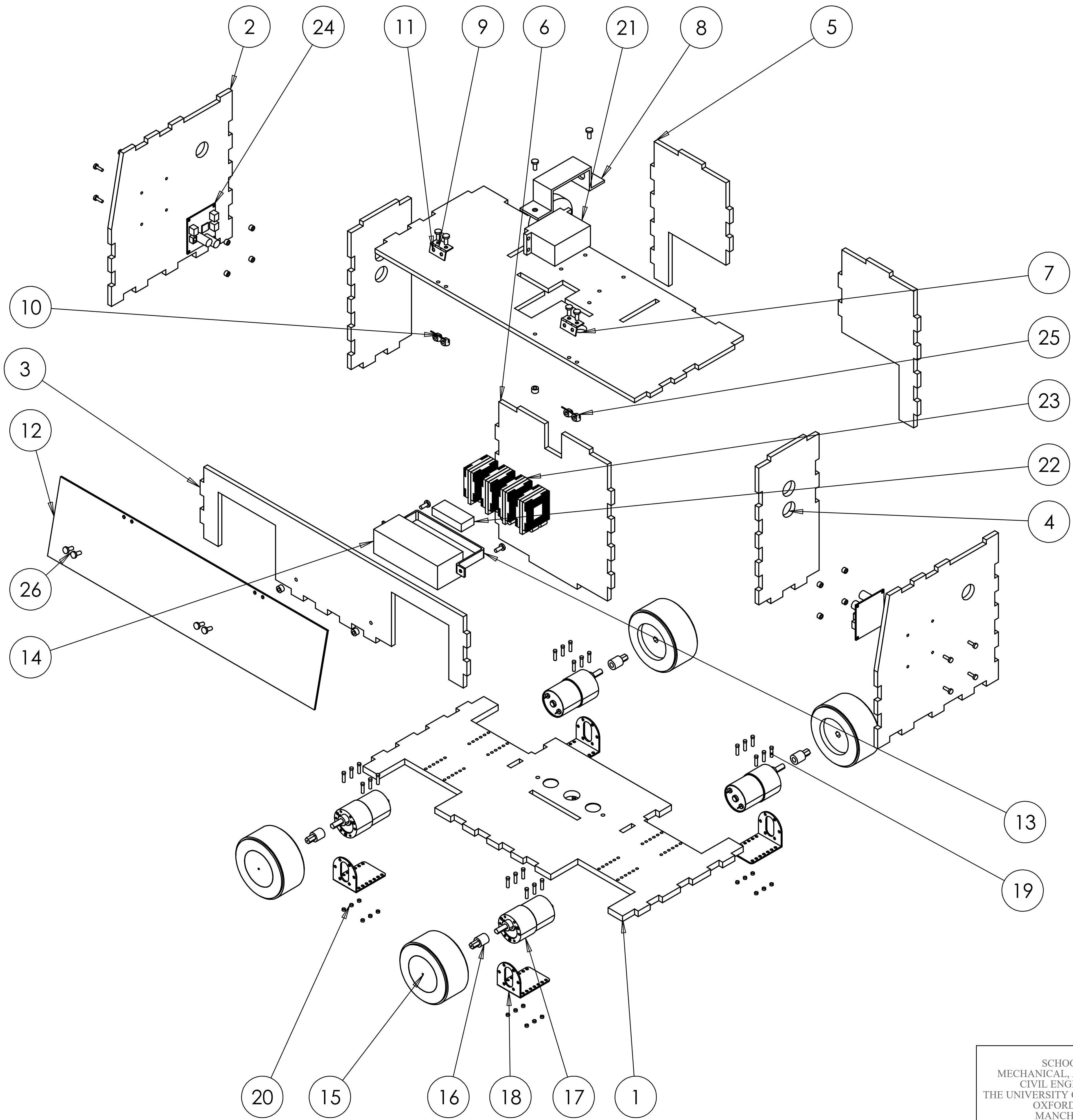
ITEM NO.	SUB-ASSEMBLY NAME	QTY.
1	Chassis and transmission	1
2	Lower arm	1
3	T-structure	1
4	Upper arm	1
5	Solar Panel Farm (12 degrees inclination)	1







SCHOOL OF MECHANICAL, AEROSPACE & CIVIL ENGINEERING THE UNIVERSITY OF MANCHESTER OXFORD ROAD MANCHESTER M13 9PL	PART DESCRIPTION	Full assembly of solar panel cleaner (SPC) with solar farm benchmark
	SCALE	1:6
	PROJECTION	First Angle

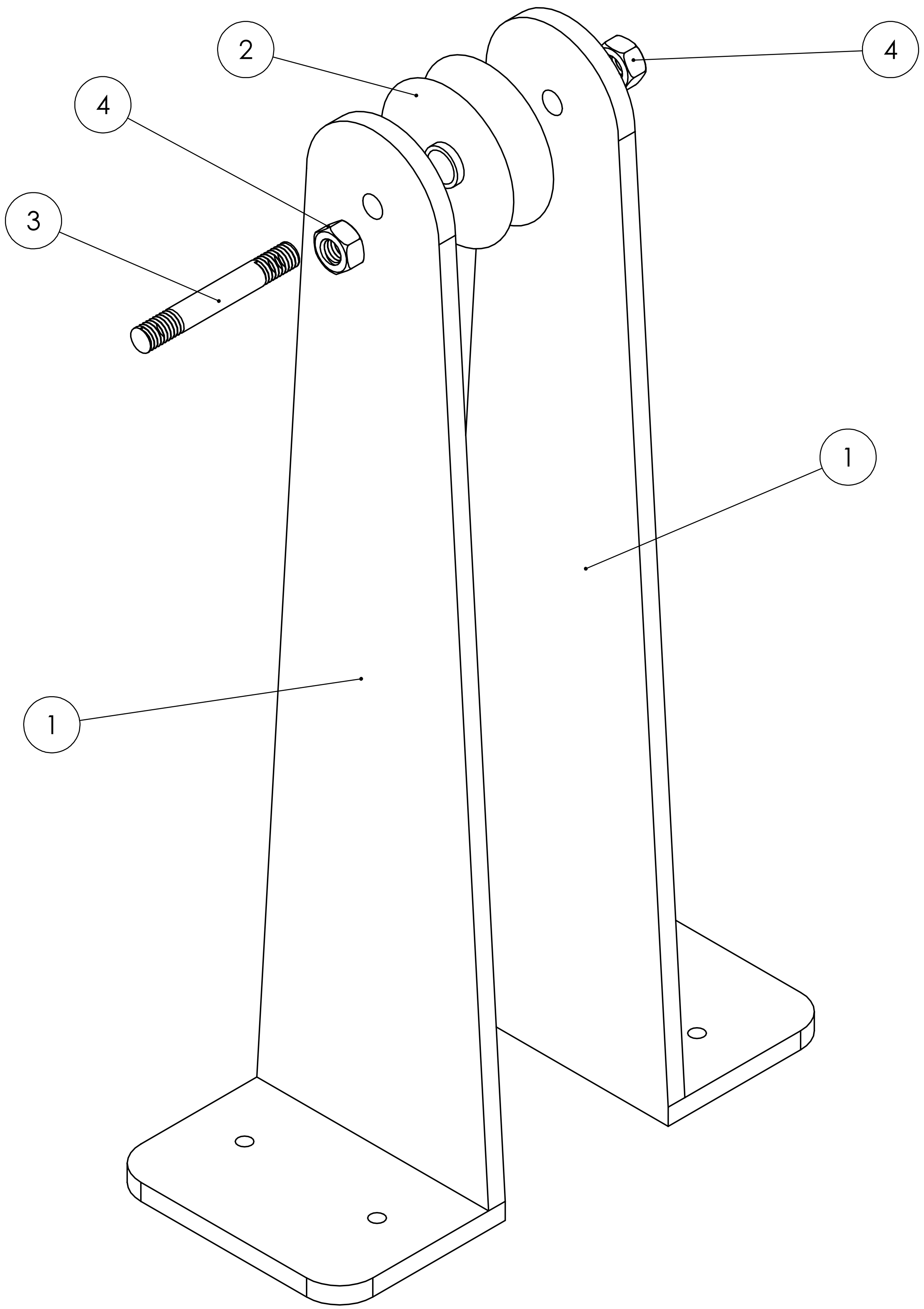


PART NUMBER	REFERENCE ID	PART NAME	QTY.
1	46	BASE PLATE	1
2	47	FRONT/BACK PLATE	2
3	48	SIDE PLATE	1
4	49	LOWER ARM LEFT/RIGHT PLATE	2
5	50	SIDE PLATE (LOWER ARM SIDE)	2
6	51	LOWER ARM BACK PLATE	1
7	52	TOP PLATE	1
8	53	SERVO WINCH CLAMP	1
9	54	HINGE LOWER	2
10	54	HINGE PIN	2
11	54	HINGE UPPER	2
12	55	LID	1
13	56	BATTERY BRACKET	1
14	33	5200mAh BATTERY	1
15	3	MECANUM WHEEL	4
16	57	WHEEL CONNECTOR	4
17	29	DRIVE MOTOR	4
18	32	DRIVE MOTOR BRACKET	4
19	58	M3 SCREW (REPRESENTATIVE)	32
20	58	M3 NUT (REPRESENTATIVE)	32
21	31	SERVO MOTOR	1
22	35	RECEIVER	1
23	37	ESC	4
24	36	DC TO DC CONVERTER	2
25	2	M4 NUT (REPRESENTATIVE)	12
26	2	M4 SCREW (REPRESENTATIVE)	12

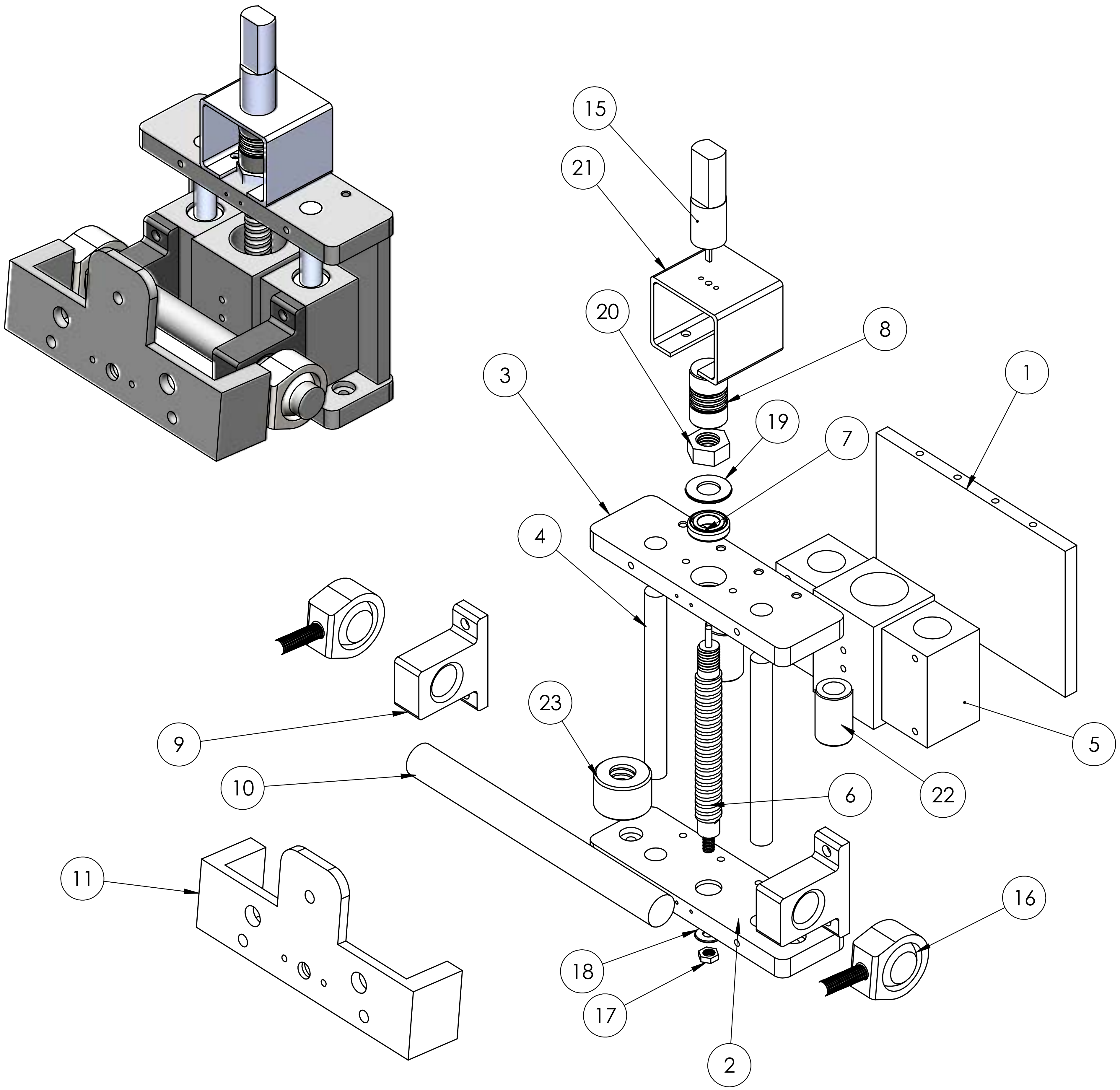
SCHOOL OF
MECHANICAL, AEROSPACE &
CIVIL ENGINEERING
THE UNIVERSITY OF MANCHESTER
OXFORD ROAD
MANCHESTER
M13 9PL

PART DESCRIPTION	CHASSIS AND TRANSMISSION		
REF ID		MATERIAL	
SCALE	1:5	MANUFACTURING PROCESS	
PROJECTION	EXPLODED		

Reference ID	Part Number	Part Name	Quantity
REF ID 20	1	T structure	2
REF ID 1	2	Pulley wheel	1
REF ID 21	3	Connection rod	1
REF ID 19	4	M6 Nut	2

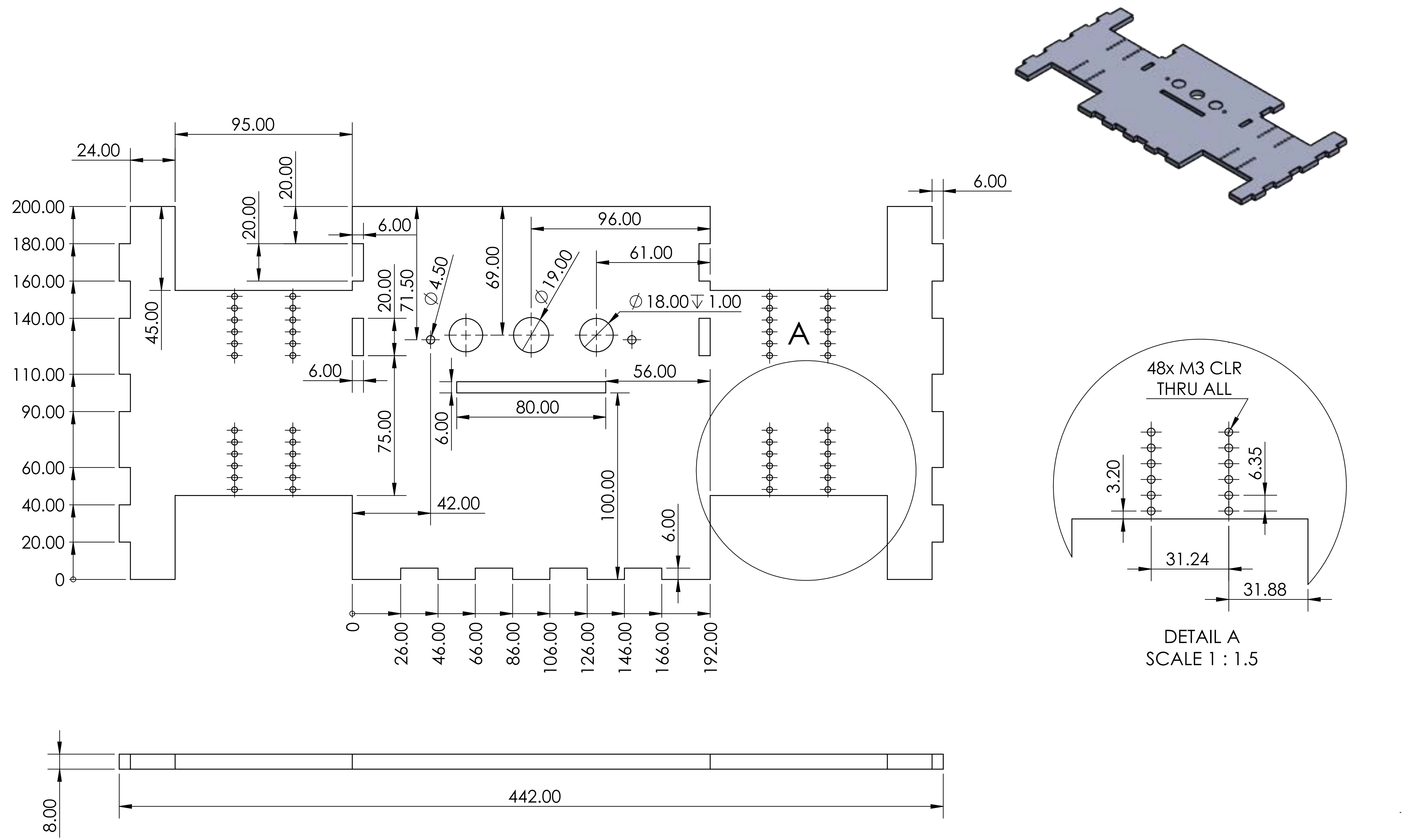


SCHOOL OF MECHANICAL, AEROSPACE & CIVIL ENGINEERING THE UNIVERSITY OF MANCHESTER OXFORD ROAD MANCHESTER M13 9PL	NAME	Shuchen Zuo	TITLE	T structure Assem
	DATE	22/11/2021	SCALE	1:1.2
	PROGRAMME	Design 4	PROJECTION	Exploded view
	EMAIL			

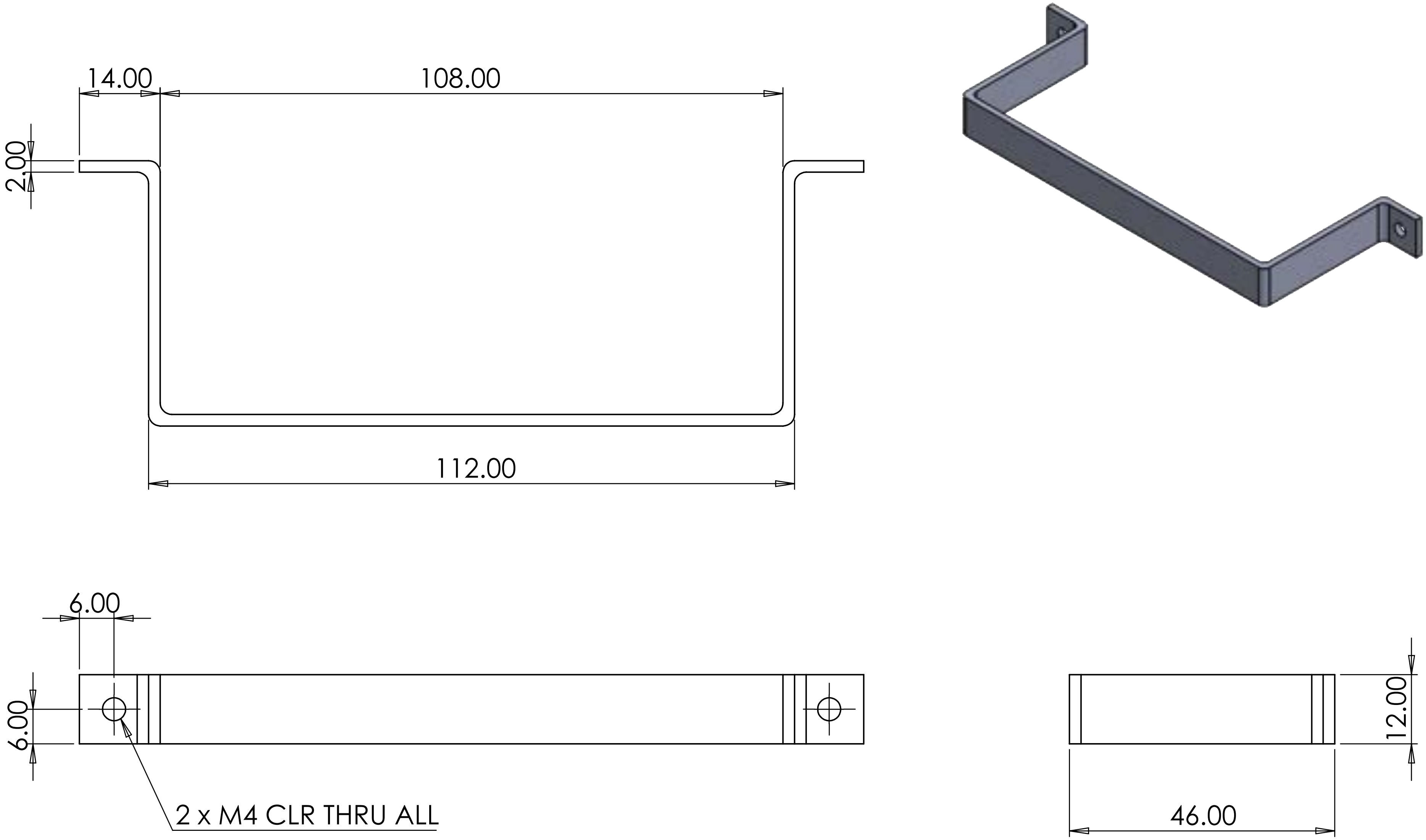


Reference ID	Part Number	Part Name	Quantity
REF ID 18	1	Base Plate	1
REF ID 13	2	Bottom Plate	1
REF ID 12	3	Top Plate	1
REF ID 11	4	Cylindrical Rods	2
REF ID 10	5	Moving Plate	1
REF ID 5	6	Lead Screw	1
REF ID 6	7	Ball Bearing (10mm Dia)	2
REF ID 8	8	Coupler	1
REF ID 9	9	Shaft Support	2
REF ID 16	10	Shaft	1
REF ID 17	11	Cleaning Arm Holder	1
REF ID 30	12	Brush Motor	1
REF ID 39	13	Motor Cover	1
REF ID 15	14	Flange Bearing	4
REF ID 23	15	Leadscrew Motor	1
REF ID 4	16	Rod End Bearing	2
REF ID 25	17	Hex Nut (M5)	1
REF ID 27	18	Washer (M5)	1
REF ID 28	19	Washer (M10)	1
REF ID 26	20	Hex Nut (M10)	1
REF ID 38	21	Motor Bracket	1
REF ID 24	22	Linear Bearing	2
REF ID 65	23	Leadscrew Nut	1

