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3D REPLICATING ROBOTIC ARM

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This report is submitted to the Department of Mechanical Engineering in partial fulfilment of the requirements for the award of Diploma in Mechanical Engineering

DEPARTMENT OF MECHANICAL ENGINEERING

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DECLARATION OF ORIGINALITY AND COPYRIGHT

TITLE : 3D REPLICATING ROBOTIC ARM

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ABSTRACT

Robotic arms are arguably the best way of executing continuous, repetitive movements accurately and precisely. 3D printing provides flexibility in designing and manufacturing products, complementing subtractive manufacturing methods, thus increasing material efficiency. 3D scanning creates many opportunities, especially when used in conjunction with 3D printing. In this research, we aim to combine these 3 technologies into a single product, simplifying engineering design processes, for a more sustainable, eco-friendly, material efficient future. In the present market, there are only 3 robotic arms capable of 3D printing available commercially. 3D replicating machines are also very limited and pricey but often with disappointing scan quality. The objective of this study is to produce a 3D Replicating machine that is as portable and cost efficient as possible. Besides, we want to build a robotic arm with both 3D printing and 3D Scanning features. We mainly used subtractive fabrication methods, namely lathing, milling, and welding to produce parts of the robotic arm. Soldering was used to connect electrical/electronic components. After all is set and built, coding was involved to program the arm. The robotic arm operates with respect to the Marlin firmware signature. It is able to create medium sized sophisticated 3D models by extruding melted plastic (ABS, PLA, and TPU) filaments through a nozzle. It is compact, user-friendly, and cost efficient. To further develop and improve this model, cheaper or more eco-friendly materials may substitute aluminium for the arm. The program code should be revised to simplify operational procedures and perfecting the quality of 3D printing and 3D scanning.

ABSTRACT (MALAY VERSION)

Lengan robot merupakan sistem mekanikal yang terbaik untuk melakukan pergerakan berterusan, berulang dengan tepat dan cekap. Percetakan tiga dimensi (3D) memberikan fleksibiliti dalam merancang dan mengeluarkan produk, melengkapkan kaedah pembuatan yang subtraktif, sehingga meningkatkan kecekapan bahan. Pengimbasan tiga dimensi (3D) menghasilkan banyak faedah atau kelebihan, terutamanya ketika digabungkan dengan mesin pencetakan tiga dimensi (3D). Dalam penyelidikan ini, kami bercadang untuk menggabungkan tiga teknologi ini menjadi satu produk, mempermudahkan proses reka bentuk kejuruteraan untuk kebaikan masa depan yang lebih lestari, mesra alam dan menghasilkan produk yang berkualiti dan efektif. Di pasaran masa kini, hanya ada 3 lengan robot yang mampu mencetak tiga dimensi (3D) yang tersedia secara komersial. Mesin replika tiga dimensi (3D) ini juga sangat terhad dan mahal tetapi sentiasa mempunyai kualiti imbasan yang mengecewakan. Melalui projek ini, kami merancang untuk menghasilkan mesin replika tiga dimensi (3D) yang mudah alih dan menjimatkan kos. Selain itu, kami ingin membina lengan robot yang mampu untuk mencetak dan mengimbas secara tiga dimensi (3D) dengan efektif. Kami mengutamakan penggunaan kaedah fabrikasi subtraktif, seperti kaedah pelarik, pengilangan, dan pengimpalan untuk menghasilkan bahagian lengan robot. Pematerian digunakan untuk menyambungkan komponen elektrik/elektronik. Setelah semuanya diatur dan dibina, proses pengekodan terlibat untuk memprogram lengan robot. Lengan robot beroperasi dengan melibatkan perisian tegar Marlin. Ia mampu membuat model tiga dimensi (3D) yang canggih bersaiz sederhana dengan mengekstrusi filamen plastik cair (ABS, PLA, dan TPU) melalui muncung. Ia ringkas, mesra pengguna dan menjimatkan kos. Untuk mengembangkan dan memperbaiki model ini, bahan yang lebih murah atau mesra alam boleh menggantikan aluminium untuk lengan robot. Kod program harus disemak semula untuk mempermudah prosedur operasi dan menyempurnakan kualiti percetakan 3D dan pengimbasan 3D.

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LIST OF ABBREVIATIONS

ABBREVIATION	
DOF	Degree of freedom
LIDAR	Light detection and ranging module
3DP	3-dimensional printing
3DS	3-dimensional scanning

CHAPTER 1

INTRODUCTION

1.1. PROJECT OVERVIEW

The 3D Replicating Robotic Arm is a 4-DOF robotic arm, attached with a 3D printing extruder, and a 3D scanner. Its main feature is having a robotic arm being able to scan an object placed within its scanning range, generating a CAD file from the scan, and 3D print out the CAD file, essentially making it be able to replicate the original object being scanned. The robotic arm is operated using Arduino, while equipped with a Fused Deposition modelling (FDM) printing extruder and micro LIDAR module. The intention of this design is to combine 3D printing and 3D scanning into one single machine, simplifying 3D designing and manufacturing processes, while utilising one of the most commonly used and popular assembly instruments, the robotic arm.

1.2. RESEARCH BACKGROUND

The increment in usage and popularity of robotic arms in manufacturing, packaging, servicing, and many other industries is irrefutable. Robotic arms are the most versatile, effective, and efficient way of executing continuous, repetitive movements in an accurate and precise manner. In fact, in the year 2015, an estimated 1.64 million industrial robots were in operation worldwide according to International Federation of Robotics (IFR). This figure increases to 2,439,543 operational industrial robots by the end of 2017, according to a study on world robotics in 2019, and is projected to reach 3,788,000 by the end of 2021. With such colossal figures, the economics involved is also extremely hefty, with an annual turnover for robot systems is estimated to be US$48.0 billion in 2018, with the inclusion of software, peripherals, and systems engineering costs. From here, a slight breakdown reveals that the biggest customer of industrial robots is automotive industry with 30% market share, then electrical/electronics industry with 25%, metal and machinery industry with 10%, rubber and plastics industry with 5%, food industry with 5%. In textiles, apparel, and leather industry, 1,580 units are operational.

As for 3D printing, it has also been a topic of much interest, having undergone much development in its technologies in recent years. This started when the patent for Fused Deposition Modelling (FDM), which was invented and patented by S. Scott Crump with his wife Lisa Crump in 1989, expired in 2009. This opened doors for new opportunities, ushering new generations of development towards FDM, which is the most commonly used 3D printing process. This is demonstrated with the price drop in FDM 3D printers, and the number of commercially available 3D printers, ranging from budget 3D printers such as the Tronxy X1 3D printer with prices as low as RM 400.00 to the state of the arc Ultimaker S3, one of the most desired commercial 3D printers available, which costs about RM19000.00. Moreover, by the 2010s, it was proven to be able to 3D print metal, an absolute eye opener for metalworking technologies. Since then, more and more industries started utilising 3D printing or similar means of additive manufacturing, including manufacturing, sociocultural sectors, and medical industries where it is used to produce a range of medical items, prosthetics, spares, and repairs. 3D printing has also entered the world of clothing, with fashion designers experimenting with 3D-printed bikinis, shoes, and dresses. Sports brands like Adidas, New Balance and Nike even print custom-fit shoes for athletes. Besides that, on a more serious note, in 2015, a Royal Air Force Eurofighter Typhoon fighter jet flew with printed parts. Since then, the United States Air Force has begun to work with 3D printers, and the Israeli Air Force has also purchased a 3D printer to print spare parts. In 2017, GE Aviation, one of the world's top and largest aircraft engine suppliers, which offers engines for the majority of commercial aircraft, revealed that it had used design for additive manufacturing to create a helicopter engine with 16 parts instead of 900, with great potential impact on reducing the complexity of supply chains. In short, 3D printing provides us with flexibility in all aspects, from designing, manufacturing, repairing, and modifying our products, complementing the old subtractive manufacturing methods, countering globalisation, and increasing material efficiency.

A close sibling to 3D printing, 3D scanning is also an essential part of engineering in the 21st century. 3D scanning is the process of analysing a real-world object or environment to collect data on its shape and possibly its appearance (e.g., colour and texture). The collected data can then be used to construct digital 3D models. In today's world, 3D scanning is applied in construction industry and civil engineering, design processes, entertainment industry, 3D photography, real estate, virtual/remote tourism, medical CADCAM, Quality assurance and industrial metrology, and even law enforcement for on-site documentation of crime scenes, bullet trajectories, bloodstain pattern analysis, accident reconstruction, bombings, plane crashes, and more. Besides that, it is also vastly used in the field of reverse engineering, where a 3D scanner is used to digitise free-form or gradually changing shaped components as well as prismatic geometries to create a usable digital model for further modifications and designing. Moreover, 3D scanning has been crucial in recent years in preserving history and cultural heritage, successfully, scanning ancient scrolls, paintings, art works, cuneiform tablets, tombs among many other items of the past to recreate them virtually or physically for inspection and research purposes. Among the most recent breakthrough include the deciphering of 1500 years old Dead Sea Scrolls that were too burnt and fragile to be unrolled. By utilising state of the arc 3D scanning and X-ray imaging, researchers were able to unroll the scrolls virtually and decipher the scrolls, bringing history back to life. 3D Scanning can also be used in conjunction with 3D printing technology to virtually teleport certain object across distances without the need of shipping them and in some cases incurring import/export tariffs. For example, a plastic object can be 3d scanned in the United states, the files can be sent off to a 3d printing facility over in Germany where the object is replicated, effectively teleporting the object across the globe, circumventing shipping costs and international import/export tariffs.

In this research, we aim to combine all 3 of these spectacular marvels of engineering and technology into one single product, to produce a product that consists of the features of these 3 technologies, further simplifying engineering and design processes, for a more sustainable, eco-friendly, material efficient future.

1.3. PROBLEM STATEMENT

In the present market, there are only about 3 robotic arms capable of 3D printing available commercially, and none with 3D scanning abilities, namely the Hexbot, its 2nd generation Rotrics, Dobot Magician, and Dobot M1. All 4 robotic arms mentioned are respectable in their own right, capable of precision and repeatability of <0.2mm. Hexbot, Rotrics, and Dobot products were all extremely well-funded projects on sites such Kickstarter and Indiegogo crowd funding sites. For example, Rotrics gathered over RM6,000,000.00 by some 3000 funders on Indiegogo. This shows just how much potential this innovation has, and the interest and attention it is given by the public.

Besides that, 3D replicating machines (conventional 3D printers equipped with 3D scanners) are also very limited and pricey. For example, AIO Robotics ZEUS 3D printer, which is the world's first all-in-one 3d printer / copy machine, costs about RM6,600.00. Whereas the XYZprinting Da Vinci 1.0 Pro 3-in-1, which is one of the very few 3D printers with built in 3D scanners, costs about RM4,000.00. Even so, for such a price, it is often complained that the 3D scanner is not user friendly and then scan quality is disappointing.

While the first robot was invented as a general-purpose machine to move materials, later on robotics moved forward with velocity to create a whole new industry – automotive and has revolutionized by involving itself into electronics, food and beverages, production, and medical and surgical worlds. There is so much room to take advantage of the existence of robotic arms to apply them into other fields and innovations – such as 3D printing and 3D scanning technology.

Therefore, we are of the opinion that this innovation, which could be the first of its kind, has much untapped potential.

1.4. RESEARCH OBJECTIVE

- To build a robotic arm with 3D printing and 3D scanning features.
- To design a 3D replicating machine that is as portable and cost efficient as possible.

1.5. RESEARCH QUESTION

- What type of robotic arm is most suitable for 3D printing?
- What type of 3D printing method is most suitable to be equipped on a robotic arm?
- What type of 3D printing and 3D scanning technology is most cost efficient?
- Where to mount the 3D scanner on a robotic arm?

1.6. RESEARCH SCOPE

The project cost around RM2,000.00. We utilised resources both within and outside the polytechnic to achieve the optimum result.

1.7. RESEARCH IMPORTANCE/FEASIBILITY

To dive into new possibilities in 3D printing, 3D scanning and robotic arm, bringing out the best of these 3 technologies through innovation in the age of IoT. As we close in on IR4.0, there is no doubt figures of automation in all industries will only rocket, and the most used device will be the robotic arm. In order for 3D printing and 3D scanning to reach its full potential, working with robotic arms is a must. This is shown when German industrial robots manufacturer KUKA, equips its robotic arms with 3D printing extruders to print out large scale items such as car parts and designer walls and structures. A 3D Replicating Robotic Arm will also enhance learning experiences in education, allowing students to experience 3 big and current technologies by using just one device.

1.8. OPERATIONAL DEFINITION

1. 3DP - 3D printing
2. 3DS - 3D scanning
3. AM - Additive Manufacturing
4. Number of axes – two axes are required to reach any point in a plane; three axes are required to reach any point in space.
5. Degrees of freedom – this is usually the same as the number of axes.
6. Working envelope – the region of space a robot can reach.
7. Kinematics – the actual arrangement of rigid members and joints in the robot, which determines the robot's possible motions.
8. Carrying capacity or payload – how much weight a robot can lift.
9. Speed – how fast the robot can position the end of its arm. This may be defined in terms of the angular or linear speed of each axis or as a compound speed i.e., the speed of the end of the arm when all axes are moving.
10. Acceleration – how quickly an axis can accelerate. Since this is a limiting factor a robot may not be able to reach its specified maximum speed for movements over a short distance or a complex path requiring frequent changes of direction.
11. Accuracy – how closely a robot can reach a commanded position. When the absolute position of the robot is measured and compared to the commanded position the error is a measure of accuracy. Accuracy can be improved with external sensing for example a vision system or Infra-Red. See robot calibration. Accuracy can vary with speed and position within the working envelope and with payload (see compliance).
12. Repeatability – how well the robot will return to a programmed position. This is not the same as accuracy. It may be that when told to go to a certain X-Y-Z position that it gets only to within 1 mm of that position. This would be its accuracy which may be improved by calibration. But if that position is taught into controller memory and

each time it is sent there it returns to within 0.1mm of the taught position then the repeatability will be within 0.1mm.

13. Motion control – for some applications, such as simple pick-and-place assembly, the robot needs merely return repeatably to a limited number of pre-taught positions.
14. Drive – some robots connect electric motors to the joints via gears; others connect the motor to the joint directly (direct drive). Using gears results in measurable 'backlash' which is free movement in an axis. Smaller robot arms frequently employ high speed, low torque DC motors, which generally require high gearing ratios; this has the disadvantage of backlash. In such cases the harmonic drive is often used.
15. Compliance - this is a measure of the amount in angle or distance that a robot axis will move when a force is applied to it. Because of compliance when a robot goes to a position carrying its maximum payload it will be at a position slightly lower than when it is carrying no payload. Compliance can also be responsible for overshoot when carrying high payloads in which case acceleration would need to be reduced.

1.9. CONCLUSION

To conclude, engineering has always been about and will always be about apply science and mathematics into daily life, fabricating sophisticated devices to make life easier, more enjoyable, and more efficient. In this project, we did nothing less than that, combining 3D printing, 3D scanning and robotic arm technologies to produce one device does it all. We plan for our final product being brought to the classroom, and hopefully see its concept being applied in major industries in the future.

CHAPTER 2

LITERATURE REVIEW

2.1. INTRODUCTION

In this chapter, we will indulge ourselves into the journey of the technologies involved in the 3D Replicating Robotic Arm, diving deep to the roots of their discoveries, inventions, and the breakthroughs and developments they experienced since then. As mentioned in the first chapter, Introduction, the 3D Replicating Robotic Arm is composed of a robotic arm, mounted with a 3D printer and 3D scanner. Therefore, the literature reviews will also be based on these 3 technologies, separating them into individual subtopics. For each of these 3 technologies, 3DP, 3DS and robotic arm respectively, the literature review will incorporate a brief introduction of the technologies and how they work, the beginning of their histories, and continued with more focused details of pivotal and prominent advancements, as well as their recent developments, especially within the past 10 years (2010-2020).

2.2. 3D PRINTING

3DP, also known as additive manufacturing (AM), desktop manufacturing, rapid manufacturing (as the logical production-level successor to rapid prototyping), and on-demand manufacturing, is a process that builds a three-dimensional object from a computer-aided design (CAD) model, usually by successively adding material layer by layer, which is fundamentally different from conventional machining, casting and forging processes, where material is removed from a stock item (subtractive manufacturing) or poured into a mould and shaped by means of dies, presses and hammers. In 3DP, no special tools are required (for example, a cutting tool with certain geometry or a mould) as objects are manufactured directly onto the built platform layer-by-layer. 3DP enables the manufacturing of complex shapes in a single process while using less material than traditional manufacturing methods. The invention of the 3DP machine is the birth of a new era for the printing technology in the sense that users are now able to print out 3-dimensional objects using these machines instead of printing on the surface of papers.

The first recorded and published concepts of printing in 3D or replicating and duplicating objects in 3D came some 6 decades ago, when British science fiction writer, science writer and futurist, inventor, undersea explorer, and television series host Sir Arthur Charles Clarke CBE FRAS predicted a device capable of replicating and duplicating 3D objects on a popular BBC science and philosophy documentary programme, Horizon, in 1964. Then, in 1974, British chemist and author David Edward Hugh Jones laid out the concept of 3DP in his regular column Ariadne in the journal New Scientist. Finally, these ideas were brought to life in 1981, by a man called Hideo Kodama. He was the first person recorded to file an application to patent in which laser beam resin curing system is described, which he calls a rapid prototyping device. Unfortunately, his application never went through. Nevertheless, Hideo Kodama of Nagoya Municipal Industrial Research Institute is the first person that invented two additive methods for fabricating three-dimensional plastic models with photo-hardening thermoset polymer, where the UV exposure area is controlled by a mask pattern or a scanning fibre transmitter. At the same time, an American engineer, inventor, designer, manufacturing entrepreneur and business advisor/mentor, William (Bill) Edward Masters is also working on this revolutionary manufacturing process. Masters filed a patent for his Computer Automated Manufacturing Process and System on July 2, 1984 (US 4665492). He is the first to hold a patent in the field of 3DP. Although this is the first, it definitely was not the last. Masters continued to file a further 4 more patents that are significant to the field of 3DP, making many consider him the father of 3DP. The following are his patents:

1. **United States 4665492**
   Filed July 2, 1984
   The first 3-D patent to shoot drops of plastic and make a part in the mid-1980s

Computer automated manufacturing process and system

2. **United States 5134569**
   Filed June 26, 1989
   3-D printing using extrusion
   System and method for computer automated manufacturing using fluent material

3. **United States 5216616**
   Filed December 1, 1989
   3-D printing
   System and method for computer automated manufacture with reduced object shape distortion

4. **United States 5546313**
   Filed September 2, 1994
   3-D printing using pin array
   Method and apparatus for producing three-dimensional articles from a computer generated design

5. **United States 5694324**
   Filed March 6, 1995
   3-D printing suited for live cell building without damage
   System and method for manufacturing articles using fluent material droplets

Shortly after Masters was a group of French researchers, Alain Le Méhauté, Olivier de Witte, and Jean Claude André. Back in the 80s, le Méhauté was working at Alcatel researching fractal geometry parts. He argued with his colleagues because they thought his thinking was “off the path”. Still, he was determined to prove himself, and so started thinking about how to produce such complex parts. Le Méhauté shared his problem with de Witte, who was working for a subsidiary of Alcatel. Having worked with lasers, de Witte knew about liquid monomers that could be cured to solids with a laser. This opened the way to building a rapid prototyping device. The two brought the new idea to André, who was working at the French National Centre for Scientific Research (CNRS). Although he was interested in the idea, the CNRS ultimately did not approve of it. Apart from a lack of equations, they claimed it simply did not have enough areas of application. The trio filed their patent for the stereolithography process on 16th July 1984, but the application of the French inventors was abandoned by the French General Electric Company (now Alcatel-Alsthom) and CILAS (The Laser Consortium). The claimed reason was "for lack of business perspective".

Only 3 weeks after, Bill Masters's countrymen, Charles (Chuck) W. Hull filed his own patent for stereolithography. Hull coined the term "stereolithography" in his U.S. Patent 4,575,330 entitled "Apparatus for Production of Three-Dimensional Objects by Stereolithography" issued on March 11, 1986. He defined stereolithography as a method and apparatus for making solid objects by successively "printing" thin layers of the ultraviolet curable material one on top of the other. In Hull's patent, a concentrated beam of ultraviolet light is focused onto the surface of a vat filled with liquid photopolymer. The light beam, moving under computer control, draws each layer of the object onto the surface of the liquid. Wherever the beam strikes the surface, the photopolymer polymerizes/crosslinks, and changes to a solid. An advanced CAD/CAM/CAE software mathematically slices the computer model of the object into a large number of thin layers. The process then builds the object layer by layer starting with the bottom layer, on an elevator that is lowered slightly after solidification of each layer. He first came up with the idea in 1983 when he was using UV light to harden tabletop coatings. Fortunately for him, His patent application was successful, making him the legal inventor of the solid imaging process known as stereolithography (3DP), the first commercial rapid prototyping technology, and the development of the STL file format — the digital files that can be read by 3D printers which allowed additive manufacturing to become what it is today. With this combination of hardware and software, it became possible to design a 3D model on a computer and have it reproduced automatically by a 3D printer. He is named on more than 60 U.S. patents as well as other patents around the world in the fields of ion optics and rapid prototyping. Hull's contribution was the STL (Stereolithography) file format and the digital slicing and infill strategies common to many processes today. In 1986, Chuck Hull's company, 3D Systems Corporation, released the world's first commercial SLA 3D printer, the SLA-1. Now anyone, who had the money, could fabricate complex 3D objects and object parts. SLA was a game changer. This new process took a fraction of the time compared to more traditional methods. He was inducted into the National Inventors Hall of Fame in 2014 and in 2017 was one of the first inductees into the TCT Hall of Fame.

In 1988, the same year that the SLA-1 was introduced, another 3DP technology was invented. This time, it was selective laser sintering (SLS), the patent for which was filed by the late Carl Robert Deckard, Ph.D., ME, who at the time was an undergraduate at the University of Texas at Austin (UT-Austin). Dr. Deckard developed the technology with the help of his academic advisor, Dr. Joe Beaman, a professor at UT-Austin. Deckard's machine, the first SLS 3D printer, was called Betsy. It was able to produce only simple chunks of plastic. In the meantime, while the patent for SLS was awaiting approval, another patent for an additive manufacturing technology was submitted to the US government. This time it was for fused deposition modelling (FDM), the most common and most cost efficient 3DP method till today, with FDM 3D printers accounting for over 40% of all 3D printers. The patent was filed by Steven Scott Crump and his wife Lisa Crump, which he co-founded Stratasys, Ltd., an American manufacturer of 3D printers and 3D production systems for office-based rapid prototyping and direct digital manufacturing solutions. The Minnesota-based company is also one of the market leaders for high precision 3D printers. They were granted the patent, and Stratasys, Ltd. released their first FDM machine in 1992. One of the first industries to take on the technology in the early 90s was medicine.

In case you have not noticed, the term 3D printing or 3DP has yet to exist or be widely used up till this point. Only in 1993, Emanuel Sachs, a professor at the prestigious Massachusetts Institution of Technology, developed a powder bed process employing standard and custom inkjet print heads, which he coined the term "3D printing" for it. This was then commercialised by Soligen Technologies, Extrude Hone Corporation, and Z Corporation. Fun fact, Z corp. was sold to Contex Holding in August 2005, and was ultimately acquired by 3D Systems on January 3, 2012. The year 1993 also saw the start of a company called Solidscape by Royden C. Sanders, a company that designs, develops, and manufactures 3D printers for rapid prototyping and rapid manufacturing, able to print solid models created in CAD, introducing a high-precision polymer jet fabrication system with soluble support structures, (categorised as a "dot-on-dot" technique). It is also around this time, automated techniques that added metal, which would later be called additive manufacturing, were beginning to challenge conventional metalworking methods that are subtractive manufacturing methods. By the mid-1990s, new techniques for material deposition were developed at Stanford and Carnegie Mellon University, including micro casting and sprayed materials. Sacrificial and support materials had also become more common, enabling new object geometries. In 1995, German research organisation Fraunhofer-Gesellschaft zur Förderung der angewandten Forschung e. V., also known as the Fraunhofer Society, developed the selective laser melting (SLM) process.

These three technologies — SLA, LS, and FDM — have remained the three dominant additive manufacturing techniques and each has their respective strengths. While LS is most widely used in manufacturing, FDM has become the most well-known method for the general public since it is the technology used in consumer-grade 3D printers, so-called "desktop 3D printers."

As exciting as these new technologies were, they still had some way to go before they made mainstream news headlines and were widely used by industries or common people. Complex 3D models, in particular, proved hard to perfect. All too often, objects would warp as the material hardened. Not to mention, the machines were also prohibitively expensive. They were certainly too costly for solo investors and hobbyists. It is for these reasons that the technology was unheard of for decades after those first inventions. Even today, a time when 3DP has become a buzz word, the real potential continues to unfold.

Nearing the turn of the century, 1999 was a phenomenal year for many reasons, Manchester United won the treble, Pokémon cards became one of the biggest trends, the establishment of Euro currency, Vladimir Vladimirovich Putin became acting president of the Russian Federation due to the resignation of former president Boris Nikolayevich Yeltsin, the administration of the Panama Canal was turned over to the Republic of Panama, and among many more distinctive incidents and events, the Sultan our polytechnic is named after, Duli Yang Maha Mulia Almarhum Sultan Salahuddin Abdul Aziz Shah Alhaj ibni Almarhum Sultan Hisamuddin Alam Shah Alhaj, was elected and installed as the 11th Yang di-Pertuan Agong of Malaysia in this year as well. 1999 also marked a massive breakthrough for 3DP, as the first 3D-printed organ was implanted in humans. Scientists at Wake Forest Institute for Regenerative Medicine printed synthetic scaffolds of a human bladder and then coated them with the cells of human patients. The newly generated tissue was then implanted into the patients, with little to no chance that their immune systems would reject them, as they were made of their own cells. Following this success, this became the decade of medical advancements in 3DP, as 3 more firsts came by, first fabricated, functional miniature kidney, first prosthetic leg which included complex components, and the first bio-printed blood vessels using human cells.

However, this was not the only field 3DP was used in. One historical movement led by Dr. Adrian Bowyer, a Senior Lecturer in mechanical engineering at the University of Bath in England, was his ambitious open-source initiative project. He aptly named this “The Replication Rapid-Prototyper Project” or RepRap for short. Launched in 2005, the RepRap initiative set out to create an affordable 3D printer that had the ability to build itself, or at least print the parts needed for the new machine. The RepRap project had participants all over the world contributing to the goal of producing cheap, effective 3D printers, thereby bringing 3DP out of the factory and into the home. The RepRap project adopted FDM technology and has inspired many desktop 3D printers which have also employed extrusion. On 13 September 2006, the RepRap 0.2 prototype successfully printed the first part of itself, which were subsequently used to replace an identical part originally created by a commercial 3D printer. On 9 February 2008, RepRap 1.0 "Darwin" successfully made at least one instance of over half its total rapid-prototyped parts. On 14 April 2008, possibly the first end-user item is made by a RepRap: a clamp to hold an iPod securely to the dashboard of a Ford Fiesta. By September of that year, it was reported that at least 100 copies have been produced in various countries.

Below *Figure 2.1 & 2.2* shows the RepRap 0.1 building an object: First part ever made by a RepRap to make a RepRap, fabricated by the Zaphod prototype, by Vik Olliver (13/09/2006)

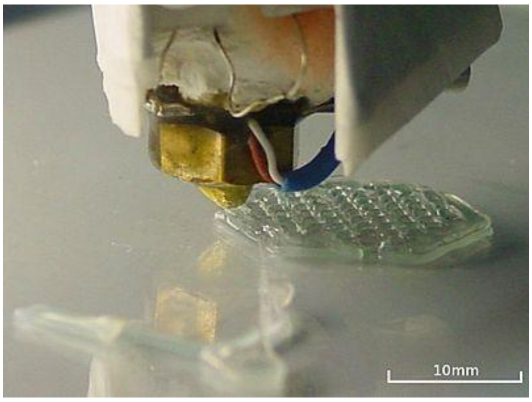


Figure 2.1

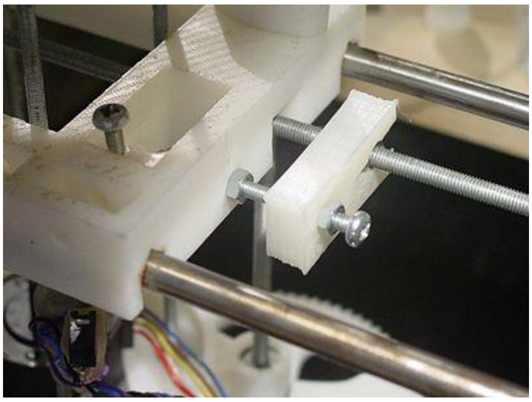


Figure 2.2

Rewind back to 1988, the brainchild of Dr. Carl Deckard, Selective laser sintering (SLS) became commercially viable in 2006, which opened the door to on-demand manufacturing of industrial parts. 3D-printing start-up Objet Geometries Ltd. (now merged with Stratasys, Ltd.) built a machine that could print in multiple materials, which allowed a single part to be fabricated in different versions, with different material properties. From an engineering standpoint, this was a huge deal, offering all sorts of options in parts production. Finally, the easily accessible 3DP marketplace had arrived. In 2007, Shapeways, the Dutch-founded, New York-based 3DP marketplace and service, start-up company was founded by Peter Weijmarshausen, Robert Schouwenburg and Marleen Vogelaar. It was a 3D-printing marketplace where designers can get feedback from consumers and other designers and then affordably fabricate their products. Lastly, approaching the end of the first decade of this new second millennium, American desktop 3D printer manufacturer company, MakerBot Industries, LLC arrived at the show. It was founded in January 2009 by Bre Pettis, Adam Mayer, and Zach "Hoeken" Smith to build on the early progress of the RepRap Project. In June 2013, it was acquired by Stratasys, Ltd. Today, MakerBot is considered one of the best brands and biggest players for desktop 3D printers. As of April 2016, MakerBot has sold over 100,000 desktop 3D printers worldwide. This shows that 3DP is getting more and more easily accessible and affordable to commoners and that the number of 3DP hobbyists and users have increased significantly.

At this point, many of the early 3DP patents have expired or are soon to expire, for example, the patent for FDM by S. Scott Trump expired in 2009. Many new windows of opportunities were up for grabs, are there came more and more new players on the field, including Ultimaker (2011), Formlabs (2011), Lulzbot (2011), XYZprinting (2013), Creality (2014), Anycubic (2015), ELEGOO (2015), Peopoly (2015), the list goes on and on. Keep in mind, these few mentions are for commercial/home use/educational desktop 3D printers, excluding industrial grade 3D printer manufacturers. While technological advancements in general in the past century have experienced exponential growth, 3DP certainly has not been missing out. As time goes by, only 5 things were certain, the plummeting of 3D printers and its filaments, the improvement in 3DP quality in terms of accuracy and repeatability, the improvement in ease of use of 3DP machines, the increase in accessibility to 3DP machines, and the increase in 3DP machine efficiency.

The next big thing in 3DP was the ability to print different types of materials. In 2012, Filabot developed a system for closing the loop with plastic and allows for any FDM 3D printer to be able to print with a wider range of plastics. Below shows a list of materials current 3D printers are able to print.

1. Acrylonitrile Butadiene Styrene thermoplastic polymer (ABS)
2. Polylactic Acid thermoplastic aliphatic polyester (PLA)
3. Polyethylene Terephthalate thermoplastic polymer (PET)
4. Polytrimethylene Terephthalate polymer (PETT)
5. Nylon/Polyamide
6. Polyvinyl Alcohol water-soluble synthetic polymer (PVA)
7. Sandstone
8. Wood
9. Metals such as aluminium, brass, bronze, copper, and stainless steel
10. High Impact Polystyrene (HIPS)
11. Magnetic Iron PLA
12. Conductive PLA
13. Carbon Fibre PLA
14. Thermoplastic Elastomers Copolymers (TPE)
15. Phosphorescence (luminous/ glow-in-the-dark material)
16. Amphora™ 3D polymer
17. Food (such as chocolate, cheese, purée, jelly, cultured meat etc.)

Not only having vast varieties of different materials to choose from to print, but some 3D printers are also able to print several colours of filament or several different materials to print at the same time, which is commonly referred to as multi material 3DP. A drawback of many existing 3DP technologies is that they only allow one material to be printed at a time, limiting many potential applications which require the integration of different materials in the same object. Multi-material 3DP solves this problem by allowing objects of complex and heterogeneous arrangements of materials to be manufactured using a single printer, which is perfect for the manufacturing of various products involving many different materials. In 2014, American scientist, entrepreneur, advisory board member, professor, and author, Benjamin S. Cook and Georgia Tech School of Electrical and Computer Engineering Ken Byers Professor in Flexible Electronics, Emmanouil (Manos) M. Tentzeris demonstrate the first multi-material, vertically integrated printed electronics additive manufacturing platform (VIPRE) which enabled 3DP of functional electronics operating up to 40 GHz. Today, this technology may be used to print Radio-frequency identification (RFID) tags and toys with electronic parts. Some 3D printers today are capable to print particles that are just a few atoms thick, which are completely invisible to the naked human eye. This demonstrates that we may be able to print electronics and electrical components such as batteries even smaller than they already are today.

Additive manufacturing of food is being developed by squeezing out food, layer by layer, into three-dimensional objects, restaurants like Food Ink and Melisse use 3D printed food as a unique selling point to attract customers from across the world. A large variety of foods are appropriate candidates, such as chocolate and candy, and flat foods such as crackers, pasta, and pizza. NASA is looking into the technology in order to create 3D printed food to limit food waste and to make food that are designed to fit an astronaut's dietary needs. In 2018, Italian bioengineer Giuseppe Scionti developed a technology allowing to generate fibrous plant-based meat analogues using a custom 3D bioprinter, mimicking meat texture and nutritional values.

However, among these materials, the one with the biggest impact was the ability to print metal. The 2010s were the first decade in which metal end use parts such as engine brackets and large nuts would be grown (either before or instead of machining) in job production rather than obligately being machined from bar stock or plate. It is still the case that casting, fabrication, stamping, and machining are more prevalent than additive manufacturing in metalworking, but AM is now beginning to make significant inroads, and with the advantages of design for additive manufacturing, it is clear to engineers that much more is to come. Below are examples of the applications of 3D metal printing.

In the jewellery business, rings, pendants, earrings, hairpins, cufflinks, tie clips, necklaces and bracelets can be printed using precious metals such as gold or silver. Shapeways is one of the marketplace platforms that provides custom 3DP services for jewellery products.

In cars, trucks, and aircraft, Additive Manufacturing is beginning to transform both unibody and fuselage design and production and powertrain design and production. For example:

- In 2010, Stratasys, Ltd. partnered with Canadian engineering group KOR Ecologic to make Urbee, which stands for “Urban electric”, the first car in the world car mounted using 3DP technology (its bodywork and car windows were "printed").
- In 2011, Engineers at the University of Southampton in the U. K. designed the world’s first 3D printed unmanned-air-vehicle (UAV).
- In early 2014, Swedish supercar manufacturer Koenigsegg announced the One:1, a supercar that utilizes many components that were 3D printed.
- In 2014, Stratasys prototyped an electric car with fully 3D-printed exterior panels, and a few printed interior parts. Development took one year, and parts were constructed using a Stratasys Objet1000.
- In 2014, Local Motors debuted Strati, a functioning vehicle that was entirely 3D Printed using ABS plastic and carbon fibre, except the powertrain
- In May 2015 Airbus announced that its new Airbus A350 XWB included over 1000 components manufactured by 3DP.
- In 2015, a Royal Air Force Eurofighter Typhoon fighter jet flew with printed parts. The United States Air Force has begun to work with 3D printers, and the Israeli Air Force has also purchased a 3D printer to print spare parts.
- In 2017, GE Aviation revealed that it had used design for additive manufacturing to create a helicopter engine with 16 parts instead of 900, with great potential impact on reducing the complexity of supply chains.

Apart from that, 3DP is also entering the real estate market. Chinese company Yingchuang Building Technique (Shanghai) Co., Ltd., founded on July 24, 2003, commonly known as Winsun, is the global leader in 3DP architecture. Starting off as a building materials supplier, Winsun aims to revolutionize this approach using 3DP technology. Having developed the first continuous 3D printer for construction, the company printed the first batch of 10 houses in 2013 – making global headlines. Using a special ink made of cement, sand, and fibre, together with a proprietary additive, the printer adds layer by layer to print walls and other components in its factory in Suzhou (China). The walls are then assembled on site. In 2015, Winsun Decoration Design Engineering constructed a five-story apartment block and an 11,840 square-foot (1,100 square-meter), residence, which cost $161,000 to construct. At the time, it was the world's tallest 3D-printed building and the world's first 3D-printed large residence. Winsun is also behind the first 3D printed office building opened in Dubai in May 2016.

Besides that, another major role 3DP plays in today's technology is the medical field, for example, assisting in Anatomical Training, surgical training, and Neurosurgery. 3DP is able to generate accurate, tangible reproductions of anatomical structures, with faithful representations of both normal and pathologic variations. A recent study reported a mean absolute error of 0.32 mm (variance 0.054 mm) for structures >10 mm in size. Additionally, the functionality of 3DP and other rapid prototyping techniques allows to produce different constituents of a specimen (such as bone, tendon, etc.) with different strength materials, thereby more accurately replicating the original. 3DP appears to be particularly easy to implement in producing bone models as dry bones, being mainly monochromatic and made of hard tissue, seem to lend themselves naturally to printing. Both the shape and weight of a real bone could be copied with a high level of accuracy, preserving the haptic value, which is of vital importance in anatomy education. A study shows improvement in veterinary students' anatomical test scores after use of 3DP to teach equine limb anatomy. Beyond the spectrum of anatomical modelling, 3DP also has important applications in the field of surgery. These include applications for both surgical training, which aim to improve the experience of trainees, and for surgical practice. The latter includes applications tailored to assist in a variety of areas, including pre-operative planning, simulation, execution, and implant/prosthetic production. 3DP can produce accurate simulations of patient specific anatomy and pathology, which can then be used for pre-operative planning and skill acquisition. These models are based on real patient data, are reproducible, represent actual pathology and human variation, and are constructed with multiple materials designed to replicate real human tissue. Trainees can practice and master individual operative steps on the models prior to practice on a real patient. This can improve confidence amongst trainees (particularly in cases involving challenging or unusual anatomy) and help to accelerate the training timeline, as skill acquisition is obtained concurrently to real patient operative experience. It also helps to circumvent rate-limiting steps in the existing apprenticeship model of training, which include the need to balance patient safety with trainee operative practice, and dilution of operative exposure secondary to rising numbers of trainees. Neurosurgical training models employing 3DP have encompassed several common neurosurgical procedures and pathologies. There have been several proposed models for skill acquisition and operative planning for cerebrovascular disease, including aneurysm repair. Rapid prototyping technology, including 3DP techniques, have been used to produce patient specific three-dimensional cerebral aneurysm models, which can be used for pre-operative simulation of clipping repair. These have been constructed with silicone or rubber-based materials, or photosensitive resin and similar models have also been successfully used to optimally shape microcatheters for intracranial aneurysm coiling. Other common neurosurgical operative steps, such as brain retraction and external ventricular drain placement have been simulated using rapid prototyped skull models, which have used multiple materials and patient specific source data to create a realistic training experience. In addition to neurosurgical simulation and training, 3DP has also been applied to the planning and execution of procedures.

In dentistry, crowns and dentures are already directly 3D printed, along with surgical guides. EnvisionTec is the most popular brand of 3D printers among dental technicians, but Stratasys and Carbon also cater to the industry with dental resins. Another 3D printed healthcare device that does a good job of being undetectable is the hearing aid. Nearly every hearing aid in the last 17 years has been 3D printed thanks to a collaboration between Materialise and Phonak, a hearing aid manufacturer. They developed Rapid Shell Modelling (RSM) in 2001. Prior to RSM, making one hearing aid required nine laborious steps involving hand sculpting and mould making, and the results were often ill-fitting. With RSM, a technician uses silicone to take an impression of the ear canal, that impression is 3D scanned, and after some minor tweaking the model is 3D printed with an SLA (stereolithography) vat photopolymerization machine. The electronics are added and then it is shipped to the user. Using this process, hundreds of thousands of hearing aids are 3D printed each year, each one customized just for its user. RSM delivers a better fit while reducing cost and requiring significantly less time to fabricate than the old manual way of making hearing aids.

In March 2014, surgeons in Swansea used 3D printed parts to rebuild the face of a motorcyclist who had been seriously injured in a road accident. In May 2018, 3DP has been used for the kidney transplant to save a three-year-old boy. As of 2012, 3D bio-printing technology has been studied by biotechnology firms and academia for possible use in tissue engineering applications in which organs and body parts are built using inkjet printing techniques. In this process, layers of living cells are deposited onto a gel medium or sugar matrix and slowly built up to form three-dimensional structures including vascular systems. Recently, a heart-on-chip has been created which matches properties of cells.

Another big proponent of 3DP is in the classrooms, the education sector. Programs such as Create Education Project enable schools to integrate additive manufacturing technologies into their curriculum for essentially no cost. The project lends a 3D printer to schools in exchange for either a blog post about the teacher's experience of using it or a sample of their lesson plan for class. This allows the company to show what 3D printers can do in an educational environment. While additive manufacturing-specific degrees are a fairly new advent, universities have long been using 3D printers in other disciplines. There are many educational courses one can take to engage with 3DP. Universities offer courses on things that are adjacent to 3DP like CAD and 3D design, which can be applied to 3DP at a certain stage. In terms of prototyping, many university programs are turning to printers. There are specialisations in additive manufacturing one can attain through architecture or industrial design degrees. Printed prototypes are also very common in the arts, animation, and fashion studies as well. Research labs in a diverse range of vocations are employing 3DP for functional use. 3DP, and open-source 3D printers in particular, are the latest technology making inroads into the classroom. Some authors have claimed that 3D printers offer an unprecedented "revolution" in STEM education. The evidence for such claims comes from both the low-cost ability for rapid prototyping in the classroom by students, but also the fabrication of low-cost high-quality scientific equipment from open hardware designs forming open-source labs.[142] Future applications for 3DP might include creating open-source scientific equipment. Many companies such as Dobot, Ultimaker and MakerBot, to name a few among many others, often do collaborations with universities and schools around the world to bring 3DP into classrooms.

In the last several years 3DP has been intensively used by in the cultural heritage field for preservation, restoration, and dissemination purposes. Many Europeans and North American Museums have purchased 3D printers and actively recreate missing pieces of their relics. The Metropolitan Museum of Art and the British Museum have started using their 3D printers to create museum souvenirs that are available in the museum shops. Other museums, like the National Museum of Military History and Varna Historical Museum, have gone further and sell through the online platform Threading digital models of their artefacts, created using Artec 3D scanners, in 3DP friendly file format, which everyone can 3D print at home.

3DP has entered the world of clothing, with fashion designers experimenting with 3D-printed bikinis, shoes, and dresses. In commercial production Nike is using 3DP to prototype and manufacture the 2012 Vapor Laser Talon football shoe for players of American football, and New Balance is 3D manufacturing custom-fit shoes for athletes. 3DP has come to the point where companies are printing consumer grade eyewear with on-demand custom fit and styling (although they cannot print the lenses). On-demand customization of glasses is possible with rapid prototyping.

Agile tooling is the process of using modular means to design tooling that is produced by additive manufacturing or 3DP methods to enable quick prototyping and responses to tooling and fixture needs. Agile tooling uses a cost-effective and high-quality method to quickly respond to customer and market needs. It can be used in hydroforming, stamping, injection moulding and other manufacturing processes.

Aerospace industries have also invested more and more in 3DP, as it proves to be extremely helpful in manufacturing complicated parts. For instance, UK start-up Orbex whom have built the world’s largest 3D printed rocket engine. The engine is unique in that it is the first one printed entirely as a single piece without any joins. The latest, human-supporting NASA Rover uses 3D-printed parts produced with help from Stratasys. In fact, NASA has numerous projects involving 3DP, including printing out food in space and making 3D printers that may operate in zero-gravity environments.

NASA aims to be able to print out spare parts for repairs or maintenance in space, as cargo resupplies to space often take weeks to months and are extremely costly. The ability to 3D print parts and tools on demand will dramatically reduce the time it takes to get parts to orbit and increase the reliability and safety of space missions, while dropping costs. Current space missions take months to years to get parts to orbit. With 3DP, parts can be built within minutes to hours. This technology demonstration is the first step toward realizing a microgravity 3D print-on-demand "machine shop" for long-duration space missions—a vital component for sustainable, deep-space human exploration, where there is extremely limited availability of Earth-based logistics support.

As of today, there are over 324,206 patents referencing 3D printing (120,333 granted patents); 153,019 patents referencing 3D printer (56,187 granted patents); 239,077 patents referencing Fused Deposition Modelling (FDM) (84,656 granted patents); 23,011 patents referencing Stereolithography (SLA) (7,924 granted patents); 108,224 referencing Selective Laser Sintering (SLS) (43,895 granted patents). Bear in mind that the first patent in the field of 3DP was filed in 1981, and the first granted patent was filed on 7th July 1984, 3DP has come a long way since its introduction to the world. What 3DP is today, is far beyond what its inventors has created, maybe even far beyond what the forefathers envisioned. The possibilities that were introduced from 3DP has been nothing short of spectacular, breath-taking, and mesmerising. It has influenced numerous industries, from food and entertainment to aerospace and military, 3DP has revolutionised how we design, create, prototype and manufacture products, and will continue to do so. There are even non-profit organisations dedicated to 3DP. Limbitless Solutions is one such example. The 2014 founded American non-profit organisation uses 3DP to create accessible, yet affordable personalized bionics and prosthetic partial arms for children with limb differences. With the computer literacy of all societies on the rise, do not be shocked in a couple decades, people could all have 3D printers at home, to print out their very own customised phone cases, mouse, earbuds, spectacles, shirts, trousers, jackets etc. We will live in world where we can easily make products from designing to producing all at home, within hours, maybe even minutes. We do not have to rely on mass produced products from hypermarkets and malls as heavily anymore, instead, we rely on our creativity, the computer, and the 3D printer. We may even be able to make our own shoes, modify our sports equipment to our comfort and liking. On the side of bigger objects, we might even see 3D printed skyscrapers and roller coasters. All in all, a world with even more freedom, more convenience, and more flexibility, all thanks to the invention of 3DP.

3DP enables people like you and me to easily manufacture complex objects from the comfort of our own homes. 3D printers are small, cheap, and easy enough to install to operate. While most people have yet to even hear the term 3DP, the process has been in use for decades. Manufacturers have long used the printers in the design process to create prototypes for traditional manufacturing. But until the last few years, the equipment has been expensive and slow. Instantly printing parts and entire products, anywhere in the world, is a game changer. But it does not stop there. 3DP will affect almost every aspect of industry and our personal lives. Medicine, architecture and construction, art and there are developments where you least expect them. 3D printers are an integral part of machinery parks of many companies and they are used as alternative to conventional production methods. Simply put, these technologies will definitely bring game changing developments and modernization for our future world.

2.3. 3D SCANNING

3DS is the process of analysing real-world objects or environment to collect data on its shape and possibly its appearance, e.g., texture and colour. The collected data can then be used to construct digital 3D models. A 3DS machine digitally captures the dimensions of an object exactly as it is to later be used for purposes like taking measurements, getting accurate description, or to be ‘photocopied’ and reprinted using 3DP machine. A 3D scanner can be based on many different technologies, each with its own limitations, advantages, and costs. Many limitations in the kind of objects that can be digitised are still present.

The first 3DS technology was developed in the 1960s within research and design fields, there was a need to be able to efficiently recreate surfaces of objects and places for a way to easily access and alter projects to make way for improvements. The early scanners used lights, cameras, and projectors to perform this task. However, due to the complex nature of the scans, in order to replicate an object accurately a lot of effort and time was required. Necessary improvement wanted to be made to the current system so that the same amount of fine detail could be collected by the scanners but at a much more efficient and effective rate than currently possible. The models used were not ideal, but the technology was restricted until hard drive storage could be increased due to the mass amount of data that was collected by the scanners.

It was not until the 1980s that laser technology was applied to 3DS; marking the beginning of techniques used in the present day. The use of optical technology was preferred as using light to measure the surface on an object not only would be faster than a physical probe but also would be non-contact. This meant that it was possible to broaden the horizon of what objects could be scanned, as soft or fragile surfaces would not be affected by optical technology.

After 1985 they were replaced with scanners that could use white light, lasers, and shadowing to capture a given surface. In the eighties, the tool making industry developed a contact probe, which enabled a precise model to be created, but it was very slow. The aim was to create a system, to capture the same amount of detail but at higher speed, resulting in a more effective application – leading experts to start developing optical technology, because the use of light was much faster than a physical probe. This also allowed scanning of soft objects, which would be threatened by prodding. It soon became apparent that the actual challenge faced was software based. The sensor would make several scans from different positions to capture an object in three dimensions. The challenge was to join those scans together, remove the duplicated data and sift out the surplus that inevitably gathers when you collect several million points of data at once. At the time, 3D laser scanners were extremely expensive, mostly inaccessible and were very limited in picking up the different colours of a surface.

With the advent of computers, it was possible to build up a highly complex model, but the problem came with creating that model. Complex surfaces defied the tape measure, so in the eighties, the toolmaking industry developed a contact probe, which enabled a precise model to be created, but it was very slow. The aim was to create a system, to capture the same amount of detail but at higher speed, resulting in a more effective application – leading experts to start developing optical technology, because the use of light was much faster than a physical probe. This also allowed scanning of soft objects, which would be threatened by prodding. At that time, three types of optical technology were available:

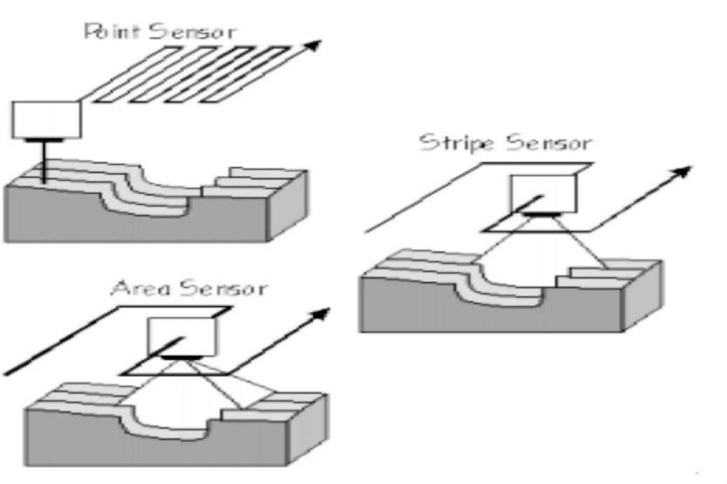


Figure 2.3 Illustration of the types of sensors

Point and area were soon disregarded as 3D laser scanning techniques due to the fact that ‘area’ was very complex technical task to perform, and ‘point’ used a single point of reference and was therefore not much faster than the older technology. Stripe, on the other hand, outshone the other two technologies by far and is still used in modern day 3D laser scanners. Stripe technology passes over an object using multiple points if reference to measure the surface area from. Due to the high amount of data collected in a fraction of the time, stripe technology is extremely accurate and fast. Stripe was clearly the way forwards, but it soon became apparent that the actual challenge faced was software based. The sensor would make several scans from different positions to capture an object in three dimensions. The challenge was to join those scans together, remove the duplicated data and sift out the surplus that inevitably gathers when you collect several million points of data at once.

One of the first applications was capturing humans for the animation industry. In the late 1980s, Cyberware Laboratories of Los Angeles developed a 3D scanner in the form of a head scanner which captured the surface areas of human features for use in the animation industry in Los Angeles. This was well received in the industry, and innovation continued to be made to the point whereby the mid-1990s top animation studios were using full body scanners to capture the data points of real human figures. The first3D scanner which they titled REPLICA launched for the first time in 1994. It allowed for fast, highly accurate scanning of very detailed objects making serious progress in laser stripe scanning. Meanwhile Cyberware were developing their own high detail scanners, some of which were able to capture object colour too, but despite this progress, true three-dimensional scanning – with these degrees of speed and accuracy – remained elusive.

By this point, 3D scanners had the capability to digitise objects from the physical world, but machines could not handle the size of the data. With storage space increasing drastically, the 90s saw a huge burst in 3DS capabilities with the first 3D scanners hitting the commercial market. And by then, the optical technology allowed for scanning fragile objects and for colour scans. Digibotics introduced a 4-axis machine, which could provide a full 3D model from a single scan, but this was based on laser point – not laser stripe – and was thus slow. It also lacked the freedom necessary to cover the entire surface of an object and could not digitise coloured surfaces. The costly optical scanners were soon forgotten once Immersion and FARO Technologies introduced low-cost manually operated digitisers. These could produce complete models, but their first editions were slow, particularly detailed models. They also lacked the ability to digitise coloured surfaces.

In 1996, 3D Scanners took the key technologies of a manually operated arm and a stripe 3D scanner, resulting in the world's first incredibly fast and flexible Reality Capture System. The ModelMaker was produced which combined the use of the stripe scanner on a manually operated arm. This system produced fast results of complex objects and could even capture surface colours of an object. It was beginning of 3D scanners that could produce results within in minutes. Since then, the focus in advancements of laser scanning has been making the technology as accessible as possible and expanding the creative use of the data point collected.

The advancing technologies now produce complex models incorporating textures and colour, which can now be produced in mere minutes. By this time, 3D modellers were united in their quest for a scanner that was accurate, fast, efficient, truly three dimensional, capable of capturing colour surfaces and reasonably priced.

The 3D Laser Scanner

It took combining a knowledge of triangulation, something discovered by the ancient Babylonians and Egyptians, with contemporary image processing systems to produce the first practical 3D object scanner in the 1990s. This was only accomplished after decades of chewing through different theoretical approaches to the problem.

When laser scanning took off in the 80s it changed the nature of 3D digitizing in significant ways. Back in the 70s, making digital models from real-world objects was labour intensive. They used contact systems that logged a point in space in reference to a known location of a probe within its environment. Laser scanning proved to be faster and opened a whole new world of objects that could be scanned. Previously, objects with soft or fragile surfaces were unsuitable subjects. Today, most laser scanners use a moving stripe of laser light to capture geometry. Other approaches were eliminated on the way, such as single point of reference (which wound up being very close to contact scanning), and scanning using a large area of laser coverage, which proved too technically complex.

The Stanford Bunny

Before 3DS was called that, it was called 'range scanning', defined by the Stanford University crew as 'a grid of distance values that tell how far the points on a physical object is from the device that creates the scans.' Range scan data was often displayed as a black and white image, with pixel brightness reflecting distance.

By the 90s computer scientists had a good idea of what they could accomplish, and how to go about it – they were only limited by their equipment. The pioneers of 3DS were working with analogue video cameras, camera tubes instead of sensors, and CPU ceilings of 512 KB and storage restricted to 5 MB. Average image resolution? 512 x 512 pixel. For this reason, early scanners were mostly limited to surface inspection, measurements, and deformation analysis.

Even though laser scanning was faster than other methods it still took considerable time and was very expensive. The industry had not worked out how to effectively combine more than one 3D scan of the same object to create a better data set for meshing 3D models. That would not happen until 1993, when Stanford University successfully combined 10 scans of a clay bunny, picked up in a shop by one of the researchers who recognized its clay surface and shape would be ideal to scan in 3D.

Although the Stanford Bunny served as a benchmark for testing computer graphics algorithms for many years (the one above was from a research project titled "Art-Based

Rendering of Fur, Grass and Trees”), today it is considered too simple a 3D model to serve as a definitive test.

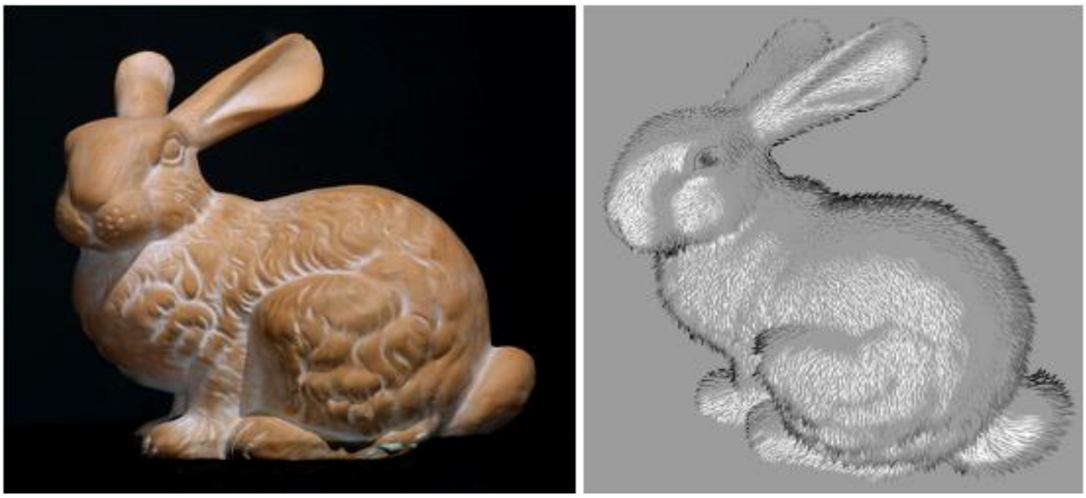


Figure 2.4 Stanford Bunny

NASA

It was improvements in digital camera quality that was the key to unlocking the full potential of high-resolution 3DS as a new technology, expanding its usefulness into territories of research far and wide.

Digital imaging technology had been advancing alongside that of laser scanning from the time of its invention in 1975. Considering we now each carry a digital camera in our pocket, it is applications back then were the most remote they could be, distance-wise, from human life: satellite technology and space probes mapping the surface of the moon.

Neptec Design Group, a Canadian vision systems company, had worked for NASA through the 90s, but it was not until after the 2003 tragedy of the Shuttle Discovery Mission STS-105, that 3DS and processing software became their primary focus.

High precision 3DS technology, like that contained in Neptec’s TriDAR system (which combines a short-range triangulation sensor and a long-range LIDAR sensor in the same optical path) was capable of inspecting a shuttle’s external surfaces during flight for damage sustained during launch. It is also the technology that has allowed for on-orbit rendezvous and docking.

Figure 2.5 Neptec's TriDAR system

3DS, much like 3DP, has revolutionised the design process. It allows for higher dimensional accuracy while working with complex shapes and parts. Instead of manually measuring objects using Vernier callipers and micrometre screw gauges, the entire object can be scanned and analysed in the computer with the assistance of CAD software. This also enable the coordination of product design using parts from multiple sources. Besides that, it allows reproduction of as-built designs to replace missing or worn-out parts, more significantly in automotive industries, thus saving costs and allowing creativity and innovation. Furthermore, through online marketplaces and forum groups, 3DS brings the plant to engineers and designers, allowing the sharing of 3D scans online. Most importantly, its significance in reverse engineering. Reverse engineering of a mechanical component requires a precise digital model of the objects to be reproduced. Rather than a set of points a precise digital model can be represented by a polygon mesh, a set of flat or curved NURBS surfaces, or ideally for mechanical components, a CAD solid model. A 3D scanner can be used to digitise free-form or gradually changing shaped components as well as prismatic geometries whereas a coordinate measuring machine is usually used only to determine simple dimensions of a highly prismatic model. These data points are then processed to create a usable digital model, usually using specialized reverse engineering software.

Today, 3DS is used in various fields for various purposes. It is used in construction industry and civil engineering for robotic control, as the laser scanner tends to act as an eye for the robot. It is also often used to scanned structures to obtain as-built drawings of bridges, industrial plants, monuments etc. This also allows documentation of historical sites such as the pyramids and Sphinx in Giza, Stonehenge, The Parthenon etc., whereby accurate CAD drawings are difficult to draw. It can also be used for site modelling and lay outing while designing buildings. Moreover, it is very helpful in quality control of constructions, quantity survey works, and payload monitoring. 3DS is also great for redesigning of structures, as a means of reverse engineering. A road or highway can be scanned and redesigned without having to design a new highway from scratch. 3DS allows the establishment of a benchmark of existing shapes and structures for comparison in case of any structural changes or deformation towards them due to the passing of time, accidents, extreme loadings, or natural disasters. 3DS is also often used to scan vast spaces of lands and mountains to create 3D maps, geographic information systems (GIS) and collection and analysation of geomatics data. A simple example that is relevant to most of us is Google Earth, which provides 3D maps of almost everywhere and anywhere on our globe, whereas a more sophisticated example would be 3DS's ability to conduct subsurface laser scanning in mines and karst void for in depth research of geography.

Complex 3DS technologies, used alongside X-ray scanning and other penetrative scanning technologies, has allowed us to preserve cultural heritage like never before. The combined use of 3DS and 3DP technologies allows the replication of real objects without the use of traditional plaster casting techniques, that in many cases can be too invasive for being performed on precious or delicate cultural heritage artefacts. In an example of a typical application scenario, a gargoyle model was digitally acquired using a 3D scanner and the produced 3D data was processed using MeshLab. The resulting digital 3D model was fed to a rapid prototyping machine to create a real resin replica of the original object. Among the renowned breakthroughs and projects in preserving history using 3DS includes detailed architectural models of Muzibu Azaala Mpanga, the main building at the complex and tomb of the Kabakas (Kings) of Uganda, also known as the Kasubi tombs, deciphering of Jewish dead sea scrolls, the Digital Hammurabi project, which visualize and extract cuneiform characters from 3D-models of cuneiform tablets, scanning of Michelangelo statues in Rome, scanning of Thomas Jefferson's Monticello etc. Thanks to 3DS, we can now go online to appreciate and admire some of the most beautiful pieces or art and history from the comfort of our homes. For example, 3D scans of Michelangelo's St. Matthew or Awakening can be obtained from The Digital Michelangelo Project's website.

3D scanners are used by the entertainment industry to create digital 3D models for movies, video games and leisure purposes. They are heavily utilized in virtual cinematography. In cases where a real-world equivalent of a model exists, it is much faster to scan the real-world object than to manually create a model using 3D modelling software. Frequently, artists sculpt physical models of what they want and scan them into digital form rather than directly creating digital models on a computer. For example, top football players are invited to a 3DS studio to perform their footballing skills. Their motions are closely monitored and scanned. The exact motion will be used in games such as FIFA video game series which are released annually. This provides an immensely realistic experience to gamers, imitating an actual football match with the best players in the world on the pitch as much as possible.

3DS also enables 3D photography. 3D scanners are evolving for the use of cameras to represent 3D objects in an accurate manner. Companies are emerging since 2010 that create 3D portraits of people (3D figurines or 3D selfies). A 3D selfie is a 3D-printed scale replica of a person or their face. These three-dimensional selfies are also known as 3D portraits, 3D figurines, 3D-printed figurines, mini-me figurines, and miniature statues. In 2014 a first 3D printed bust of a President, Barack Obama, was made. 3D-digital-imaging specialists used handheld 3D scanners to create an accurate representation of the President. Many systems use one or more digital cameras to take 2D pictures of the subject, under normal lighting, under projected light patterns, or a combination of these. Inexpensive systems use a single camera which is moved around the subject in 360° at various heights, over minutes, while the subject stays immobile. More elaborate systems have a vertical bar of cameras rotate around the subject, usually achieving a full scan in 10 seconds. Most expensive systems have an enclosed 3D photo booth with 50 to 100 cameras statically embedded in walls and the ceiling, firing all at once, eliminating differences in image capture caused by movements of the subject. A piece of software then reconstructs a 3D model of the subject from these pictures. One of the 3D photo booths, which creates life-like portraits, is called Veronica Chorographic Scanner. The scanner participated in the project of Royal Academy of Arts, where people could have themselves scanned. The scanner utilized 8 cameras taking 96 photographs of a person from each angle.

From a quality assurance and industrial metrology standpoint, the digitalisation of real-world objects is of vital importance in various application domains. This method is especially applied in industrial quality assurance to measure the geometric dimension accuracy. Industrial processes such as assembly are complex, highly automated, and typically based on CAD (Computer Aided Design) data. The problem is that the same degree of automation is also required for quality assurance. It is, for example, a very complex task to assemble a modern car, since it consists of many parts that must fit together at the very end of the production line. The optimal performance of this process is guaranteed by quality assurance systems. Especially the geometry of the metal parts must be checked in order to assure that they have the correct dimensions, fit together and finally work reliably. Within highly automated processes, the resulting geometric measures are transferred to machines that manufacture the desired objects. Due to mechanical uncertainties and abrasions, the result may differ from its digital nominal. In order to automatically capture and evaluate these deviations, the manufactured part must be digitised as well. For this purpose, 3D scanners are applied to generate point samples from the object's surface which are finally compared against the nominal data. The process of comparing 3D data against a CAD model is referred to as CAD-Compare and can be a useful technique for applications such as determining wear patterns on moulds and tooling, determining accuracy of final build, analysing gap, and flush, or analysing highly complex sculpted surfaces. At present, laser triangulation scanners, structured light and contact scanning are the predominant technologies employed for industrial purposes, with contact scanning remaining the slowest, but overall, most accurate option. Nevertheless, 3DS technology offers distinct advantages compared to traditional touch probe measurements. White-light or laser scanners accurately digitize objects all around, capturing fine details and freeform surfaces without reference points or spray. The entire surface is covered at record speed without the risk of damaging the part. Graphic comparison charts illustrate geometric deviations of full object level, providing deeper insights into potential causes.

In the medical industry, 3DS enables 3D reconstruction. In computer vision and computer graphics, 3D reconstruction is the process of capturing the shape and appearance of real objects. This process can be accomplished either by active or passive methods. If the model is allowed to change its shape in time, this is referred to as non-rigid or spatiotemporal reconstruction. This technology successfully helps to create parts like prosthetics, dental appliances, custom implant, prosthetic limbs by using 3DP technologies which look and feel like a real thing.36,37 3D objects can be easily produced from a printer, which takes inputs from 3D scanner through a 3D digital file. The service of 3DS is just as crucial to the medical field as crucial it is to the printer. 38,39 3D scanner & printer have already produced kidney cells that are acting like a real. One of the critical impacts of this technology is in the pharmaceutical industry. By using 3DS instrument, anyone will get directly what organ he or she requires, and a large number of patients will be saved.

In the 21st century, 3DS also plays an important role in law enforcement. 3DS technology allows documentation of forensic evidence in the sense that the entire crime scene may be scanned and put into a computer, whereby a team of forensics IT officers will be able to analyse every little single detail without fearing evidence being moved and deteriorating as time passes. It allows clear and accurate simulation and calculation of bullet trajectories, blood stain pattern analysis, and may even be able to reconstruct entire incidents, such as bombings, murders, robberies, thefts, plane crashes, plane hijacks etc. Cases become clearer and easier to solved, with more concrete evidence, increasing crime solving rates while decreasing misjudgements and wrong convictions.

To wind-up, 3D scanners are getting involved in many applications and with time, the possibilities are being widened. Today, with the help of 3D scanners, a lot of work can be accomplished in a matter of time which used to take days for completion. This has paved the way for a well-organised and simple workflow. More and more people are looking for an answer to the question: what 3DS is. It is because of its immense benefits that are not limited to just a few applications, but a bunch of users that spread across many niches. Utilizing 3D scanners, one can make many things possible. The only concern, just as it concerns 3DP as well, is copyright. Just like 3DP, copyright will not apply as cleanly to 3DS as it does to seemingly analogous activities such as digital photography. Or perhaps it will, but in ways that force us to re-examine the relationship between copyright and photography. Regardless, today's utilitarian focus on turning physical things digital will often lack the creative flexibility that is required to obtain copyright protection. At the same time, 3DS cannot be categorically excluded from the world of copyright. There are files that started as 3D scans today that easily fall within the scope of copyright protection. As 3D scanners become smaller, cheaper, and more ubiquitous, it is all but inevitable that they will migrate away from their functional uses towards more creative applications. The challenge then is to recognise that there are probably no clean rules of thumb about 3D scans and copyrightability today, and to accept that clarity may not come in the near future. This ambiguity is simply the cost of doing something new. Commercial use of 3D laser scanning of full environments such as manufacturing systems and use of associated point cloud has developed dramatically during the last half decade. The increase can be seen in the field of both hardware and software as new and improved scanners has been introduced to the market and the software support of point clouds has grown. Given this trend of increased supply of actors and products in the 3D laser scanning market in combination with the natural increase in accessible computational power as stated by Moore's law it is rather safe to conclude that the use of 3D laser scanning and point cloud handling will become more widespread and more advanced in the next decade.