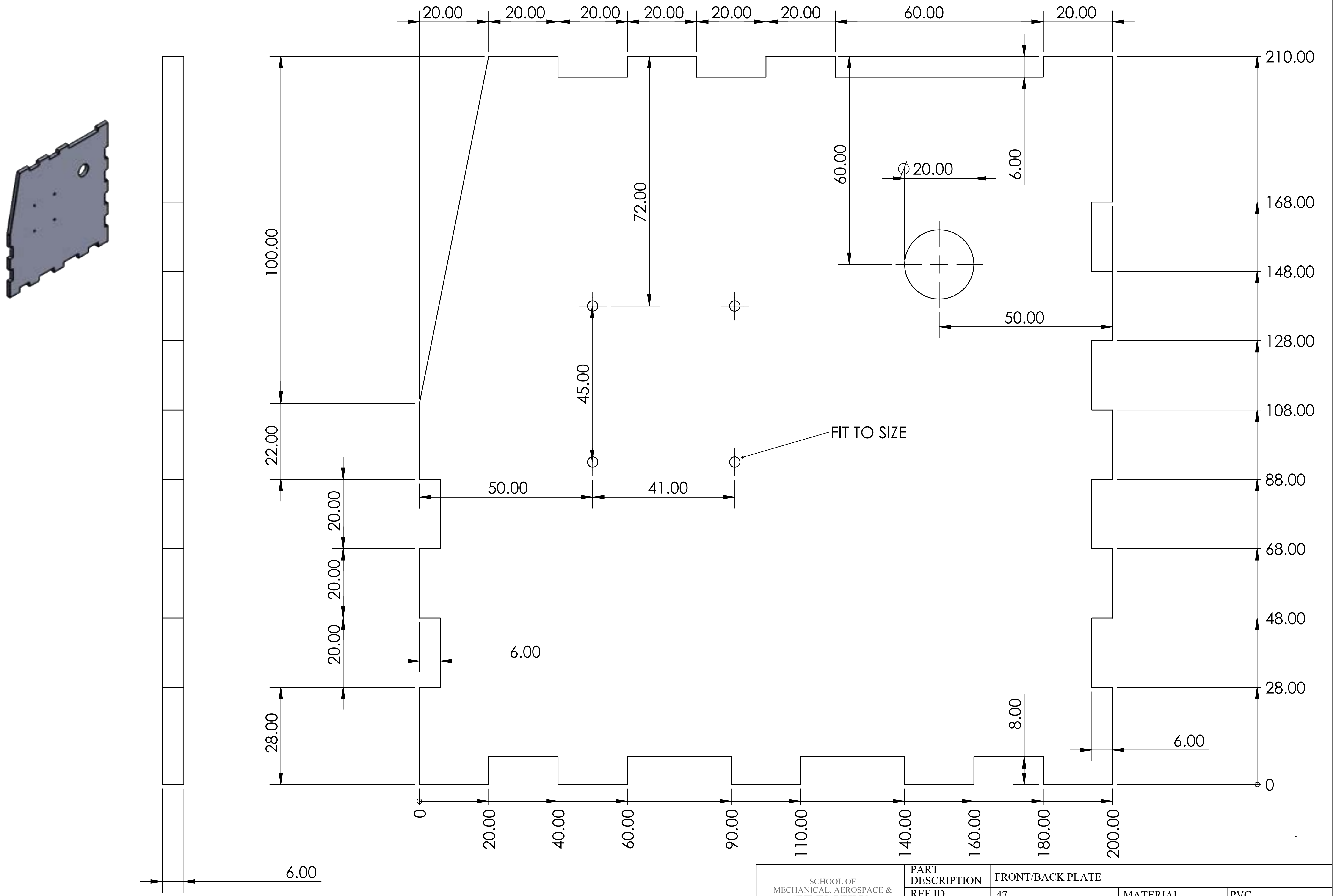
<table>
<tr><td rowspan="4">SCHOOL OF
MECHANICAL, AEROSPACE &
CIVIL ENGINEERING
THE UNIVERSITY OF MANCHESTER
OXFORD ROAD
MANCHESTER
M13 9PL</td><td>PART DESCRIPTION</td><td colspan="3">LOWER ARM SUB-ASSEMBLY</td></tr>
<tr><td>REF ID</td><td></td><td>MATERIAL</td><td></td></tr>
<tr><td>SCALE</td><td>1:2</td><td rowspan="2">MANUFACTURING PROCESS</td><td rowspan="2"></td></tr>
<tr><td>PROJECTION</td><td>FIRST ANGLE</td></tr>
</table>



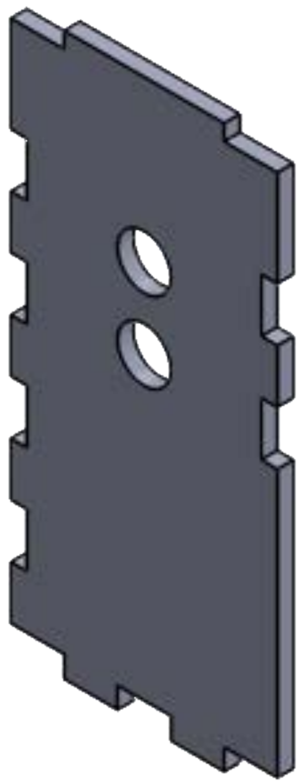
SCHOOL OF MECHANICAL, AEROSPACE & CIVIL ENGINEERING THE UNIVERSITY OF MANCHESTER OXFORD ROAD MANCHESTER M13 9PL	PART DESCRIPTION	BASE PLATE		
	REF ID	46	MATERIAL	PVC
	SCALE	1:2	MANUFACTURING PROCESS	CNC LASER CUTTING
	PROJECTION	ORTHOGRAPHIC		

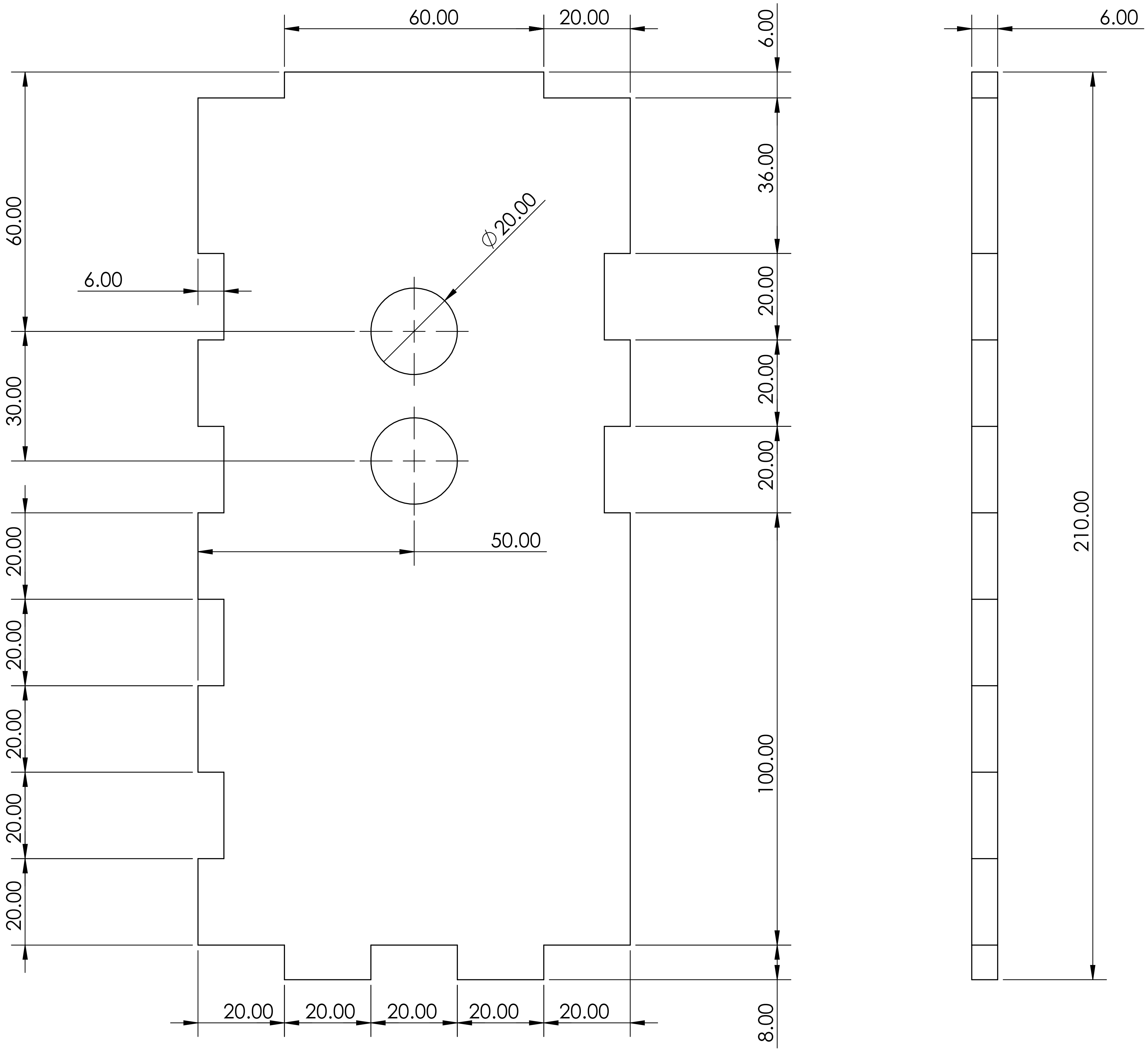


SCHOOL OF MECHANICAL, AEROSPACE & CIVIL ENGINEERING THE UNIVERSITY OF MANCHESTER OXFORD ROAD MANCHESTER M13 9PL	PART DESCRIPTION	BATTERY BRACKET		
	REF ID	56	MATERIAL	ALUMINIUM
	SCALE	1:1	MANUFACTURING PROCESS	METAL BENDING
	PROJECTION	FIRST ANGLE		

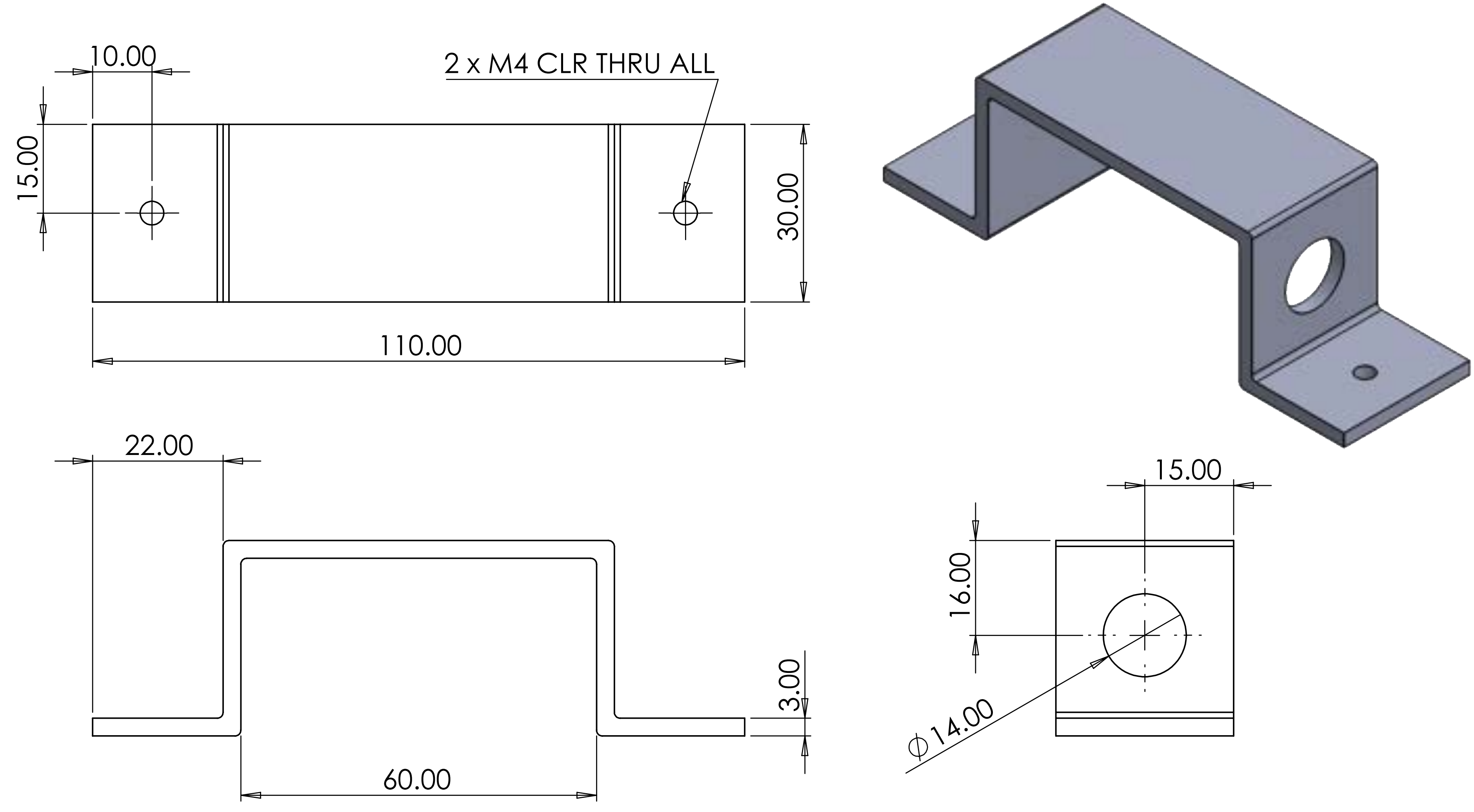


SCHOOL OF MECHANICAL, AEROSPACE & CIVIL ENGINEERING THE UNIVERSITY OF MANCHESTER OXFORD ROAD MANCHESTER M13 9PL	PART DESCRIPTION	FRONT/BACK PLATE		
	REF ID	47	MATERIAL	PVC
	SCALE	1:1	MANUFACTURING PROCESS	CNC LASER CUTTING
	PROJECTION	ORTHOGRAPHIC		

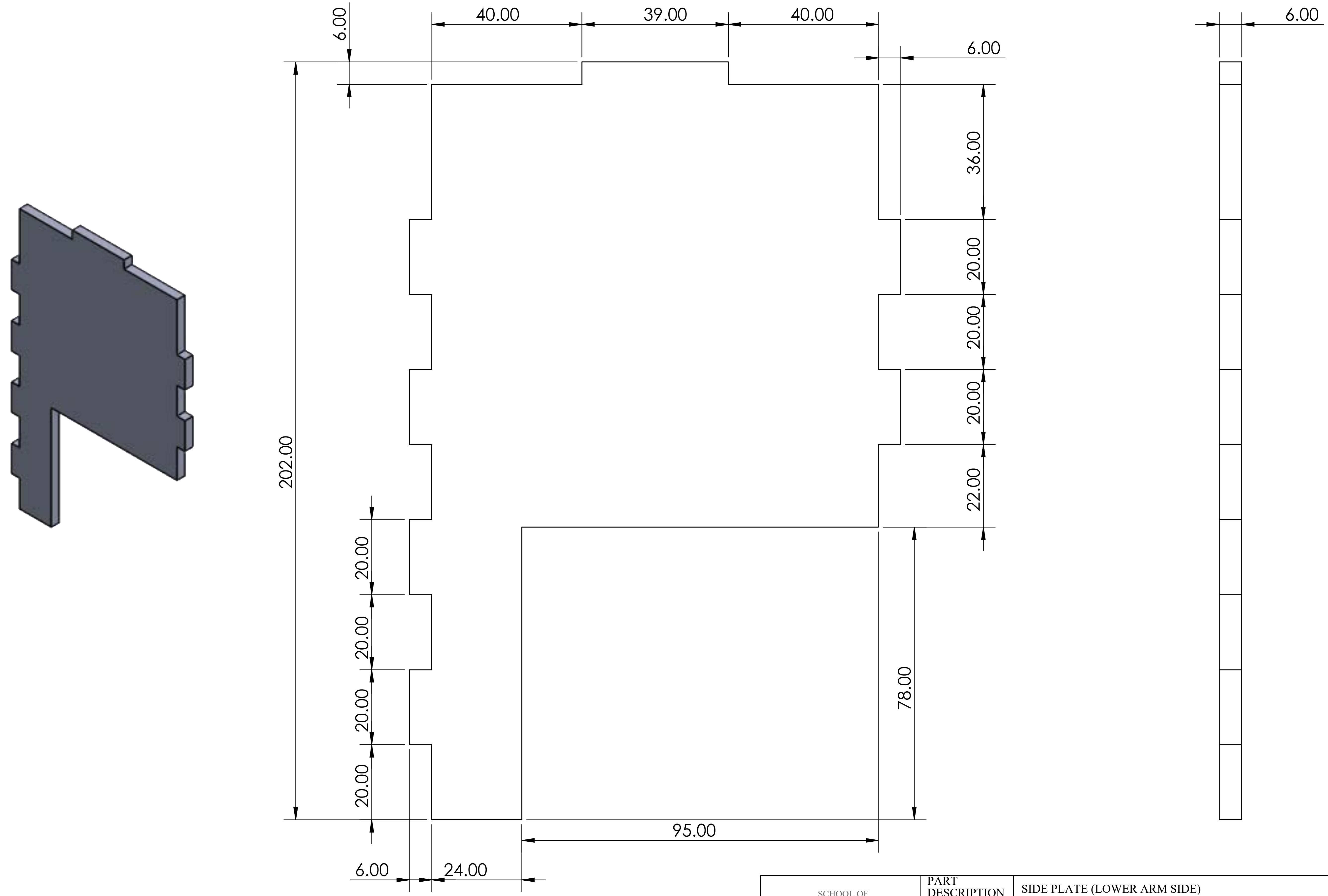




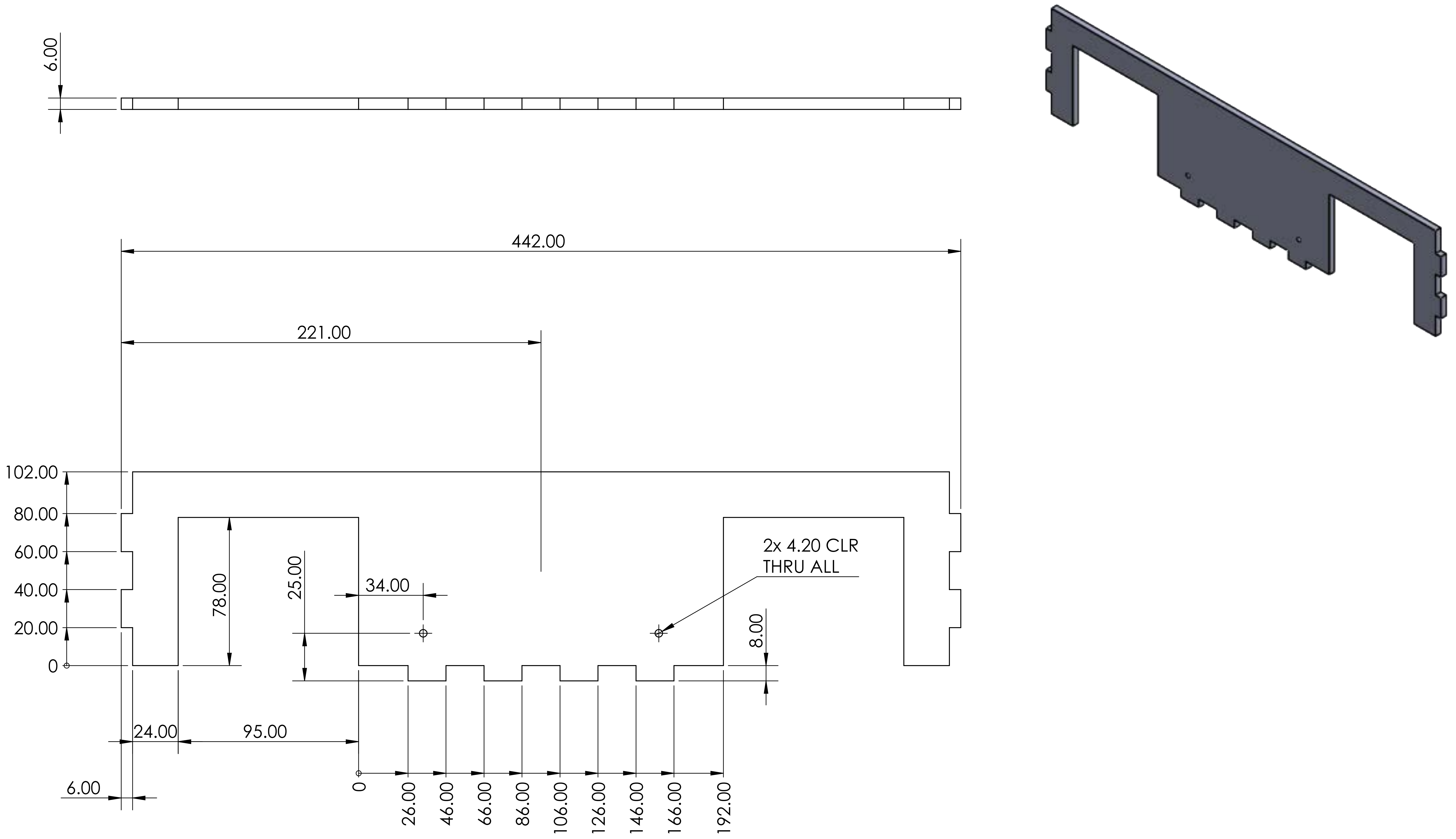
SCHOOL OF MECHANICAL, AEROSPACE & CIVIL ENGINEERING THE UNIVERSITY OF MANCHESTER OXFORD ROAD MANCHESTER M13 9PL	PART DESCRIPTION	LOWER ARM LEFT/RIGHT PLATE		
	REF ID	49	MATERIAL	PVC
	SCALE	1:1	MANUFACTURING PROCESS	CNC LASER CUTTING
	PROJECTION	ORTHOGRAPHIC		