2.4. ROBOTIC ARM

Humans have always fascinated about robots. From comics to movies such as Star Wars and Terminator, we have produced many iconic sci-fi robots and bionic humans, C3PO, R2D2, Alita, Big Hero, Atom from Real Steel, the list goes on and on, and will keep going on for the foreseeable future. With such inspirations, it led to inventors and engineers bringing making it a reality. The robotic arm is one such invention. One of the most prolific marvels of engineering for industrial purposes such and manufacturing and packaging within the last century, robotic arms still catches the eye of many until today. The term robotic arm is made of 2 words. Robotics is an interdisciplinary branch of engineering and science that includes mechanical engineering, electronic engineering, information engineering, computer science, and others. Robotics involves design, construction, operation, and use of robots, as well as computer systems for their perception, control, sensory feedback, and information processing. The goal of robotics is to design intelligent machines that can help and assist humans in their day-to-day lives and keep everyone safe. Whereas an arm is the limb of the human body which extends from the shoulder to the hand, or forelimb of most animals. When combined, the robotic arm becomes a category of mechanical arms, in the current world, usually programmable, and aims to be used in a similar fashion and functions of a human arm.

Some robotic arms are just a device by itself, while others may be attached to other more complex systems or robots. The links of such a manipulator are connected by joints allowing either rotational motion, such as in an articulated robot, or translational /linear displacement. The links of the manipulator can be considered to form a kinematic chain. The terminus of the kinematic chain of the manipulator is called the end effector and it is analogous to the human hand. For industrial usage, these are referred to as industrial robots. An industrial robot is a robot system used for manufacturing. Industrial robots are automated, programmable, and capable of movement on three or more axes. Typical applications of robots include welding, painting, assembly, disassembly, pick and place for printed circuit boards, packaging and labelling, palletising, product inspection, and testing; all accomplished with high endurance, speed, and precision. They can assist in material handling.

The first of such an invention came from the Renaissance period by no other than the father of palaeontology, ichnology, and architecture, and is widely considered one of the greatest painters of all time, Italian polymath Leonardo di ser Piero da Vinci. In the early 1950s, investigators at the University of California scrutinized detailed drawings from da Vinci's notebooks which together form a tome exceeding 1,119 pages dating from 1480 to 1518 and therefore referred to, like the great Atlantic Ocean, as the Codex Atlanticus. da Vinci was profoundly influenced by classical Greek thinkers in art and in engineering. Modern investigations increasingly make it clear that he singularly pursued knowledge of everything known to these ancient scholars. He, in effect, was following in the footsteps of such figures as Hero of Alexandria, Philon, and Cstebius who were all reported to be interested in mechanically simulating motion and human attributes. Possibly inspired by quotes from Homer's Iliad, "...since he was working on twenty tripods which were to stand against the wall of his strong-founded dwelling. And he had set golden wheels underneath the base of each one so that of their own motion they could wheel into the immortal gathering and return to his house: a wonder to look at." (Homer the Iliad, book 18). da Vinci began a systematic method of devising and building the sophisticated mechanical device that was 500 years ahead of its time. His first robotic design was in December 1478, at the age of 26, before he moved to Milan. In the Codex Atlanticus, folio 812, is a power mechanism that features a front wheel drive, rack-and-pinion automobile. Impressive as it is, it was also fully programmable, with the ability to control its own motion and direction. It is now thought that this "base" would form the basis of his ultimate goal, a fully functional automaton.

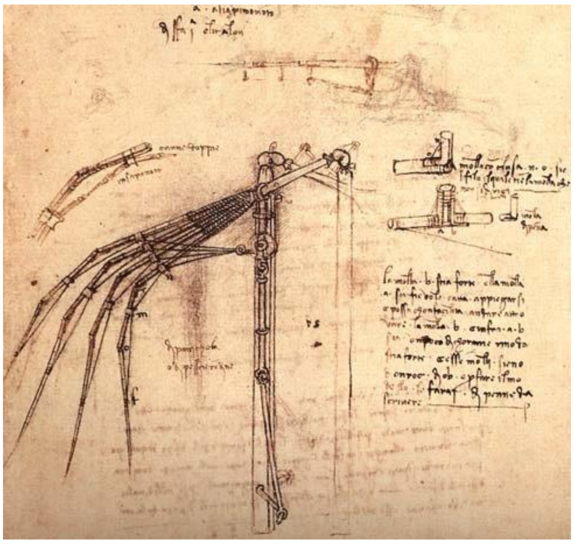


Figure 2.6

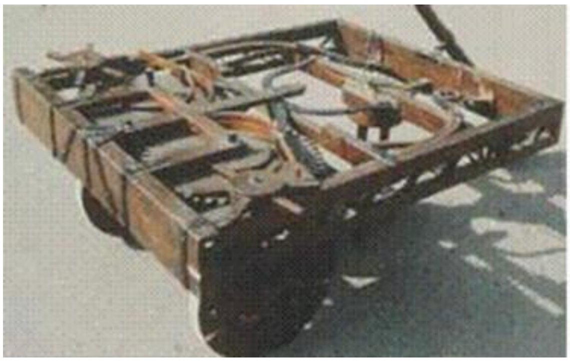


Figure 2.7

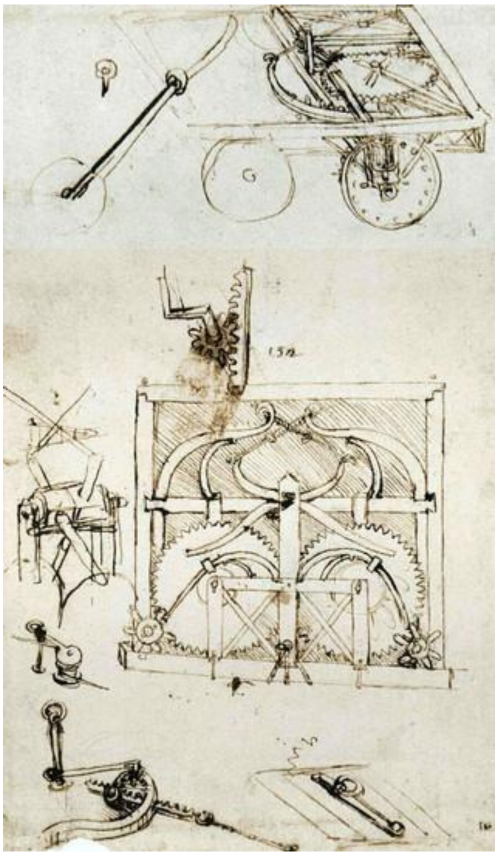


Figure 2.8

To animate a humanoid machine, he was cognisant of his need to develop a more detailed database of human kinesiology. Leonardo grounded his knowledge further with drafting, anatomy, metal working, tool making, and armour design, in addition to painting and sculpture. Leonardo was not content with a simple understanding of human anatomy, so he began to investigate and draw comparative anatomy, to better appreciate form and function. "You should make a discourse concerning the hands of each of the animals, in order to show in what way they vary.". In 1495, at about the time he was working on his method of painting on wet plaster and the Last Supper, da Vinci designed and probably built the first of several programmable humanoid robots. From research ongoing at the Florence-based Institute and Museum of the History of Science and work by Rosheim it is now apparent his robot could open and close its anatomically correct jaw, sit up, wave its arms, and move its head. This robot consisted of two independent systems. The lower extremities had three degrees-of-freedom—legs, ankles, knees, and hips. The upper extremities had four degrees-of-freedom—arms with articulated shoulders, elbows, wrists, and hands. The orientation of the arms indicates it could only whole-arm grasp with the joints moving in unison. The device had an "onboard" programmable controller within the chest providing for power and control over the arms. The legs were powered by an external crank arrangement. The Florence-based Institute and Museum of the History of Science has developed sophisticated computer models of this design with streaming video animations. Leonardo probably returned to this design again to impress his erstwhile potential royal patron, Francis I of France. From Lomazzo's writing about Leonardo in 1584, Francesco Melzi (one of his pupils, and heirs) states that Leonardo made several automatons from "birds, of certain material that flew through the air and a lion that could walk...the lion, constructed with marvellous artifice, to walk from its place in a room and then stop, opening its breast which was full of lilies and different flowers." Rosheim believes that the leaf spring-powered cart could have powered the mechanical lion and his automaton knight. Leonardo's multi-degrees-of-freedom automaton is an appropriate starting point for man's technical interest in recapitulating form and function. da Vinci's intense attention to detail will be a recurrent theme throughout this historical sojourn. In Leonardo's own words, "With what words, O Writer, will you describe with like perfection the entire configuration which the drawing here does?" (da Vinci, 1513).

We fast forward to the 1st Industrial Revolution, the first major existence of machines in manufacturing, paving the way for the advancement of engineering in manufacturing speed, precision, accuracy, and efficiency as a whole. These machines of the 1st industrial may very well be considered the predecessors of industrial robots today. In 1738, Jacques de Vaucanson, a gifted mechanical designer and builder of some of the most complex, clockwork automata throughout the eighteenth century, had designed and built an automaton flute player, which was called an "androide". By 1739 he had added two other automata to his exhibition, a pipe-and-drum player, and a mechanical duck, which of all his mechanical contrivances, was by far, the most popular.

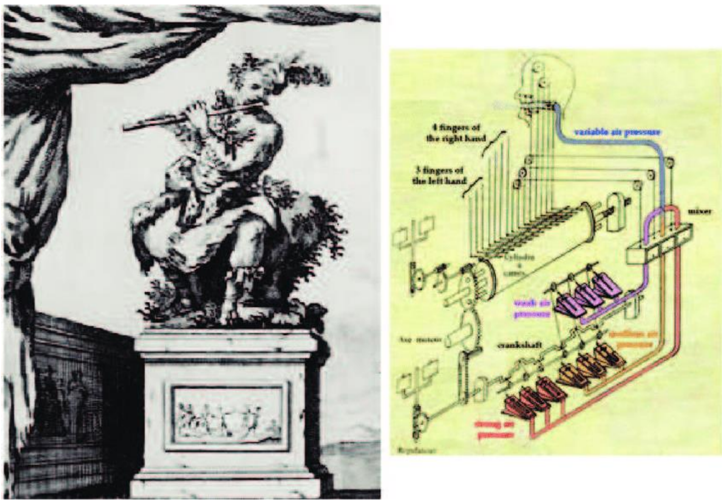


Figure 2.9 Jacques de Vaucanson's pipe-and-drum player

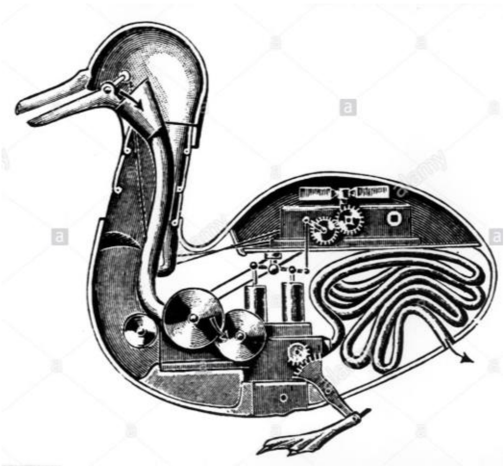


Figure 2.10 Jacques de Vaucanson's mechanical duck

Others followed in Vaucanson's wake. Most significant were the Swiss clock-making family named Jaquet-Droz. In 1774, the father, Pierre, with his son Henri-Louis, began to execute three life-sized automata with particular emphasis on their human-like capabilities. It is likely that the village surgeon helped with the development of the arms and hands of these androids. These craftsmen made every attempt to simulate a real human's anatomy. They created an artist, a writer, and a musician. The musician played a clavichord by applying pressure to the keys with her fingertips.

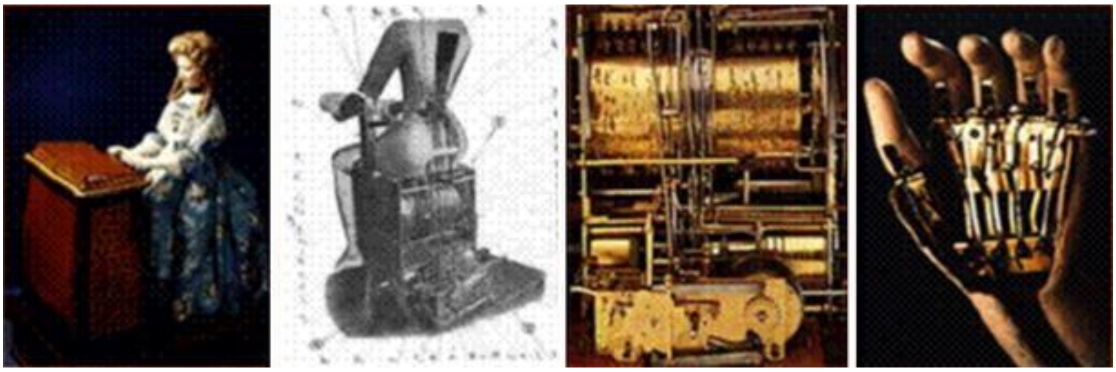


Figure 2.11 Jaquet-Droz's inventions

In 1769, Wolfgang von Kempelen's chess player, often called the Turk or Automaton Chess Player was constructed for the Empress Maria Therese. The Turk was an elaborate hoax with a human operator concealed inside the complex cabinetry underneath the chessboard. The automaton though, had an ingenious system of mechanisms that automated the chess player's left arm and hand. The chess player was a carved-wood figure that sat behind a wooden chest dressed in Turkish garb. The head moved on his neck, the eyes moved in their sockets, but the left arm and hand were magnificently orchestrated. The Turk engendered a wide variety of writings about the possibility of animating human reason and human activities. The mechanics of the arm were controlled by the "director", the name given by those who knew that the games were human controlled. Kempelen had designed a pantograph, a device that enabled the director to steer the automaton's left arm from inside of the chest. The limb would first be raised, then the hand would centre over the desired chess piece to be moved. The arm would lower towards the piece and a collar would be turned to allow the end of a lever in his hand make the Turk's fingers grasp the chess piece. The automaton's fingers were wooden and during a match, the hand was placed inside a glove so it could grasp the chess pieces with more agility. Each finger had its own series of cables connected to the director's pantograph.

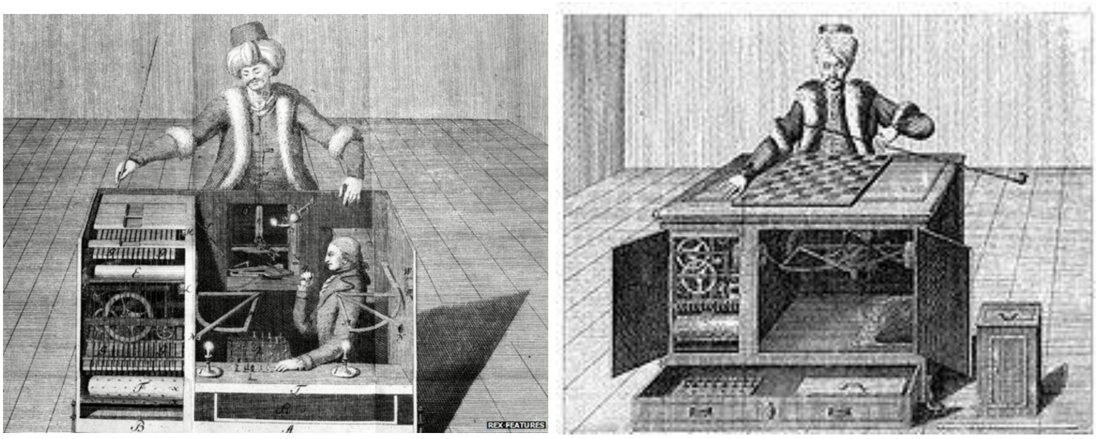


Figure 2.12 The Turk

Finally, we reach the 20th century, where it all really began. If you have not realised, up until this point, the term was automaton or even android, but not robots, robotics, or robotic arm. The term robot came from an old Slavic word “Rabota”, meaning forced labour or servitude, made famous by Czech playwright Karel Čapek in a hit 1920s science fiction play Rossumovi Univerzální Roboti (R.U.R.), which translate to Rossum's Universal Robots. Since then, researchers have classified the robotic arm by showing its industrial application, medical application, and technology, etc. It has been first introduced in the late 1930s by William Pollard and Harold A. Roseland, where they developed a sprayer that had about five degrees of freedom and an electric control system. Pollard's was called “first position controlling apparatus.” William Pollard never designed or built his arm, but it was a base for other inventors in the future. The development of Numerically Controlled (NC) machines, and the rising popularity of the computer both helped bring out about the first industrial robots. The earliest known industrial robot, conforming to the ISO definition was completed by "Bill" Griffith P. Taylor in 1937 and published in Meccano Magazine, March 1938. The crane-like device was built almost entirely using Meccano parts, and powered by a single electric motor. Five axes of movement were possible, including grab and grab rotation. Automation was achieved using punched paper tape to energise solenoids, which would facilitate the movement of the crane's control levers. The robot could stack wooden blocks in pre-programmed patterns. The number of motor revolutions required for each desired movement was first plotted on graph paper. This information was then transferred to the paper tape, which was also driven by the robot's single motor. Chris Shute built a complete replica of the robot in 1997.

In 1954, American inventor George Charles Devol Jr. filed for the first robotics patent “programmed article transfer” in 1954. His robot was able to transfer objects from one point to another within a distance of 12 feet or less. Devol's invention earned him the title "Grandfather of Robotics". As recognised by the National Inventors Hall of Fame, "Devol's patent for the first digitally operated programmable robotic arm represents the foundation of the modern robotics industry." At fateful meeting at a cocktail party in 1956, George Devol met American physicist, engineer, and entrepreneur Joseph Frederick Engelberger, who would go on to contribute massively to the field of industrial robots and become widely known as the “Father of Robotic”. They discovered a shared excitement for science fiction and entrepreneurship. This started them down to becoming business partners – dramatically changing the future of robotics. Together, they founded the world's first robotics company, Unimation, an abbreviation of the term “universal automation.”, producing the world’s first industrial robot, Unimate #001 in 1959. Unimation robots were also called programmable transfer machines since their main use at first was to transfer objects from one point to another, less than a dozen feet or so apart. They used hydraulic actuators and were programmed in joint coordinates, i.e., the angles of the various joints were stored during a teaching phase and replayed in operation. They were accurate to within 1/10,000 of an inch. The arm weighed about 1,815 kilograms and cost $25,000. In 1961, Devol was awarded the patent for his robot invention. In 1962, a 2700-pound Unimate prototype was installed at the General Motors die-casting plant in Trenton, New Jersey. The Unimate 1900 series became the very first produced robotic arm for die-casting, was essentially the company's flagship. During a very short period of time, it had produced at least 450 robotic arms were being used. It remains one of the most significant contributions in the last one hundred years. Unimation went on to develop robots to assist with welding and other applications in the fast-growing automotive industry. While the first robot was invented as a general-purpose machine to move materials, Engelberger and Devol recognized the device’s value to manufacturing. The automotive industry is still the largest market for robotic automation, but other industries - including electronics assembly; life sciences; food and beverage; and metal and plastics manufacturing are rapidly deploying robots as part of a push towards automation. Engelberger was also interested in the many ways that robots could be used in service of humanity. For example, he was especially interested in how robotics could be leveraged in the service industries and healthcare. By 1966, Unimation granted licenses to Nokia in Finland and

Kawasaki Heavy Industries of Japan to manufacture and market the Unimate, expanding the use of programmable robot arms into a global market. For some time Unimation's only competitor was Cincinnati Milacron Inc. of Ohio. This changed radically in the late 1970s when several big Japanese conglomerates began producing similar industrial robots.

Figure 2.13 Unimate, 1^{st} Industrial Robot

Around the same period, there were several other noteworthy projects going on as well. In 1963, researchers at the Rancho Los Amigos Hospital developed the Rancho Arm to help move disabled patients. It was the first computer-controlled robotic arm and was equipped with six joints to let it move like a human arm. In 1968, American cognitive scientist, AI and philosophy author, co-founder of the Massachusetts Institute of Technology's AI laboratory, Marvin Lee Minsky created the Minsky Tentacle Arm. This robotic arm had twelve single degree freedom joints in this electric- hydraulic-high dexterity arm, and users could control it with a computer or a joystick. Minsky designed the arm for use in medicine rather than manufacturing, capable of lifting a person but gentle enough to do so without harming them. There was also some speculation that it was for the office of Naval Research, possibly for underwater explorations. In 1969, Victor Scheinman from Stanford University invented the Stanford arm, where it had electronically powered arms that could move through six axes. This new technology opened up the possibility for manufacturers to use robots in assembly and welding tasks. Scheinman then designed a second arm for the MIT AI Lab, called the "MIT arm." Scheinman, after receiving a fellowship from Unimation to develop his designs, sold those designs to Unimation who further developed them with support from General Motors and later marketed it as the Programmable Universal Machine for Assembly (PUMA). In 1969, Unimation, Inc. received a massive order from GM. The automotive manufacturer was rebuilding its plant in Lordstown, Ohio, with the goal of creating the most automated automotive plant in the world. By the time, the factory was up and running, it could produce 110 cars every hour. This rate was more than double the production rate of any other plant at the time. This productivity jump encouraged other car manufacturers, from BMW and Volvo to Leyland, Fiat and Mercedes-Benz, to do the same, effectively securing Unimation's European market in the process. 1969 also proved to be the last year Unimation had a monopoly over the robotics market. Nachi Robotics launched an industrial robotics program in 1969 in Tokyo.

Industrial robotics took off quite quickly in Europe, with both ABB Robotics and KUKA Robotics bringing robots to the market in 1973. ABB Robotics (formerly ASEA) introduced IRB 6, among the world's first commercially available all electric micro-processor-controlled robot. The first two IRB 6 robots were sold to Magnusson in Sweden for grinding and polishing pipe bends and were installed in production in January 1974. In 1973, Germany joined the robotic arms race. Its company, called Kuka, developed the first industrial robotic arm driven by six electromagnetic axels. Dubbed "Famulus," this robotic arm was the first of its kind, moving the industry away from the traditional hydraulically operated arms. 1974 was an exciting year for robotics. David Silver, at the time a student at MIT, invented the Silver Arm. Designed for small parts assembly, it was the first robotic arm to feature touch sensors to provide tactile feedback to its operator.

Also, Stanford University mechanical engineering student Victor Scheinman created a similar arm, known as the Stanford Arm, which a company called Vicarm, Inc. marketed. In this same year, FANUC — Factory Automation Numerical Control — developed and installed robotic arms for assembly in their factory in Japan. Yaskawa Robotics introduced its first robotic arm in 1977 — the Motoman L10. This robot had five axes and could manipulate up to 10 kilograms, or 22 pounds. ASEA also introduced two electric industrial robots which were programmable with microcomputers. Unimation purchased Vicarm toward the end of this year as well. In 1978, the PUMA robot arm was released by Vicarm and Unimation, with support from General motors.

This arm was originally used in assembly lines and is still used today by researchers in robotics. Finally, OTC Japan released the first generation of dedicated arc welding robots in 1979.

Interest in robotics increased in the late 1970s and many US companies entered the field, including large firms like General Electric, and General Motors (which formed joint venture FANUC Robotics with FANUC LTD of Japan). U.S. start-up companies included Automatix and Adept Technology, Inc. At the height of the robot boom in 1984, Unimation was acquired by Westinghouse Electric Corporation for 107 million U.S. dollars. Westinghouse sold Unimation to Stäubli Faverges SCA of France in 1988, which is still making articulated robots for general industrial and cleanroom applications and even bought the robotic division of Bosch in late 2004. Only a few non-Japanese companies ultimately managed to survive in this market, the major ones being: Adept Technology, Stäubli, the Swedish-Swiss company ABB Asea Brown Boveri, the German company KUKA Robotics and the Italian company Comau.

While 1974 might have been an exciting year for robotics, the 1980s proved to be the most significant decade for industry growth. In 1980, robotics start-ups or new robots hit the market nearly every month, at exponential rates. 1981 brought about the introduction of the first direct-drive arm — a robotic arm with motors installed directly into each of its joints. It was the most accurate robotic arm of its time. 1981 also saw the introduction of pneumatic robotic arms — ones that use compressed air instead of electricity or hydraulic fluid. Takeo Kanade created the first robotic arm with motors installed directly in the joint in 1981. It was much faster and more accurate than its predecessors. In 1985, OTC Daihen began supplying robots to the Miller Electronics company, and ASEA and BBC Brown Boveri Ltd. merged into a single company with each member holding half of the company's assets. Nachi established a branch in the United States, and Yaskawa Robotics introduced a new control computer that was capable of controlling up to 12 axes at a time. Yaskawa America Inc. introduced the Motoman ERC control system in 1988. This has the power to control up to 12 axes, which was the highest number possible at the time. FANUC robotics also created the first prototype of an intelligent robot in 1992. Two years later, in 1994, the Motoman ERC system was upgraded to support up to 21 axes. It soon lost ground to the XRC controller, which could control up to 27 axes across up to 4 robots. This controller debuted in 1998, backed by Honda for use in their factories. Robotic arms also saw the first applications in prosthetics in this decade. In 1993, a Scottish man named Campbell Aird received the first cybernetic robotic arm after he lost his arm to muscular cancer in 1982. Aird could manipulate this arm by flexing the muscles in his shoulder.

Approaching the contemporary, the 2000s through today, have proven to be the most exciting time for the robotics industry. Advances in technology enabled robots to become even more efficient and effective in their duties. 2000 saw the introduction of the da Vinci Surgical System, named after one of the first people to come up with the concept of robotics, is a collection of robotic arms capable of precise microsurgery. To date, this system has been installed in more than 1,700 hospitals and performed three-quarters of a million surgeries. The first collaborative robot (cobot) was installed at Linatex in 2008. This Danish supplier of plastics and rubber decided to place the robot on the floor, as opposed to locking it behind a safety fence. Instead of hiring a programmer, they were able to program the robot through a touchscreen tool. These robots are usually complex to integrate and program, but once installed, require minimal human interaction. Collaborative robots are smaller, lightweight, and flexible automation tools that are easily programmed, even with no previous robotics experience. Collaborative robot arms can easily be redeployed to support low-volume, high-mix production. They are designed to work alongside human workers in production applications that combine repetitive tasks (ideal for automation) with more complex tasks (requiring human dexterity and/or problem-solving).

Figure 2.14 KUKA industrial arms

However, the biggest user of industrials robots is still the automotive industry, accounting for about half of all industrial robots in operation. Nearly every automotive manufacturer in the world now has robotic arms installed in its factories, speeding up the assembly process. In a single shift, the average factory can now assemble more than 200 cars — more than 600 if they run the factory 24/7. Recently, the National University of Singapore (NUS) decided to make even further advancements by inventing a mechanical arm that can lift up to 80 times its original weight. Not only did this arm expand its lift strength, but the arm could also extend to five times its original length. These advancements were first introduced in 2012 and car companies can greatly benefit from this new scientific knowledge. At the assembly line, industrial robots give automotive companies a competitive advantage. They improve quality and reduce warranty costs; increase capacity and relieve bottlenecks; and protect workers from dirty, difficult, and dangerous jobs. Car assembly plants use robots exclusively for spot welding and painting, but there are many other opportunities to use robots throughout the supply chain. OEMs, Tier 1s and other part producers all stand to gain from using robots in the car manufacturing industry. Among the processes these robots perform include: -

- Welding (Spot and Arc): Large robots with high payload capabilities and long reach can spot weld car body panels; while smaller robots weld subassemblies such as brackets and mounts. Robotic MIG and TIG arc welding position the torch in the same orientation on every cycle, and repeatable speed and arc gap ensure every fabrication is welded to the same high standard.
- Assembly: Tasks such as screw driving, windshield installation and wheel mounting are all candidates for robotic arms in car manufacturing plants. In many automotive part plants, robots — for example, the high-speed “Delta” machines — are assembling smaller component assemblies such as pumps and motors.
- Machine Tending: Unloading hot mouldings from an injection moulding or die casting machine and loading and unloading CNC machining centres are all good examples of robots tending production machines.
- Material Removal: Because it can follow a complex path repeatedly, a robot is an ideal tool for light trimming and cutting tasks. Examples include cutting fabrics such as headliners, trimming flash from plastic mouldings and die

castings, and polishing moulds. Force-sensing technology lets the robot maintain constant pressure against a surface in applications like these.

- Part Transfer: Pouring molten metal in a foundry and transferring a metal stamp from one press to the next are unpleasant jobs for human workers, but they are ideal robot tasks.
- Painting, Coating and Sealing: Able to follow a programmed path consistently, robots are widely used for painting in car assembly plants but are also good for spraying coatings such as sealants, primers, and adhesives. Plus, they can lay a uniform bead of sealant prior to assembly.

Outside of industrial usage, robotic arms have transformed researching, innovation, and education. In space, the Space Shuttle Remote Manipulator System also known as Canadarm or SRMS (Shuttle Remote Manipulator System) and its successor Canadarm2 are examples of multi degree of freedom robotic arms. These robotic arms have been used to perform a variety of tasks such as inspection of the Space Shuttle using a specially deployed boom with cameras and sensors attached at the end effector, and also satellite deployment and retrieval manoeuvres from the cargo bay of the Space Shuttle. The Curiosity rover a car-sized rover designed to explore the crater Gale on the planet Mars also uses a robotic arm. TAGSAM (Touch-and-Go Sample Acquisition Mechanism) is a robotic arm for collecting a sample from a small asteroid in space on the spacecraft OSIRIS-Rex (Origins, Spectral Interpretation, Resource Identification, Security, Regolith Explorer), a NASA asteroid study and sample-return mission. The 2018 Mars lander InSight (Interior Exploration using Seismic Investigations, Geodesy and Heat Transport) mission, a robotic lander designed to study the deep interior of the planet Mars has a robotic arm called the IDA, it has camera, grappler, is used to move special instruments. As we are yet to be able to send humans to other planets, robotic arms are the only arms we can rely on out there.

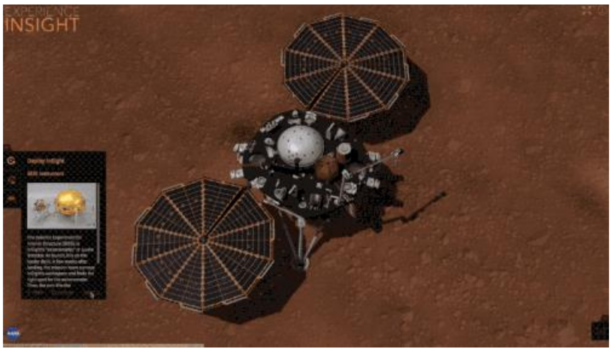


Figure 2.15 Mars lander InSight

For educational purposes and home use, robotic arms such as Dobot Magician, Dorna, Robolink, Rotrics, Hexbot, are often found in classrooms, research institutions, colleges, and universities. Due to its versatility, whereby the head of the robotic arm may not only be clippers, but may be exchanged with tool bits, drill bits, laser scanner, 3DP extruders etc., they can be used to train students at various types of programming and machine control. For example, it may be used as CNC machines running on G-code for CNC milling. It can also be controlled using Arduino, to teach basic programming for movement control of mechanical arms. Just like how hands are one of the most used parts of the body for day-to-day operations, allowing us to hold, pick up, put down, pull, push, and twist objects, robotic arms prove to be one of the most versatile devices ever created as well. This wow factor is what makes it so interesting and fascinating, making robotic arm start up projects often perform well in Kickstarter and Indiegogo fund raising campaign. The history of the robotic arm is long and varied, from da Vinci's original designs to the advanced robotics that are widespread today. Right now, robots are roaming the surfaces of planets in our solar system, collecting data that will advance our knowledge of our universe for years to come. The applications for these robotic arms will continue to grow and evolve, and our imaginations will only limit its potential applications.

Figure 2.16 Dobot Magician

Figure 2.17 Bionic robotic arm

2.5. CONCLUSION

With almost 30 pages of review, we journey through the ups and downs, thick and thins of 3DP, 3DS, and robotic arms. Firstly, we must address several issues. All 3 of these technologies have had their concept from old times. The concept of 3DP and 3DS trace back to ancient times, whereby Ancient Egyptians made 3D plaster-casted replicas of mummy heads. Whereas robotic arms can be traced back to the twelve-volume, bound set of drawings and writings by the one and only Leonardo da Vinci, Codex Atlanticus, from the 1400s. To be able to live in a world whereby the dreams on these great men have been fulfilled, we express our utmost gratitude and admiration towards them. We live in an era whereby we can a 3D Replicating Robotic Arm as a final year project, which would not even be far fetch but entirely inconceivable half a century ago, what not half a millennium ago. Next, we realised the complexity of these technologies, and the calculations and research involved in their development to the current state. Many inventors around the world had their own views, stance, and methods, but all to achieve similar results, resulting in many different techniques and approaches to these 3 technologies, enabling them to each be better suited for various functions. For example, there is FDM, SLS and SLA for 3DP; Laser triangulation, structured light scanning and photogrammetry for 3DS; while robotic arms may have hydraulic joint, electromagnetic joints, rotor servo joints etc. Thus, we understand what is necessary to be focused on to increase the success rate of this project, while minimising costs and material waste. Thirdly, through this review, we further realised the significance of our project, and what it may bring to the world. This motivated us further to put our heart and soul into the 3D Replicating Robotic Arm, to be committed towards reaching our objectives of this project successfully, not only to score well in grades, but to cultivate our skills relevant to IoT and IR4.0 and prepare ourselves as future mechanical technicians or engineers who are innovative and zealous towards our field of study.

Over the course of this review, we discussed the technologies from various standpoints, especially in technical, economical, and legal perspectives. As engineering students, technicality is pivot. However, they never work without the support of the other 2, after all, we live in a capitalist world of supply and demand. To determine the balance between cost and quality is key, to minimalise cost but not compromise quality.

The review provides us with a clearer direction heading into the next chapter, methodology. We begin to have a better estimation of the cost of our project. Planning and research will be key to minimalising cost that might be used on wasted material or faults in projects. Due to our inexperience and lack of expertise, we will reach out to industry and field experts relevant to our project for consultation and advice. We stand by our objective to design a 3D replicating machine that is as portable and cost efficient as possible.

CHAPTER 3

RESEARCH METHODOLOGY

3.1. INTRODUCTION

Methodology is defined as a system of methods used in a particular area of study or activity, or to be more specific, the systematic, theoretical analysis of the methods applied to a field of study. It comprises the theoretical analysis of the body of methods and principles associated with a branch of knowledge. For this project, most of the research is online based, a lot, a lot, of Googling, rather than questionnaires, surveys, trial and errors etc. This is due to the fact that is survey opinion will not weigh much towards the project, being a highly theoretical project, requiring a great deal of commitment towards the research and design process. As you will see in this chapter, the unfolding of the design of the 3D Replicating Robotic Arm from concept to a complete prototype design with specifications, simulations, and drawings. This was achievable through the use of Google Docs to collect and share information while researching, WhatsApp to communicate and coordinate between group members and supervisor, Microsoft Word to compile data and write report, and Autodesk Inventor 2020 to draw produce drawings of the 3D Replicating Robotic Arm. Below shoes a simple methodology flow chart which suitably describes our design process.

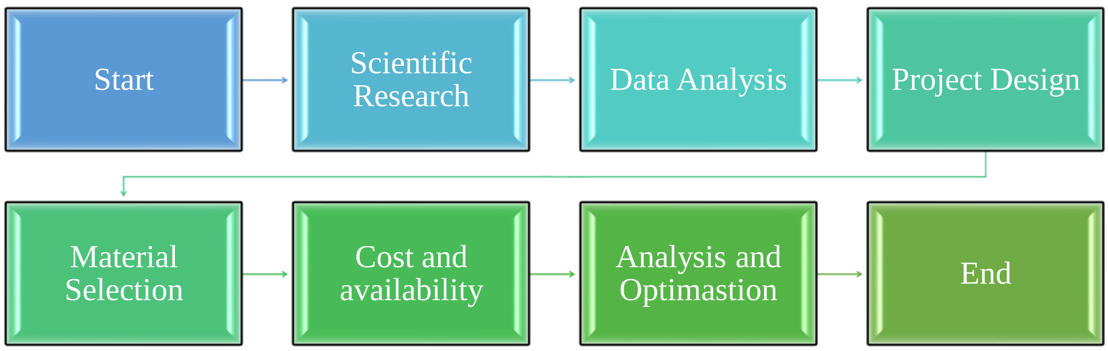


Figure 3.1 Research Flow Chart

The steps involved in the process of this flow chart will be explained in detail in the following subchapters.

3.2. RESEARCH INSTRUMENT

Throughout the weeks of the semester, a total of 4 instruments of research were employed. These include: -

- Online sources : Most of the research were done through Googling, reading through dozens of scholarly articles regarding out topic, or watching lectures, presentations, and tutorials on YouTube. This is because our topic of research requires high expertise in the field of 3DP, 3DS, and robotic arms, which are niche fields of studies in Malaysia, whereby experts of these fields are hard to come by.
- Lectures : We attended 1 demonstration session of a structured light 3D scanner on the 18^{th} of February 2020.
- Field experts: We consulted specialists in relevant fields to our topic of research to get advice and guidance.
- Online survey : We distributed a 10 – question google form to see how well accepted our idea is.

3.3. FUNCTION OF PRODUCT

Firstly, we revisited the objectives of our product in closer detail. This was to re-examine the feasibility of our project, to see if information from the preliminary research and literature review supports our goals.

- To make innovations towards 3D printers and 3D scanners.
- To make innovations towards robotic arms.
- To combine some of the most outstanding discoveries of the past century.
- To enable 3DP and 3DS in a single device.

- To decrease size of 3D printers without compromising printing volume.
- To contribute to efforts of commercialising and popularising robotic arms, 3DP, and 3DS in our society.

Next, we ask classical 5W1H questions to confirm the relevancy of our product.

1. What functions are yet to be available on robotic arm?

   3DS.

2. Who will use the 3D Replicating robotic arm?

   3DP and 3DS experts, enthusiasts, design engineers, inventors, educational institutions, research institutions etc.

3. Where is the 3D Replicating robotic arm needed?

   It is of great assistance in the field of 3D replicating, product designing, and education.

4. Why do we need the 3D Replicating robotic arm?

   It enables multiple functions in a single device, simplifying 3DP and 3DS processes, while also saving space and effort.

5. When is 3DP and 3DS required?

   The more present, the more frequent such devices are used in industries and at home.

6. How do we simplify the process of 3DP and 3DS?

   Build a 3D replicating machine like the 3D Replicating Robotic Arm.

This demonstrates our project's ability to satisfy increasing needs of technological advancements in designing and manufacturing industries. This also shows our project's relevancy to the age of IoT and oncoming IR4.0. We aim to see a Malaysia whereby many have devices similar to what we are making presently, and Malaysians are capable of creating and innovating their own products, relying less of ready-made mass-produced products in supermarkets.

3.4. DATA COLLECTION/SCIENTIFIC RESEARCH

This is research conducted after the literature review, with more specific information regarding out project. Similar to the Literature Review, this subchapter will be broken into 3 parts, 3DP, 3DS, and robotic arm. However, before that, we have some collected data from the responses of our Google Form survey.

3.4.1. 3D Printing

Every 3D printer builds parts based on the same main principle: a digital model is turned into a physical three-dimensional object by adding material a layer at a time. This where the alternative term Additive Manufacturing comes from. 3DP is a fundamentally different way of producing parts compared to traditional subtractive (CNC machining) or formative (Injection moulding) manufacturing technologies. In 3DP, no special tools are required (for example, a cutting tool with certain geometry or a mould). Instead, the part is manufactured directly onto the built platform layer-by-layer, which leads to a unique set of benefits and limitations - more on this below. To create an object, you need a digital 3D-model. You can scan a set of 3D images, or draw it using computer-assisted design or CAD software. You can also download them from internet. The digital 3D-model is usually saved in STL format and then sent to the printer. The process of "printing" a three-dimensional object layer-by-layer with equipment, which is quite similar with ink-jet printers.

From here, the way a 3D printer works varies by process. For example, desktop FDM printers melt plastic filaments and lay it down onto the print platform through a nozzle (like a high-precision, computer-controlled glue gun). Large industrial SLS machines use a laser to melt (or sinter) thin layers of metal or plastic powders. The available materials also vary by process. Plastics are by far the most common, but metals can also be 3D printed. The produced parts can also have a wide range of specific physical properties, ranging from optically clear to rubber-like objects. Depending on the size of the part and the type of printer, a print usually takes about 4 to 18 hours to complete. 3D printed parts are rarely ready-to-use out of the machine though. They often require some post-processing to achieve the desired level of surface finish. These steps take additional time and (usually manual) effort.

3DP allows easy fabrication of complex shapes, many of which cannot be produced by any other manufacturing method. The additive nature of the technology means that geometric complexity does not come at a higher price. Parts with complex or organic geometry optimized for performance cost just as much to 3D print as simpler parts designed for traditional manufacturing (and sometimes even cheaper since less material is used).

In formative manufacturing (think Injection Moulding and Metal Casting) each part requires a unique mould. These custom tools come at a high price (from thousands to hundreds of thousands each). To recoup these costs identical parts in the thousands are manufactured. Since 3DP does not need any specialized tooling, there are essentially no start-up costs. The cost of a 3D printed part depends only on the amount of material used, the time it took the machine to print it and the post-processing - if any - required to achieve the desired finish.

One of the main uses of 3DP today is prototyping - both for form and function. This is done at a fraction of the cost of other processes and at speeds, that no other manufacturing technology can compete with parts printed on a desktop 3D printer are usually ready overnight and orders placed to a professional service with large industrial machines are ready for delivery in 2-5 days. The speed of prototyping greatly accelerates the design cycle (design, test, improve, re-design). Products that would require 8+ months to develop, now can be ready in only 8-10 weeks. The most common 3DP materials used today are plastics. Metal 3DP also finds an increasing number of industrial applications. The 3DP pallet also includes speciality materials with properties tailored for specific applications. 3D printed parts today can have high heat resistance, high strength or stiffness and even be biocompatible. Composites are also common in 3DP. The materials can be filled with metal, ceramic, wood, or carbon particles, or reinforced with carbon fibres. This results in parts with unique properties suitable for specific applications.

Following are types of 3DP technologies/techniques.

Fused Deposition Modelling (FDM)

In FDM, a spool of filament is loaded into the printer and then fed to the extrusion head, which is equipped with a heated nozzle. Once the nozzle reaches the desired temperature, a motor drives the filament through it, melting it. The printer moves the extrusion head, laying down melted material at precise locations, where it cools and solidifies (like a very precise hot-glue gun). When a layer is finished, the build platform moves down, and the process repeats until the part is complete. After printing, the part is usually ready to use but it might require some post-processing, such as removal of the support structures or surface smoothing. FDM is the most cost-effective way of producing custom thermoplastic parts and prototypes. It also has the shortest lead times - as fast as next-day-delivery - due to the high availability of the technology. A wide range of thermoplastic materials is available for FDM, suitable for both prototyping and some functional applications. As of limitations, FDM has the lowest dimensional accuracy and resolution compared to the other 3DP technologies. FDM parts are likely to have visible layer lines, so post-processing is often required for a smooth surface finish. Additionally, the layer adhesion mechanism makes FDM parts inherently anisotropic. This means that they will be weaker in one direction and are generally unsuitable for critical applications.

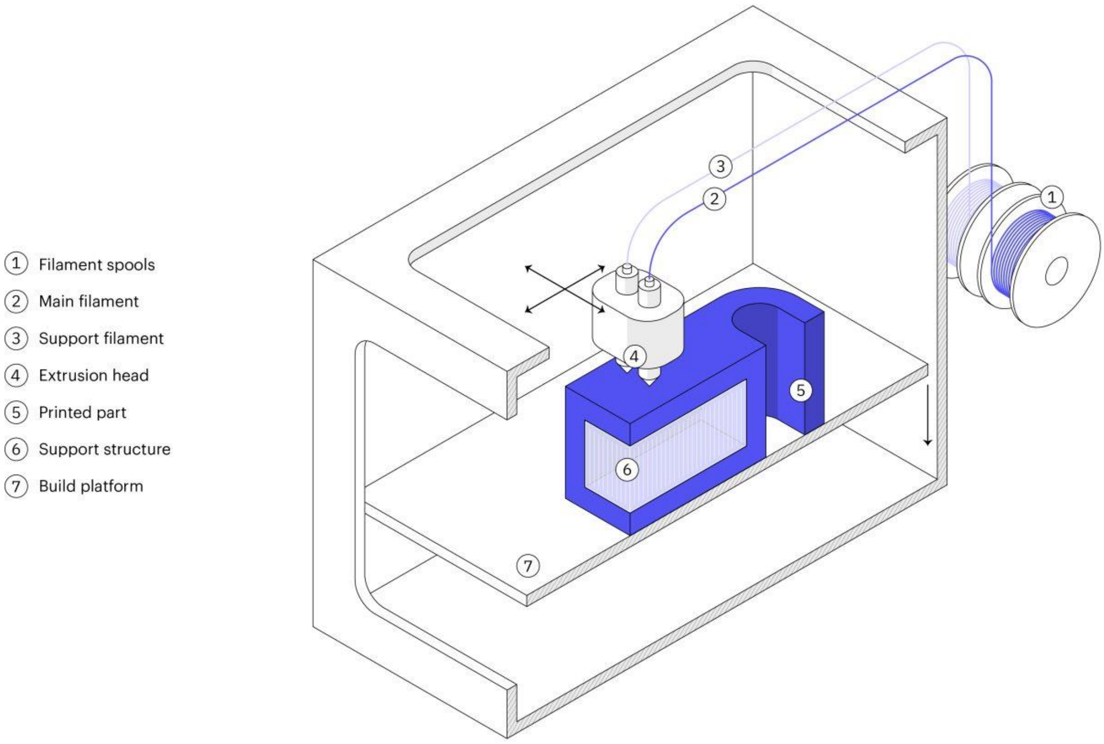


Figure 3.2 FDM

Stereolithography & Digital Light Processing (SLA & DLP)

SLA and DLP are similar processes that both use a UV light source to cure (solidify) liquid resin in a vat layer-by-layer. SLA uses a single-point laser to cure the resin, while DLP uses a digital light projector to flash a single image of each layer all at once. After printing, the part needs to be cleaned from the resin and exposed to a UV source to improve its strength. Next, the support structures are removed and, if a high-quality surface finish is required, additional post-processing steps are carried out. SLA/DLP can produce parts with very high dimensional accuracy, intricate details and a very smooth surface finish ideal that are ideal for visual prototypes. A large range of speciality materials, such as clear, flexible, castable and biocompatible resins, or materials tailored for specific industrial applications, are also available. Generally, SLA/DLP parts are more brittle than FDM parts, so they are not best suited for functional prototypes. Also, SLA parts must not be used outdoors, as their mechanical properties and colour degrades when they are exposed to UV radiation from the sun. Support structures are always required in SLA/DLP which may leave small blemishes in the surfaces they come in contact with that need extra post-processing to remove.

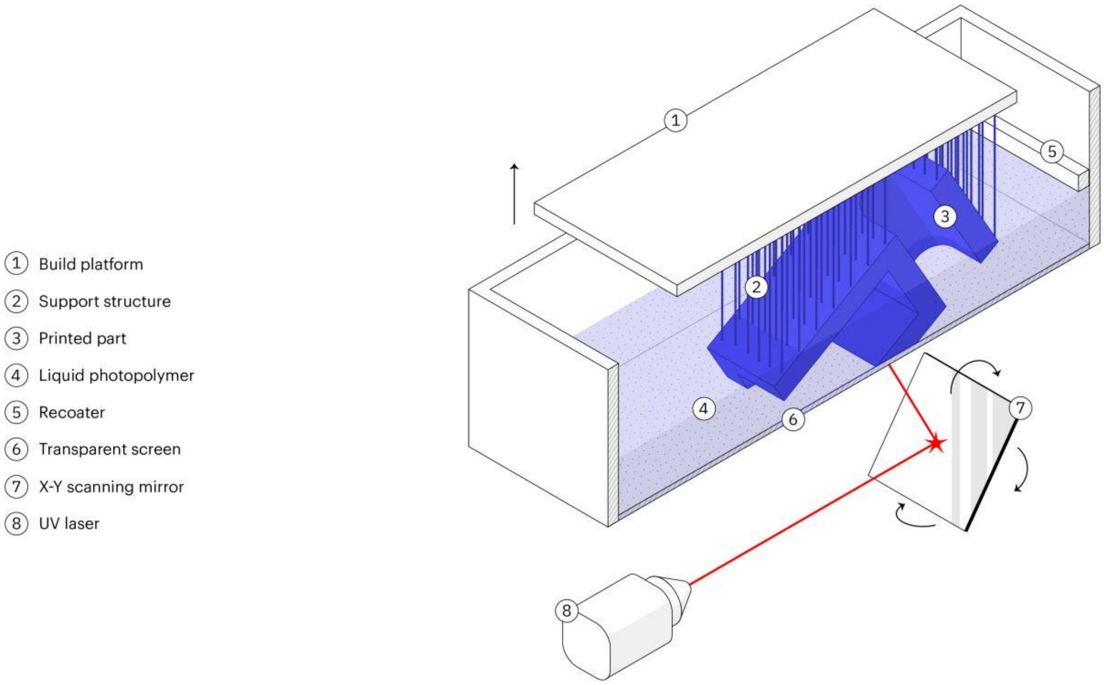


Figure 3.3 SLA & DLP

Selective Laser Sintering (SLS)

The SLS process begins with heating up a bit of polymer powder to a temperature just below the melting point of the material. A recoating blade or roller then deposits a very thin layer of powder - typically 0.1 mm thick - onto the build platform. A CO2 laser scans the surface of the powder bed and selectively sinters the particles, binding them together. When the entire cross-section is scanned, the building platform moves down one layer and the process repeats. The result is a bin filled with parts surrounded by unsintered powder. After printing, the bin needs to cool before the parts are removed from the unsintered powder and cleaned. Some post-processing steps can then be employed to improve their visual appearance, such as polishing or dying. SLS parts have very good, almost-isotropic mechanical properties, so they are ideal for functional parts and prototypes. Since no support structures are required (the unsintered powder acts as support), designs with very complex geometries can be easily manufactured. SLS is also excellent for small-to-medium batch production (up to 100 parts), since the bin can be filled throughout its volume and multiple parts can be printed at a single production run. SLS printers are usually high-end industrial systems. This limits the availability of the technology and increases its cost and turn-around times (compared to FDM or SLA, for example). SLS parts have a naturally grainy surface and some internal porosity. If a smooth surface or watertightness is required, additional post-processing steps are needed. Beware that large flat surfaces and small holes need special attention, as they are susceptible to thermal warping and over sintering.

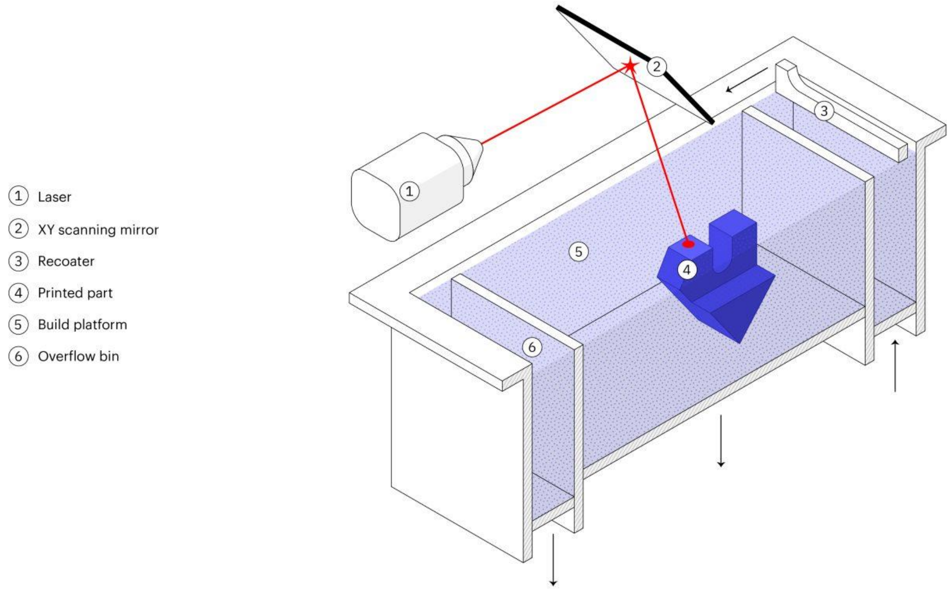


Figure 3.4 SLS

Material Jetting (PolyJet)

Material Jetting works in a similar way to standard inkjet printing. However, instead of printing a single layer of ink on a piece of paper, multiple layers of material are deposited upon each other to create a solid part. Multiple print heads jet hundreds of tiny droplets of photopolymer onto the build platform, which are then solidified (cured) by the UV light source. After a layer is complete, the build platform moves down one layer and the process repeats. Support structures are always required in Material Jetting. A water-soluble material is used as support that can be easily dissolved during post-processing and that is printed at the same time as the structural material. Material Jetting is the most precise 3DP technology (with SLA/DLP being a close second). It is one of the few 3DP processes that offers multi-material and full-colour printing capabilities. Material Jetted parts have a very smooth surface - comparable to injection moulding - and very high dimensional accuracy, making them ideal for realistic prototypes and parts that need an excellent visual appearance. Material Jetting is one of the most expensive 3DP processes and this high cost may make it financially unviable for some applications. Moreover, parts produced with Material Jetting are not best suited for functional applications. Like SLA/DLP, the materials used with this process are thermosets, so the produced parts tend to be brittle. They are also photosensitive, and their properties will degrade over time with exposure to sunlight.

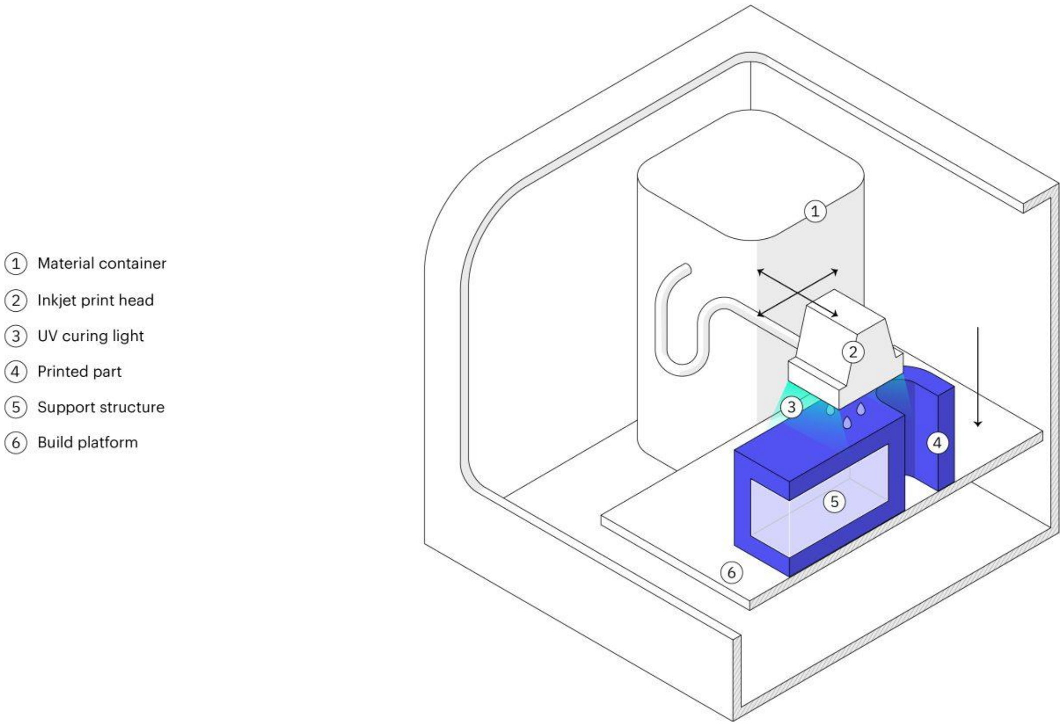


Figure 3.5 PolyJet

Direct Metal Laser Sintering & Selective Laser Melting (DMLS & SLM)

Direct Metal Laser Sintering (DMLS) and Selective Laser Melting (SLM) produce parts in a similar way to SLS: a laser source selectively bonds together powder particles layer-by-layer. The main difference, of course, is that DMLS and SLM produce parts out of metal. The difference between the DMLS and SLM processes is subtle: SLM achieves a full melt of the powder particles, while DMLS heats the metal particles to a point that they fuse together on a molecular level instead. Support structures are always required in DMLS and SLM to minimize the distortion caused by the high temperatures required to fuse the metal particles. After printing, the metal supports need to be removed either manually or through CNC machining. Machining can also be employed to improve the accuracy of critical features (e.g., holes). Finally, the parts are thermally treated to eliminate any residual stresses. DMLS/SLM is ideal for manufacturing metal parts with complex geometries that traditional manufacturing methods cannot produce. DMLS/SLM parts can be (and should be) topology optimized to maximize their performance while minimizing their weight and amount of material used. DMLS/SLM parts have excellent physical properties, often surpassing the strength of the rough metal. Many metal alloys that are difficult to process with other technologies, such as metal superalloys, are available in DMLS/SLM. The costs associated with DMLS/SLM 3DP are high: parts produced with these processes typically cost between $5,000 and $25,000. For this reason, DMLS/SLM should only be used to manufacture parts that cannot be produced with any other method. Moreover, the build size of modern metal 3DP systems is limited, as the required precise manufacturing conditions are difficult to maintain for bigger build volumes.

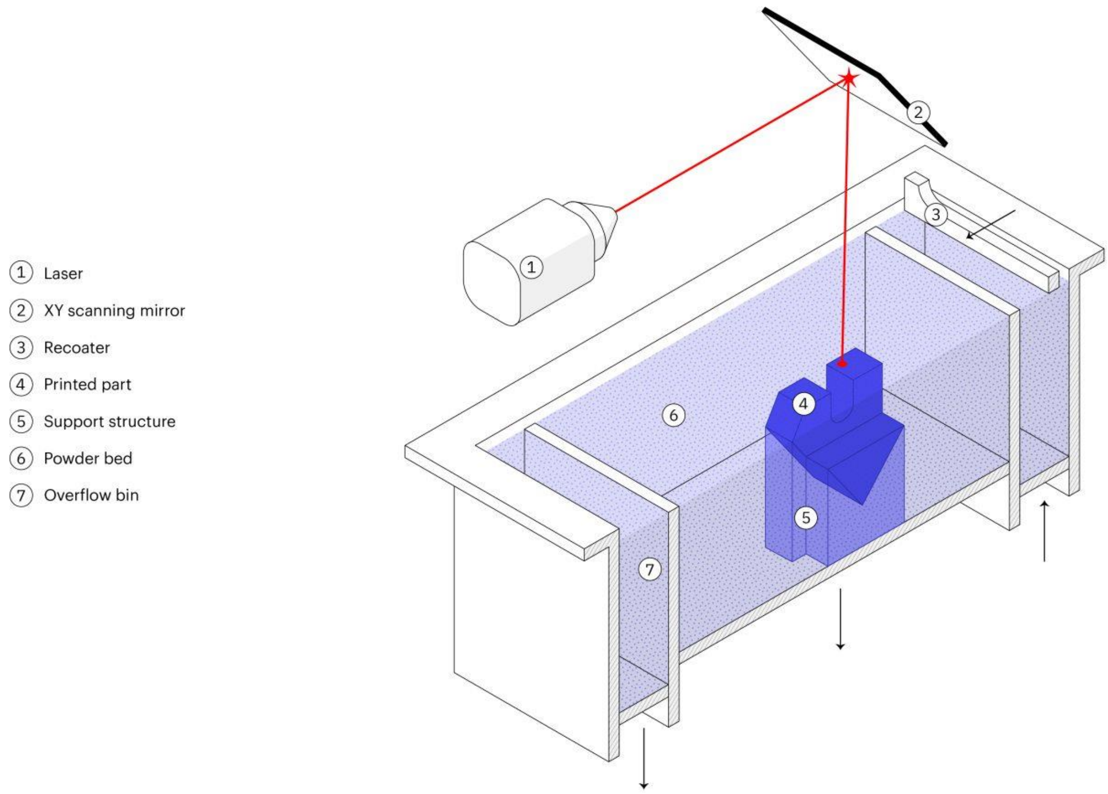


Figure 3.6 DMLS & SLM

Binder Jetting

Binder Jetting is a flexible technology with diverse applications, ranging from low-cost metal 3DP, to full-colour prototyping and large sand-casting mould production. In Binder Jetting, a thin layer of powder particles (metal, acrylic, or sandstone) is first deposited onto the build platform. Then droplets of adhesive are ejected by an inkjet printhead to selectively bind the powder particles together and build a part layer-by-layer. After the print is complete, the part is removed from the powder and cleaned. At this stage it is very brittle and additional post-processing is required. For metal parts this involves thermal sintering (similar to Metal Injection Moulding) or infiltration with a low melting-point metal (for example, bronze), while full-colour parts are infiltrated with cyanoacrylate adhesive. Binder Jetting can produce metal parts and full-colour prototypes at a fraction of the cost of DMLS/SLM or Material Jetting, respectively. Very large sandstone parts can also be manufactured with Binder Jetting, as the process is not limited by thermal effects (for example, warping). Since no support structures are needed during printing, metal Binder Jetting parts can have very complex geometries and, like SLS, low-to-medium batch production is possible by filling up the whole build volume. Metal Binder Jetting parts have lower mechanical properties than the bulk material though, due to their porosity. Due to the special post-processing requirements of Binder Jetting, special design restrictions apply. Very small details, for example, cannot be printed, as the parts are very brittle out of the printer and may break. Metal parts might also deform during the sintering or infiltration step if not supported properly.

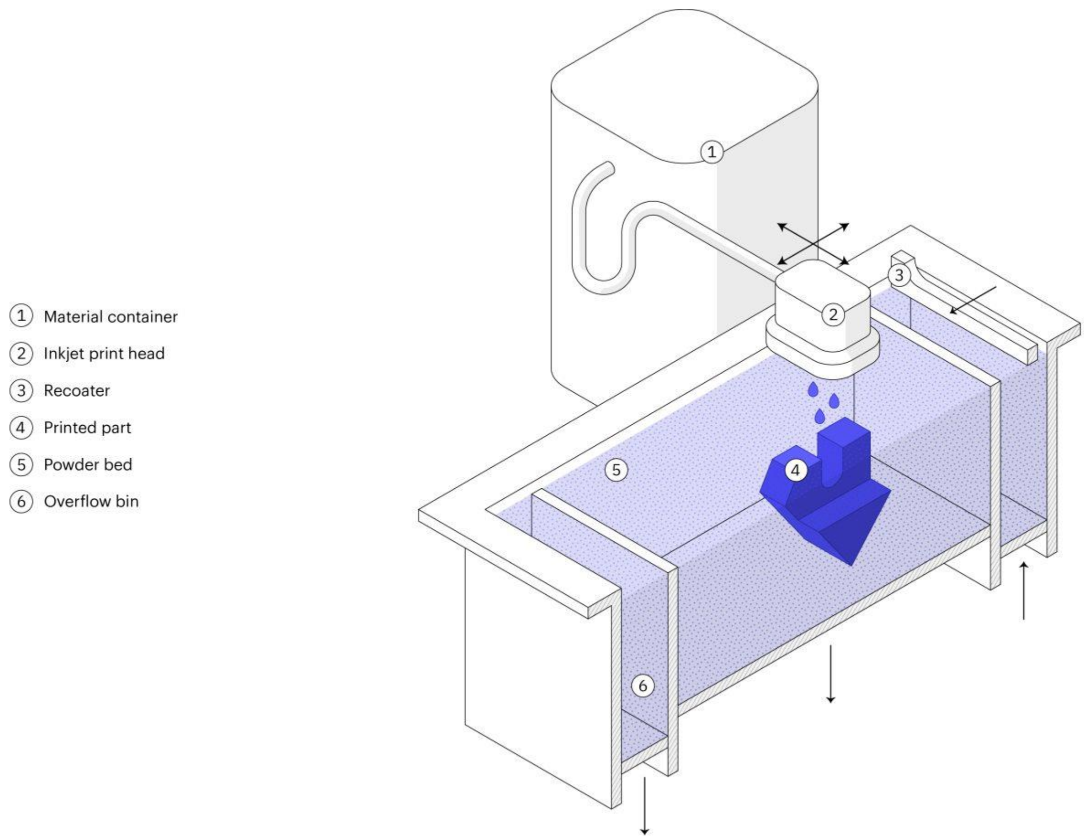


Figure 3.7 Binder Jetting

Directed Energy Deposition (DED)

This process is mostly used in the high-tech metal industry and in rapid manufacturing applications. A typical DED machine consists of a nozzle mounted on a multi axis arm, which deposits melted material onto the specified surface, where it solidifies. The process is similar in principle to material extrusion, but the nozzle can move in multiple directions and is not fixed to a specific axis. The material, which can be deposited from any angle due to 4 and 5 axis machines, is melted upon deposition with a laser or electron beam. The process can be used with polymers, ceramics but is typically used with metals, in the form of either powder or wire.

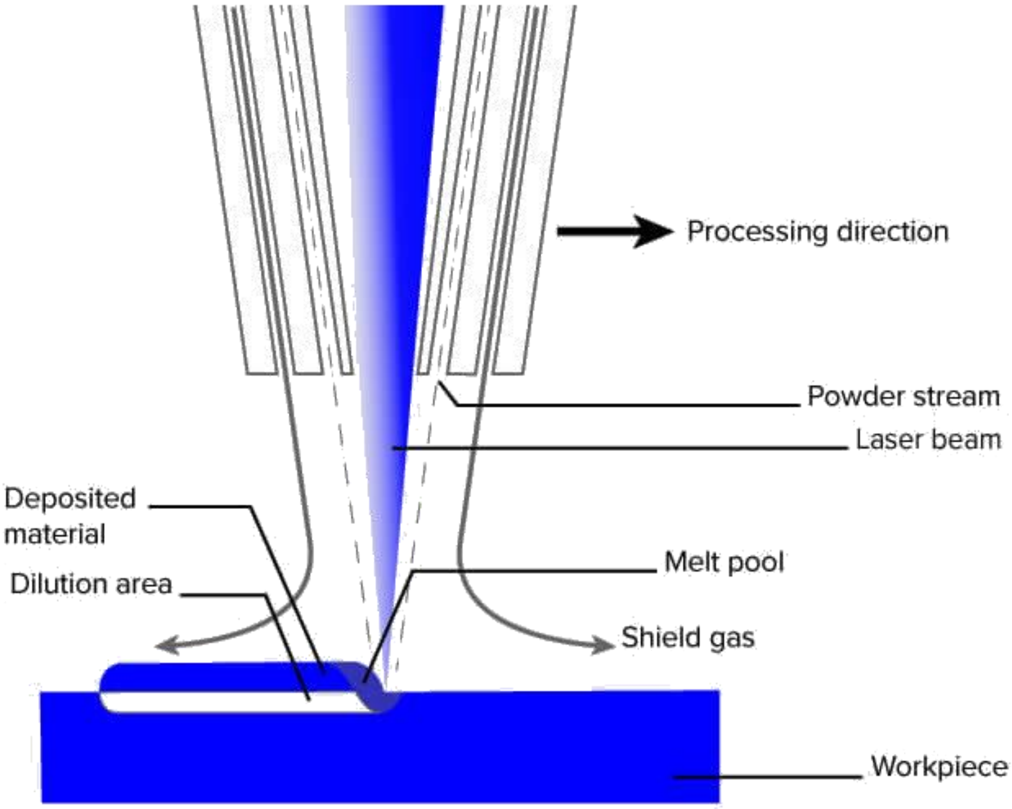


Figure 3.8 DED

To sum up, the following is an illustration of 3DP technologies by 3D HUBS.