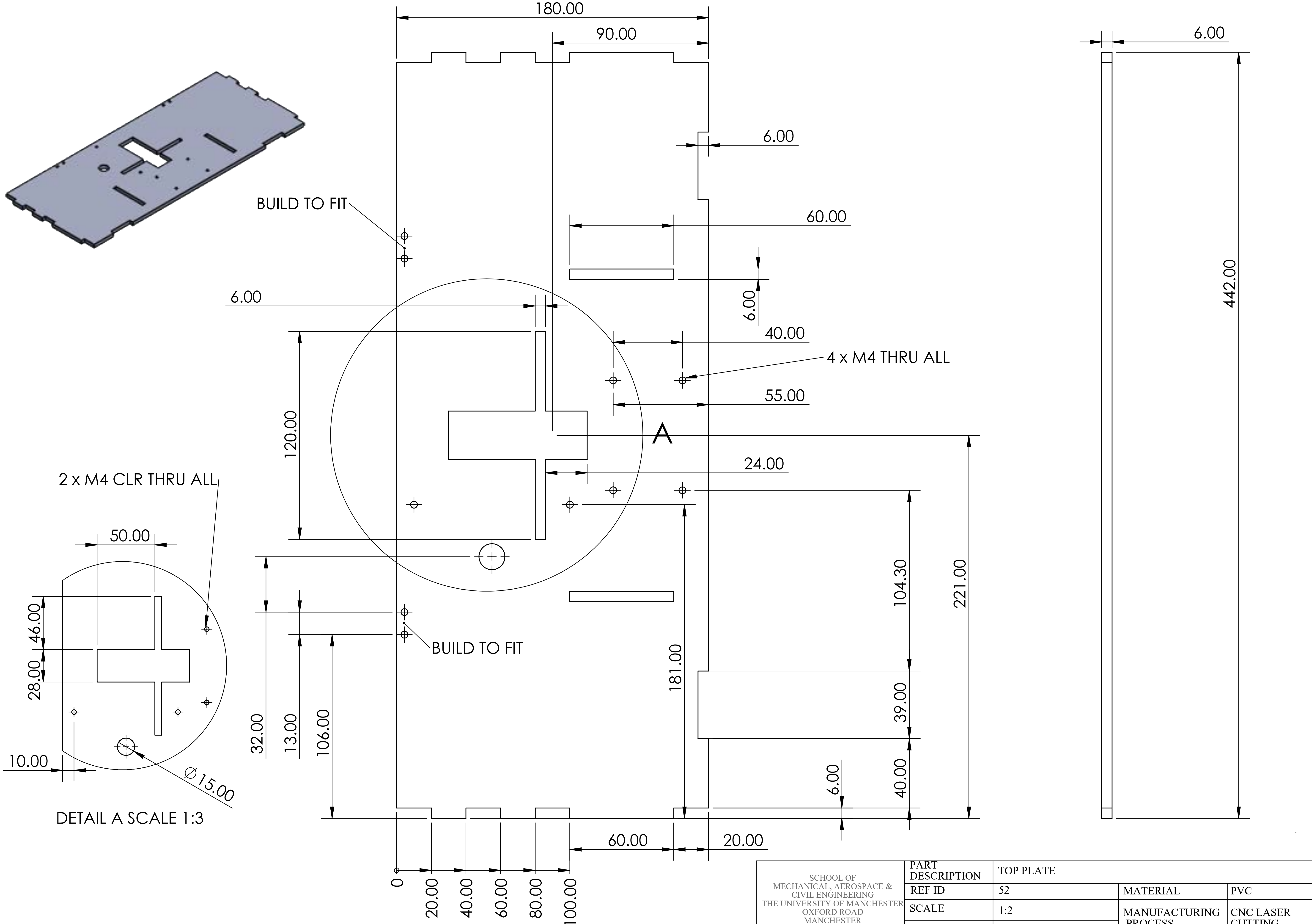
SCHOOL OF MECHANICAL, AEROSPACE & CIVIL ENGINEERING THE UNIVERSITY OF MANCHESTER OXFORD ROAD MANCHESTER M13 9PL	PART DESCRIPTION	SERVO WINCH CLAMP		
	REF ID	53	MATERIAL	ALUMINIUM
	SCALE	1:1	MANUFACTURING PROCESS	METAL BENDING
	PROJECTION	FIRST ANGLE		



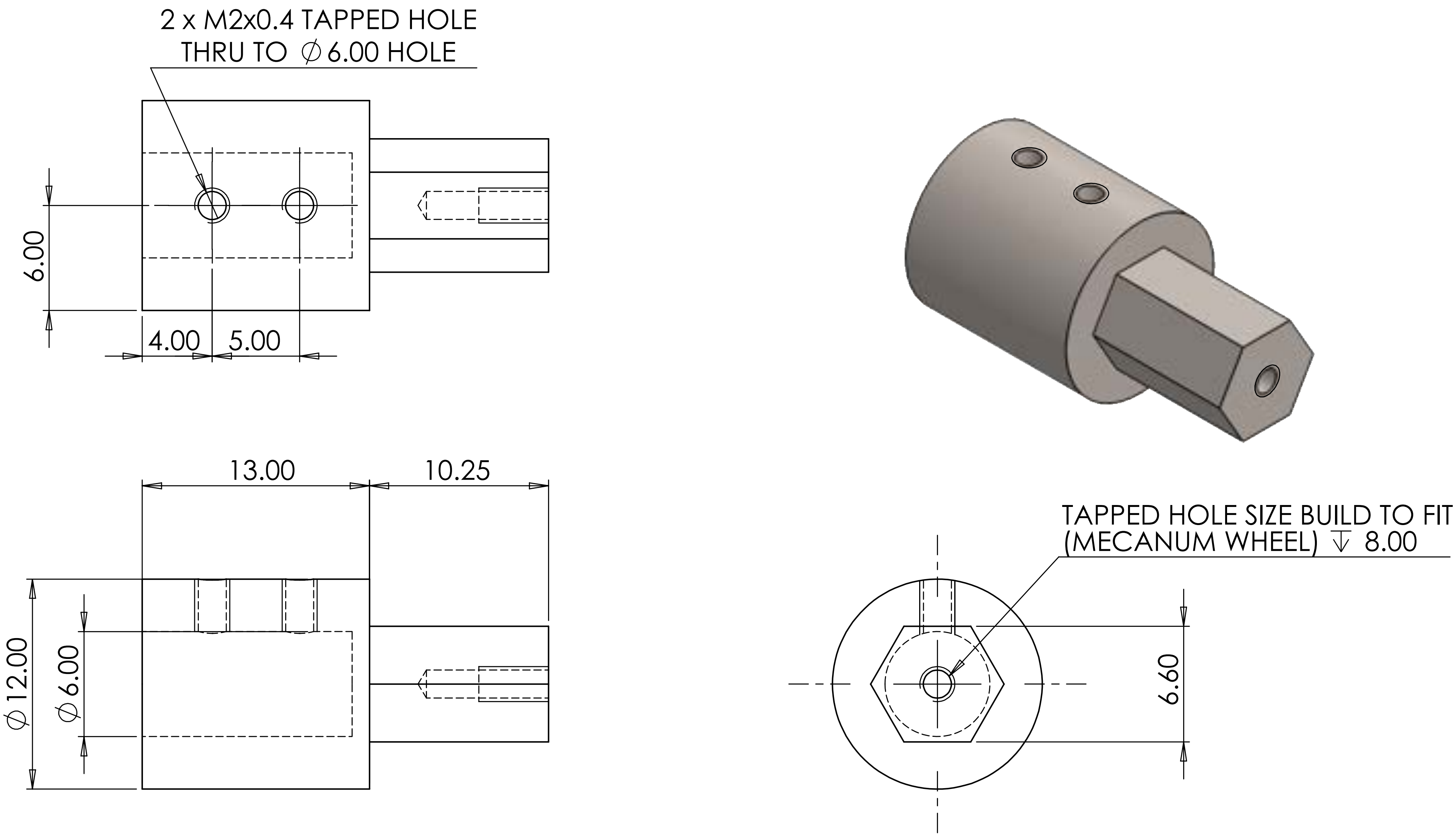
SCHOOL OF MECHANICAL, AEROSPACE & CIVIL ENGINEERING THE UNIVERSITY OF MANCHESTER OXFORD ROAD MANCHESTER M13 9PL	PART DESCRIPTION	SIDE PLATE (LOWER ARM SIDE)		
	REF ID	50	MATERIAL	PVC
	SCALE	1:1	MANUFACTURING PROCESS	CNC LASER CUTTING
	PROJECTION	ORTHOGRAPHIC		



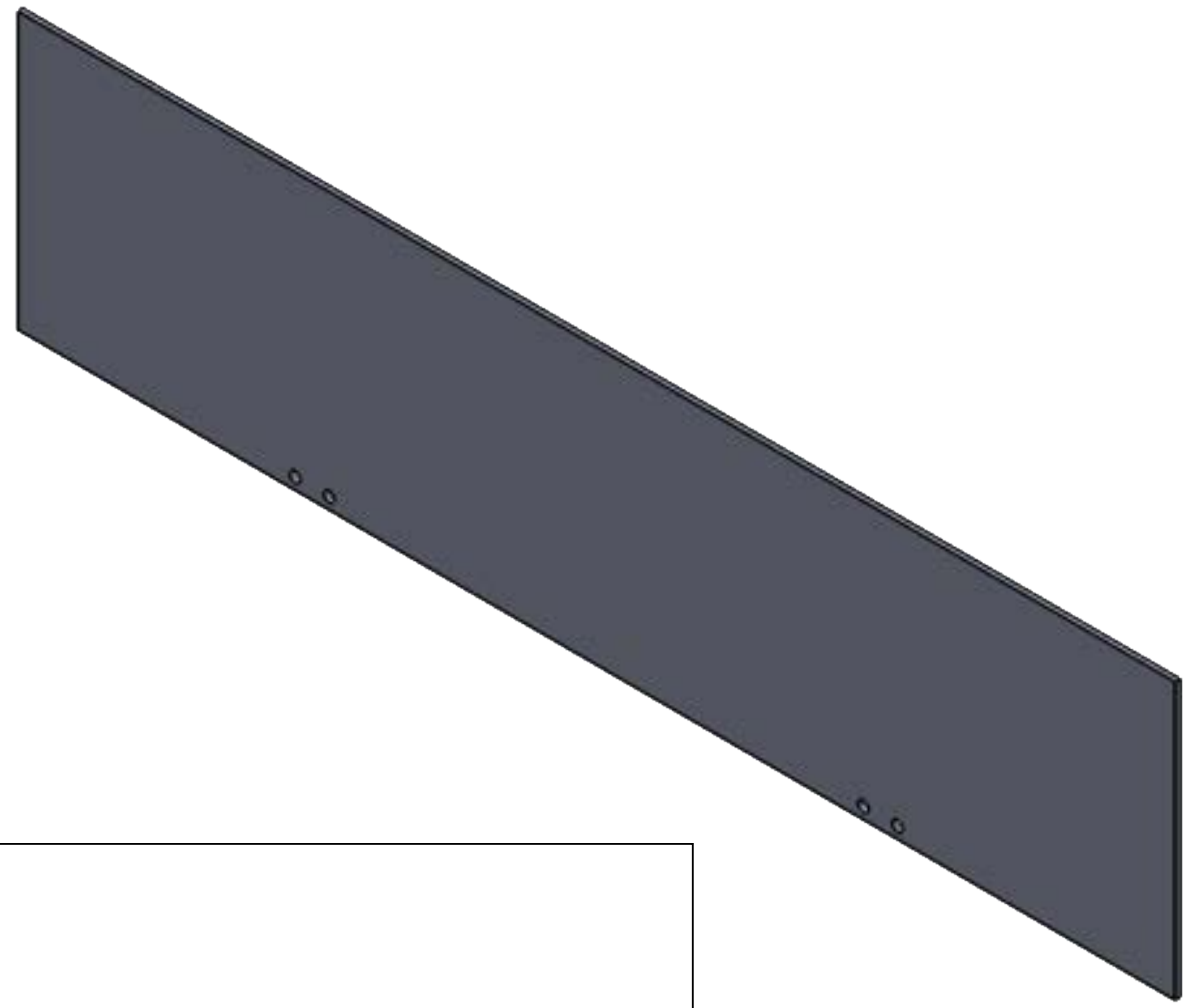
SCHOOL OF MECHANICAL, AEROSPACE & CIVIL ENGINEERING THE UNIVERSITY OF MANCHESTER OXFORD ROAD MANCHESTER M13 9PL	PART DESCRIPTION	SIDE PLATE		
	REF ID	48	MATERIAL	PVC
	SCALE	1:2	MANUFACTURING PROCESS	CNC LASER CUTTING
	PROJECTION	ORTHOGRAPHIC		

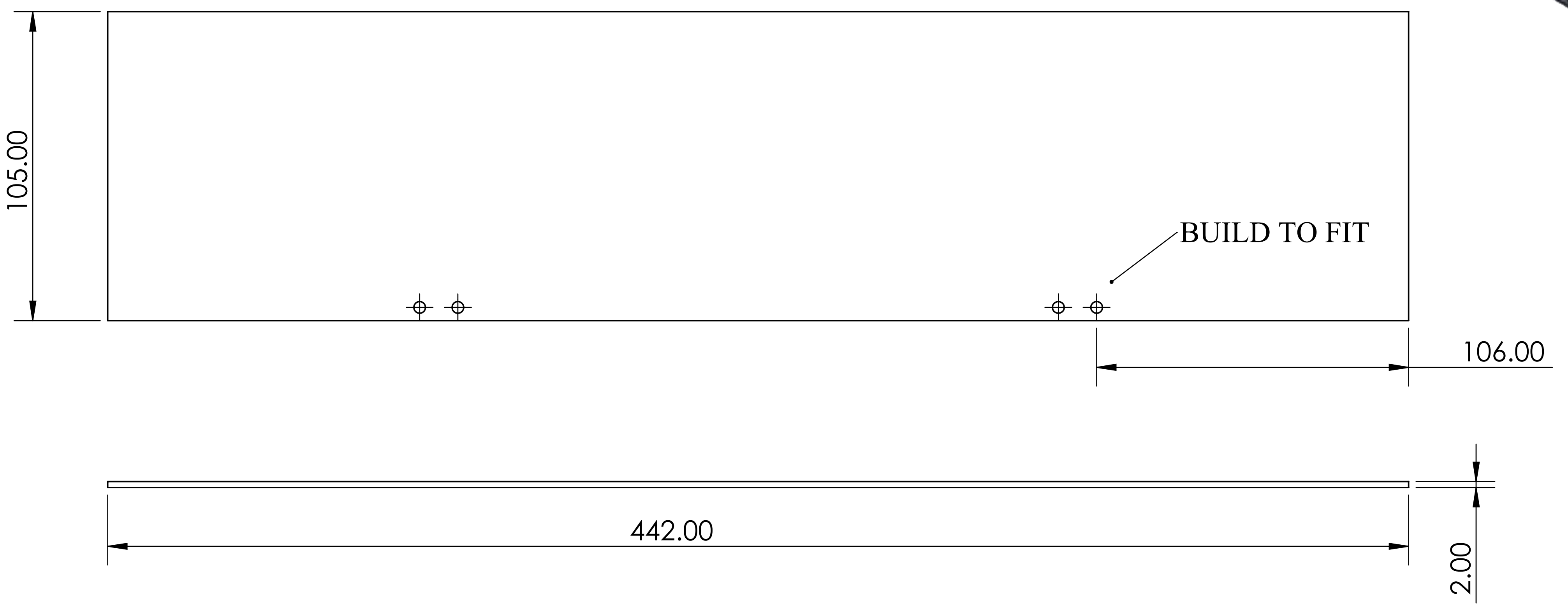


SCHOOL OF MECHANICAL, AEROSPACE & CIVIL ENGINEERING THE UNIVERSITY OF MANCHESTER OXFORD ROAD MANCHESTER M13 9PL	PART DESCRIPTION	TOP PLATE			
	REF ID	52	MATERIAL	PVC	
	SCALE	1:2	MANUFACTURING PROCESS	CNC LASER CUTTING	
	PROJECTION	ORTHOGRAPHIC			

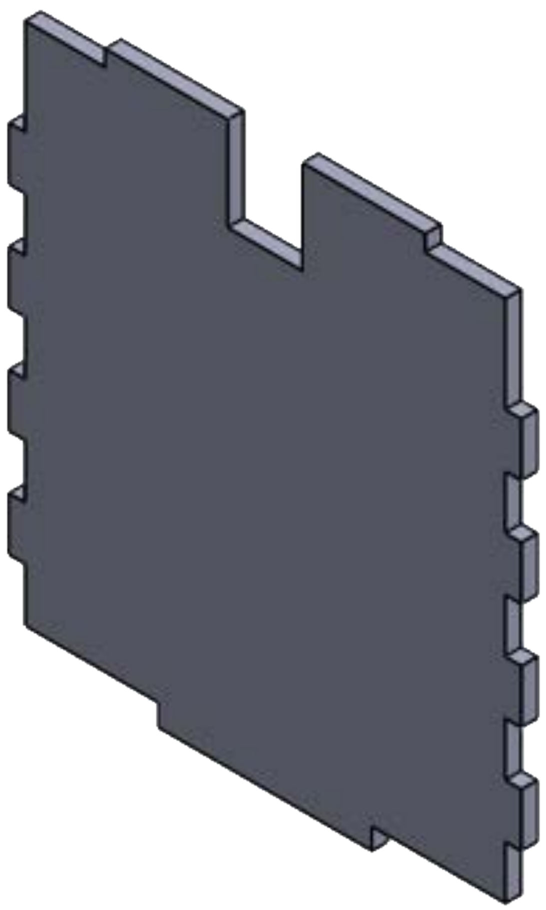


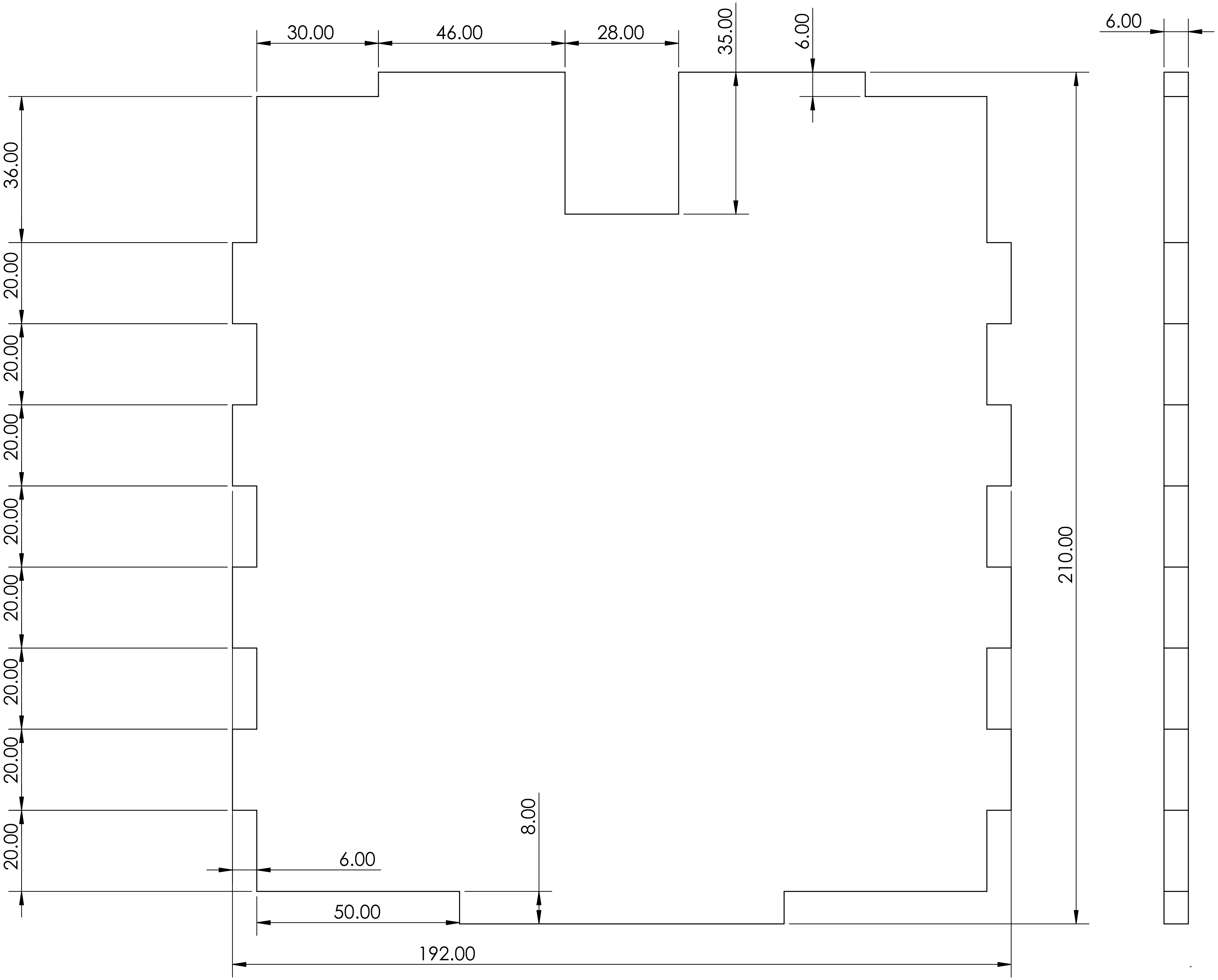
SCHOOL OF MECHANICAL, AEROSPACE & CIVIL ENGINEERING THE UNIVERSITY OF MANCHESTER OXFORD ROAD MANCHESTER M13 9PL	PART DESCRIPTION	WHEEL CONNECTOR		
	REF ID	57	MATERIAL	STAINLESS STEEL
	SCALE	3:1	MANUFACTURING PROCESS	CNC MACHINING
	PROJECTION	FIRST ANGLE		