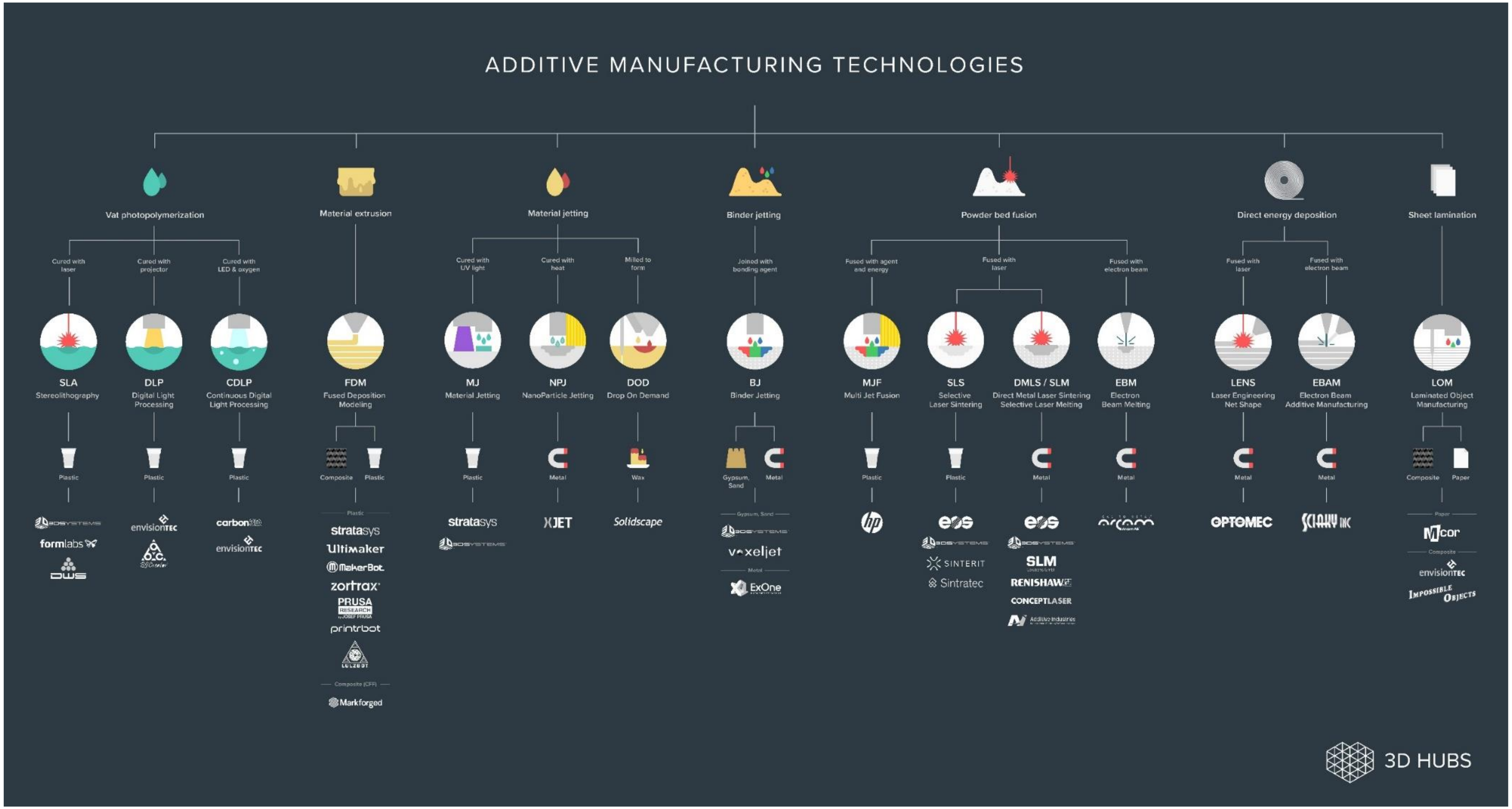


Figure 3.9 3DP technologies

3.4.2. 3D Scanning

3DS has myriad essential applications in the world we live. 3DS is a key initial technology in the process of 3D Fabrication as it enables key 3D data to be referenced prior to CAD Modelling in the course of both new product development and the development of modifications to existing structures & product. 3DS then enables 3D data post development in quality & compliance processes. It is most common for us to visualize 3D data in "space" via a 3D grid system. From a "Zero" datum (a fixed point from which all data can be referenced), we can project outwards an X, Y, Z measurement model. X is lengthways, Y is width, Z is height. Most of humanity's great structures throughout time feature a combination of horizontal and vertical elements, these structures will have required forethought & spatial planning and will have utilized a similar system. Without a fixed or otherwise referenced datum/s, 3D data can have no control or meaning. 3DS is performed, and the outcome is 3D file datapoints. The shape of the object appears as millions of points called a "point cloud" on the computer monitor as the laser moves around capturing the entire surface shape of the object. The process is very fast, gathering up to 750,000 points per second and very precise (to ±.0005″). After the huge point cloud data files are created, they are registered and merged into one three-dimensional representation of the object and post-processed with various software packages suitable for a specific application. If the data is to be used for inspection, the scanned object can be compared to the designer's CAD nominal data. The result of this comparison process is delivered in the form of a "colour map deviation report," in PDF format, which pictorially describes the differences between the scan data and the CAD data.

Laser Triangulation 3D Scanning

Laser triangulation-based 3D scanners use either a laser line or a single laser point to scan across an object. The laser is first cast by the 3D scanner. As the laser light reflects off the 3D scanned object, its initial trajectory is modified and picked up by a sensor. From the modification of the laser trajectory and trigonometric triangulation, the system can discern a specific deviation angle. The calculated angle is directly linked to the distance from the object to the scanner. When the 3D scanner collects enough distances, it is capable of mapping the surface's object and of creating a 3D scan. Laser scanning is the fastest, most accurate, and automated way to acquire 3D digital data for reverse engineering. Again, using specialized software, the point cloud data is used to create a 3D CAD model of the part's geometry. The CAD model enables the precise reproduction of the scanned object, or the object can be modified in the CAD model to correct imperfections. Laser Design can provide a surface model or the more complex solid model, whichever results are needed for the application.

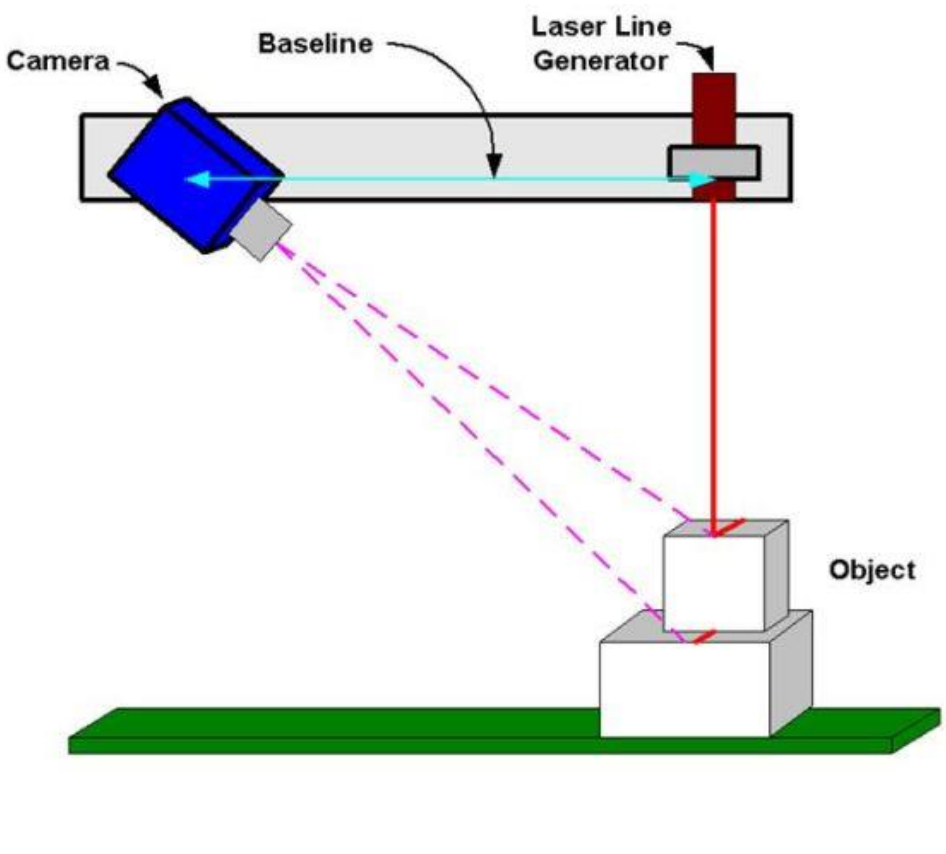


Figure 3.10 Laser Triangulation 3D Scanning

Photogrammetry 3D Scanning

Photogrammetry is the science of making measurements from photographs, especially for recovering the exact positions of surface points., also known as 3D photography. Photogrammetry is based on a mix of computer vision and powerful computational geometry algorithms. This technology uses photographs to measure the dimensions of the objects. This helps in realizing the exact distances of surface points. The data input required from the user are the parameters of the camera such as focal length and lens distortion. Photogrammetry considers the power of computational geometry algorithms and the computer vision to come to the final digital file. To do so, the method employs analysing various photographs of a static object that needed to be scanned. These pictures must be taken from different angles. This method automatically detects pixels equivalent to a similar physical point. The principle requires the user to mention the parameters of the camera. For example, the focal length, lens distortion, etc. This technology is impressive. However, it has its limitations. The major challenge comes when there is a need for analysing lots of photos and hundreds and thousands of surface points taking accuracy into account. Apart from the 3D scanner, one must own a high-end computer to run photogrammetry algorithms. The advantages include high precision and speed of acquisition. Photogrammetric technology can even recreate objects with varying scales. The technology also has a problem with resolution sensitivity; hence, it can have problems with low-resolution photos.

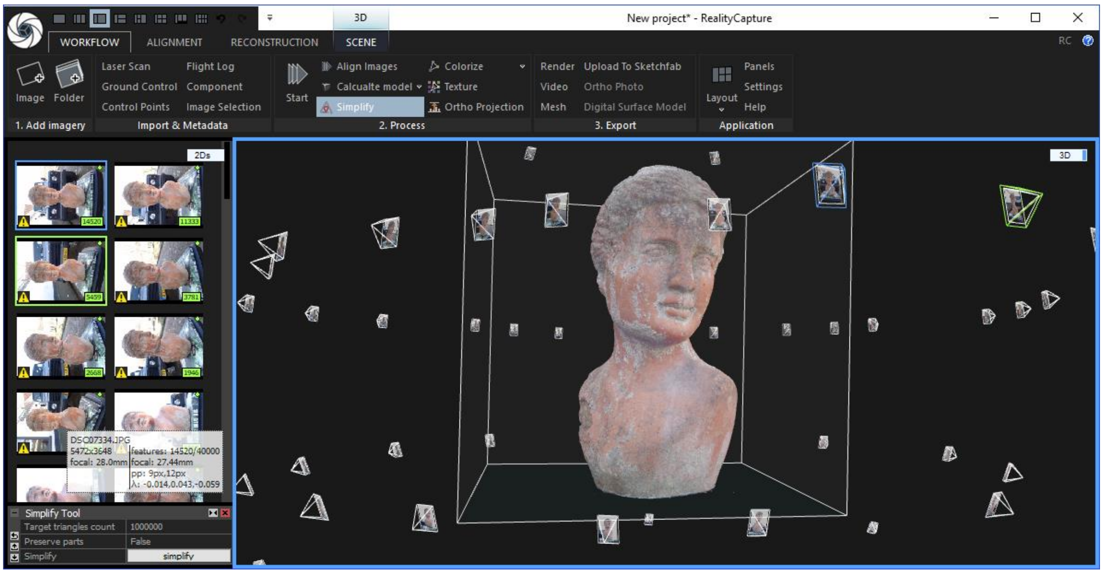


Figure 3.11 Photogrammetry 3D Scanning

Structured Light 3D Scanning

Structured light 3D scanners use trigonometric triangulation but do not rely on a laser. Instead, the structured light 3DS technology works with the projection of a series of linear patterns onto an object. The system is then capable to examine the edges of each line in the pattern and to calculate the distance from the scanner to the object's surface. The structured light used for 3DS can be white or blue and generated by numerous types of projectors, such as Digital Light Processing (DLP) technology. The projected pattern is usually a series of light rays but can also be a randomized dot matrix. Contact 3DS is widely used for performing quality control of parts after fabrication or during maintenance operations. The main advantages 0f the contact technology for 3DS are its precision and ability to 3D scan transparent or reflective surfaces. The downsides of contact 3DS technology are its speed and inadequacy to work with organic, freeform shapes.

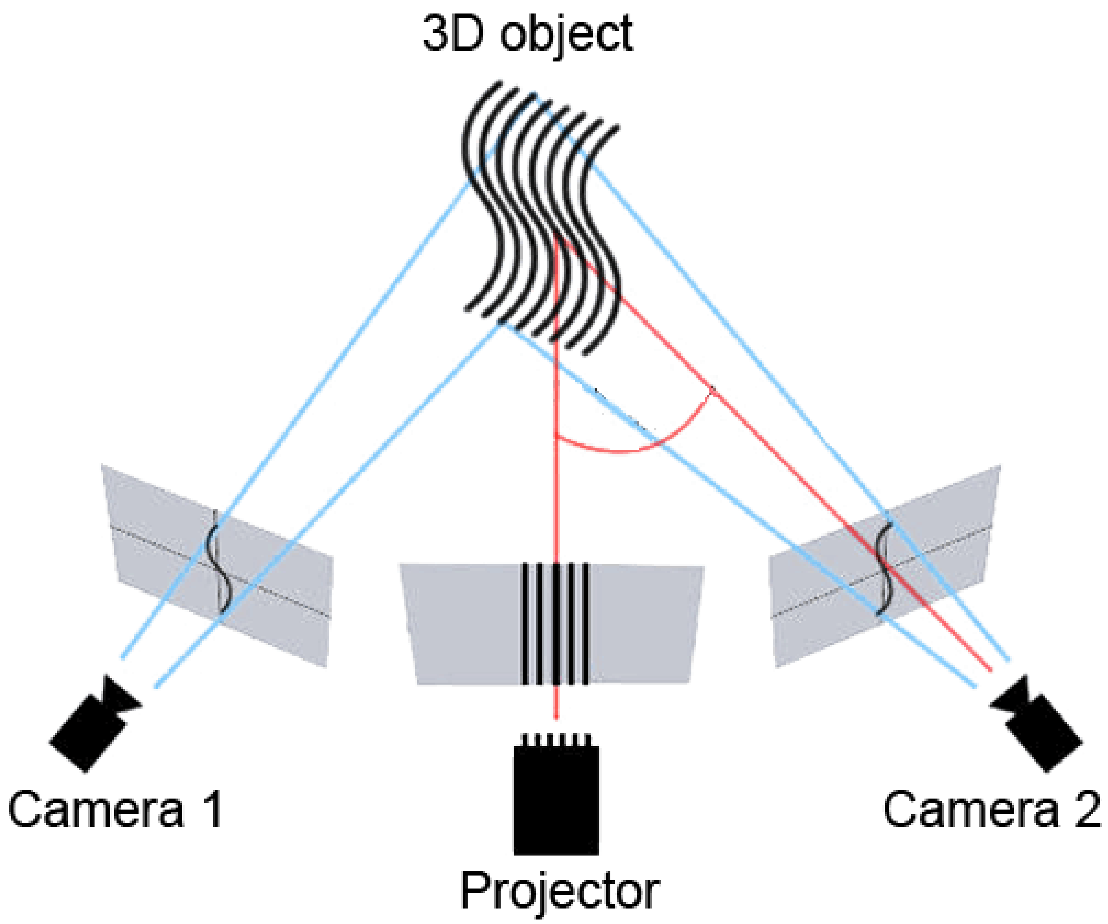


Figure 3.12 Structured Light 3D Scanning

Laser Pulse 3D Scanning

The Laser pulse-based 3D scanners can also be cited as LiDAR or Time-of-Flight scanner. It works by measuring how much time laser takes when projected on an object to come back. The speed of light is known, and the time is calculated which ultimately provides the distance travelled by the laser. With the help of the distance, speed, and time formula, one can easily conclude the distance between the object and the 3D scanner. The laser scanner is capable of measuring millions of laser distance in a picosecond. To work properly, the 3D scanner must the laser 360 degrees around one point. To ensure this is taken care of, the 3D scanners are equipped with mirrors which helps in changing the orientation of the laser. The resulting array of laser pulses reflect a single data point each from the environment and a comprehensive 3D data file is the result. Precision can be adjusted per application; however, very high resolution and quality settings generate very large 3DS files. There is another type of 3D scanner technology known as Phase shift laser 3D scanners. These are the sub-category of a laser pulse. The difference between a pulse shift laser and laser pulse is that the phase shift system modulates the laser beam's power as well apart from pulsing the laser. In fact, the phase shift lasers provide better, and accurate results as compared to the laser pulse 3D scanners.

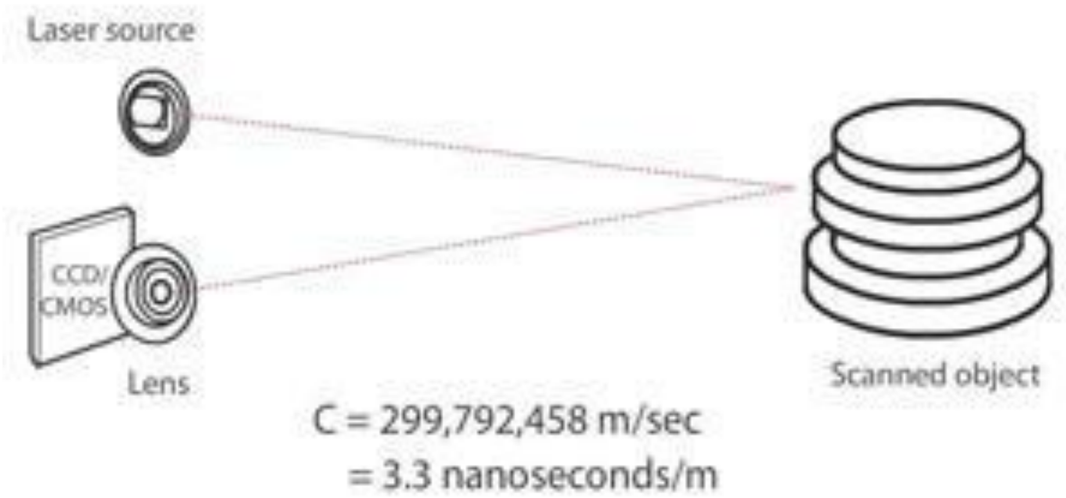


Figure 3.13 Laser Pulse3D Scanning

Contact-based/Touch Sensors 3D Scanning

Contact-based 3DS is also known as digitizing. The contact technology for 3DS implies a contact-based form of 3D data collection. Contact 3D scanners probe the subject through physical touch, while the object is firmly held in place. A touching probe is moved on the surface to various points of the object to record 3D information. The probe is sometimes attached to an articulated arm capable of collecting all its respective configurations and angles for more precision. Some specific configurations of contact-based 3D scanners are called Coordinated Measuring Machines (CMM). Contact 3DS is widely used for performing quality control of parts after fabrication or during maintenance operations. The main advantages 0f the contact technology for 3DS are its precision and ability to 3D scan transparent or reflective surfaces. The downsides of contact 3DS technology are its speed and inadequacy to work with organic, freeform shapes.

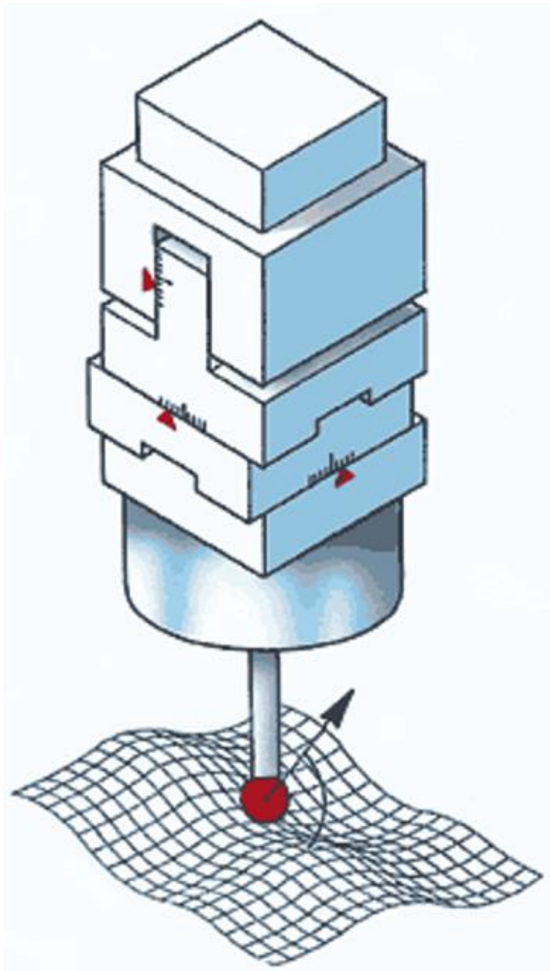


Figure 3.14 & Figure 3.15 Contact-based/Touch Sensors 3D Scanning

3.4.3. Robotic Arm

Most to all robotic arms have one similarity, which is its objective to mimic a human arm, whether in terms of design, build, function, or all 3. Robotic arms have various segments which closely resemble the shoulder, an elbow, and a wrist. A robotic arm is programmable and can be directed to perform a variety of functions just like the human arm can. The robotic arm is the most common type of manufacturing robot. It is typically made up of seven segments with six joints driven using step motors. A user can control the robotic arm via a computer by controlling the step motors in the joints. Since step motors move in controlled increments, the robotic arm can be made to move in a very precise manner repeatedly with a high level of accuracy and reliability. There are motion sensors on the robotic arm joints which provide feedback and enable the robot to move in a controlled manner. Because of the repeatability and accuracy, robotic arms are used for functions which are difficult, repetitive, and often boring to humans. Functions which are considered dangerous for human beings can also be performed using robotic arms. A typical industrial robot arm includes a series of joints, articulations and manipulators that work together to closely resemble the motion and functionality of a human arm (at least from a purely mechanical perspective). A programmable robotic arm can be a complete machine in and of itself, or it can function as an individual robot part of a larger and more complex piece of equipment. A great many smaller robotic arms used in countless industries and workplace applications today are benchtop-mounted and controlled electronically. Larger versions might be floor-mounted, but either way they tend to be constructed from sturdy and durable metal (often steel or cast iron), and most will feature between 4-6 articulating joints. Again, from a mechanical perspective, the key joints on a robotic arm are designed to closely resemble the main parts of its human equivalent - including the shoulder, elbow, forearm, and wrist. Such is the speed and power that industrial robot arms can work at, there is a pressing need to be extremely safety-conscious when programming and using them. However, when deployed appropriately, they can vastly increase production rates and accuracy of placement and picking tasks, as well as performing heavy-duty lifting and repositioning functions that would be impossible even for groups of multiple human workers to carry out at any sort of pace.

There are numerous different robotic arm types available on today's market, each designed with important core abilities and functions that make various specific types particularly well-suited for particular roles or industrial environments. The majority of robotic arms have up to six joints connecting seven sections, most or all of which are driven by various forms of stepper motors and controlled by computer. This allows for incredibly precise positioning of the 'hand' or end effector part of the arm, which in most industrial uses will generally be some sort of specialised tool or attachment, designed to carry out a highly specific action or repeatable series of articulations. For the most part, the key distinction between different sorts of robotic arms lies in the way their joints are designed to articulate - and subsequently the range of movement and functions they are able to perform - as well as the type of framework they are supported by and the footprint they require for installation and operation.

A serial robot arm can be described as a chain of links that are moved by joints which are actuated by motors. An end-effector, also called a robot hand, can be attached to the end of the chain. As other robotic mechanisms, robot arms are typically classified in terms of the number of degrees of freedom. Usually, the number of degrees of freedom is equal to the number of joints that move the links of the robot arm. At least six degrees of freedom are required to enable the robot hand to reach an arbitrary pose (position and orientation) in three-dimensional space. Additional degrees of freedom allow to change the configuration of some link on the arm (e.g., elbow up/down), while keeping the robot hand in the same pose. Inverse kinematics is the mathematical process to calculate the configuration of an arm, typically in terms of joint angles, given a desired pose of the robot hand in three-dimensional space. The end effector, or robotic hand, can be designed to perform any desired task such as welding, gripping, spinning etc., depending on the application. For example, robot arms in automotive assembly lines perform a variety of tasks such as welding and parts rotation and placement during assembly. In some circumstances, close emulation of the human hand is desired, as in robots designed to conduct bomb disarmament and disposal.

Based on mechanical structures, robotic arms can be characterised into 7 categories.

Cartesian Robot/Gantry Robot

A cartesian coordinate robot (also called linear robot) is an industrial robot whose three principal axes of control are linear and are at right angles to each other, standard X-Y-Z Cartesian axes. The three sliding joints correspond to moving the wrist up-down, in-out, back-forth. Among other advantages, this mechanical arrangement simplifies the Robot control arm solution. It has high reliability and precision when operating in three-dimensional space. As a robot coordinate system, it is also effective for horizontal travel and for stacking bins. Cartesian coordinate robots with the horizontal member supported at both ends are sometimes called Gantry robots; mechanically, they resemble gantry cranes, although the latter are not generally robots. Gantry robots are often quite large. A popular application for this type of robot is a computer numerical control machine (CNC machine) and 3DP. The simplest application is used in milling and drawing machines where a pen or router translates across an x-y plane while a tool is raised and lowered onto a surface to create a precise design. Pick and place machines and plotters are also based on the principal of the cartesian coordinate robot. Industrial gantry type cartesian robot is applied on CNC lathes production line for continuous parts loading and unloading. It performs 3-axis (X, Y, and Z) linear movement in high-speed performance to save numbers of operators. In addition, the robot is able to handle heavy loads of pick and place parts feeding procedure with high positioning accuracy. Some special requirements might be low noise and customized supply table, which is made according to number of storages. Since handling is usually above the CNC, overhead gantry is also a common term to describe this type of robotic arm. Overhead design is suitable for most automation system.

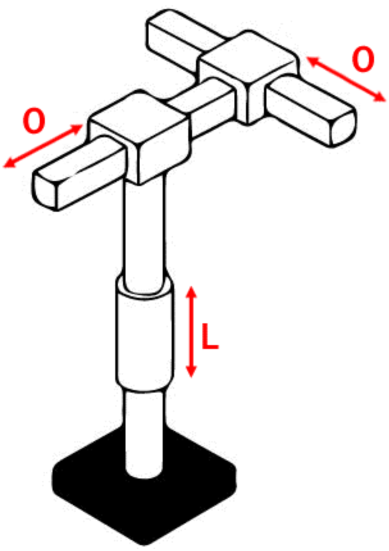


Figure 3.16 Cartesian Robot/Gantry Robot

SCARA Robot

The SCARA acronym stands for Selective Compliance Assembly Robot Arm or Selective Compliance Articulated Robot Arm. Its arm is rigid in the Z-axis and pliable in the XY-axes, which allows it to adapt to holes in the XY-axes. By virtue of the SCARA's parallel-axis joint layout, the arm is slightly compliant in the X-Y direction but rigid in the 'Z' direction, hence the term: Selective Compliant. This is advantageous for many types of assembly operations, i.e., inserting a round pin in a round hole without binding. The second attribute of the SCARA is the jointed two-link arm layout similar to our human arms, hence the often-used term, Articulated. This feature allows the arm to extend into confined areas and then retract or "fold up" out of the way. This is advantageous for transferring parts from one cell to another or for loading/ unloading process stations that are enclosed. SCARAs are generally faster than comparable Cartesian robot systems. Their single pedestal mount requires a small footprint and provides an easy, unhindered form of mounting. On the other hand, SCARAs can be more expensive than comparable Cartesian systems and the controlling software requires inverse kinematics for linear interpolated moves. This software typically comes with the SCARA though and is usually transparent to the end-user.

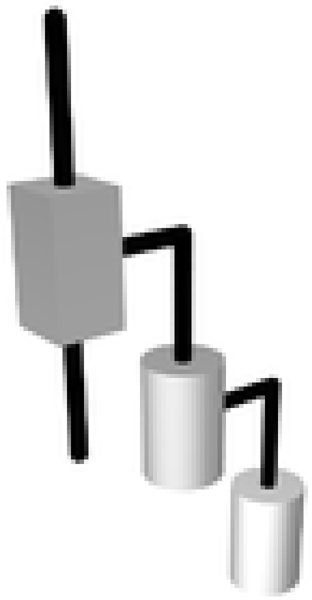


Figure 3.17 & Figure 3.18 SCARA Robot

Articulated Robot

An articulated robot is a robot with rotary joints. Articulated robots can range from simple two-jointed structures to systems with 10 or more interacting joints and materials. Each joint is considered to be an axis and can provide an additional degree of freedom. They are powered by a variety of means, including electric motors. They are most commonly used configuration because of their flexibility in reaching any part of the working envelope. Mostly used in such complex application as welding, drilling and soldering operations.

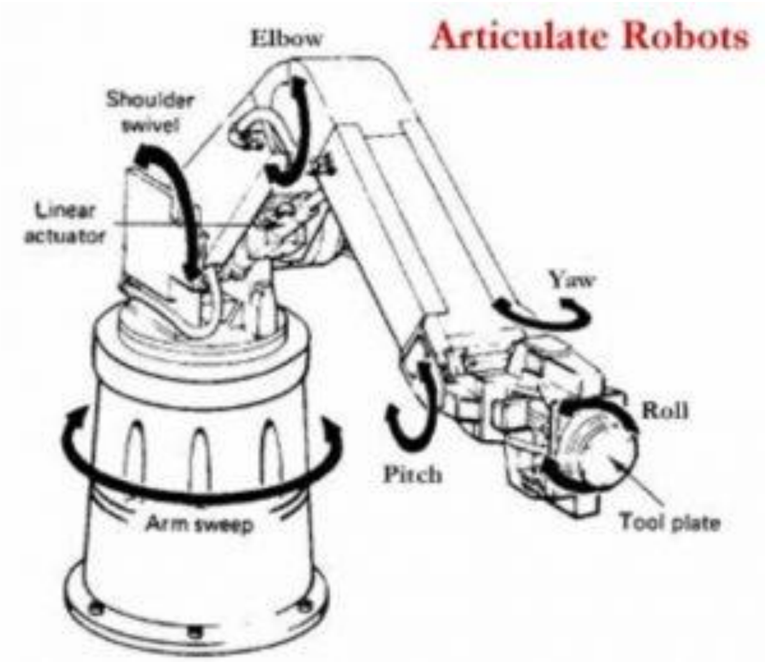


Figure 3.19

Figure 3.20

Articulated Robot

Parallel Manipulator/Robot

A parallel manipulator is a mechanical system that uses several computer-controlled serial chains to support a single platform, or end-effector. Perhaps, the best-known parallel manipulator is formed from six linear actuators that support a movable base for devices such as flight simulators. Also known as parallel robots, or generalized Stewart platforms, these systems are articulated robots that use similar mechanisms for the movement of either the robot on its base, or one or more manipulator arms. Their 'parallel' distinction, as opposed to a serial manipulator, is that the end effector (or 'hand') of this linkage (or 'arm') is directly connected to its base by a number of (usually three or six) separate and independent linkages working simultaneously. No geometrical parallelism is implied. A parallel manipulator is designed so that each chain is usually short, simple and can thus be rigid against unwanted movement, compared to a serial manipulator. Errors in one chain's positioning are averaged in conjunction with the others, rather than being cumulative. Each actuator must still move within its own degree of freedom, as for a serial robot; however, in the parallel robot the off-axis flexibility of a joint is also constrained by the effect of the other chains. It is this closed-loop stiffness that makes the overall parallel manipulator stiff relative to its components, unlike the serial chain that becomes progressively less rigid with more components.

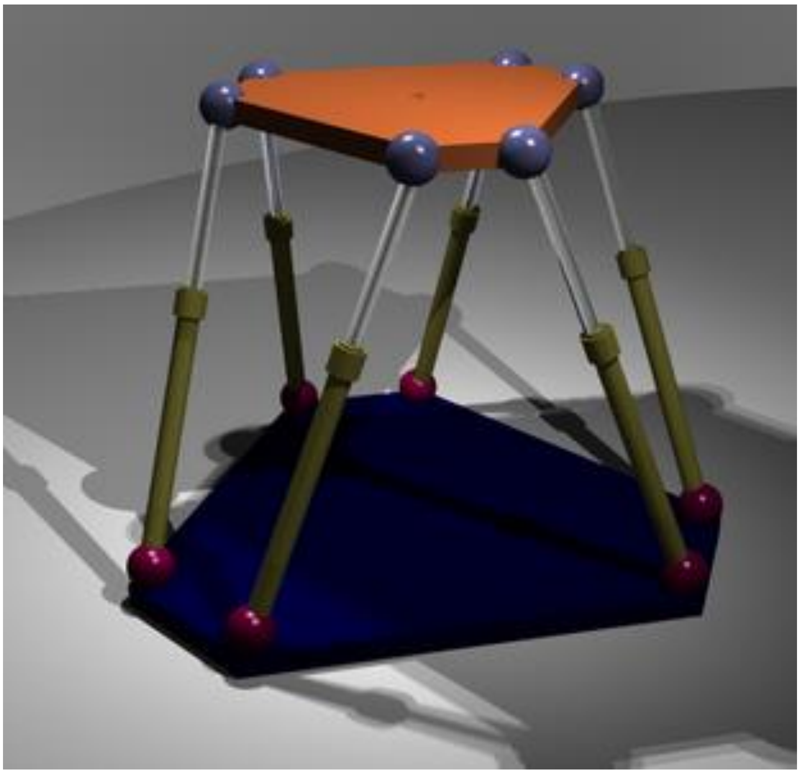


Figure 3.21 Parallel Manipulator/Robot

Cylindrical Robot

Cylindrical robot has a number of joints that rotate on cylindrical axes, which rotate on one fixed rod, whereby their programmed movements take place within a cylinder-shaped space (up, down, and around). Cylindrical robotic arms can be used for spot welding, handling diecast machines and other machine tools, as well as for assembly operations.

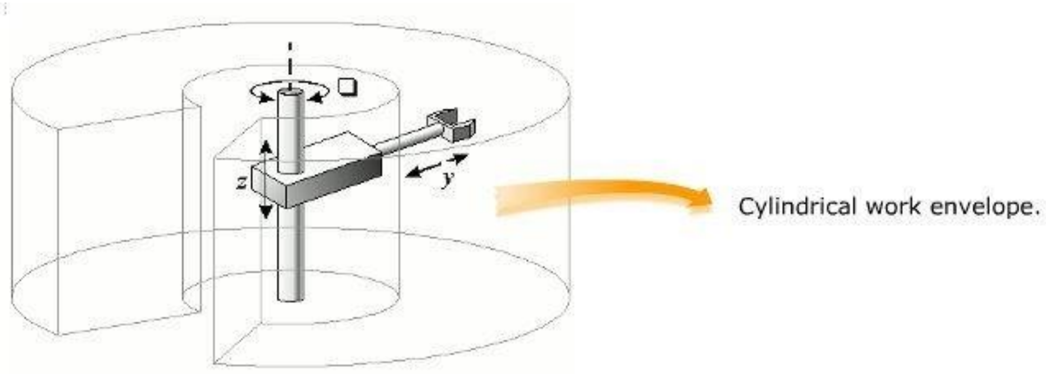


Figure 3.22 Cylindrical Robot

Spherical/Polar Robot

This type of robotic arm has axes which operates within a spherical ‘work envelope’ or potential locus of movement. This is achieved through a combined rotational joint, two rotary joints, and a linear joint. The polar robotic arm is connected to its base via a twisting joint, and the subsequent spherical workspace it has access to make it useful for performing similar roles as cylindrical robotic arms - handling machine tools, spot welding, die casting and arc welding.