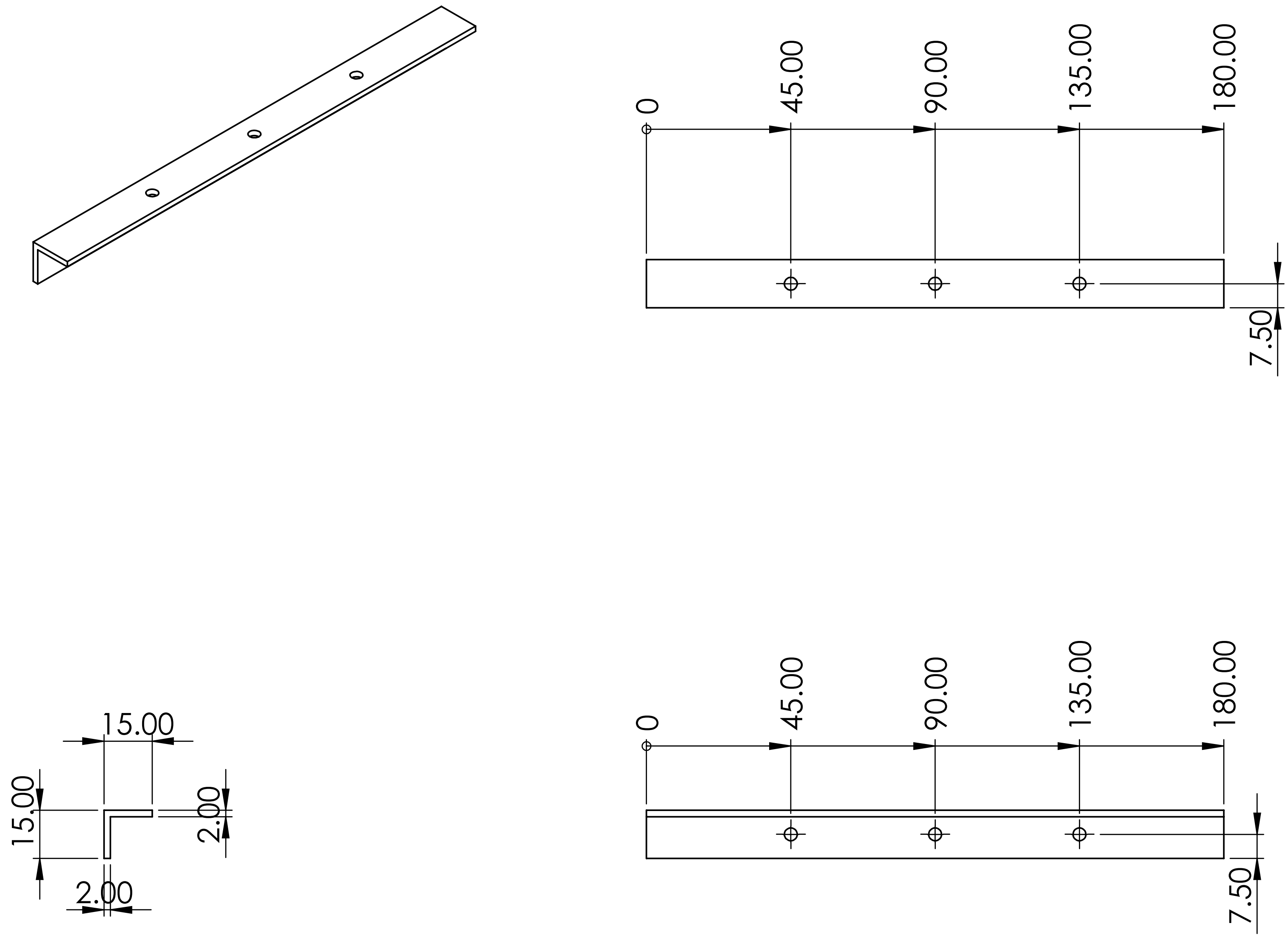


SCHOOL OF MECHANICAL, AEROSPACE & CIVIL ENGINEERING THE UNIVERSITY OF MANCHESTER OXFORD ROAD MANCHESTER M13 9PL	PART DESCRIPTION	LID		
	REF ID	55	MATERIAL	PVC
	SCALE	1:2	MANUFACTURING PROCESS	CNC LASER CUTTING
	PROJECTION	ORTHOGRAPHIC		

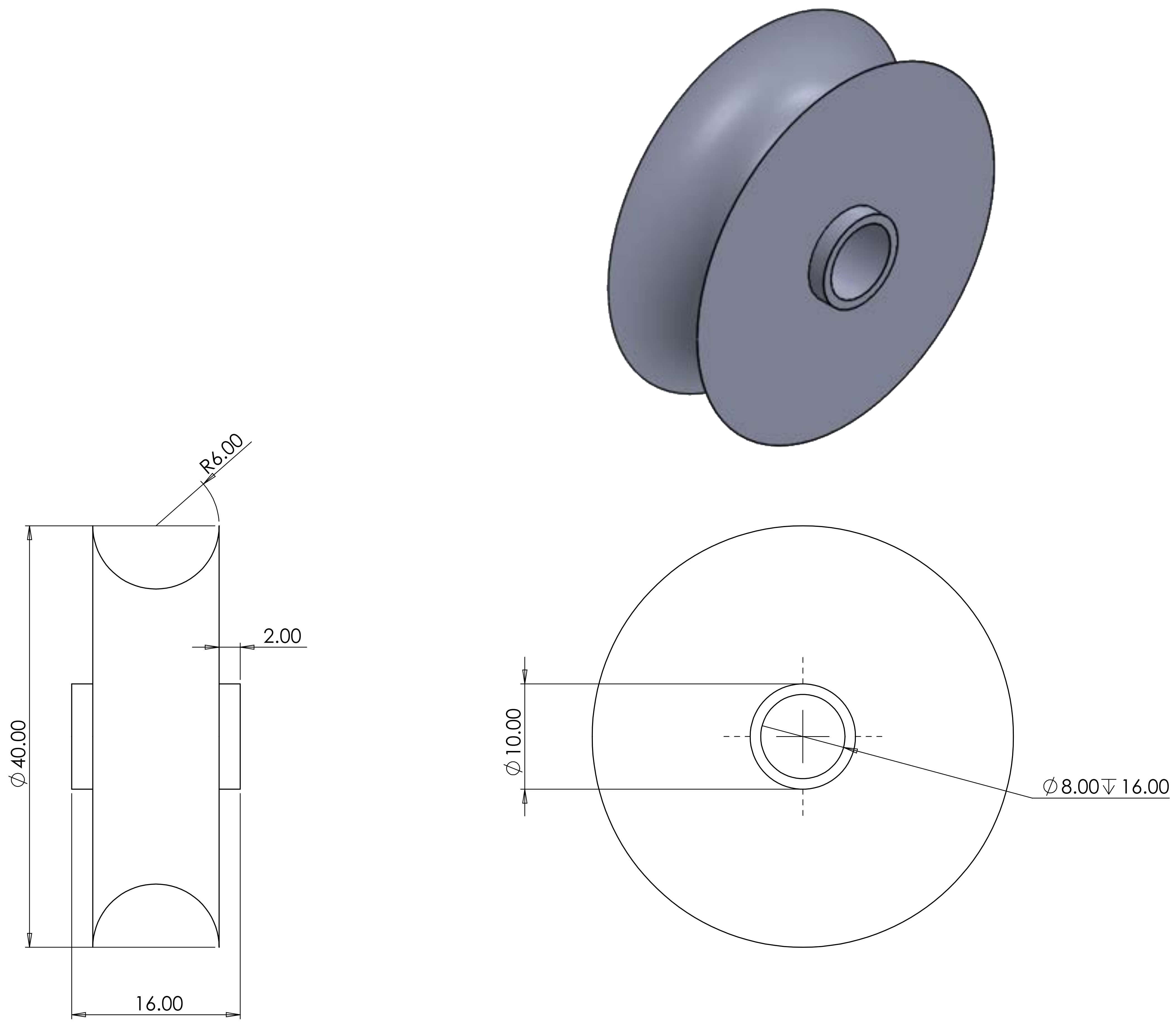




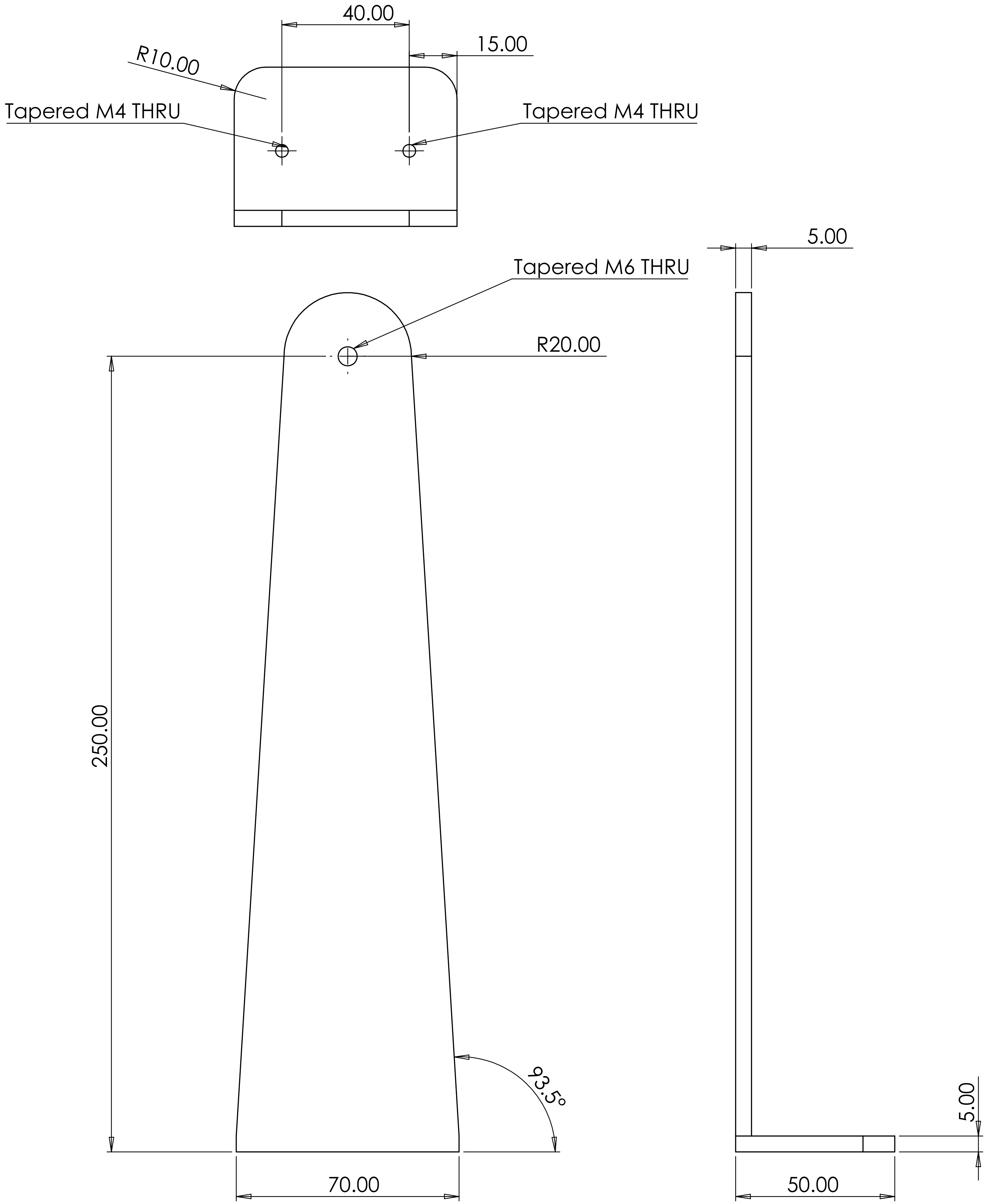
SCHOOL OF MECHANICAL, AEROSPACE & CIVIL ENGINEERING THE UNIVERSITY OF MANCHESTER OXFORD ROAD MANCHESTER M13 9PL	PART DESCRIPTION	LOWER ARM BACK PLATE		
	REF ID	51	MATERIAL	PVC
	SCALE	1:1	MANUFACTURING PROCESS	CNC LASER CUTTING
	PROJECTION	ORTHOGRAPHIC		

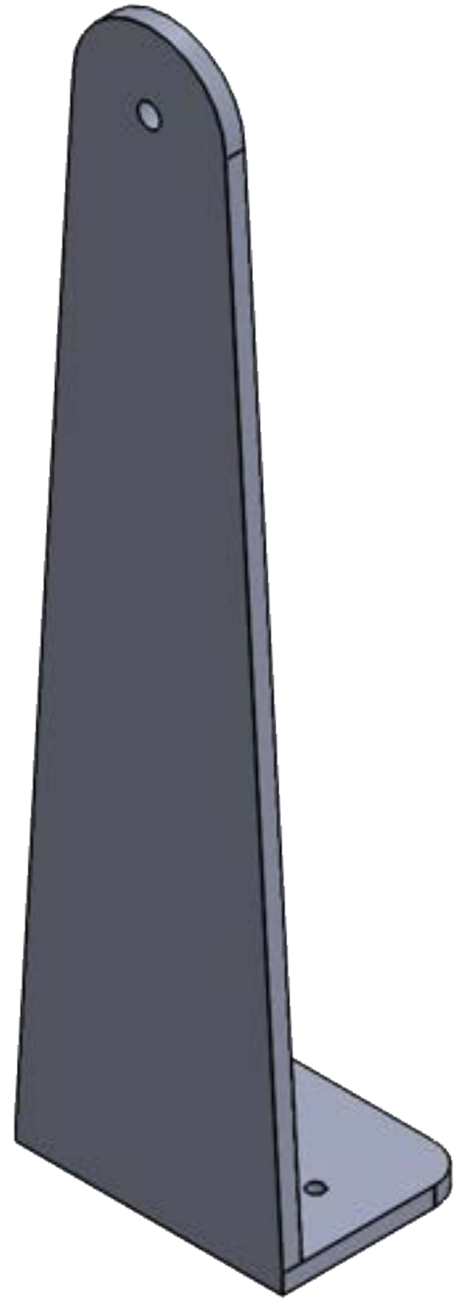


SCHOOL OF MECHANICAL, AEROSPACE & CIVIL ENGINEERING THE UNIVERSITY OF MANCHESTER OXFORD ROAD MANCHESTER M13 9PL	PART DESCRIPTION	L bracket		
	REF ID	67	MATERIAL	Aluminium
	SCALE	1:2	MANUFACTURING PROCESS	Drilling
	PROJECTION	First angle		

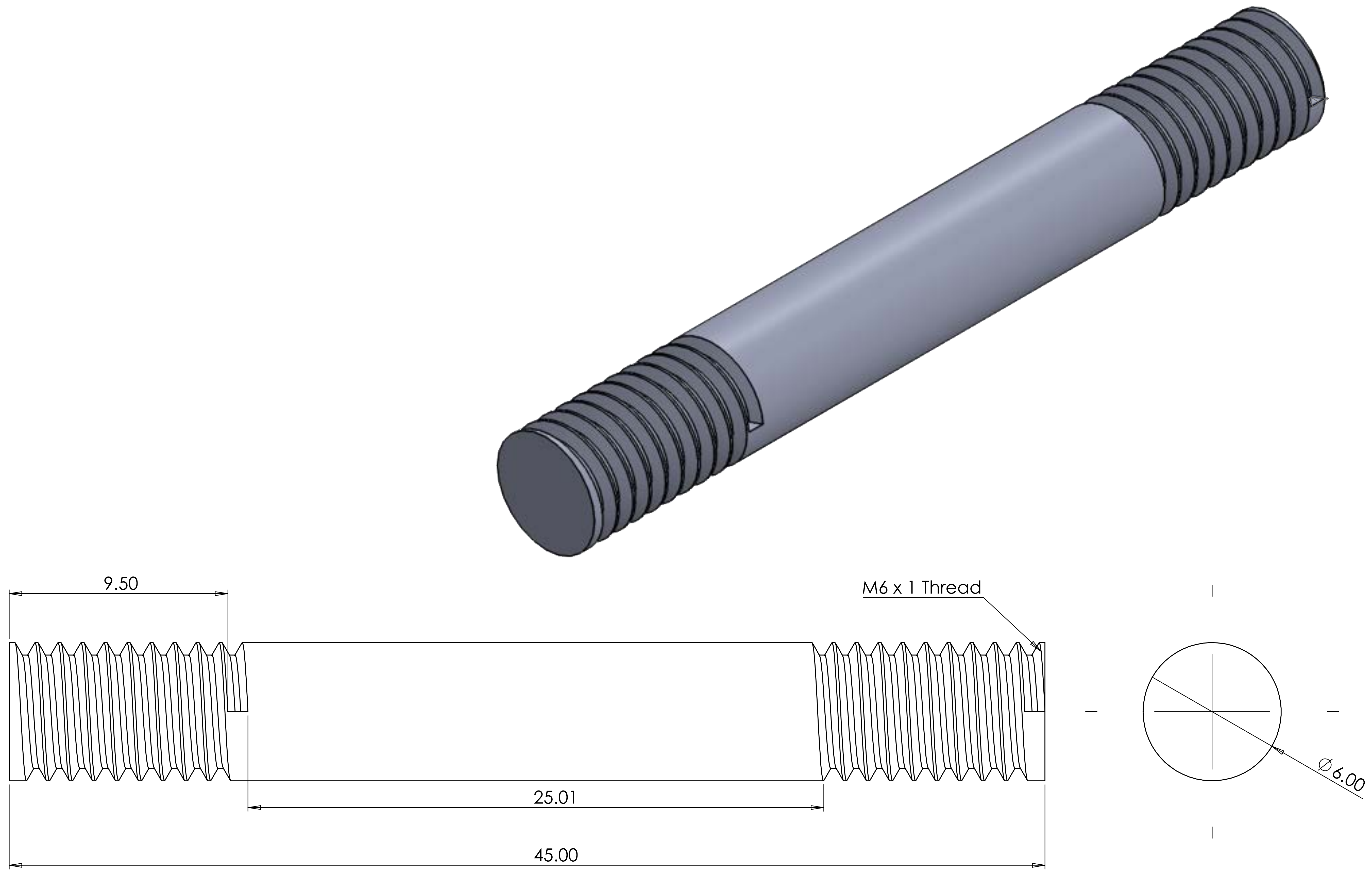


SCHOOL OF MECHANICAL, AEROSPACE & CIVIL ENGINEERING THE UNIVERSITY OF MANCHESTER OXFORD ROAD MANCHESTER M13 9PL	PART DESCRIPTION	T structure pulley wheel		
	REF ID	REF ID 1	MATERIAL	Delrin
	SCALE	2.5:1	MANUFACTURING PROCESS	Turning
	PROJECTION	First Angle		