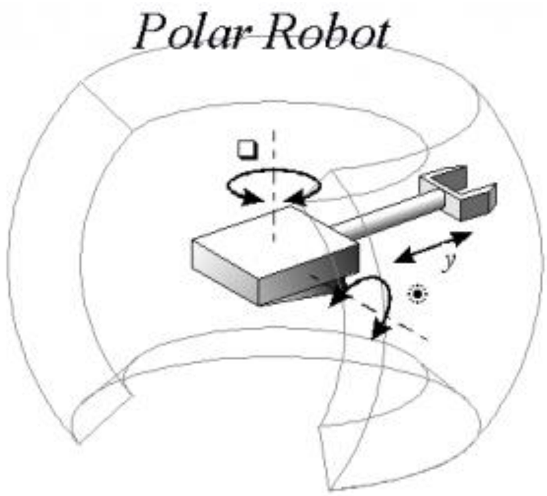


Figure 3.23 Spherical/Polar Robot

Anthropomorphic Robot

This type of robotic arm is the closest mechanical system to resemble the human arm. It has fingers and thumbs. It can perform a wide variety of functions.

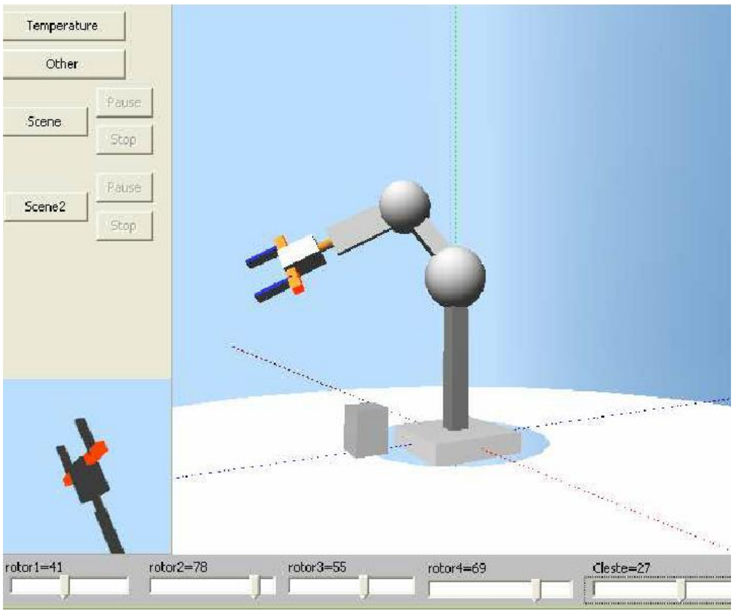


Figure 3.24

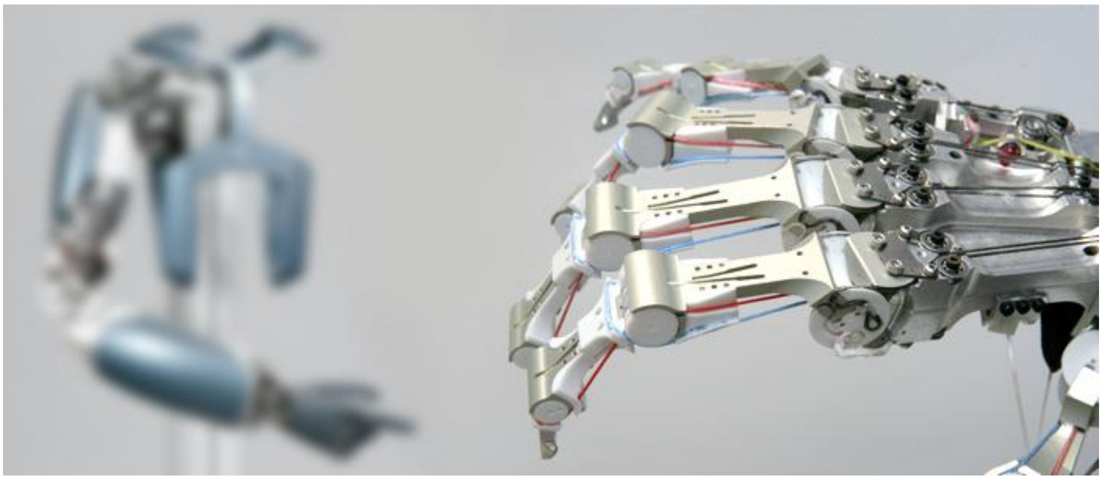


Figure 3.25 Anthropomorphic Robot

Collaborative Robot

Cobots, or collaborative robots, are robots intended to interact with humans in a shared space or to work safely in close proximity. Cobots stand in contrast to traditional industrial robots which are designed to work autonomously with safety assured by isolation from human contact. Cobot safety may rely on lightweight construction materials, rounded edges, and limits on speed or force. Safety may also require sensors and software to assure good collaborative behaviour.

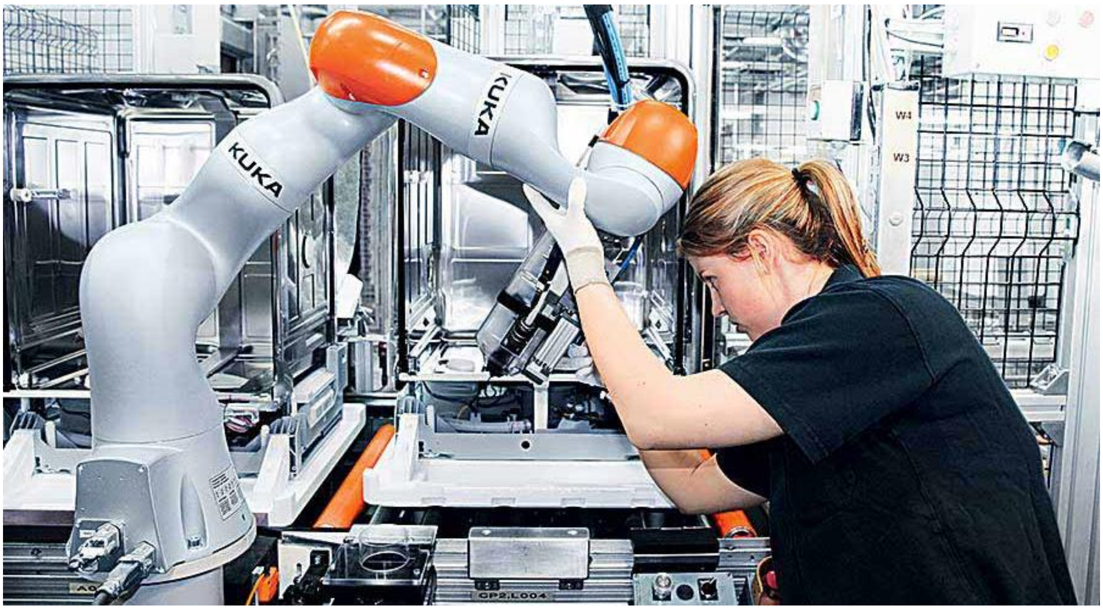


Figure 3.26 Collaborative Robot

Figure 3.27

In the future, it is almost certain such robots will increase in workforce. Reliable, never complaining partners who catch up quick but make few mistakes.

3.5. DATA ANALYSIS

Now, we reached the analytical process of the research. Here, we made decisions, the choices we made determined the path and direction of our project, and to quite a degree, affected the success rate of the project as well.

At this stage, 3 topics involved in this project are starting to come together. However, the analysis of scientific research data is conducted in an individual manner. Before that, we shall take a look at the responses from the Google Form survey.

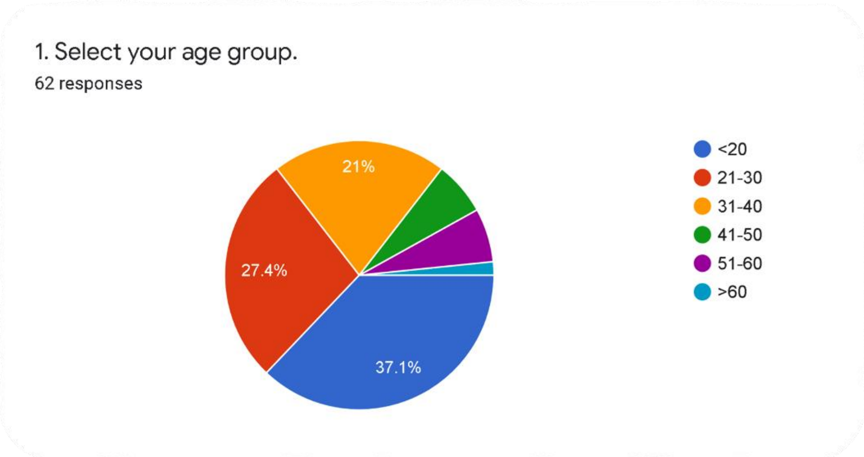


Figure 3.28 Age group

People of all ages participated in the survey. However, the biggest group, the <20 years old, are more than the 21-30 years old by a margin of almost 10%, or 6 respondents. There were 4 respondents each in the 41-50 years old group and 51-60 years old group. Only 1 respondent was over 60 years old.

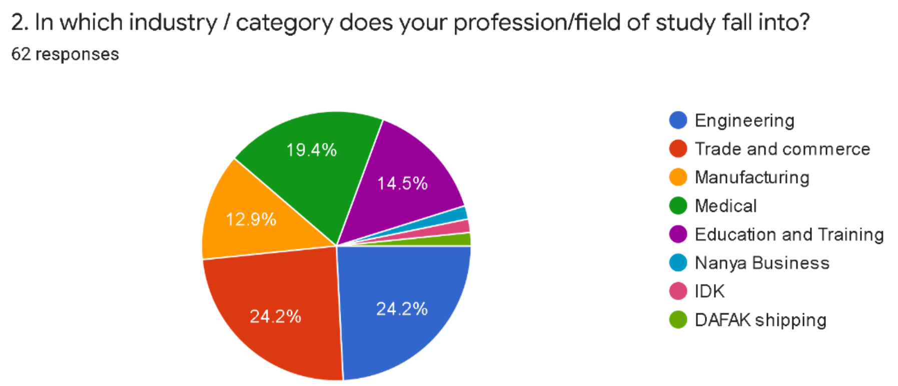


Figure 3.29 Industry

People of all backgrounds participated in the survey. Trade and commerce and Engineering each represent 24.2% of the respondents. 3 respondents did not belong to any of the 5 main categories of profession/ field of study.

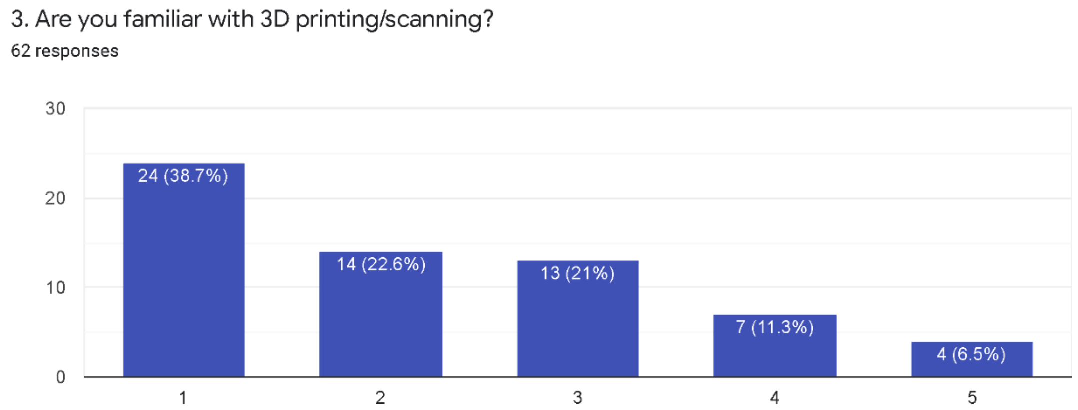


Figure 3.30 Familiarity

As you can see, more people were unfamiliar with 3DP/3DS than those who were familiar.

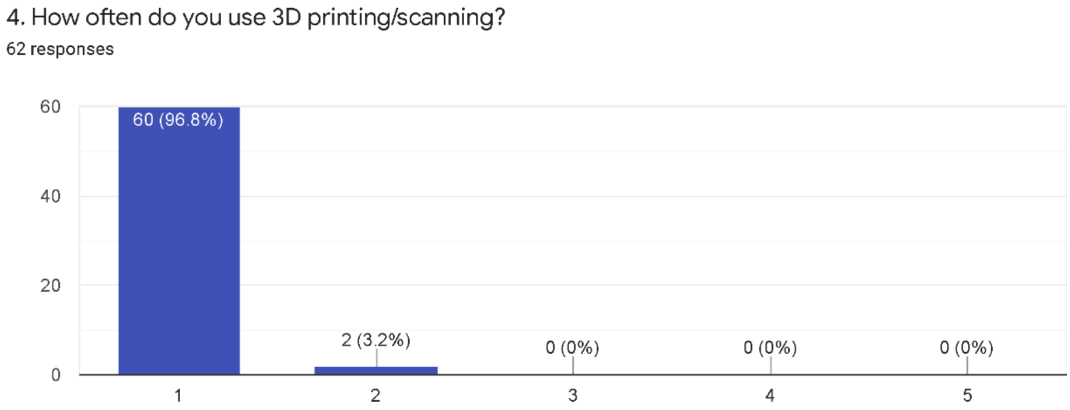


Figure 3.31 Usage

Out of 62 respondents, a whopping 60 do not use 3DP/3DS at all, and only 2 others rarely use these technologies.

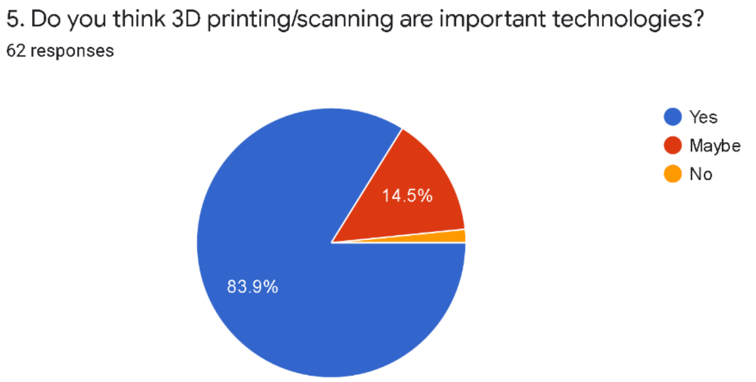


Figure 3.32 Importance

A vast majority of respondents agree that 3DP/3DS are important technologies.

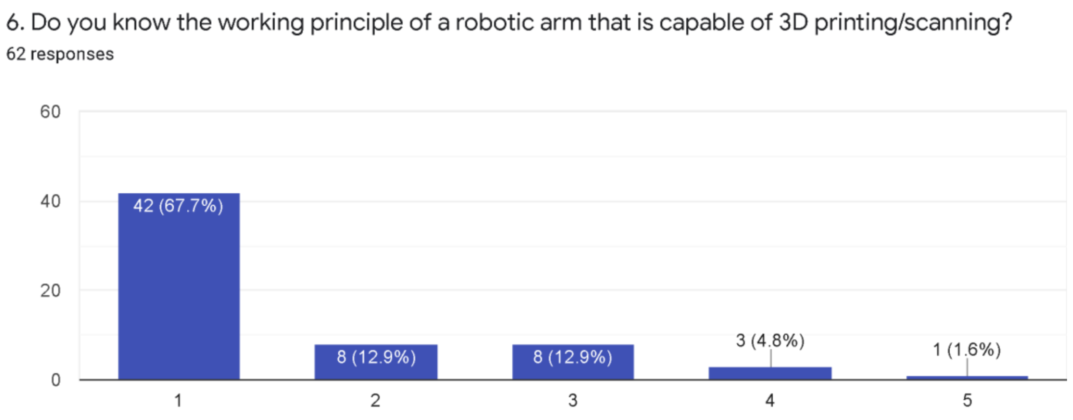


Figure 3.33 Working principle

More than two-thirds of respondents do not know the working principle of a robotic arm capable of 3DP/3DS.

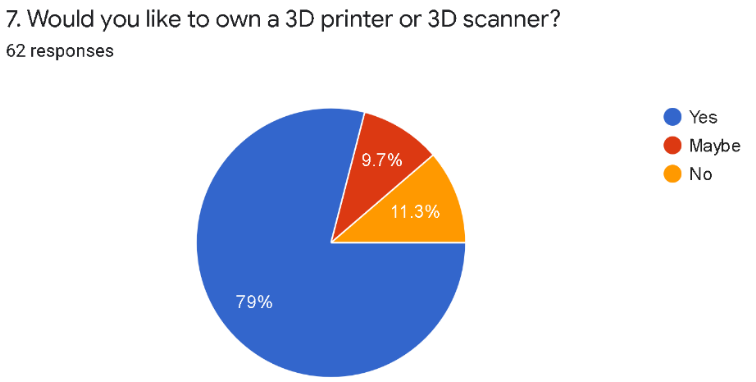


Figure 3.34 Likeability of 3DP/3DS

More than three quarters of respondents would like to own a 3D printer/scanner.

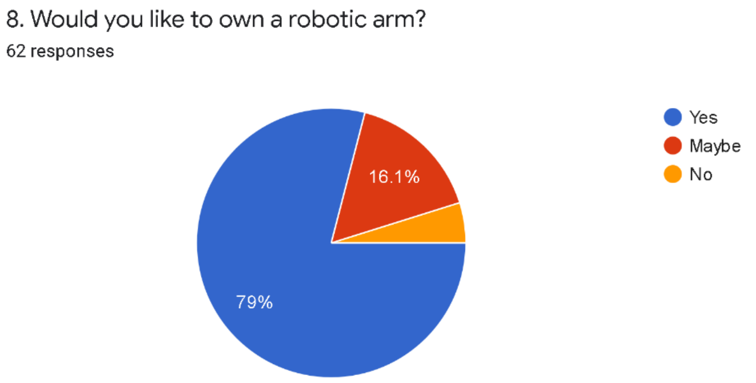


Figure 3.35 Likeability of robotic arm

The same number of respondents would like to own a robotic arm.

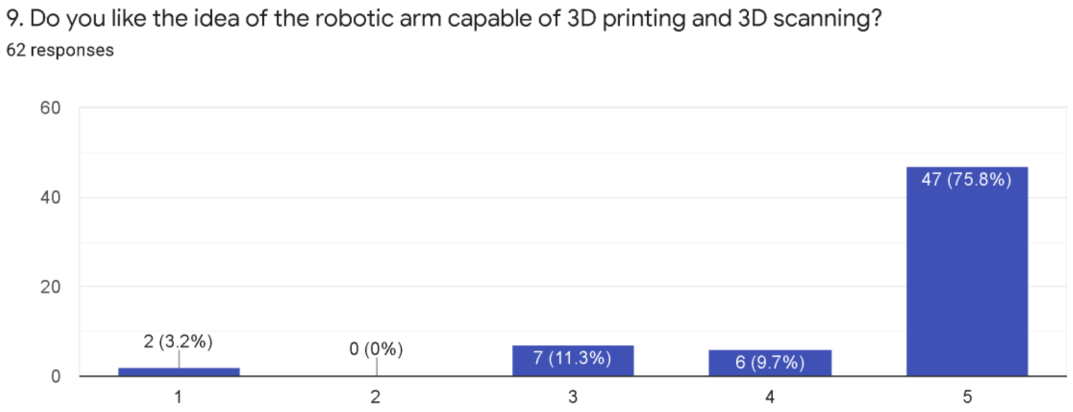


Figure 3.36 Likeability of project

Although most of the respondents lack knowledge in 3DP/3DS and had never used 3DP/3DS before, slightly more than three-quarters of the respondents very much like the 3D Replicating Robotic Arm concept.

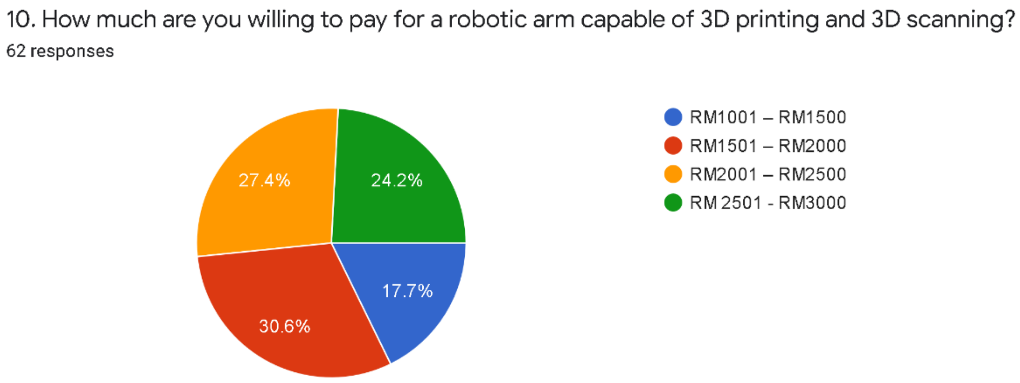


Figure 3.37 Affordability

No option has a convincing majority. Each respondent value 3DP/3DS devices differently.

3.5.1. 3D Printing

With the data obtained, we analysed the different 3DP technologies, to see the pros and cons of each metal. Notes to keep in mind, cost efficiency, ease of use, suitability of use using a robotic arm. Selecting the optimal 3DP process for a particular application can be quite confusing, considering none of us are trained in this field or have sufficient exposure, experience in 3DP. There is often more than one process that are suitable and each of them offers different benefits, like greater dimensional accuracy, superior material properties or better surface finish. Generally, 3 aspects are considered, the required material properties: strength, hardness, impact strength etc.; the functional & visual design requirements: smooth surface, strength, heat resistance etc.; the capabilities of the 3DP process: accuracy, available print volume, layer height etc. Fortunately, after several articles and videos, we found a relatively clear guide. The figure is shown below.

A clear leader from the start was FDM, not only it is most cost efficient, but it is the most popular 3DP technology by far, accounting for about half of all 3D printers. The numbers increase even more when it comes to home use, or non-industrial 3D printers. Furthermore, it is also the most well-known 3DP technology. Prior to this research, we did not know of the existence of technologies such as SLS, SLS, DMLS etc. Only FDM stood out, due to its simple mechanism is also far simpler to understand, the way extruders heat print filament to melt and layer by layer, it is reshaped into a new object. It is mindboggling how FDM was invented and developed later than SLA and SLS, which required complex combination of mirrors and lasers. Until today, maintenance of SLA and SLS machines are still much more tedious when compared to FDM. All we needed at this point was a concrete reason to give us the confidence to trust our intuition and the majority of people.

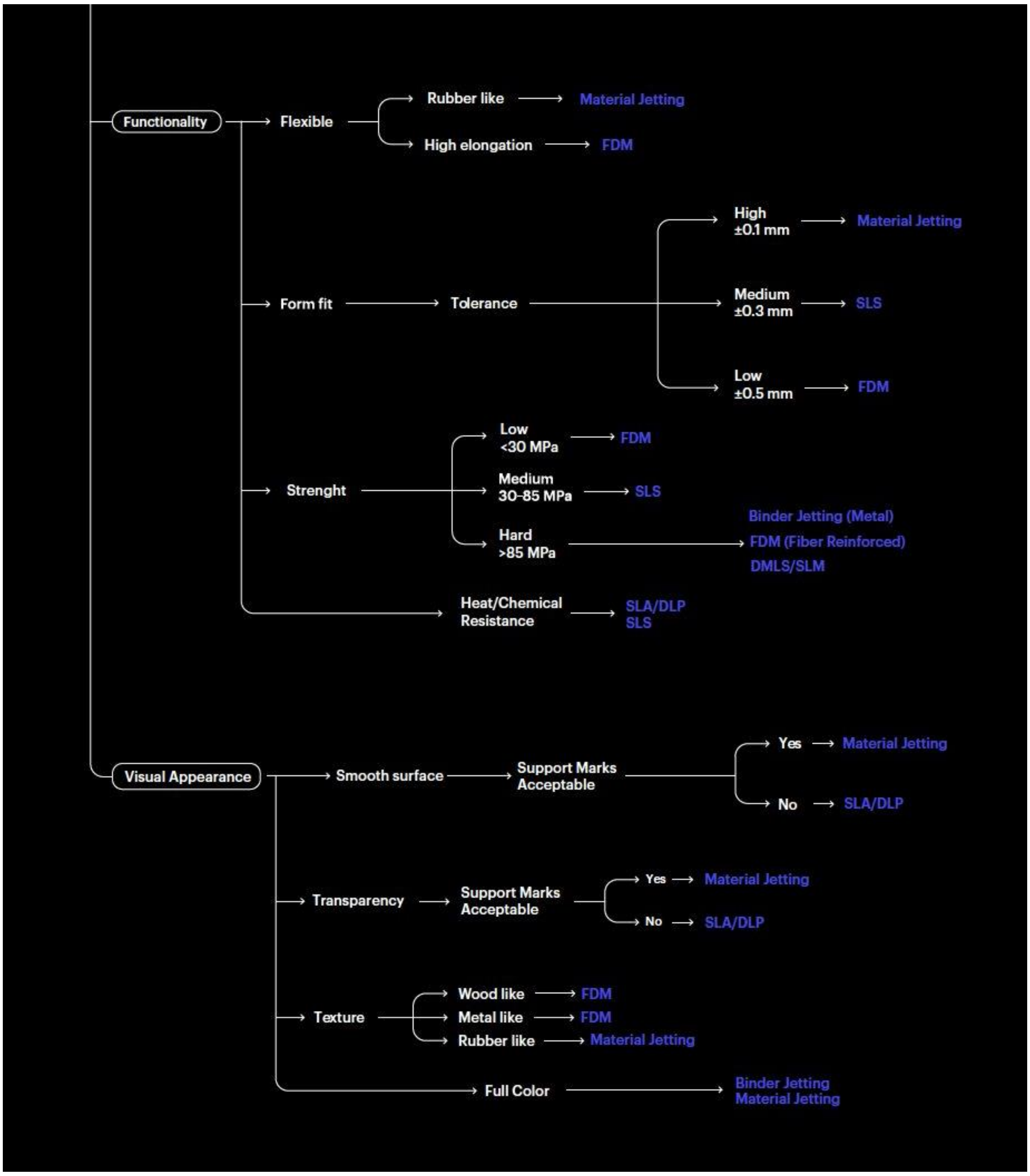


Figure 3.38 "What is your main design requirement?" decision tree by 3D Hubs

FDM was confirmed as our choice of 3DP technology for this project, we proceeded to go into a deeper, more specialised research of FDM. The following is the fabrication process of FDM.

1. A spool of thermoplastic filament is first loaded into the printer. Once the nozzle has reached the desired temperature, the filament is fed to the extrusion head and in the nozzle where it melts.
2. The extrusion head is attached to a 3-axis system that allows it to move in the X, Y and Z directions. The melted material is extruded in thin strands and is deposited layer-by-layer in predetermined locations, where it cools and solidifies. Sometimes the cooling of the material is accelerated through the use of cooling fans attached on the extrusion head.
3. To fill an area, multiple passes are required (similar to colouring a rectangle with a marker). When a layer is finished, the build platform moves down (or in other machine setups, the extrusion head moves up) and a new layer is deposited. This process is repeated until the part is complete.

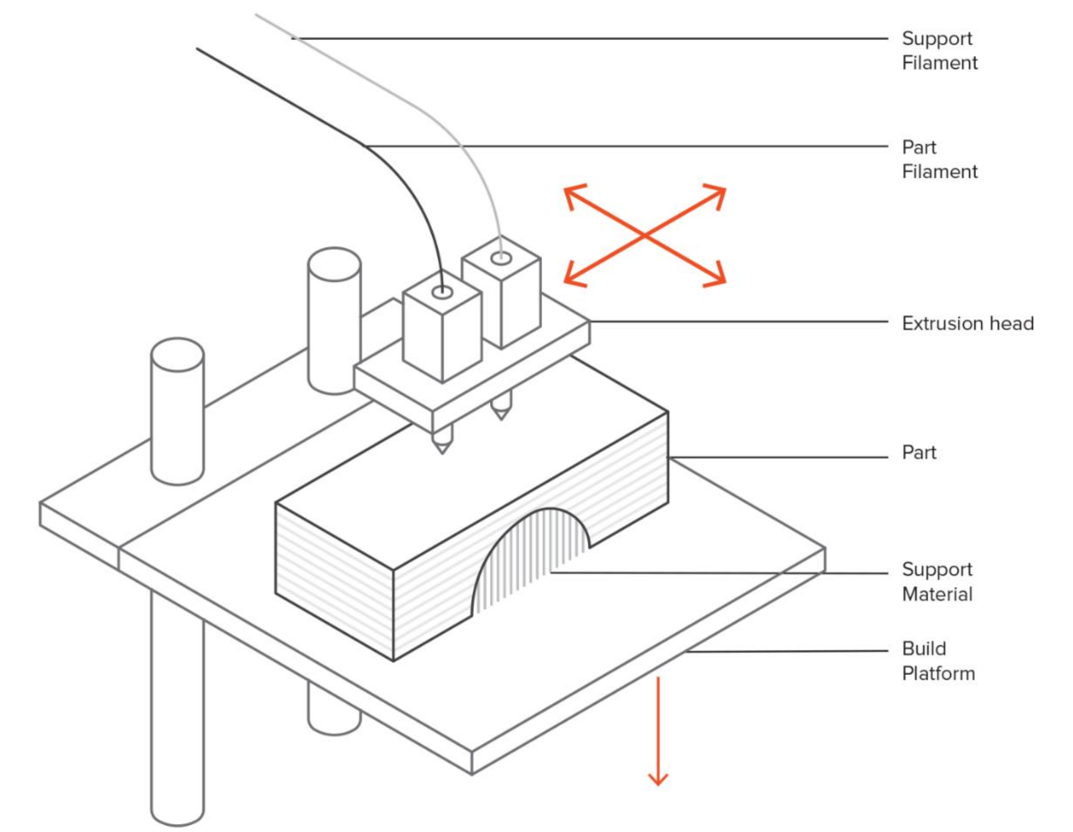


Figure 3.39 FDM illustration

A basic FDM 3DP machine consists of:

- Print bed - a platform to limit the dimension of the product being printed, and to set the product during the printing process.
- Hot end - component that melts the filament for extrusion and maintain a consistent and accurate temperature for successful prints.
- Cooling fan – fan to blow a stream of cold air just under the nozzle, cooling off freshly-extruded plastic to take the needed form.
- Extruder - part that ejects material in liquid or semi-liquid form in order to deposit it in successive layers within the 3DP volume.
- Filament - thermoplastic feedstock for fused deposition through extruders for modelling
- Print display - the firmware of your printer will determine how things are displayed, what options you are given, and navigational functions.

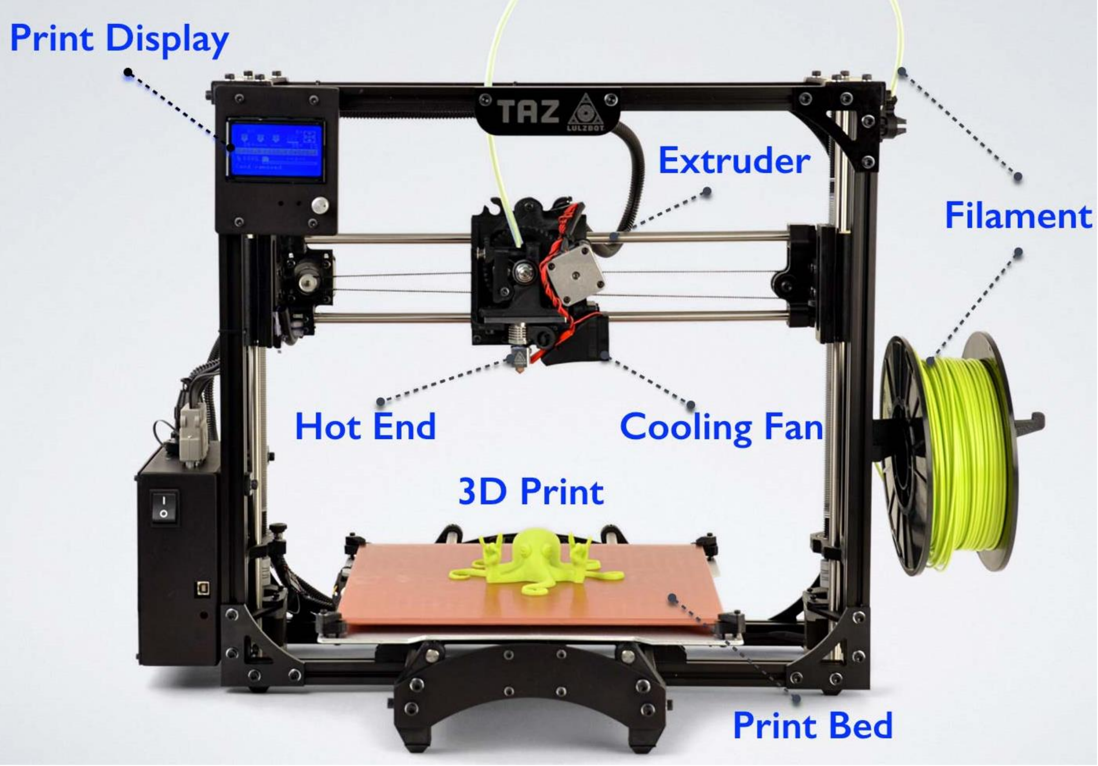


Figure 3.40 FDM printer labelled

Print Parameters

Most FDM systems allow the adjustment of several process parameters, including the temperature of both the nozzle and the build platform, the build speed, the layer height and the speed of the cooling fan. These are generally set by the operator, so they should be of little concern to the designer.

What is important from a designer's perspective is build size and layer height:

The available build size of a desktop 3D printer is commonly 200 x 200 x 200 mm, while for industrial machines this can be as big as 1000 x 1000 x 1000 mm. If a desktop machine is preferred (for example for reducing the cost) a big model can be broken into smaller parts and then assembled. The typical layer height used in FDM varies between 50 and 400 microns and can be determined upon placing an order. A smaller layer height produces smoother parts and captures curved geometries more accurately, while a larger height produces parts faster and at a lower cost. A layer height of 200 microns is most commonly used. An article discussing the impact of layer height in a 3D printed part can be found here.

Warping

Warping is one of the most common defects in FDM. When the extruded material cools during solidification, its dimensions decrease. As different sections of the print cool at different rates, their dimensions also change at different speeds. Differential cooling causes the build-up of internal stresses that pull the underlying layer upwards, causing it to warp, as seen in figure 3. From a technology standpoint, warping can be prevented by closer monitoring of the temperature of the FDM system (e.g., of the build platform and the chamber) and by increasing the adhesion between the part and the build platform.

The choices of the designer can also reduce the probability of warping:

- Large flat areas (think of a rectangular box) are more prone to warping and should be avoided when possible.
- Thin protruding features (think of the prongs of a fork) are also prone to warping. In this case, warping can be avoided by adding some sacrificial

material at the edge of the thin feature (for example 200 microns thick rectangle) to increase the area that touches the build platform.

- Sharp corners are warping more often than rounded shapes, so adding fillets to your design is a good practice.
- Different materials are more susceptible to warping: ABS is generally more sensitive to warping compared to PLA or PETG, due to its higher glass transition temperature and relatively high coefficient of thermal expansion.

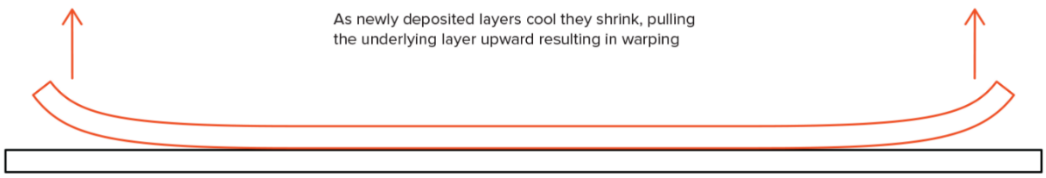


Figure 3.41 Illustration of warping

Figure 3.42 A warped FDM part printed in ABS

Layer Adhesion

Good adhesion between the deposited layers is very important for an FDM part. When the molten thermoplastic is extruded through the nozzle, it is pressed against the previous layer. The high temperature and the pressure re-melts the surface of the previous layer and enables the bonding of the new layer with the previously printed part. The bond strength between the different layers is always lower than the base strength of the material.

This means that FDM parts are inherently anisotropic: their strength in the Z-axis is always smaller than their strength in the XY-plane. For this reason, it is important to keep part orientation mind when designing parts for FDM.

For example, tensile test pieces printed horizontally in ABS at 50% infill were compared to test pieces printed vertically and were found to have almost 4 times greater tensile strength in the X, Y print direction compared to the Z direction (17.0 MPa compared to 4.4 MPa) and elongated almost 10 times more before breaking (4.8% compared to 0.5%).

Moreover, since the molten material is pressed against the previous layer, its shape is deformed to an oval. This means that FDM parts will always have a wavy surface, even for low layer height, and that small features, such as small holes or threads may need to be post processed after printing.

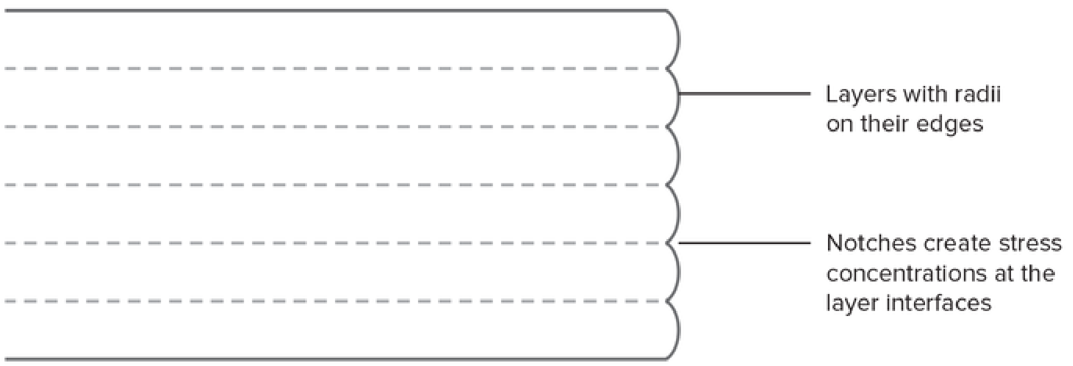


Figure 3.43 Illustration of layer adhesion

Figure 3.44 close up of layers of a FDM print

Support Structure

Support structure is essential for creating geometries with overhangs in FDM. The melted thermoplastic cannot be deposited on thin air. For this reason, some geometries require support structure. A detailed article explaining the use of support structure can be found here.

Surfaces printed on support will generally be of lower surface quality than the rest of the part. For this reason, it is recommended that the part is designed in such a way to minimize the need for support.

Support is usually printed in the same material as the part. Support materials that dissolve in liquid also exist, but they are used mainly in high-end desktop or industrial FDM 3D printers. Printing on dissolvable supports significantly improves the surface quality of the part, but increases the overall cost of a print, as specialist machine (with dual extrusion) are required and because the cost of the dissolvable material is relatively high.

Infill & Shell Thickness

FDM parts are usually not printed solid to reduce the print time and save material. Instead, the outer perimeter is traced using several passes, called the shell, and the interior is filled with an internal, low-density structure, called the infill.

Infill and shell thickness affect greatly the strength of a part. For desktop FDM printers, the default setting is 25% infill density and 1 mm shell thickness, which is a good compromise between strength and speed for quick prints.

Figure 3.45 Infill & Shell Thickness

Print Materials

One of the key strengths of FDM is the wide range of available materials. These can range from commodity thermoplastics (such as PLA and ABS) to engineering materials (such as PA, TPU, and PETG) and high-performance thermoplastics (such as PEEK and PEI).

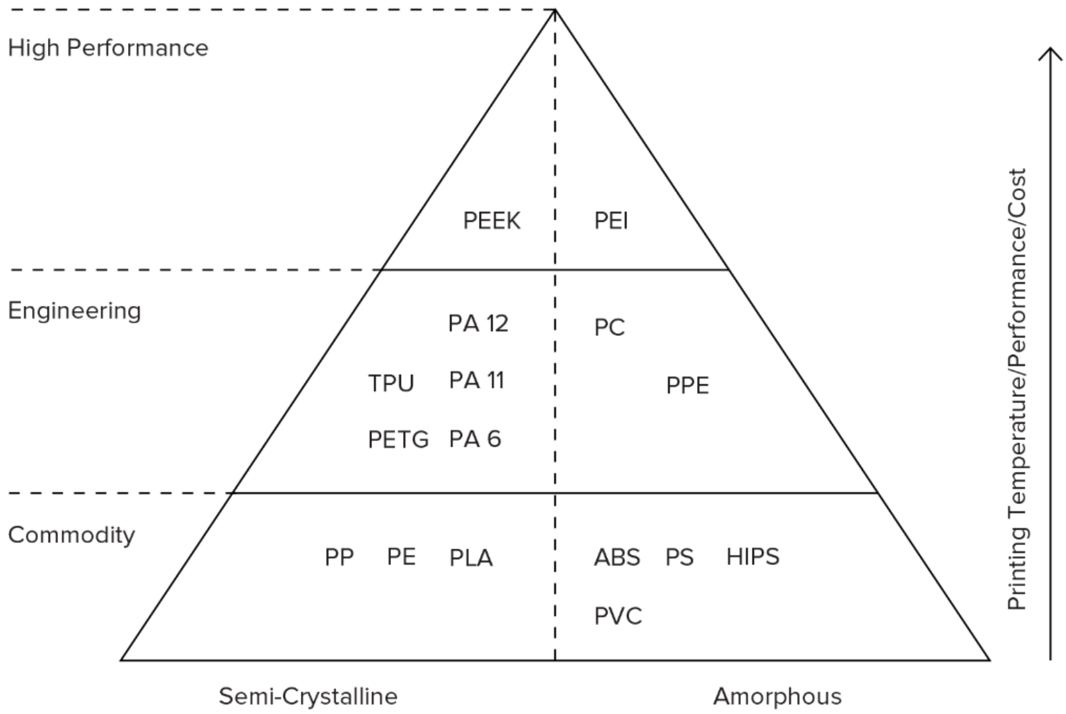


Figure 3.46 Pyramid of print material

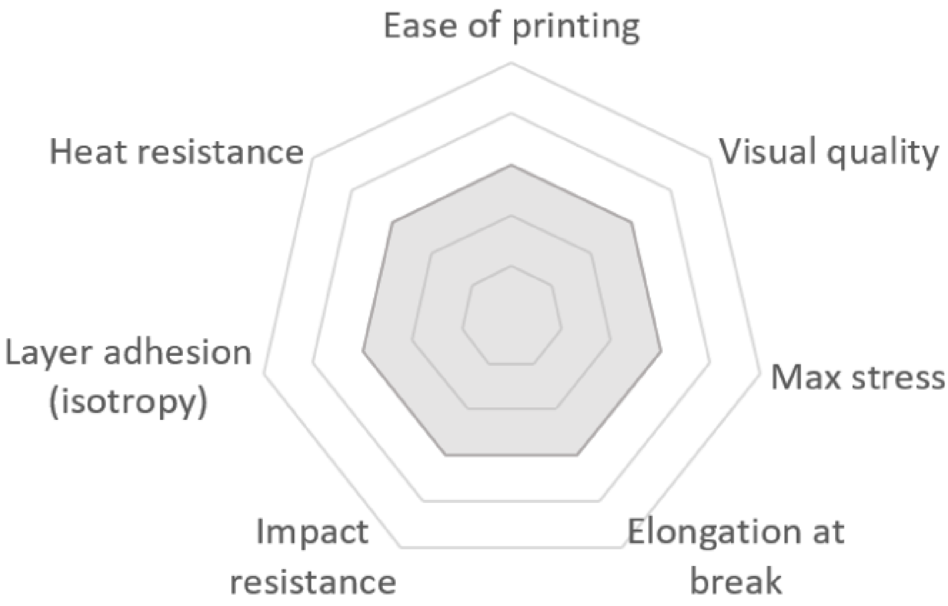


Figure 3.47 A spider web graph showing the material properties that will be compared

- **Ease of printing:** How easy it is to print a material: bed adhesion, max printing speed, frequency of failed prints, flow accuracy, ease to feed into the printer etc.
- **Visual quality:** How good the finished object looks.
- **Max stress:** Maximum stress the object can undergo before breaking when slowly pulling on it.
- **Elongation at break:** Maximum length the object has been stretched before breaking.
- **Impact resistance:** Energy needed to break an object with a sudden impact.
- **Layer adhesion (isotropy):** How good the adhesion between layers of material is. It is linked to "isotropy" (=uniformity in all directions): the better the layer adhesion, the more isotropic the object will be.
- **Heat resistance:** Max temperature the object can sustain before softening and deforming.

1. Acrylonitrile butadiene styrene (ABS) - Usually picked over PLA when higher temperature resistance and higher toughness is required.

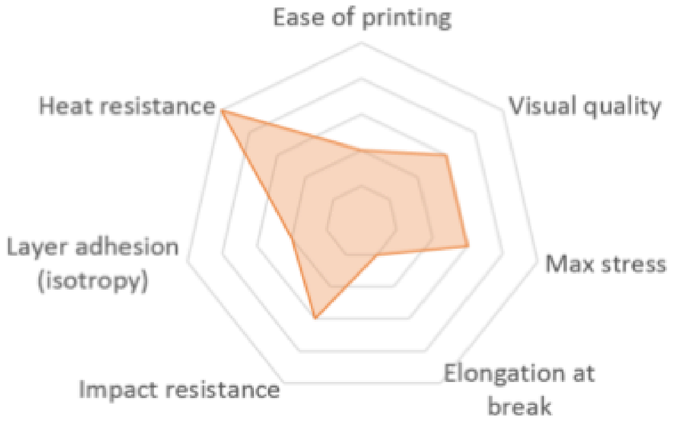


Figure 3.48 ABS

Pros	**Cons**
Can be post-processed with acetone vapours for a glossy finish	UV sensitive
Can be post-processed with sanding paper and painted with acrylics	Odour when printing
Acetone can also be used as strong glue	Potentially high fume emissions
Good abrasion resistance	

Table 3.1 ABS

2. Polylactic acid (PLA) - Easiest polymer to print and provides good visual quality. It is very rigid and actually quite strong but is very brittle.

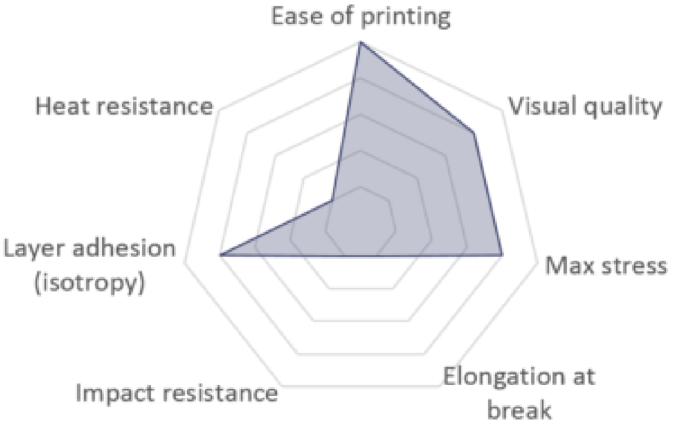


Figure 3.49 PLA

Pros	**Cons**
Biosourced, biodegradable	Low humidity resistance
Odourless	Cannot be glued easily
Can be post-processed with sanding paper and painted with acrylics	
Good UV resistance	

Table 3.2 PLA

3. Polyamide Nylon (PA) - Possesses great mechanical properties, and in particular, the best impact resistance for a non-flexible filament. However, layer adhesion can be an issue.

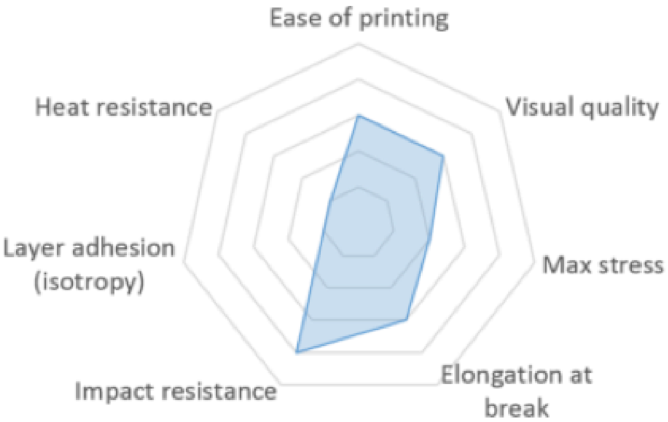


Figure 3.50 Nylon

Pros	**Cons**
Good chemical resistance	Absorbs moisture
High strength	Potentially high fume emissions

Table 3.3 Nylon

4. Polyethylene terephthalate (PET) - Slightly softer polymer that is well rounded and possesses interesting additional properties with few major drawbacks.

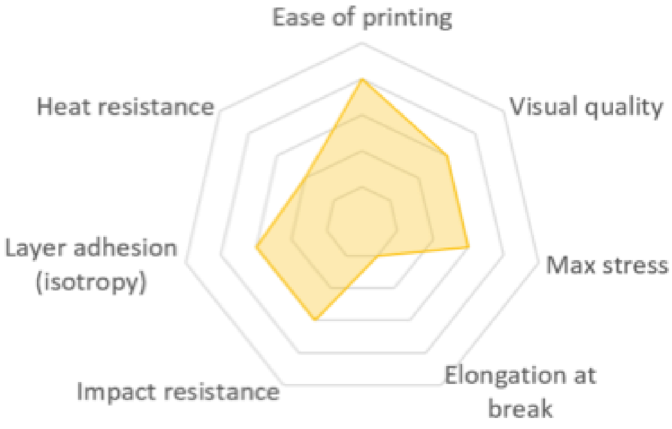


Figure 3.51 PET

Pros	**Cons**
Can come in contact with foods	Heavier than PLA and ABS
High humidity resistance	
High chemical resistance	
Recyclable	
Good abrasion resistance	
Can be post-processes with sanding paper and painted with acrylics	

Table 3.4 PET

5. Thermoplastic polyurethane (TPU) - Mostly used for flexible applications, but it is very high impact resistance can open for other applications.

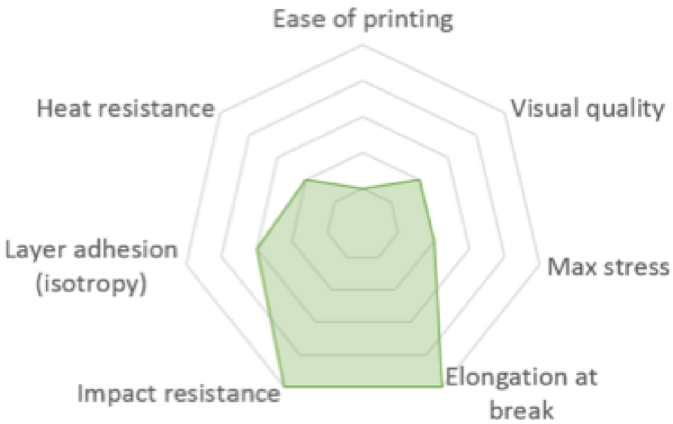


Figure 3.52 TPU

Pros	**Cons**
Good abrasion resistance	Difficult to post process
Good resistance to oil and grease	Cannot be glued easily

Table 3.5 TPU

6. Polycarbonate (PC) - Strongest material of all and can be an interesting alternative to ABS as the properties are quite similar.

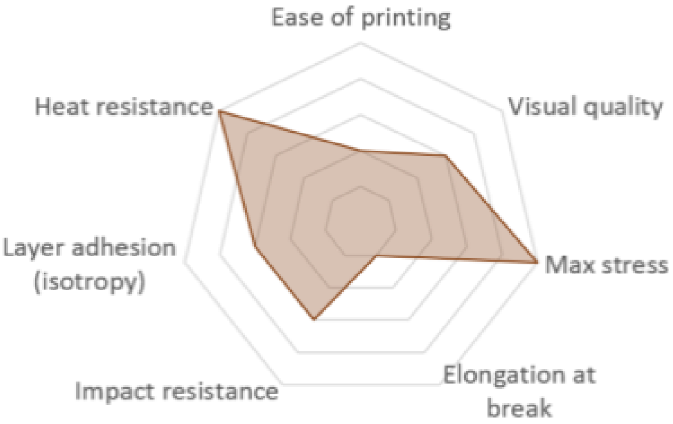


Figure 3.53 PC

Pros	Cons
Can be sterilized	UV sensitive
Easy to post-process (sanding)	

Table 3.6 PC

Post Processing

FDM parts can be finished to a very high standard using various post-processing methods, such as sanding and polishing, priming, and painting, cold welding, vapor smoothing, epoxy coating and metal plating.

The table below summarises the main characteristics of Fused Deposition Modelling (FDM).

Materials	Thermoplastics (PLA, ABS, PETG, PC, PEI etc)
Dimensional accuracy	± 0.5% (lower limit ± 0.5 mm) – desktop ± 0.15% (lower limit ± 0.2 mm) - industrial
Typical build size	200 x 200 x 200 mm – desktop 1000 x 1000 x 1000 mm - industrial
Common layer height	50 to 400 microns
Support	Not always required (dissolvable available), refer to table

Table 3.7 FDM characteristics

Benefits & Limitations of FDM

The key advantages and disadvantages of the technology are summarised below:

- FDM is the most cost-effective way of producing custom thermoplastic parts and prototypes.
- The lead times of FDM are short (as fast as next-day-delivery), due to the high availability of the technology.
- A wide range of thermoplastic materials is available, suitable for both prototyping and some non-commercial functional applications.
- FDM has the lowest dimensional accuracy and resolution compared to other 3DP technologies, so it is not suitable for parts with intricate details.
- FDM parts are likely to have visible layer lines, so post processing is required for a smooth finish.
- The layer adhesion mechanism makes FDM parts inherently anisotropic.

3.5.2. 3D Scanning

Much like 3DP technologies, although there are many types of 3DS technologies, there were only very few clear contenders for our project. This round, the fight was between laser triangulation, photogrammetry, and structured light scanning. Structured light was very interesting and attractive, as it enables both high resolution & speed and is effective for Human Body Scans. Structured light can achieve higher accuracy than laser scanning due to the noise caused by laser speckle patterns. In general, structured light scanning provides the best resolution and accuracy, typically slightly higher than laser scanning. However, there was no feasible way to assembling a structured light 3D scanner on our 3D Replicating Robotic Arm.

It now narrows down to Laser Triangulation and Photogrammetry.

LASER TRIANGULATION	3D PHOTOGRAMMETRY
-To capture 3D measurements by pairing a laser illumination source with camera.	-Process that estimate 3D coordinate of surface points using pictures of single

-Laser Triangulation set-up using the fixed angular offset of the camera & laser position, it is possible to derive the linear distance between the inspection surface & camera sensor. -The scanners used comprise three main elements (which form the three verticals of a triangle): a laser transmitter, a camera, and the object to be scanned.	physical object taken from different angle. -shot 50-80 pictures to capture every detail and some pictures might get discarded if the program does not find enough similarities with other pictures. -Software: • Colmap • 3df zephr • Visual SFM • Meshroom
-through the camera, the 3d scanner analyses the deformation of the line limited by the laser on the reliefs of the object in order to determine, by means of trigonometric calculation, its position in space. -the angle formed between the camera and the beam of the laser, the distance from the camera to the object and that of the laser source to the object (known by calculating the time taken by the laser to make a round trip), are all parameters which make it possible to determine the spatial coordinates of the object.	Process for scanning: 1.take the bunch of pictures of object from all directions by using camera or phone. 2.use as an input for a specialised software. 3.this software will look for features that are visible in multiple pictures. 4.try to guess which point was the picture taken. 5.after knowing the positions & orientations, it creates a 3d point that corresponds to the 2d feature on the photo (basically a pixel) 6.ideally, you finished 3d mesh as an input.

Table 3.8 Laser triangulation vs photogrammetry

From the table above, we can see that Photogrammetry would require a camera with at least the quality of a modern smartphone camera, more suitable for large scale scanning, such as using a drone to plot a 3D map of an area, and is less precise and accurate compared to laser triangulation 3DS, therefore we decided that laser triangulation 3DS is most suitable for the 3D Replicating Robotic Arm.

There was the thought of using camera lenses from disposed phones, but we failed to get together the logistics of the movements of the robotic arm taking images of the object to be scanned. Firstly, the range of scanning and the size of objects abled to be scanned would be very small. Secondly, it would be too time consuming. After all, building a turntable for the Laser Triangulation 3D scanner was unavoidable.

Laser Triangulation 3D Scanning

Laser triangulation is a machine technique used to capture 3-dimensional measurements by pairing a laser illumination source with a camera. The laser beam and the camera are both aimed at the inspection target, however by adopting a known angular offset between the laser source and the camera sensor, it is possible to measure depth differences using trigonometry.

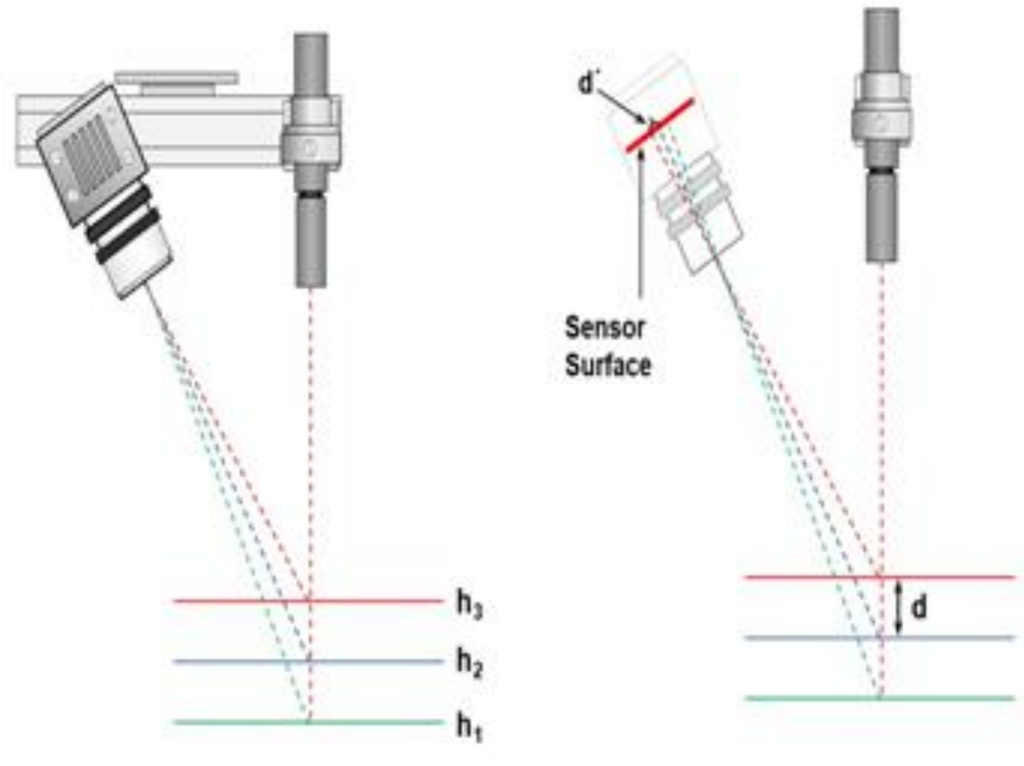


Figure 3.54 Laser triangulation

The red, green and the blue dotted lines in *Figure 3.54* illustrate how the reflected laser light will strike different sensor locations, depending on the distance between the laser source and the inspection target (or "surface"). Notice that the position where the reflected laser light strikes the sensor's surface is dependent on the vertical offset of the target from the laser/camera assembly. In the other words, as the distance between the laser light source and inspection point changes, so changes the location on the sensor where the light is detected. Changes from the nominal vertical distance (denoted by distance d from line h2 in *Figure 3.54* will produce proportional changes in position (d') at the sensor. Larger changes vertical distance will result in a larger positional deflection at the sensor.

One by-product of this technique that you might notice when looking at *Figure 3.54* is the inherent trade-off between range and precision. If you want maximize depth precision, you will also need to maximize the positional offset sensitivity at the sensor. In the other words, a very small change in the vertical distance of the target produces a proportionally large shift of position at the sensor. In this case, the variability of the target position must be limited. When a small change in the vertical distance produces a wider sweep at the sensor, it follows that you may soon exceed the physical size of the sensor with increasing target depth variability.

On the other hand, if u need a wider vertical range in order to capture more depth possibilities for your target, then you must be prepared to accept the inevitable reduction in the measurement resolution that goes hand in hand with this increased measurement range. The limiting factor is physical size and pixel resolution of the sensor. The ability of the system to differentiate one depth from next will depend on the sensor's ability to detect a measurable difference in response to the reflected laser light. If change in target distance produces no measurable change at the sensor, then the change in position is not within the resolution limits of the system. In practice, an experienced vision system designer will balance range and measurement resolution based on the characteristics and variability of the inspection target to arrive at the optimal compromise.

Types of Laser Triangulation Systems

In most cases, a visible light laser diode is used. A point or line projection optic is used to focus the beam onto the target, and a 2-D complementary metal oxide semiconductor (CMOS) or charge-coupled device (CCD) camera is used as the sensor. The system can be assembled from complementor all of these elements can be incorporated into convenient (and popular) "sensor head" format. Several options are available, depending on your specific requirements.

The simplest triangulation sensor is a 1-D distance sensor, which projects a single laser point onto the surface. The light bounces back to a positionally sensitive sensor or CMOS/CCD array. The triangulation method discussed in the previous section is used to calculate the effective distance from sensor to surface. Using a single point, it is possible to measure a single point distance, or with the addition of a motion system, a point-by-point profile scan or surface scan is also possible.

2 ½-D and 3-D Sensors

Scanning the entire area of a large surface using a single point 1-D sensor can be time consuming. The so-called "2 ½-D" systems are more practical for surface scanning applications. 2 ½ D sensors function in the same way as the 1-D sensors, however rather than utilizing a single laser point, a laser line is projected on the target. Rather than just a single point, the reflected laser line provides a complete cross-section of the inspection target. With the addition of a 1-D motion stage, an entire 3-D surface map can be reconstructed by appending the individual cross-sections. While the 2 ½-D sensors are a dramatic improvement over single point, 1-D sensors when you need to scan an entire surface, they are still not as convenient as a true 3-D triangulation system. True 3D triangulation sensors incorporate memory buffers so that a multitude of 2 ½ D scans can be captured and stored. Using software algorithms (stored in firmware), 3-D sensors can assemble a complete 3-D image and perform sophisticated image processing on the image before delivering it for display or further analysis. True 3-D cameras and sensors typically return a 16-bit "height map" image. The X and Y positions correspond to the expected positions you would see in a 2-D image, but the intensity (brightness) values for each pixel in the image corresponds to the Z (height) information. If the sensor has been calibrated, a floating-point image can be generated, with height values in millimetres (mm) for example.

Figure 3.55 illustrates the output of a 3D triangulation system that is used to detect glue bead flaws. Detecting Flaws in a Glue Bead with Laser Triangulation.

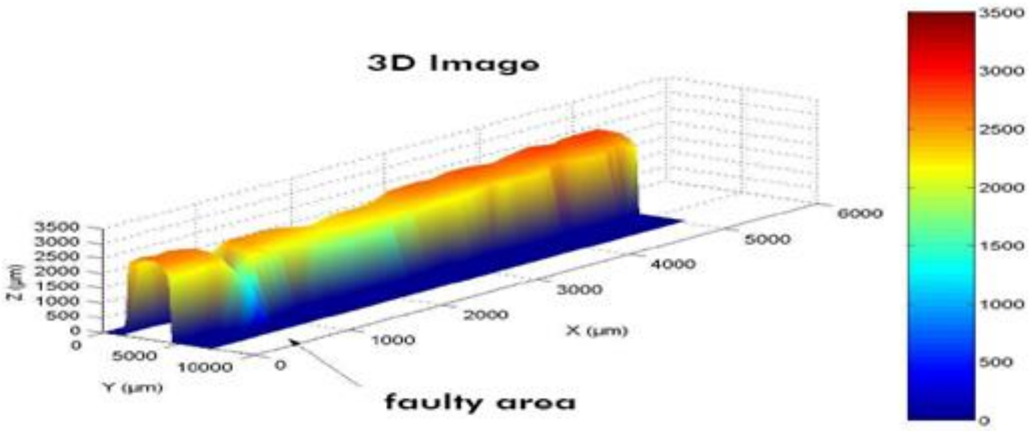


Figure 3.55 Illustration of 3D triangulation output

Laser triangulation is commonly used for machine vision because it offers a useful balance between resolution & precision and can be used in high-speed applications. It offers flexibility with respect to working distance and field front view and can be used to meet a wide range of practical challenges.

Advantages

- Its low price, with the first DIY models available for only a few hundred Ringgit.
- Its acquisition speed (less than 10minutes on average for an object) and its precision level (of the order of 0.01mm) also make it a popular technology.

Disadvantages

- It should be noted that the digitization of transparent or reflective surfaces can be prove difficult, a problem that can be circumvented by using a white powder.
- Its limited range (only a few meters) also reduces the number of possible applications. However, this does not concern us as our project only involves 3DS of objects on the turntable.

3.5.3. Robotic Arm

Lastly, we have the robotic arm, the main body of our device. After studying countless robotic arms, including both for professional and non-professional usage, industrial and home use, mechanical and pneumatic, some even electromagnetic, we realised robotic arm dwarfs both 3DP and 3DS in terms of development and varieties. Our focus was more towards home-use and semi-professional robotic arms that are often used in education institutions. There were several robotic arms we took much exceptional inspiration from, due to their ability of having submillimetre precision and repeatability for 3DP operations.

The first is Rotrics, or before it changed its named, Hexbot, The Modular All-In-1 Desktop Robot Arm for Everyone. It was a fund raiser start up project campaign on IndieGoGo which reach their campaign goal within 5 minutes. Its features are shown below. It was the first commercially available 4- axis robotic arm with 0.1mm precision and 0.05mm repeatability that is able to laser engrave and cut, print in 3D, do pick and placing tasks, draw, and write.

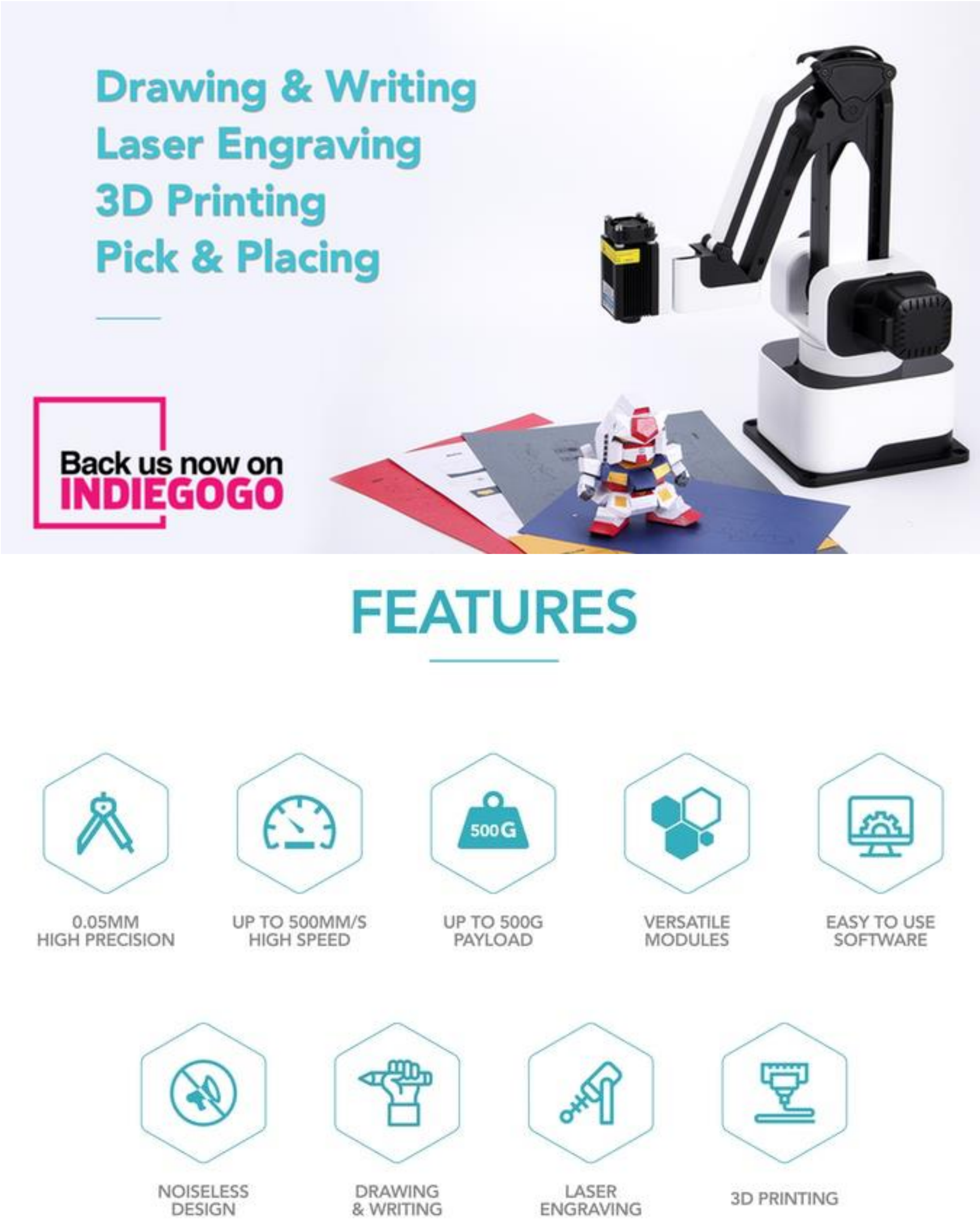


Figure 3.56 Rotrics

Next is the Dobot M1, a SCARA Collaborative Robot Arm. Its SCARA design also led to some of our prototypes being SCARA as well. DOBOT M1 is a cost-effective intelligent robotic arm for light industry. With high precision, wide working range, complete functions, and secondary development, it provides users more ways to use. M1 can realize multiple functions of assembly line work such as soldering, visual recognition and PCB plug-in, helping to construct the intelligent industrial system. It is capable of not only FDM printing, but SLA printing as well, truly revolutionary, and astounding achievements by the bold Chinese company.