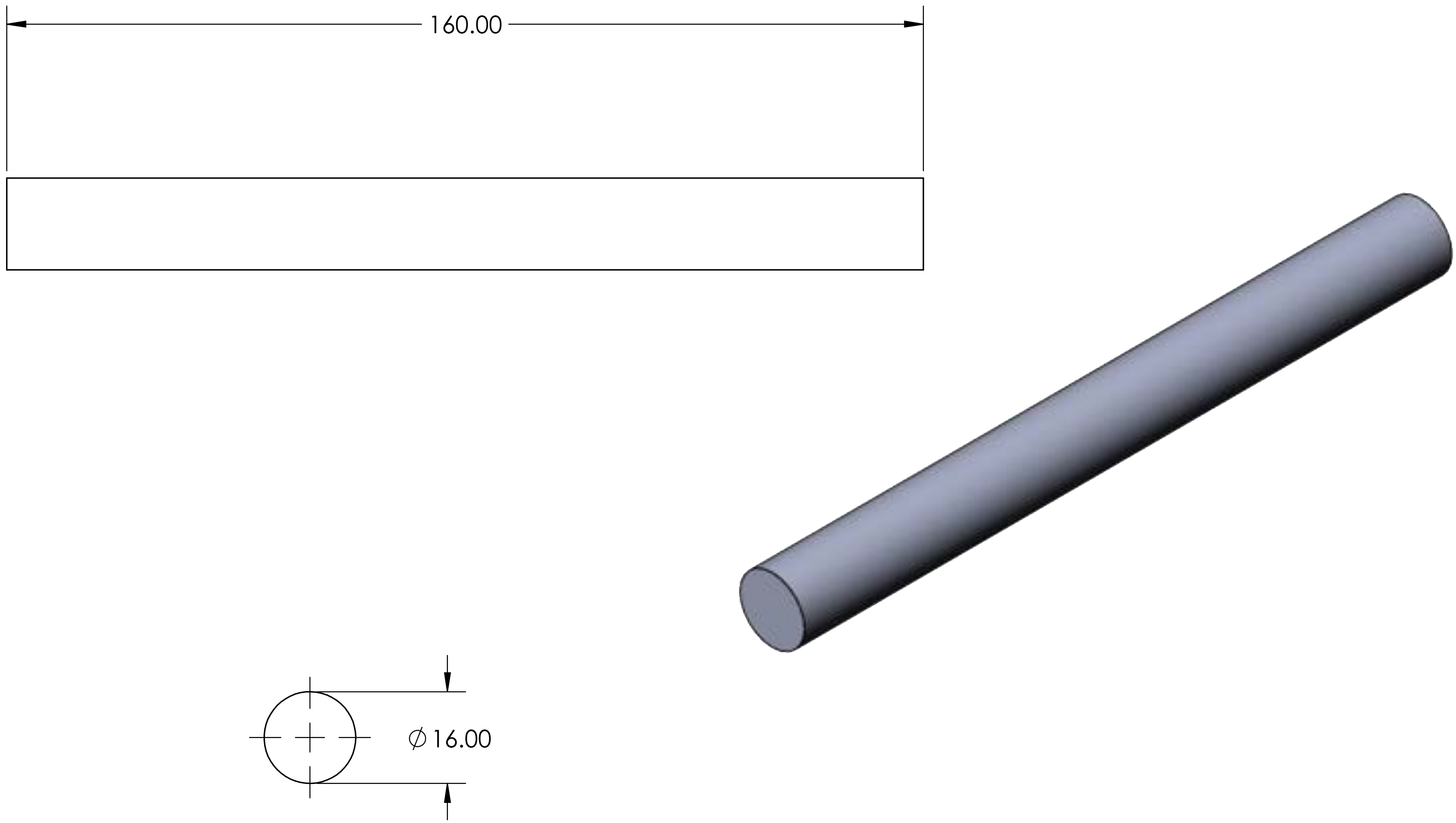




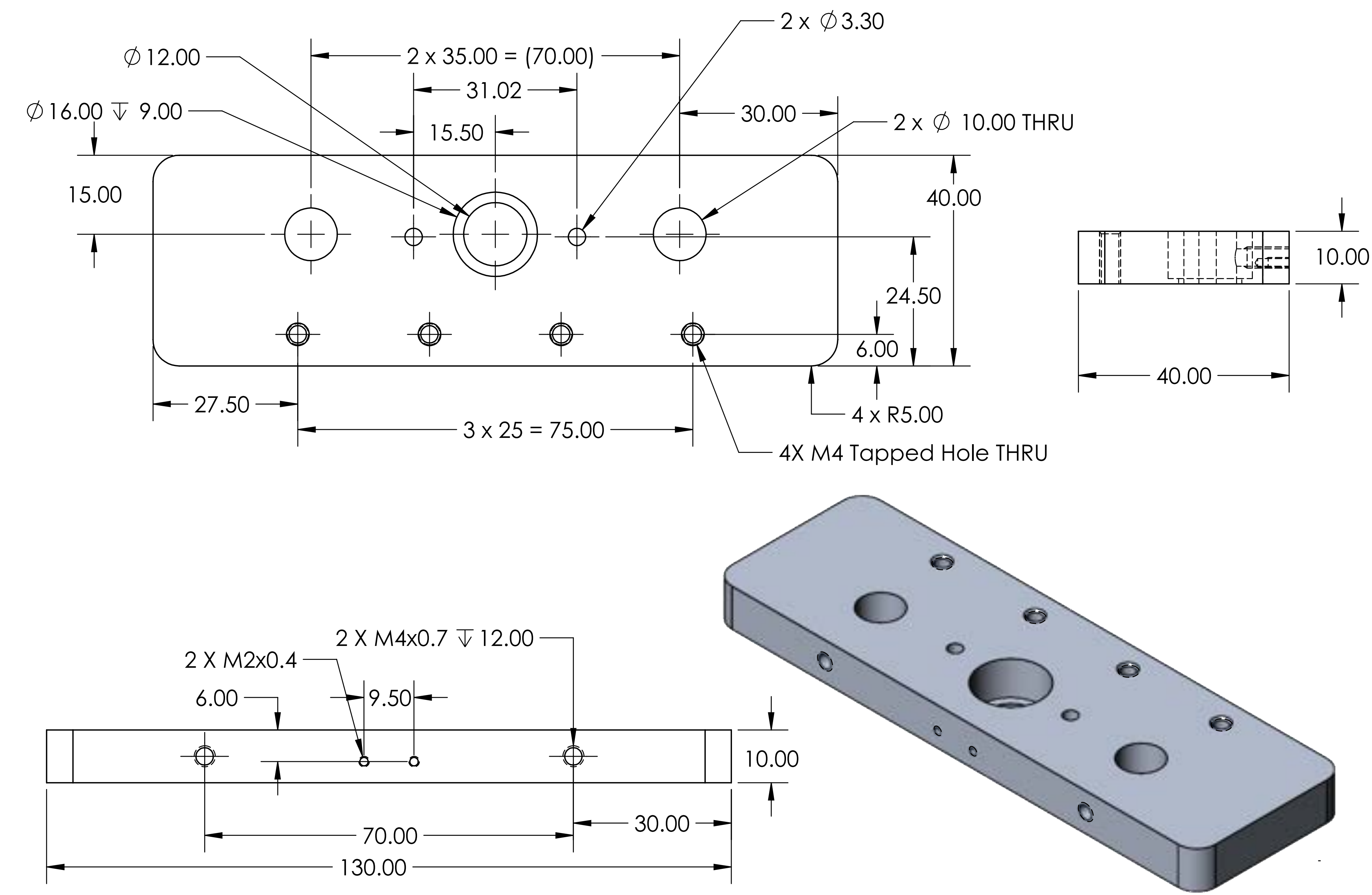
SCHOOL OF MECHANICAL, AEROSPACE & CIVIL ENGINEERING THE UNIVERSITY OF MANCHESTER OXFORD ROAD MANCHESTER M13 9PL	PART DESCRIPTION	T structure		
	REF ID	REF ID 20	MATERIAL	Aluminium
	SCALE	1:1.4	MANUFACTURING PROCESS	CNC Machining
	PROJECTION	First Angle		



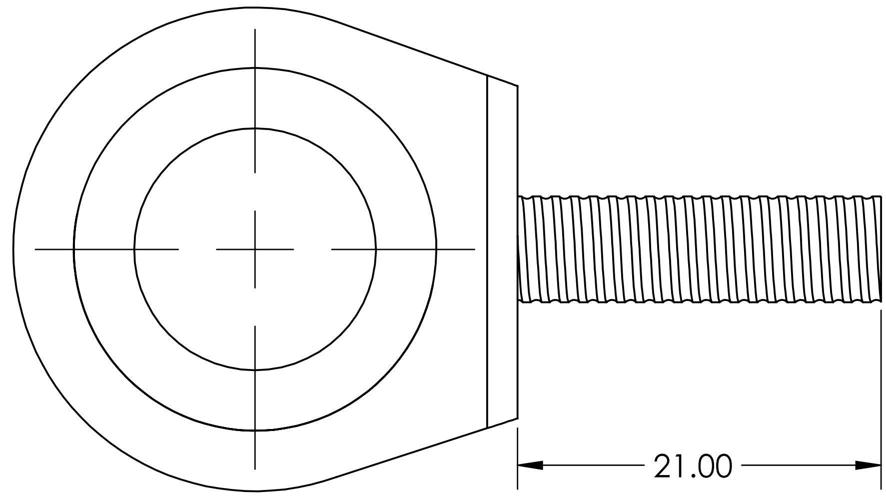
SCHOOL OF MECHANICAL, AEROSPACE & CIVIL ENGINEERING THE UNIVERSITY OF MANCHESTER OXFORD ROAD MANCHESTER M13 9PL	PART DESCRIPTION	T structure connection rod		
	REF ID	REF ID 21	MATERIAL	Aluminium
	SCALE	6:1	MANUFACTURING PROCESS	CNC machining
	PROJECTION	First Angle		

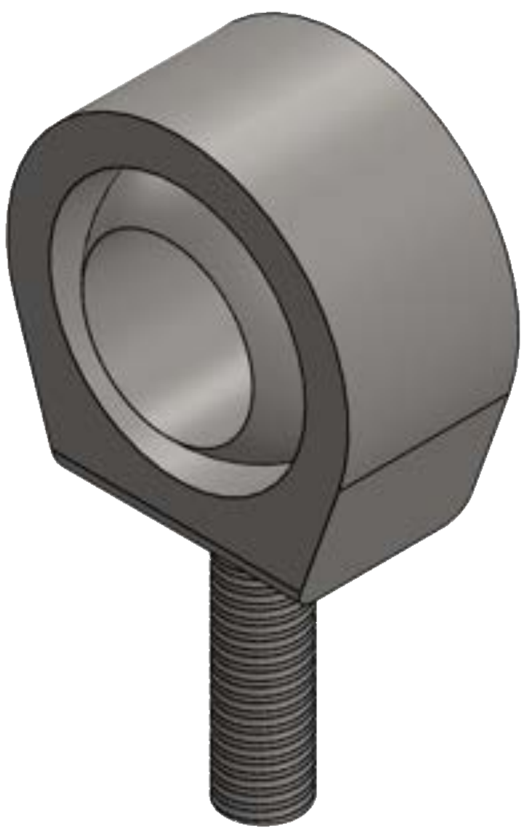


SCHOOL OF MECHANICAL, AEROSPACE & CIVIL ENGINEERING THE UNIVERSITY OF MANCHESTER OXFORD ROAD MANCHESTER M13 9PL	PART DESCRIPTION	16mm SHAFT		
	REF ID	16	MATERIAL	ALUMINIUM
	SCALE	1:1	MANUFACTURING PROCESS	TURNING
	PROJECTION	FIRST ANGLE		



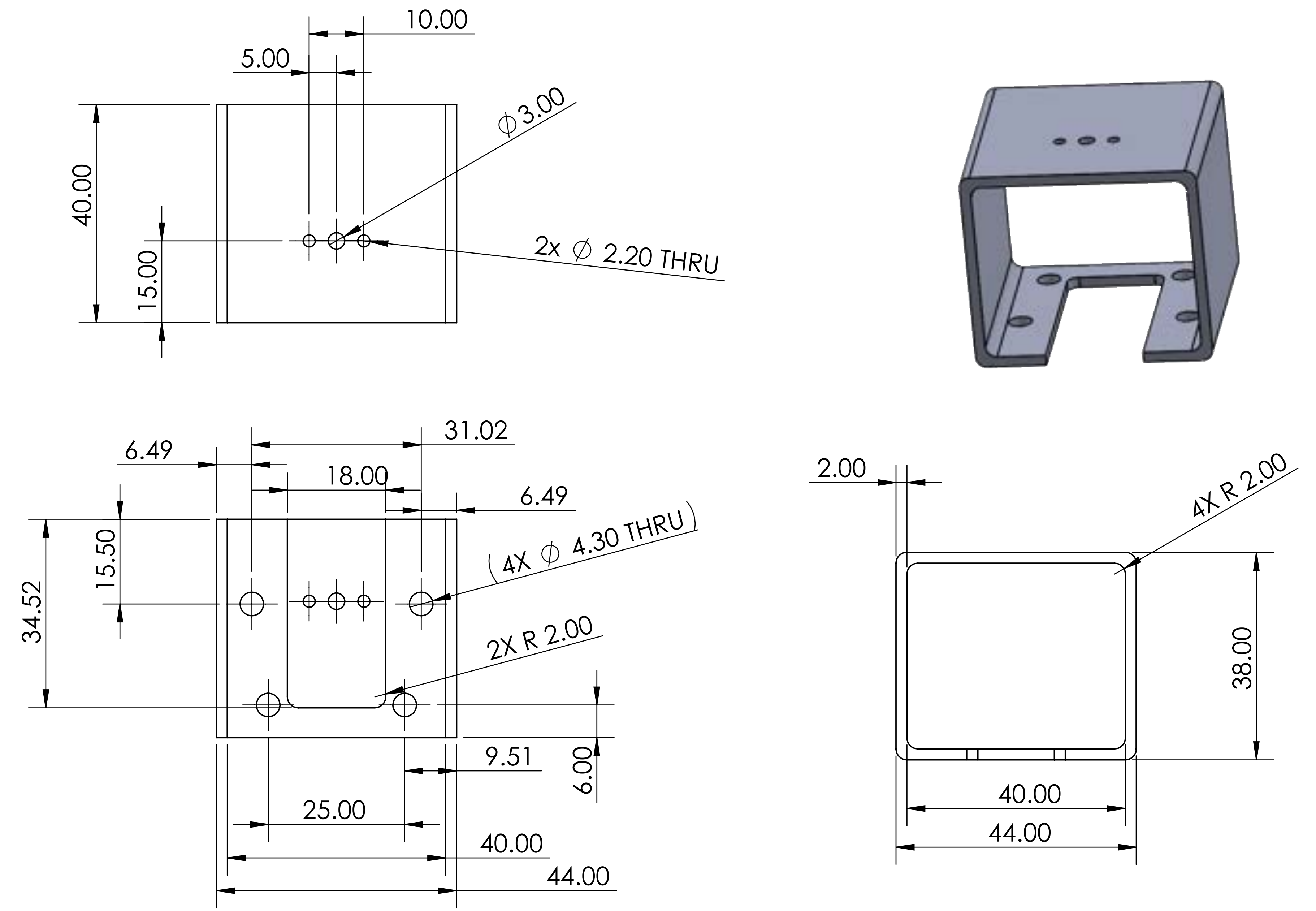
SCHOOL OF MECHANICAL, AEROSPACE & CIVIL ENGINEERING THE UNIVERSITY OF MANCHESTER OXFORD ROAD MANCHESTER M13 9PL	PART DESCRIPTION	TOP PLATE		
	REF ID		MATERIAL	ALUMINIUM
	SCALE	1:1	MANUFACTURING PROCESS	CNC MACHINING
	PROJECTION	FIRST ANGLE		



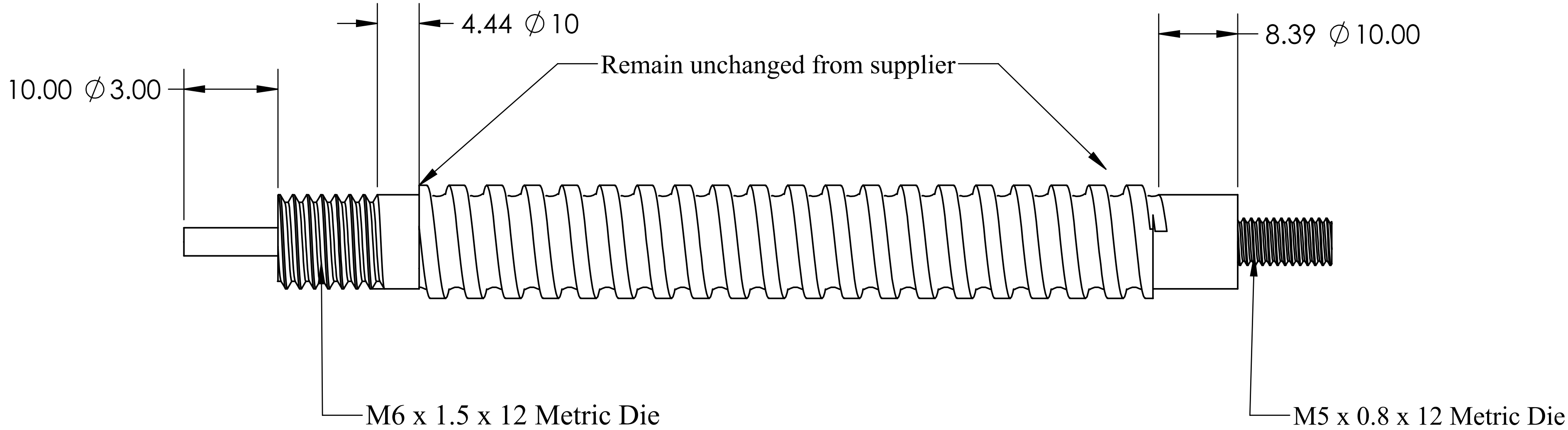


All other dimensions remain unchanged from the supplier

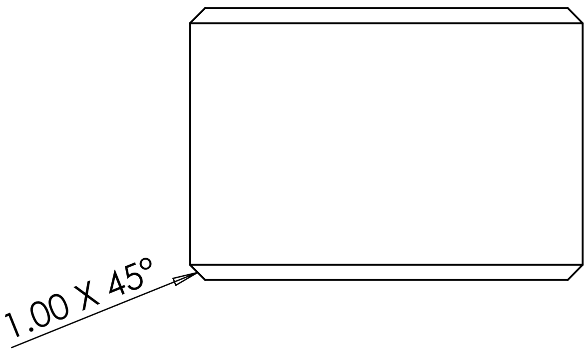
SCHOOL OF MECHANICAL, AEROSPACE & CIVIL ENGINEERING THE UNIVERSITY OF MANCHESTER OXFORD ROAD MANCHESTER M13 9PL	PART DESCRIPTION	ROD END BEARING, 16mm INNER DIAMETER		
	REF ID	4	MATERIALS	STEEL & BRONZE
	SCALE	2:1	MANUFACTURING PROCESS	Sawing
	PROJECTION	FIRST ANGLE		

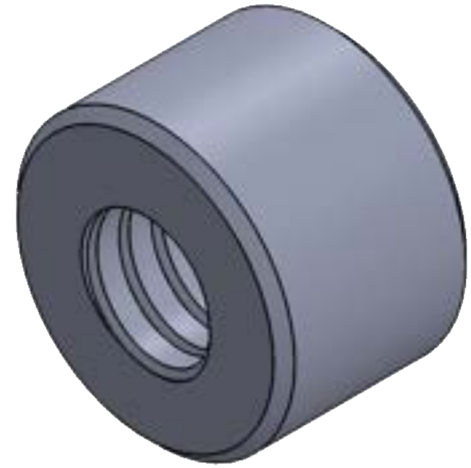


SCHOOL OF MECHANICAL, AEROSPACE & CIVIL ENGINEERING THE UNIVERSITY OF MANCHESTER OXFORD ROAD MANCHESTER M13 9PL	NAME	Motor Holder	TITLE	
	DATE		SCALE	
	GROUP	MENG 6	MATERIAL	ALUMINIUM
	EMAIL			

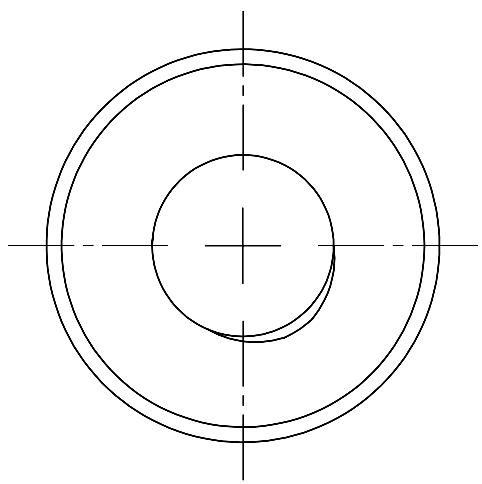


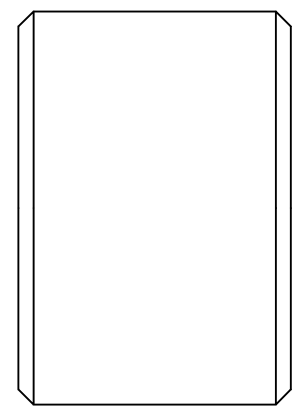
SCHOOL OF MECHANICAL, AEROSPACE & CIVIL ENGINEERING THE UNIVERSITY OF MANCHESTER OXFORD ROAD MANCHESTER M13 9PL	PART DESCRIPTION	RS PRO Lead Screw, 12mm Shaft Diameter		
	REF ID	5	MATERIAL	STEEL
	SCALE	1:1	MANUFACTURING PROCESS	TURNING, SAWING
	PROJECTION	FIRST ANGLE		



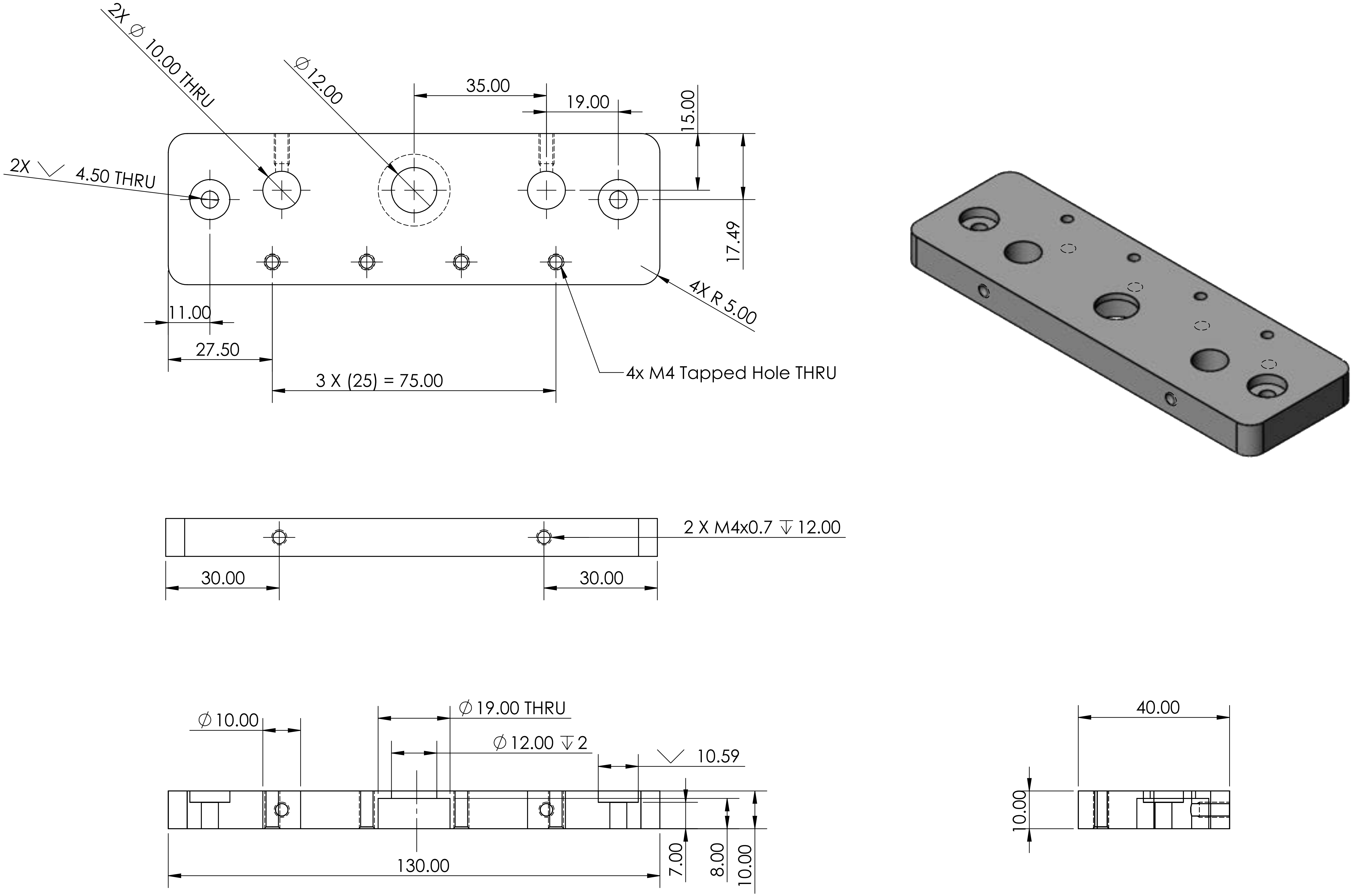


This part is obtained from the supplier.
The chamfer in the dimension above need to be removed.

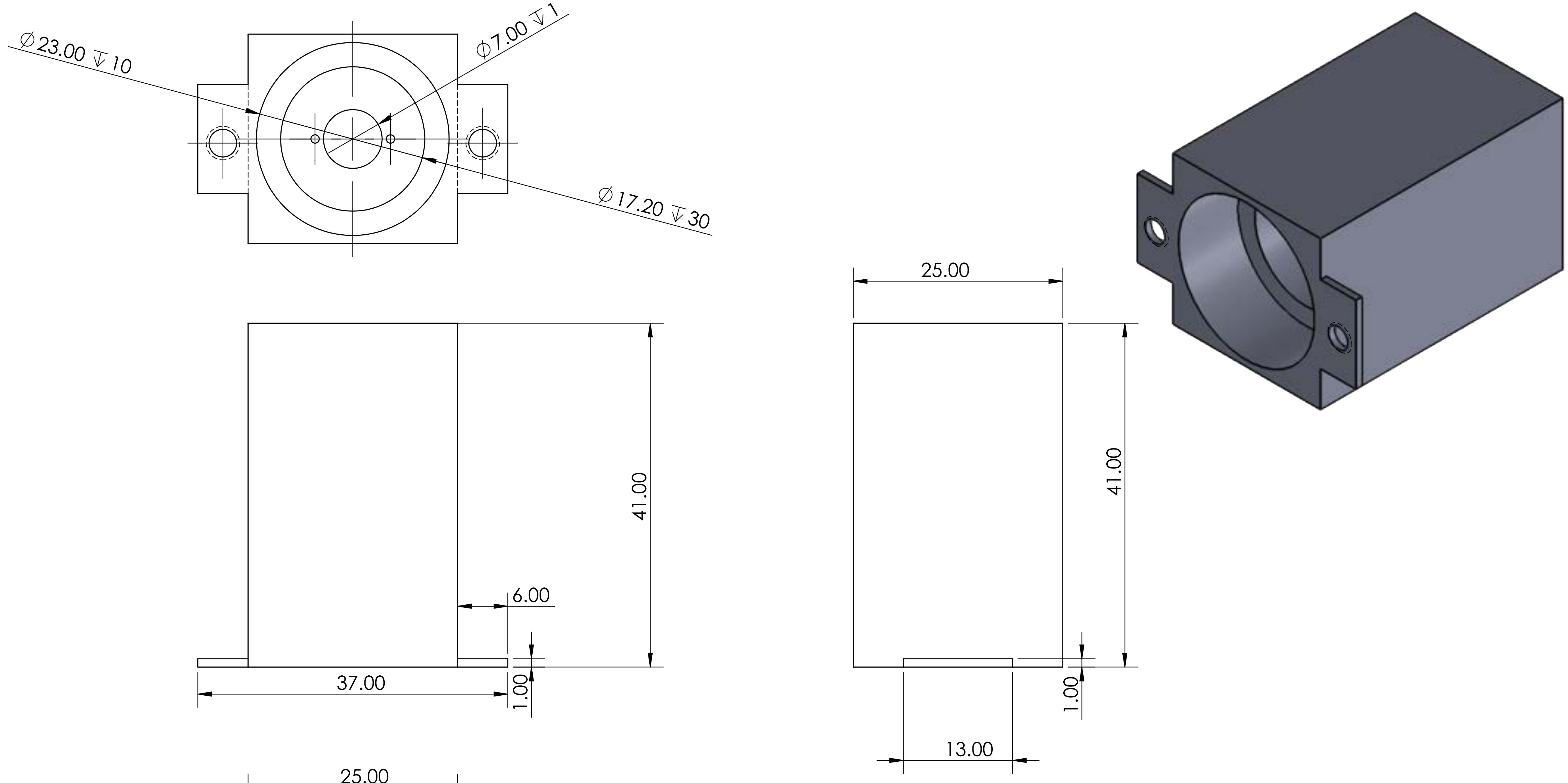


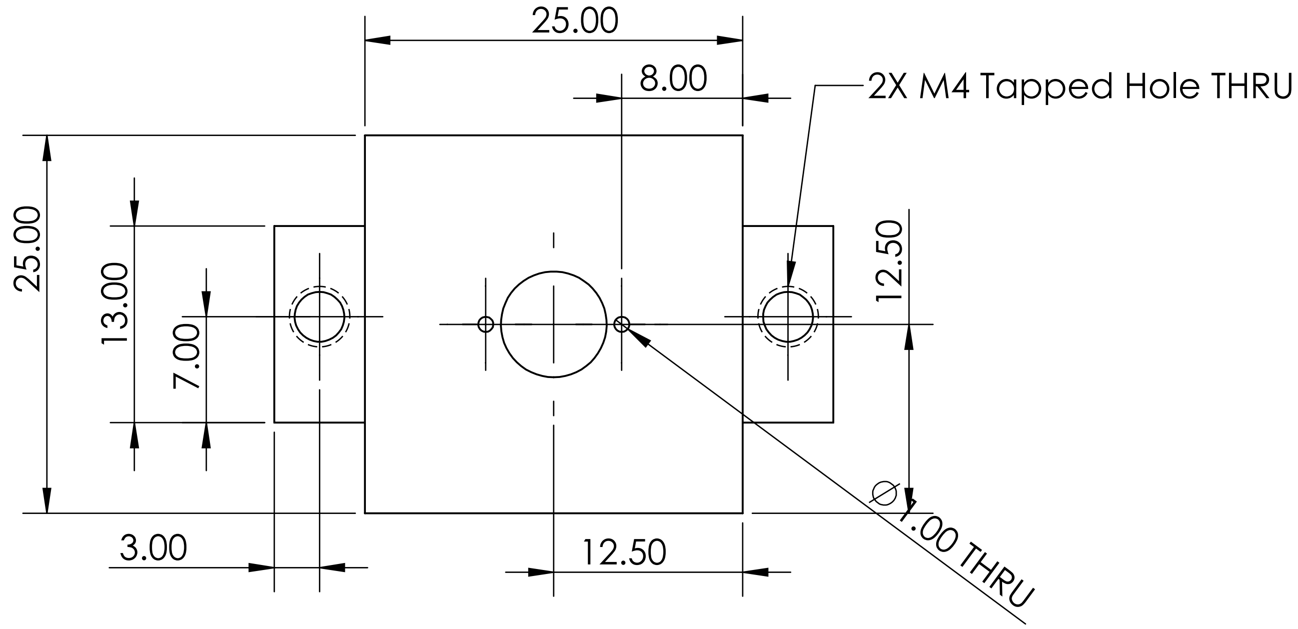


SCHOOL OF MECHANICAL, AEROSPACE & CIVIL ENGINEERING THE UNIVERSITY OF MANCHESTER OXFORD ROAD MANCHESTER M13 9PL	PART DESCRIPTION	LEADSCREW NUT		
	REF ID	REF ID 65	MATERIAL	STEEL
	SCALE	2:1	MANUFACTURING PROCESS	MILING
	PROJECTION	FIRST ANGLE		

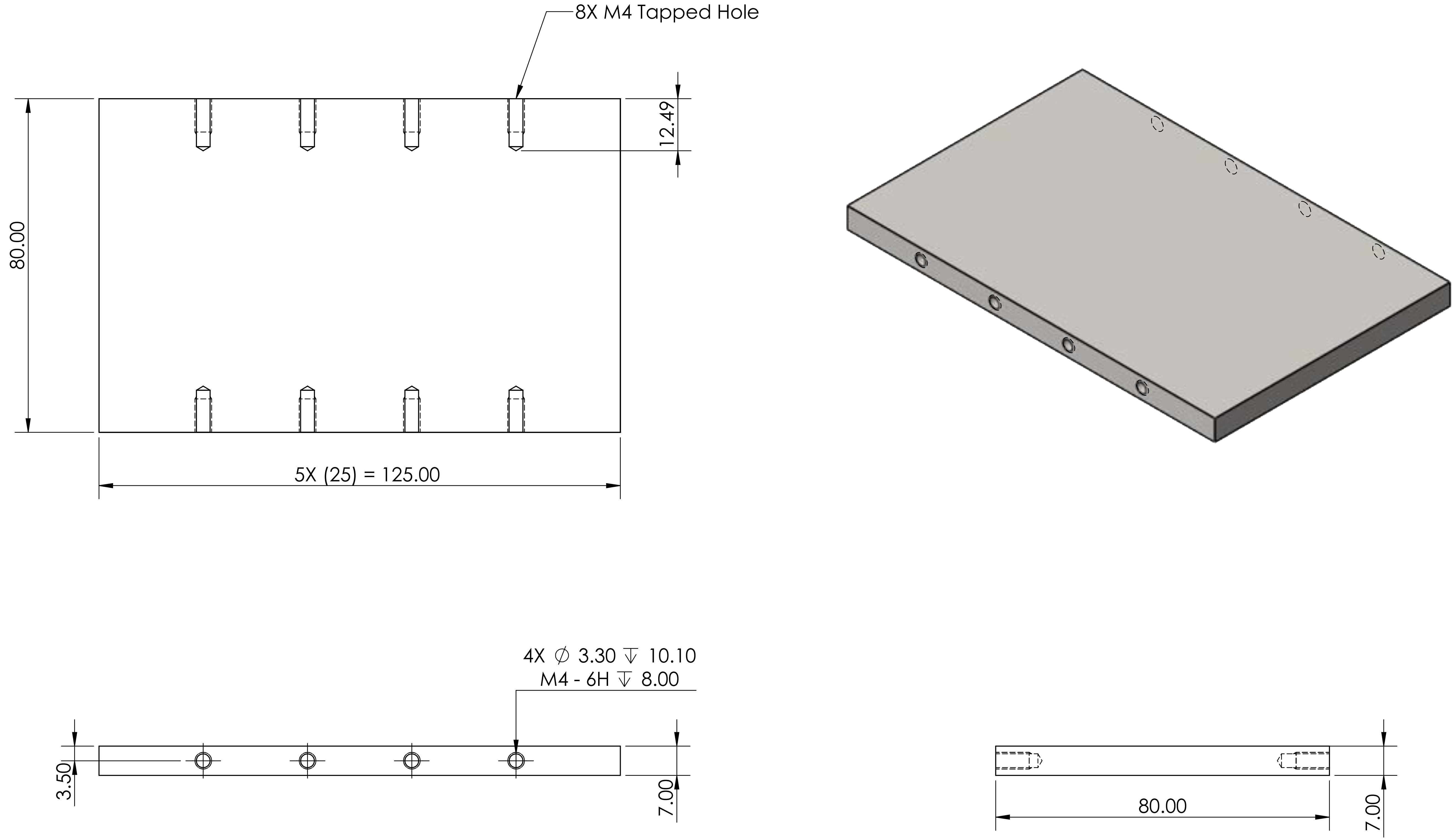


SCHOOL OF MECHANICAL, AEROSPACE & CIVIL ENGINEERING THE UNIVERSITY OF MANCHESTER OXFORD ROAD MANCHESTER M13 9PL	PART DESCRIPTION	BOTTOM PLATE		
	REF ID	REF ID 13	MATERIAL	ALUMINIUM
	SCALE	1:1	MANUFACTURING PROCESS	CNC MACHINING
	PROJECTION	FIRST ANGLE		

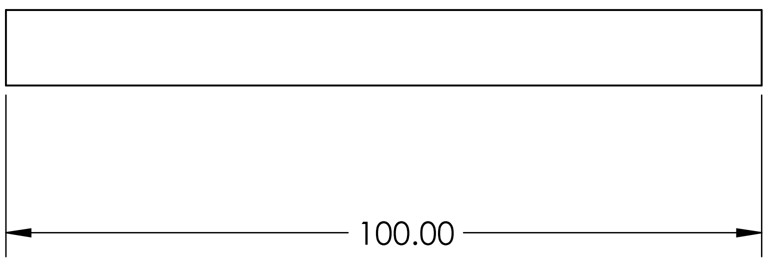


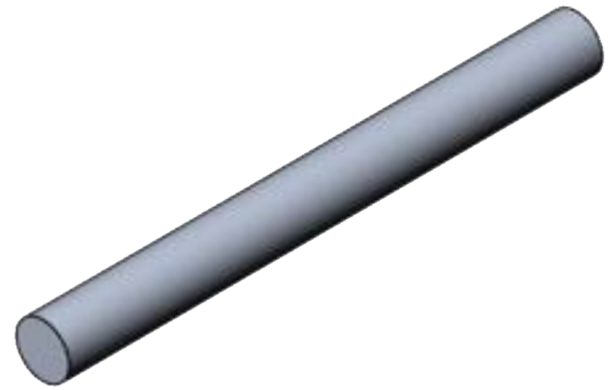


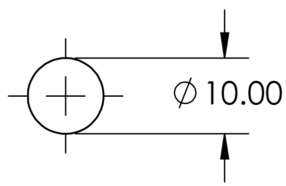
SCHOOL OF MECHANICAL, AEROSPACE & CIVIL ENGINEERING THE UNIVERSITY OF MANCHESTER OXFORD ROAD MANCHESTER M13 9PL	PART DESCRIPTION	MOTOR BRACKET		
	REF ID	REF ID 38	MATERIAL	ABS
	SCALE	2:1	MANUFACTURING PROCESS	3D Printing
	PROJECTION	FIRST ANGLE		



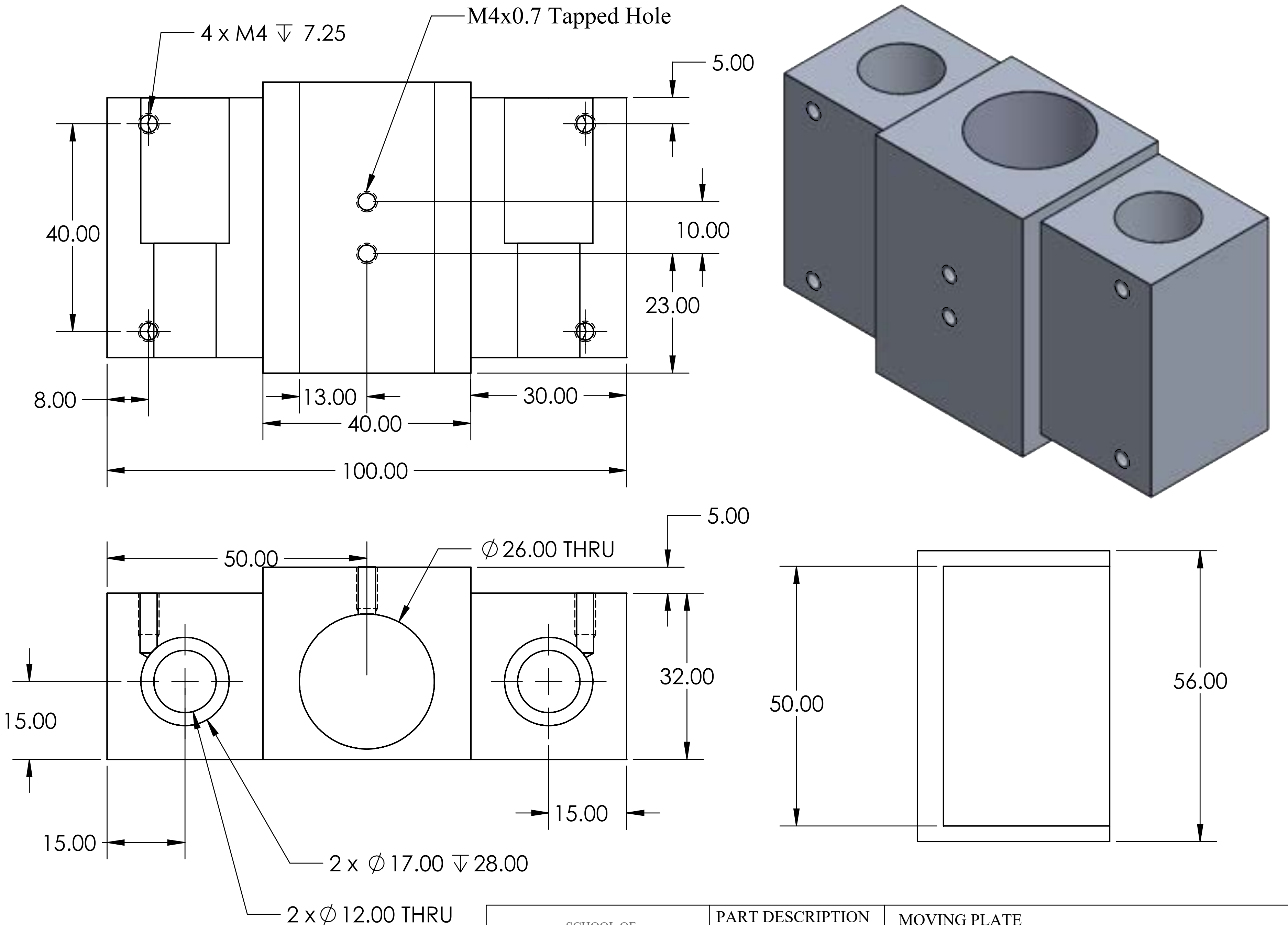
SCHOOL OF MECHANICAL, AEROSPACE & CIVIL ENGINEERING THE UNIVERSITY OF MANCHESTER OXFORD ROAD MANCHESTER M13 9PL	PART DESCRIPTION	BASE PLATE		
	REF ID	REF ID 18	MATERIAL	ALUMINIUM
	SCALE	1:1	MANUFACTURING PROCESS	CNC MACHINING
	PROJECTION	FIRST ANGLE		



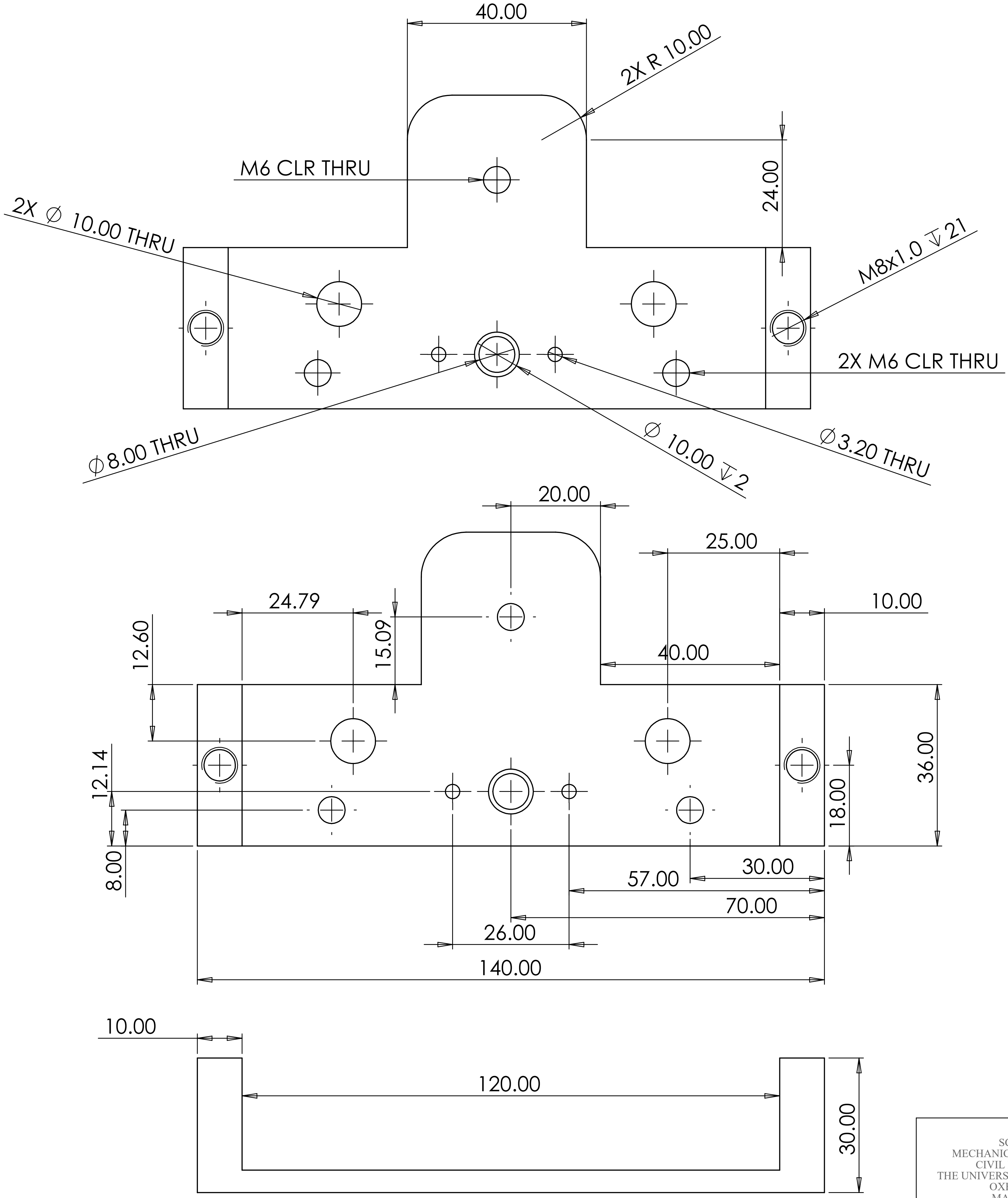


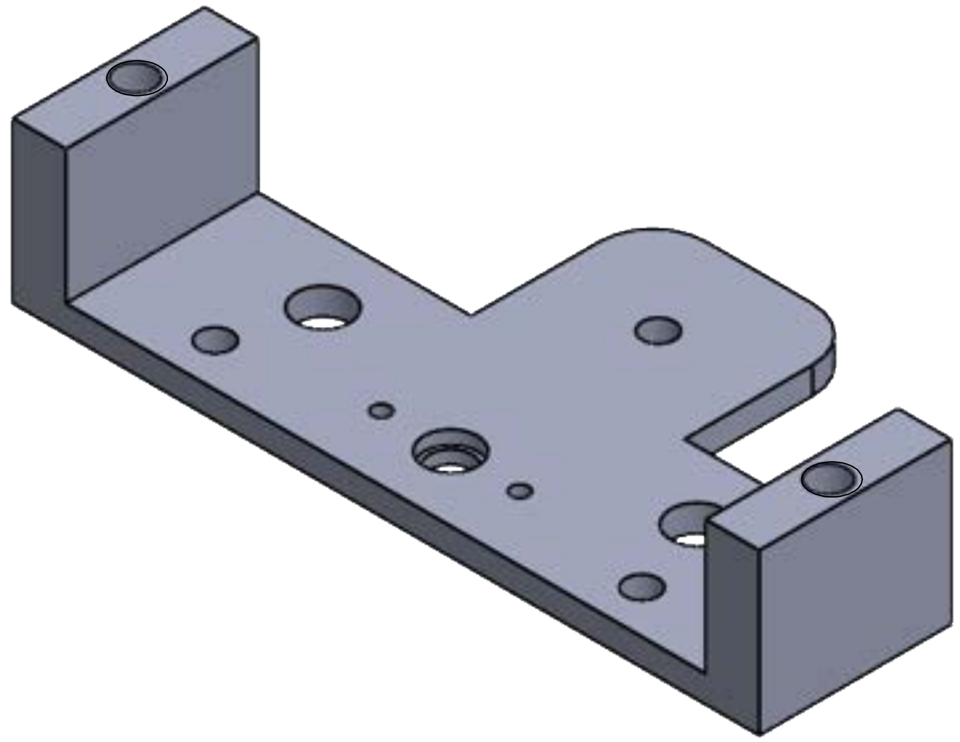


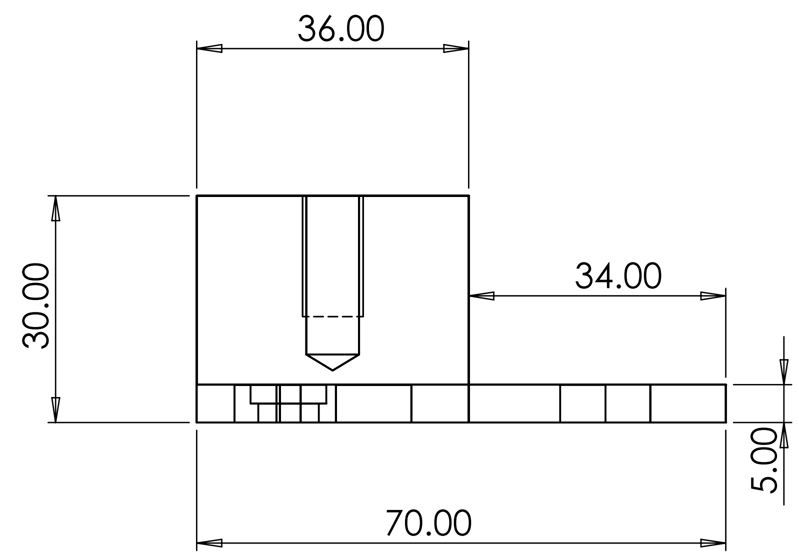
SCHOOL OF MECHANICAL, AEROSPACE & CIVIL ENGINEERING THE UNIVERSITY OF MANCHESTER OXFORD ROAD MANCHESTER M13 9PL	PART DESCRIPTION	SLIDING RODS		
	REF ID	11	MATERIAL	STAINLESS STEEL
	SCALE	1:1	MANUFACTURING PROCESS	TURNING
	PROJECTION	FIRST ANGLE		



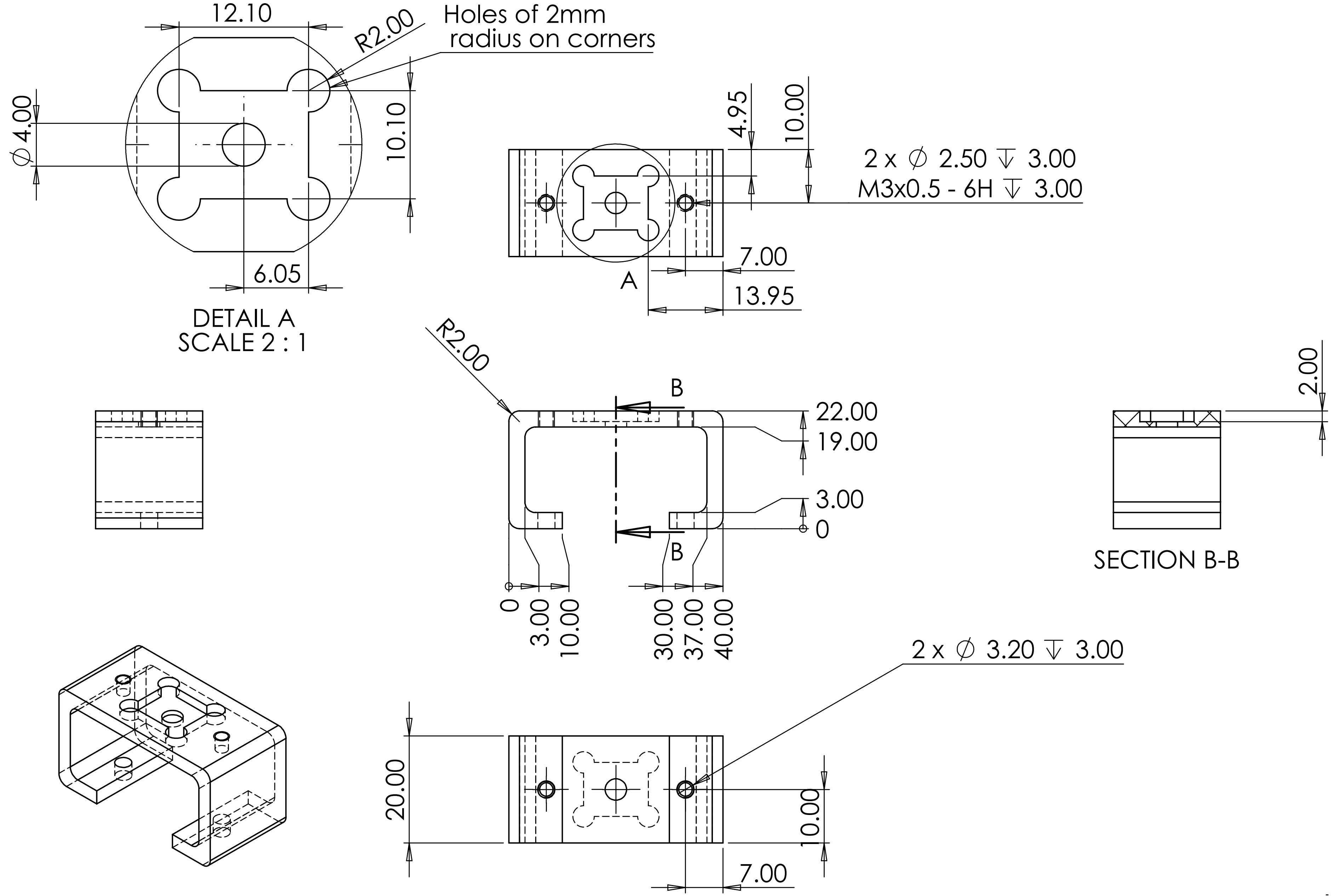
SCHOOL OF MECHANICAL, AEROSPACE & CIVIL ENGINEERING THE UNIVERSITY OF MANCHESTER OXFORD ROAD MANCHESTER M13 9PL	PART DESCRIPTION	MOVING PLATE		
	REF ID	10	MATERIAL	ALUMINIUM
	SCALE	1:1	MANUFACTURING PROCESS	CNC MACHINING
	PROJECTION	FIRST ANGLE		



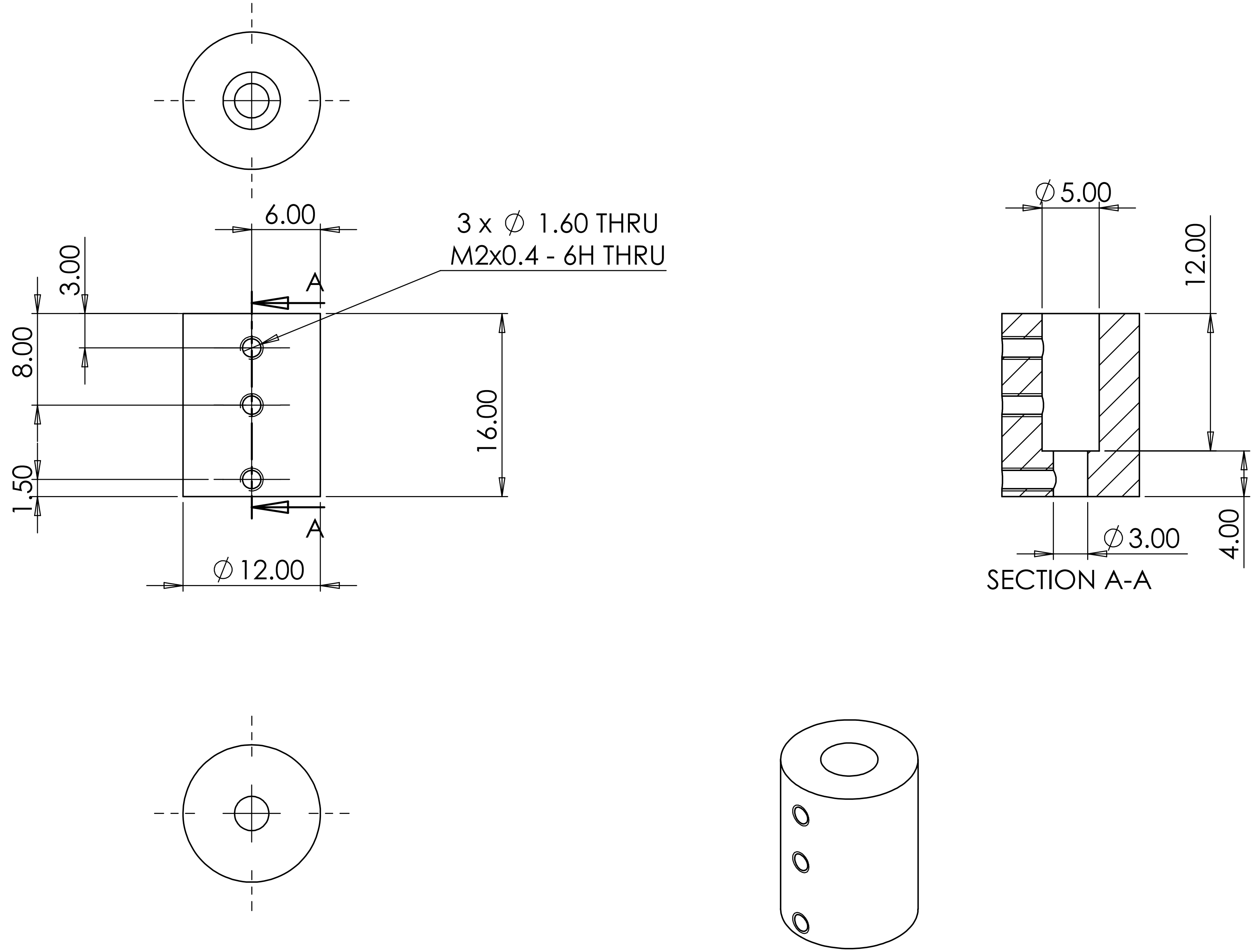




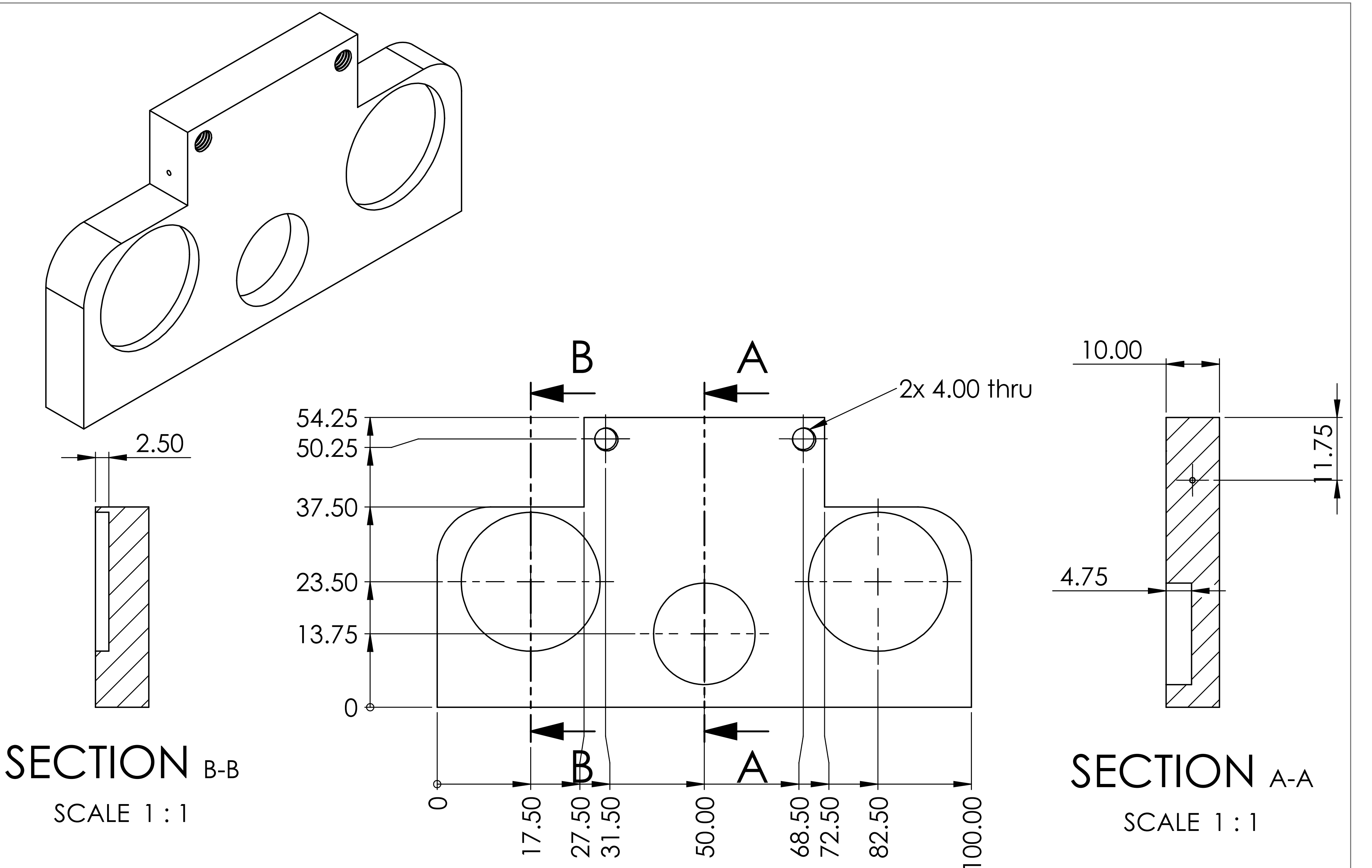
SCHOOL OF MECHANICAL, AEROSPACE & CIVIL ENGINEERING THE UNIVERSITY OF MANCHESTER OXFORD ROAD MANCHESTER M13 9PL	PART DESCRIPTION	CLEANING ARM HOLDER		
	REF ID	REF ID 17	MATERIAL	ALUMINIUM
	SCALE	1:1	PROCESS	CNC MACHINING
	PROJECTION	FIRST ANGLE		



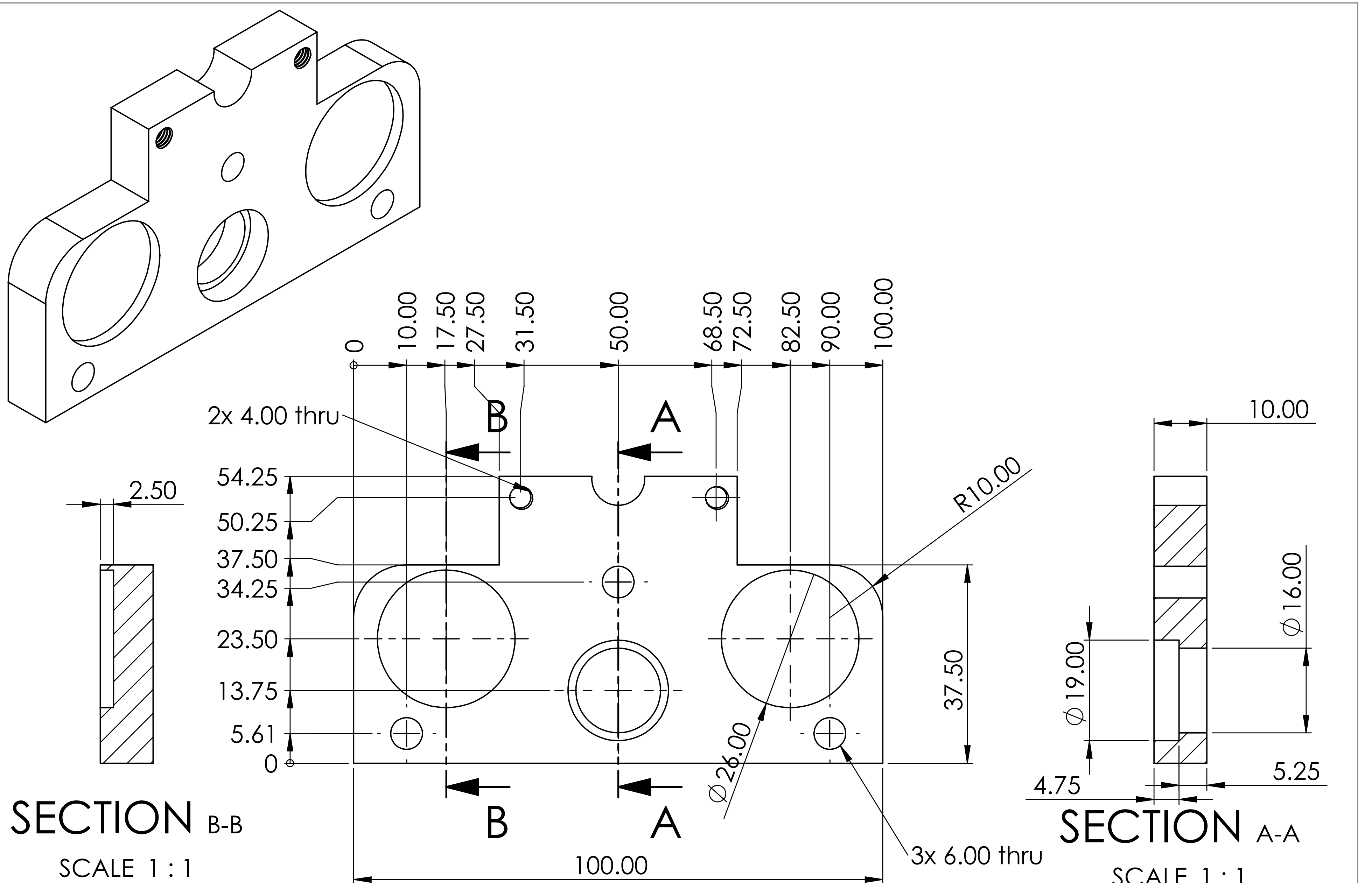
SCHOOL OF MECHANICAL, AEROSPACE & CIVIL ENGINEERING THE UNIVERSITY OF MANCHESTER OXFORD ROAD MANCHESTER M13 9PL	NAME		TITLE	
	DATE		SCALE	
	PROGRAMME		PROJECTION	
	EMAIL			



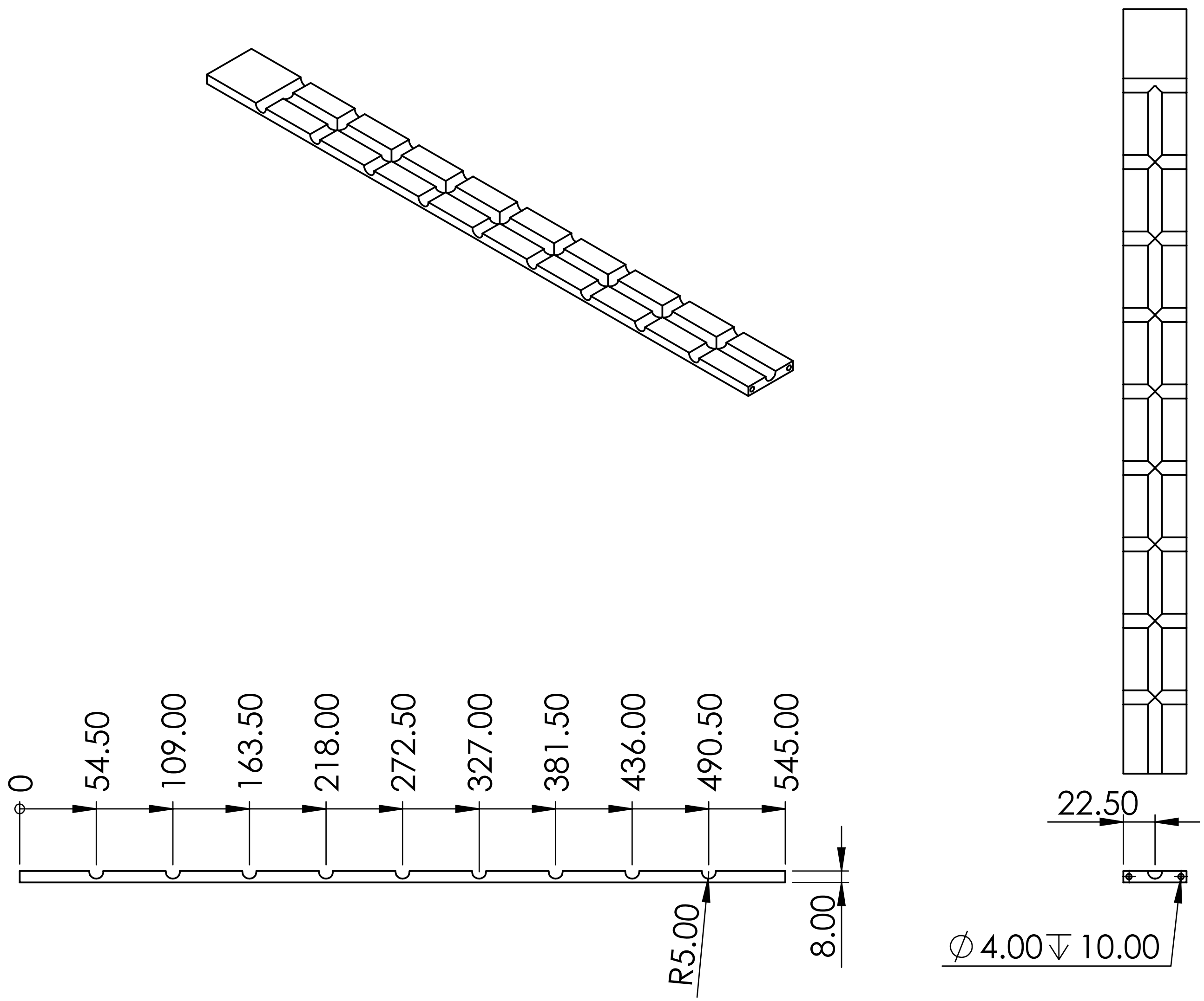
SCHOOL OF MECHANICAL, AEROSPACE & CIVIL ENGINEERING THE UNIVERSITY OF MANCHESTER OXFORD ROAD MANCHESTER M13 9PL	NAME		TITLE	
	DATE		SCALE	
	PROGRAMME		PROJECTION	
	EMAIL			



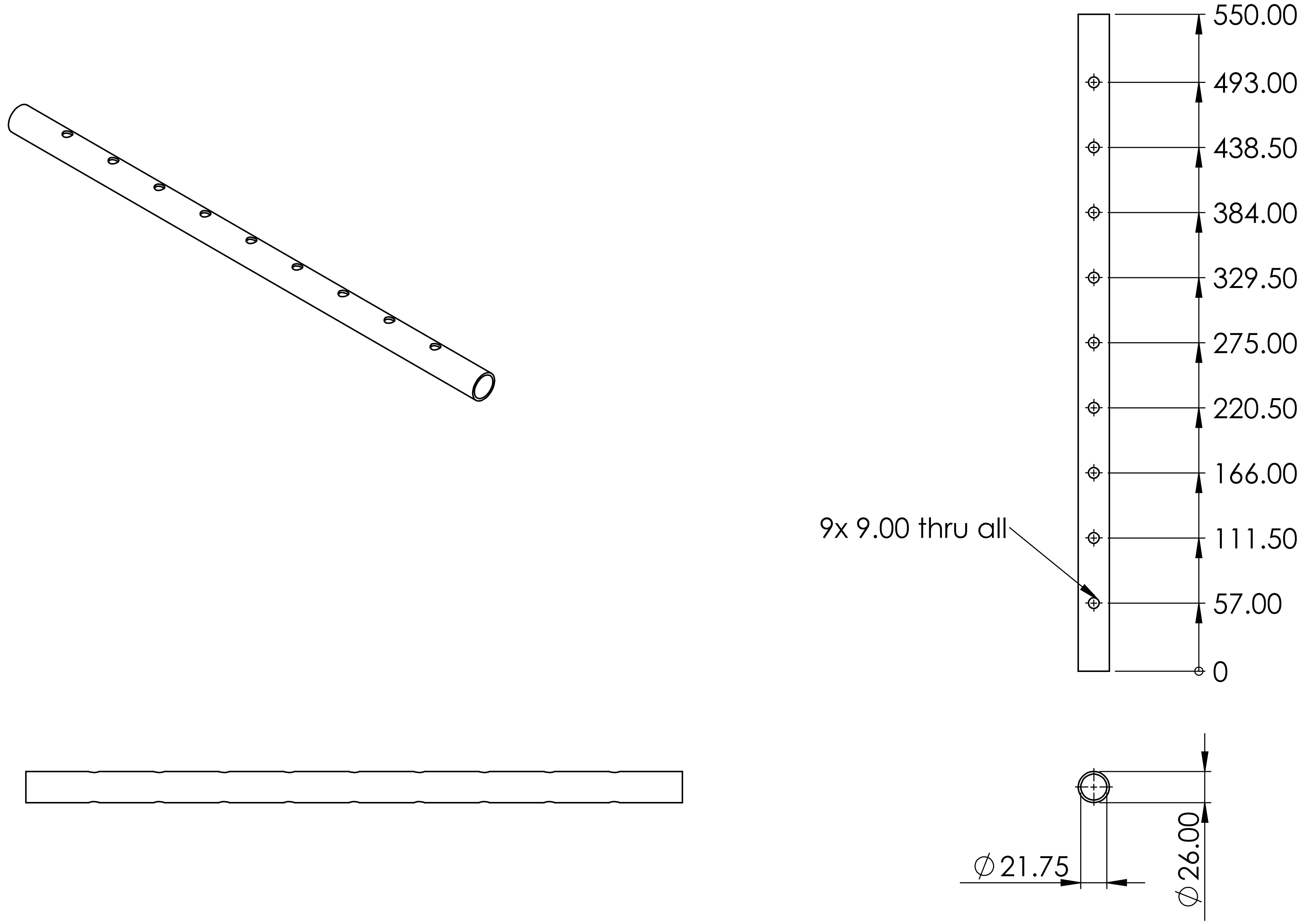
SCHOOL OF MECHANICAL, AEROSPACE & CIVIL ENGINEERING THE UNIVERSITY OF MANCHESTER OXFORD ROAD MANCHESTER M13 9PL	PART DESCRIPTION	Upper Arm End Piece		
	REF ID	42	MATERIAL	PVC
	SCALE	1:1	MANUFACTURING PROCESS	CNC machining
	PROJECTION	First Angle		



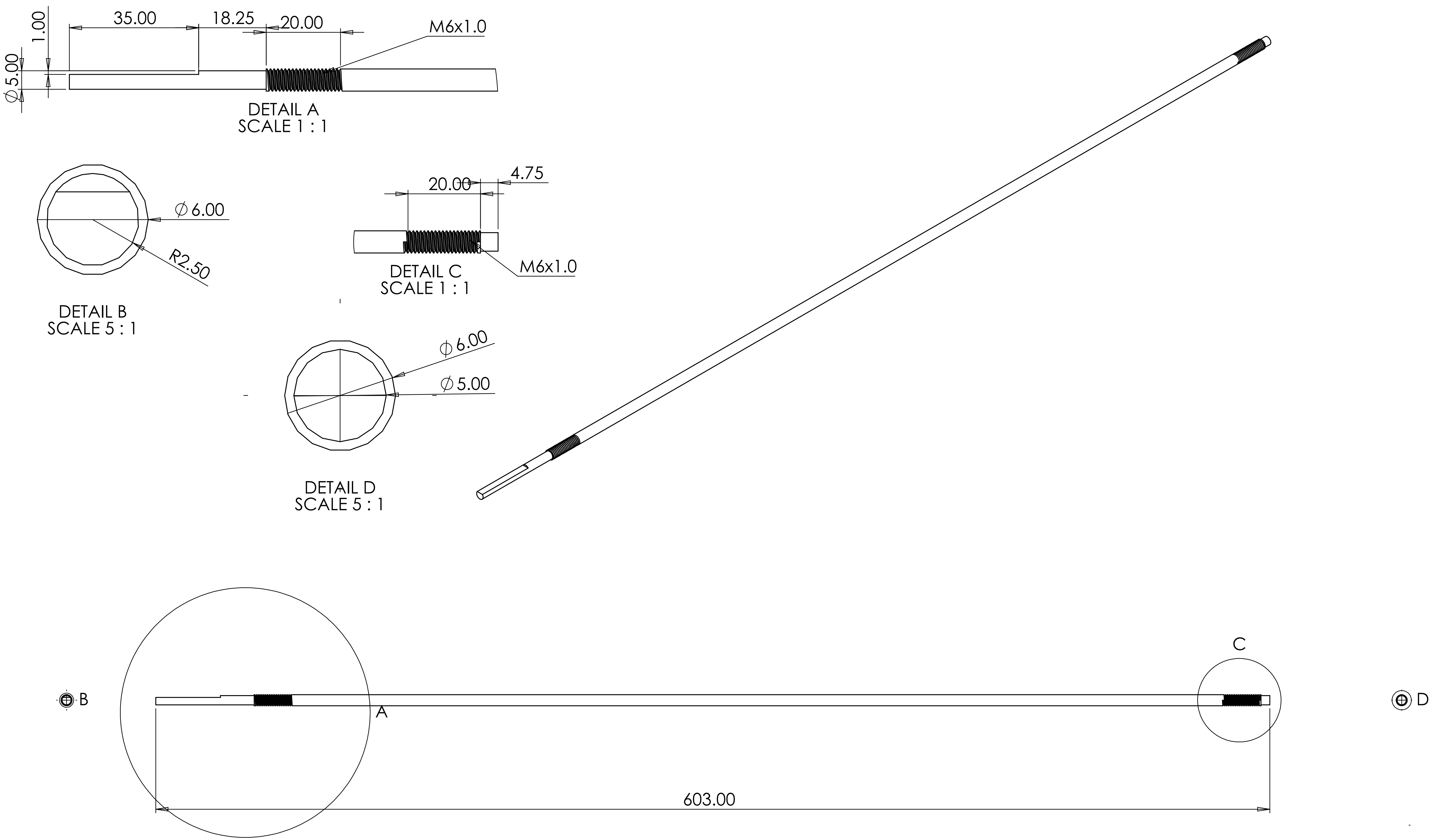
SCHOOL OF MECHANICAL, AEROSPACE & CIVIL ENGINEERING THE UNIVERSITY OF MANCHESTER OXFORD ROAD MANCHESTER M13 9PL	PART DESCRIPTION	Upper Arm Beginning Piece		
	REF ID	41	MATERIAL	PVC
	SCALE	1:1	MANUFACTURING PROCESS	CNC machining
	PROJECTION	First angle		



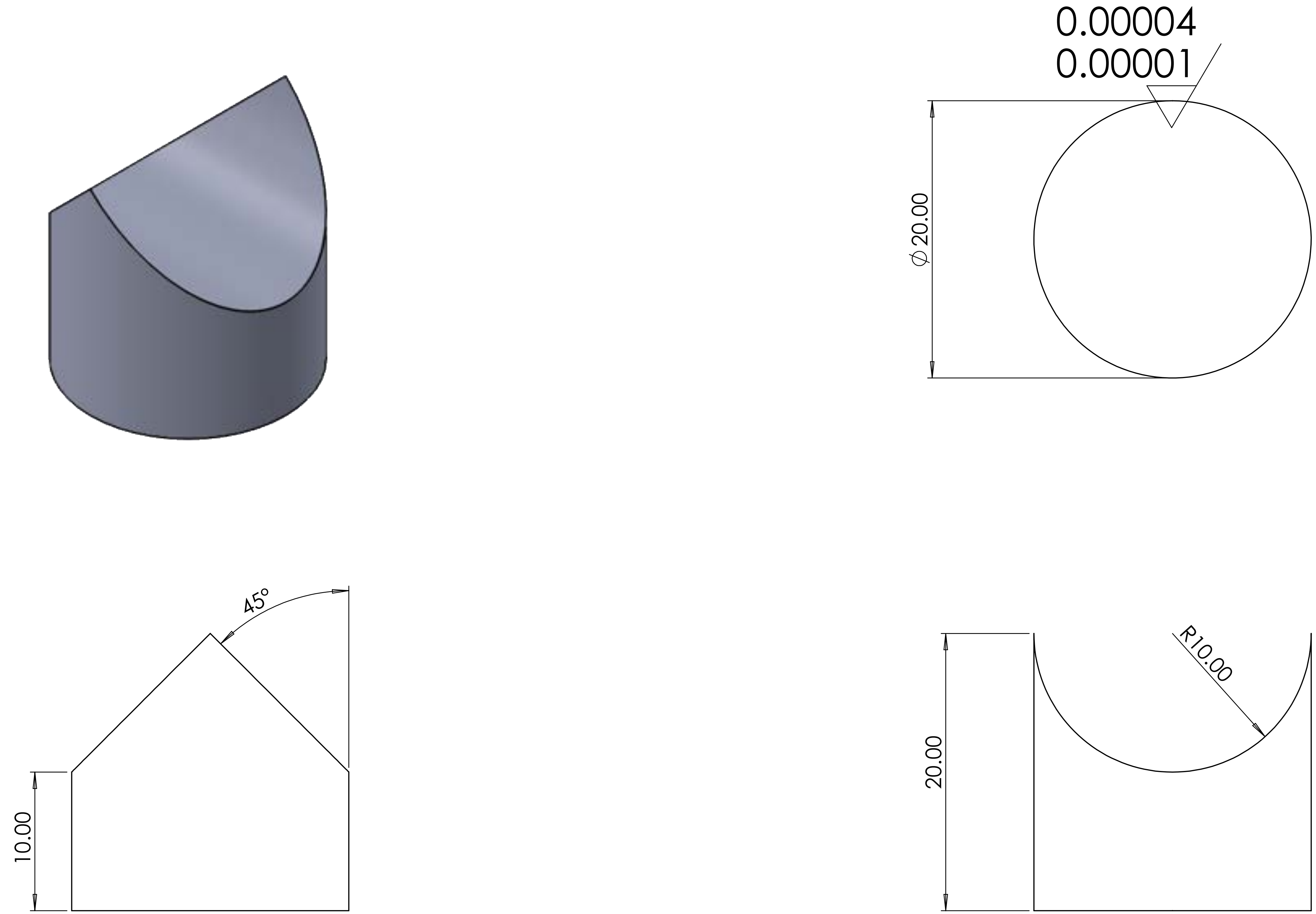
SCHOOL OF MECHANICAL, AEROSPACE & CIVIL ENGINEERING THE UNIVERSITY OF MANCHESTER OXFORD ROAD MANCHESTER M13 9PL	PART DESCRIPTION	Top Piece		
	REF ID	43	MATERIAL	PVC
	SCALE	4:1	MANUFACTURING PROCESS	CNC
	PROJECTION	Orthographic		



SCHOOL OF MECHANICAL, AEROSPACE & CIVIL ENGINEERING THE UNIVERSITY OF MANCHESTER OXFORD ROAD MANCHESTER M13 9PL	PART DESCRIPTION	Upper Arm side support		
	REF ID	44	MATERIAL	PVC
	SCALE	1:5	MANUFACTURING PROCESS	Drilling
	PROJECTION	Orthographic		



SCHOOL OF MECHANICAL, AEROSPACE & CIVIL ENGINEERING THE UNIVERSITY OF MANCHESTER OXFORD ROAD MANCHESTER M13 9PL	NAME		TITLE	
	DATE		SCALE	
	PROGRAMME		PROJECTION	
	EMAIL			



SCHOOL OF MECHANICAL, AEROSPACE & CIVIL ENGINEERING THE UNIVERSITY OF MANCHESTER OXFORD ROAD MANCHESTER M13 9PL	PART DESCRIPTION	Upper Arm Nylon Support Foot		
	REF ID	REF ID 45	MATERIAL	NYLON
	SCALE	3:1	MANUFACTURING PROCESS	Drilling
	PROJECTION	First Angle		