Figure 3.57 DOBOT M1

Figure 3.58 DOBOT M1 2^{nd} generation

Last but not least, another robotic arm from Dobot, Lightweight Intelligent Training Robotic Arm - An all-in-one STEAM Education Platform, Dobot Magician. The Dobot Magician is a multifunctional desktop robotic arm for practical training education. Installed with different end-tools, DOBOT Magician can realize interesting functions such as 3DP, laser engraving, writing, and drawing. It supports secondary development by 13 extensible interfaces and over 20 programming languages, which really makes your creativity and imagination increase without any limitation. As the good performance both in hardware design and software application, DOBOT Magician has won the CES 2018 Innovation Award and iF DESIGN AWARD 2018. It has a 4-axis robotic arm with repeatability of 0.2mm, maximum payload of 500g, and maximum reach of 320g.

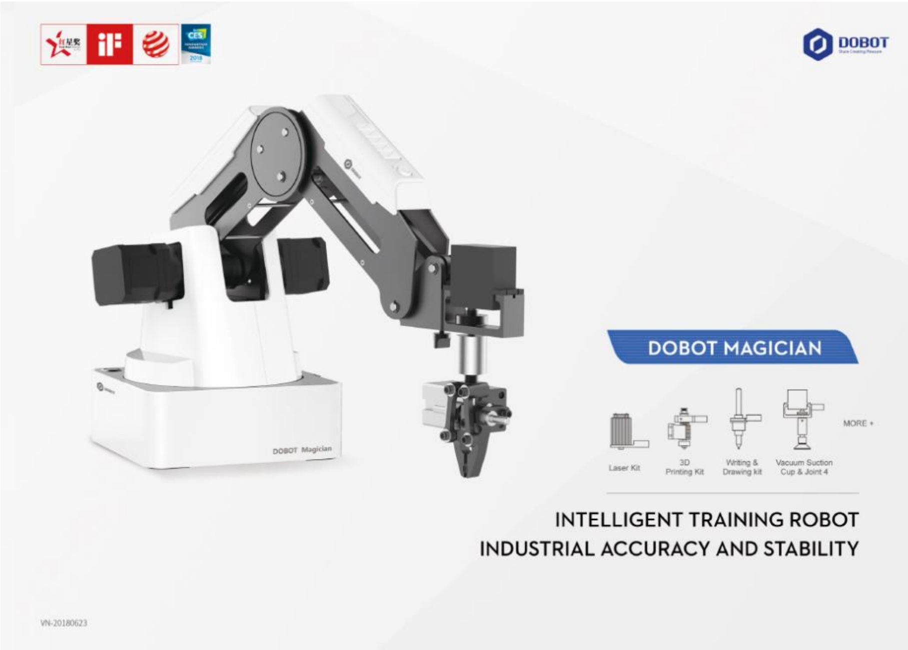


Figure 3.59 DOBOT Magician

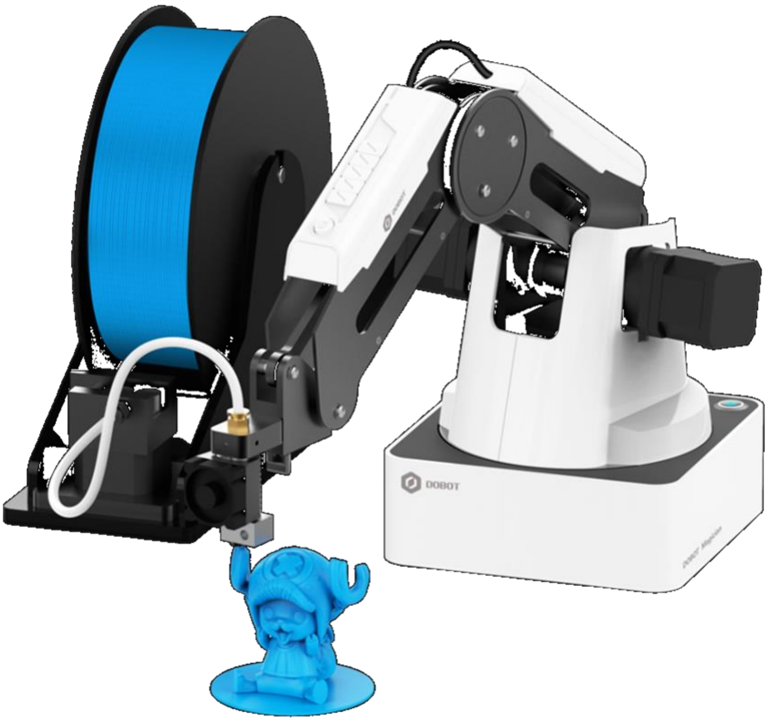


Figure 3.60 DOBOT Magician 3D printing

Due to similarities in usage, the above-mentioned robotic arms played a crucial part in our research, especially due to our lack of knowledge and skills in the field. These robotic arms indirectly influenced the design of our own project in many ways, from number of axis, the use of SCARA designs, the length of the robotic arms etc., as you will observe in the following subchapter, Project Design.

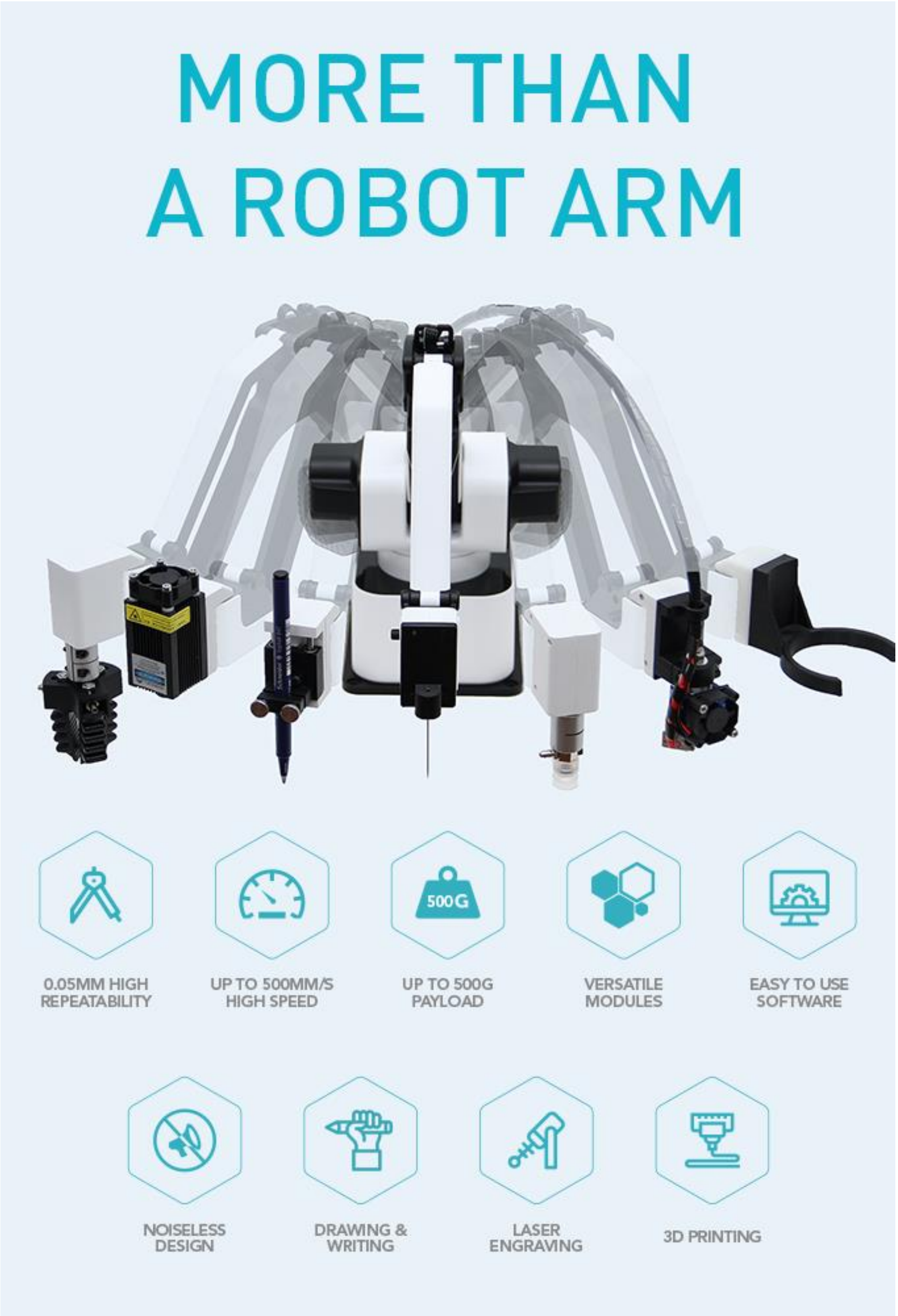


Figure 3.61 DOBOT Magician feature poster

To recap, for 3DP technology, we chose Fused Deposition Modelling (FDM), whereas for 3DS technology, we chose Laser Triangulation 3DS. One important aspect of the project we have yet to mention and discuss is the program and interface. After several discussion at group meetings, we decided that we lack the expertise for any complicated programs or coming up with an operating system ourselves, and have decided to use the very fundamental, Arduino to operate our robotic arm, FDM printer and Laser scanner.

3.6. PROJECT DESIGN

Among all the steps and processes involved in the project, the design of the project itself, the outlook, shape, and build of the 3D Replicating Robotic Arm, by miles, was the individual task that took the most amount of time. A quick look at the Gantt chart, and you will see Project Design stretching from week 5 all through week 14, the only activity taking more than 3 weeks, as a matter of fact, it tripled 3 weeks. The constant loop of sketching, drawing, discussing, then comes new concepts, and repeating the sketching, drawing, discussing process, again and again, up until week 14, whereby a prototype design that is ready to be proposed becomes ready.

Starting at week 4, we had the first sketches of the project.

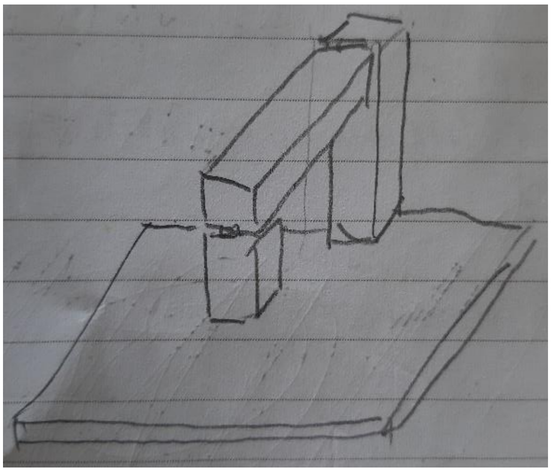


Figure 3.62 Drawing 1

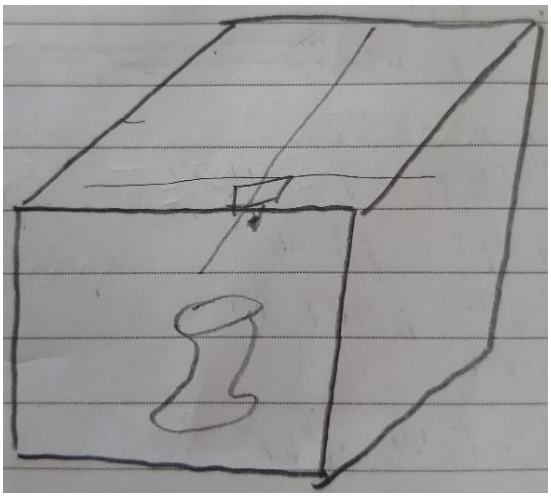
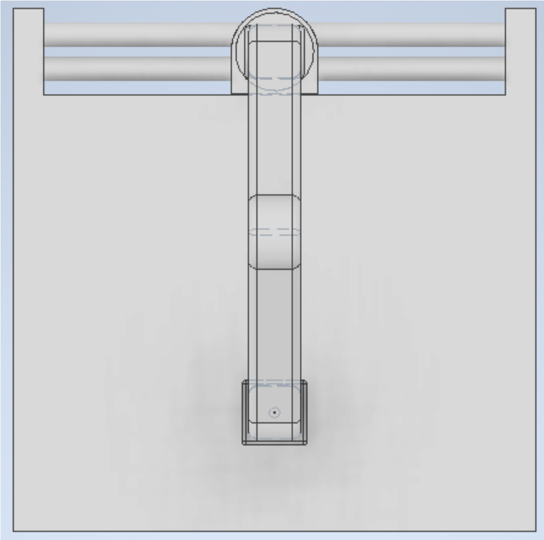


Figure 3.63 Drawing 2

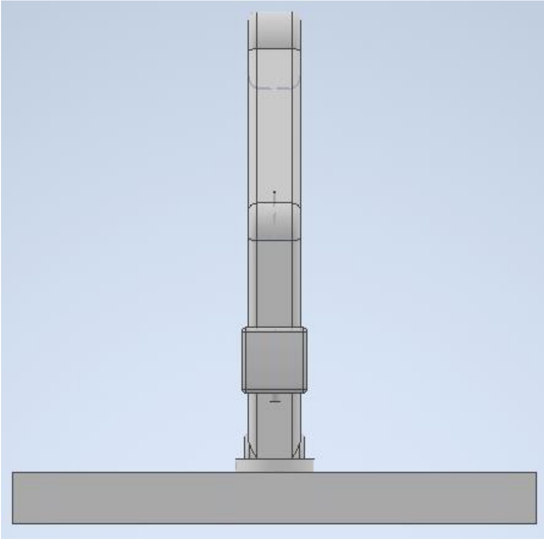
At this point, we were far from what we wanted yet, still only just toying with ideas of 3D replicating, as 3D replicating devices are extremely limited. The supervisor made affirmative remarks towards these ideas. *Figure 3.62 Drawing 1*, which was a concept of a robotic arm 3D printer, is surprisingly similar to what the project has become now, although not showing any signs of 3DS features. *Figure 3.63 Drawing 2* on the other hand was a concept of a cuboid box shaped replicator inspired from Makerbot Replicator Mini+ and Ultimaker 3, which was more boxed-like, as high end non-industrial 3D printers in the market at present are often boxed-like, some even looked like microwaves and ovens. The objective was to prevent foreign contamination during the printing process.

On the 6th week, the first technical drawings were drawn. These were standard (.ipt) part drawings on Autodesk Inventor 2020.

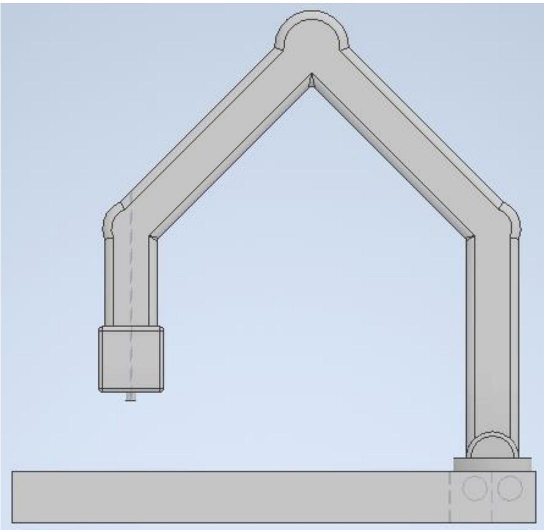
Figures 3.64 – 3.67 Fyp 1



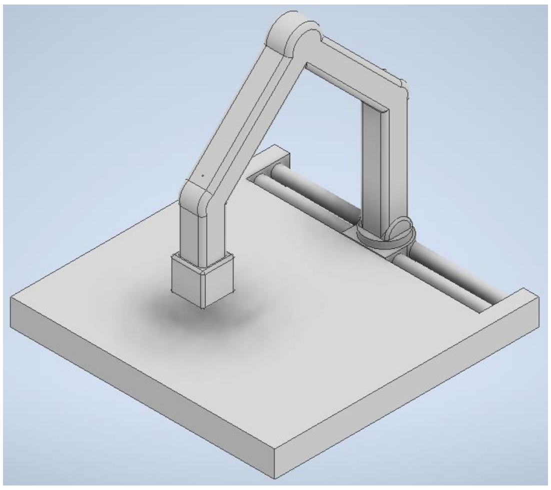
Top view



Front view



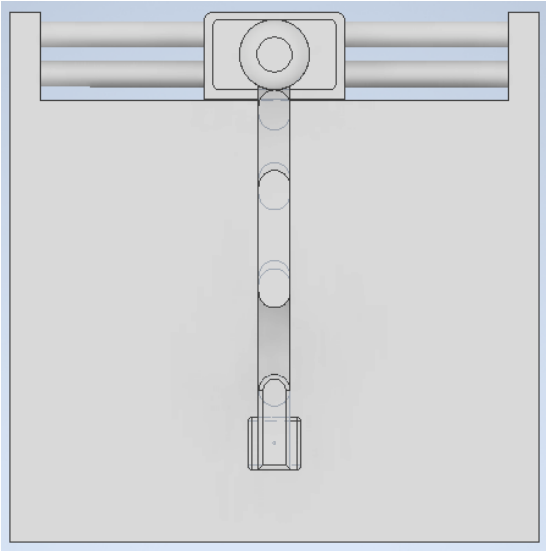
Side view

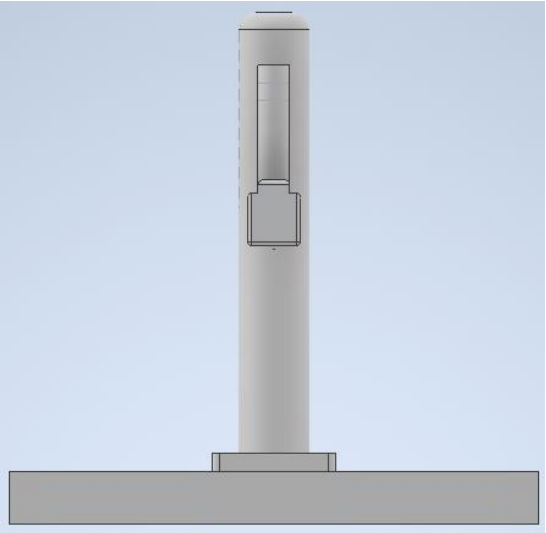


Isometric view

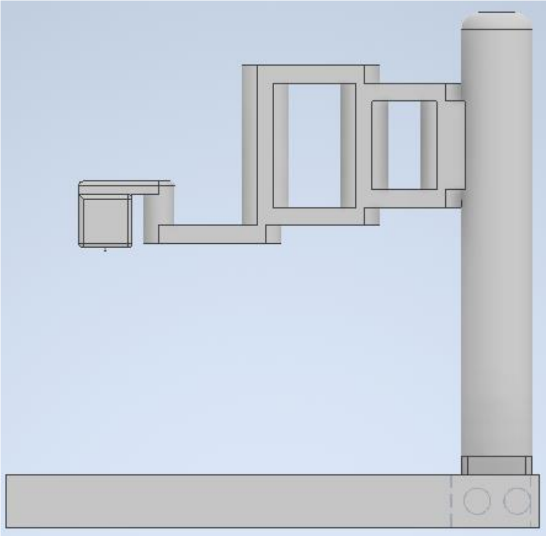
This is *figure 3.62 Drawing 1* in .ipt format. It shows a robotic arm with 5 DOF, fitted with an FDM extruder at the wrist. The robotic arm is also assembled on double cylinder rail to allow longitudinal movement for extended range of movement and working envelope.

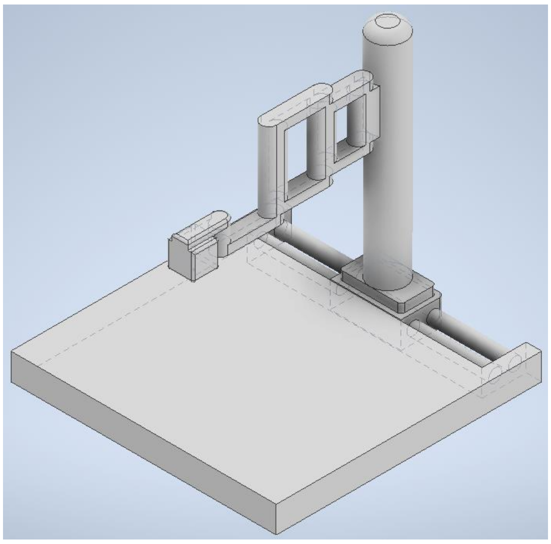
Figures 3.68 – 3.71 Fyp 2





Top view *Front view*



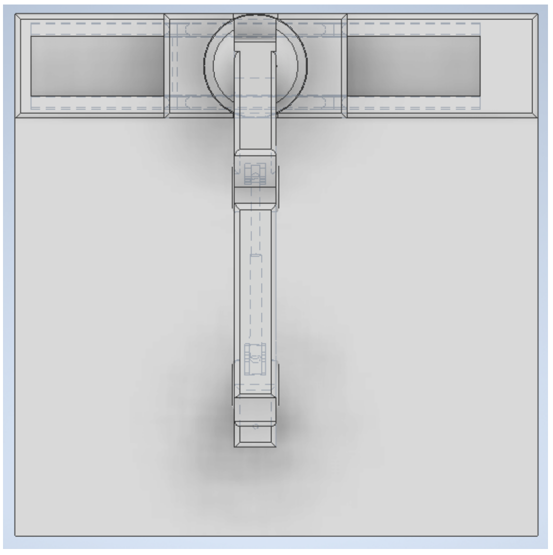


Side view *Isometric view*

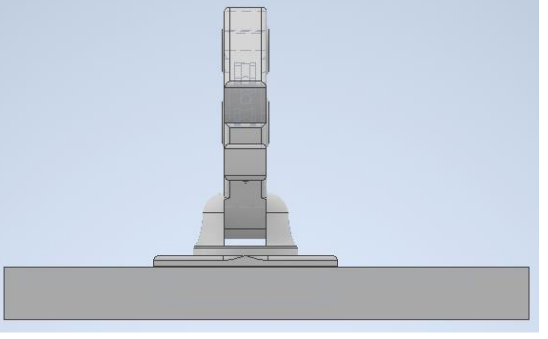
A SCARA robotic arm, inspired by non-other than the 1st generation Dobot Magician. The SCARA robotic arm design gives the arm a much more solid feel and would seemingly be able to print much faster. The downside was that it would require a solid tower support, which would be rigid, long, and heavy, which was against the spirit of the research objective in terms of portability. This version of the drawings featured 5 axes as well, and the double cylinder rail to allow longitudinal movement for extended range of movement and working envelope.

Approaching the halfway mark of the semester, week 7, we still could not figure out which design go for. Therefore, more refined drawings were produced to have better analysis and discussions with more clarity.

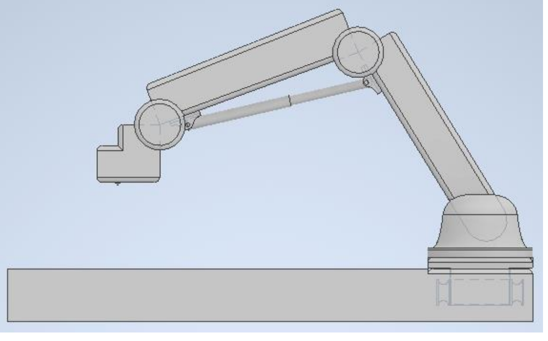
Figures 3.72 – 3.75 Fyp 1.2



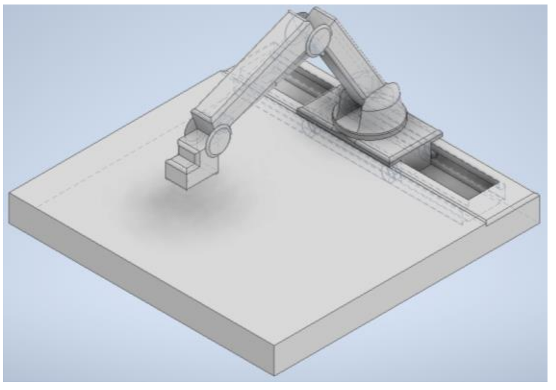
Top view



Front view



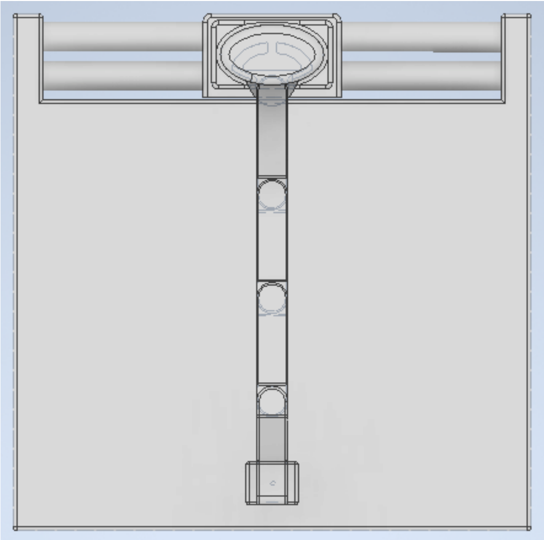
Side view



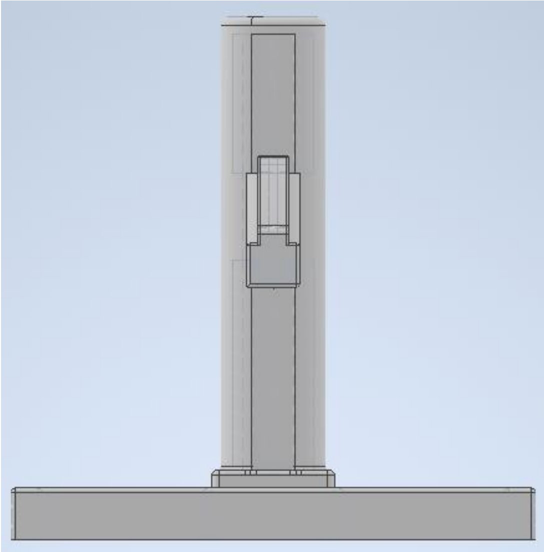
Isometric view

Drawing Fyp 1.2, which is the 2nd generation of Fyp 1, was drawn with more details, including covers, fillets, screws, and motor rotors. It features a pneumatic support between the upper arm and lower arm for stability and accuracy of movements. The numbers of axes were lowered by 1 to 4 axes, while the double cylinder bar rail was exchanged with a sliding rail. The robotic arm was meant to be detachable from the rail platform, which is equipped with 4 wheels to allow smooth movement along the rail. The mechanism of the movement along the rail would include a rotor and a rubber timing drive belt. This drawing had positive reception when shown to friends and classmates.

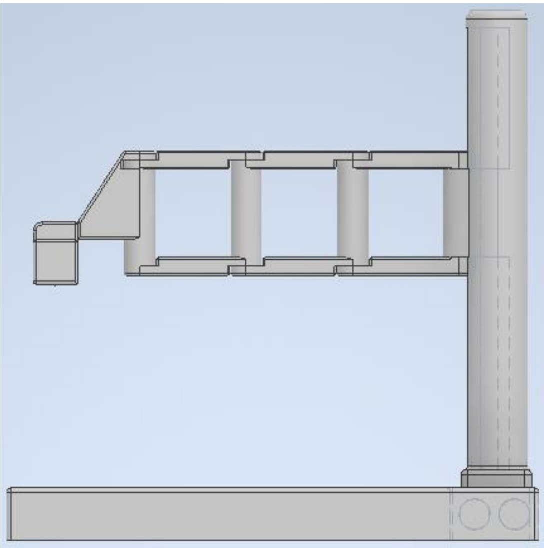
Figures 3.76 – 3.79 Fyp 2.2



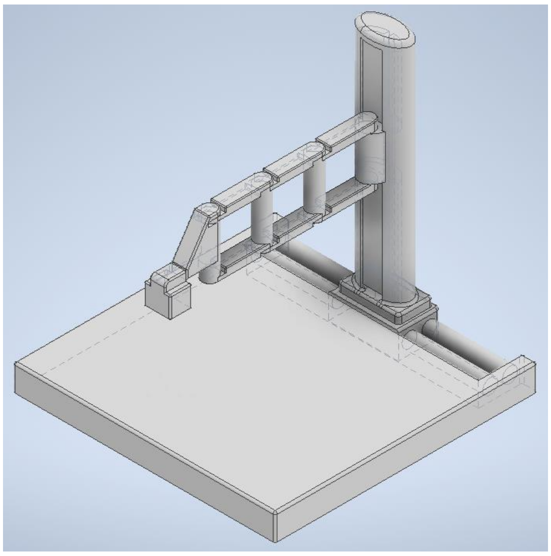
Top view



Front view



Side view

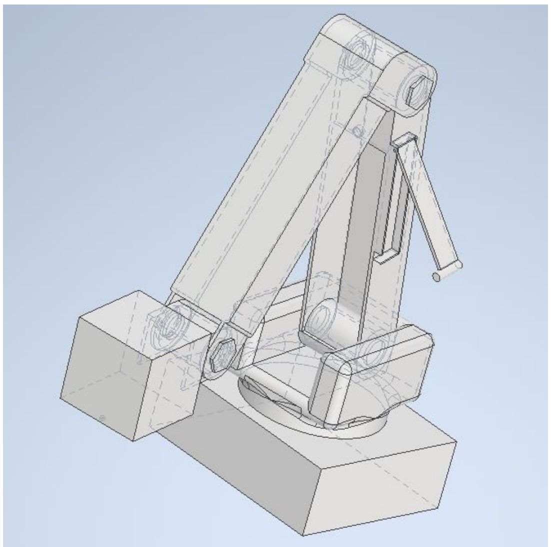


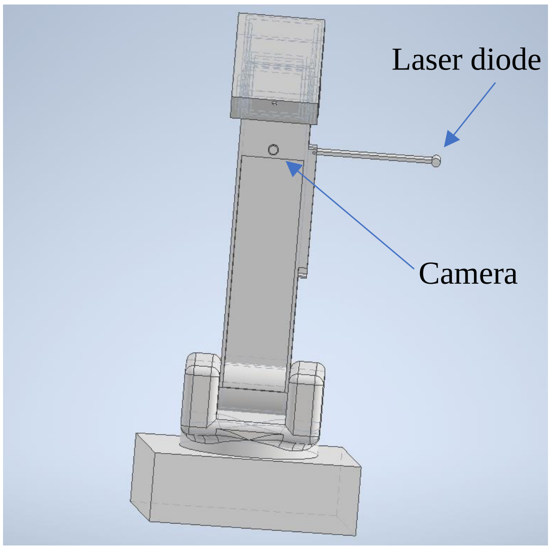
Isometric view

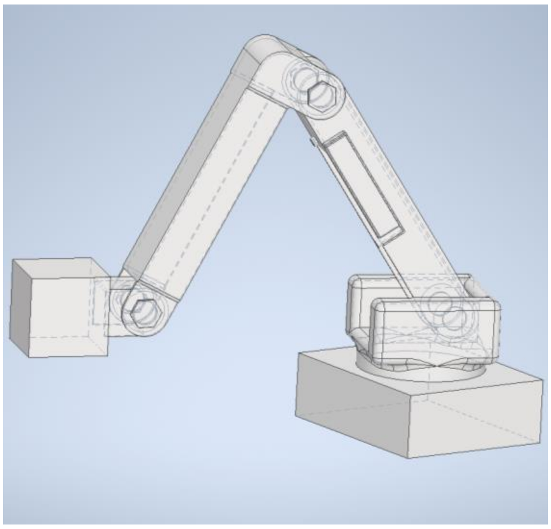
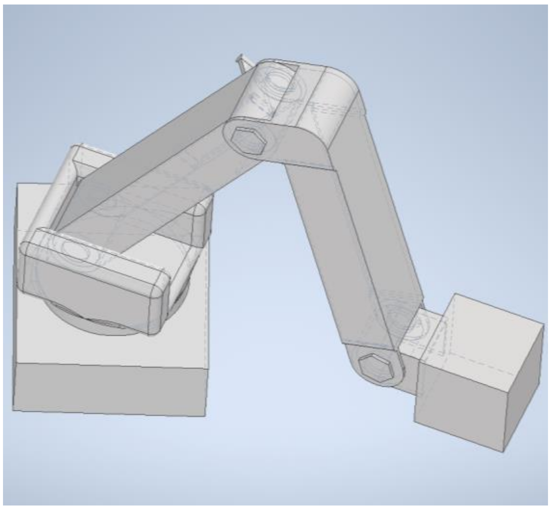
Drawing Fyp 2.2 included several experimental features. Firstly, it was designed to have SCARA arms of the similar dimensions. This was to decrease material usage and lessen the weight of the arms while not compromising its sturdiness and stability. The arms may also be added and detached to suit the operation. Furthermore, the double cylinder bar rail was retained, but increased in diameter, as it will be required to support the tall heavy supporting tower. In total, it features 5 DOF in this drawing, which includes a default 4 DOF similar to drawing Fyp 1.2, and an extra detachable arm to demonstrate its ability to undergo modifications when needed.

With that being said, a decision was made. We will proceed with the Fyp 1 series and drop the idea of a SCARA robot. This was mainly due to the lack of portability of SCARA robotic arms, and it would cost more to build. Therefore, we stuck by the classic 4-axis desktop robotic arm. Another concern was the assembly of the laser scanner. For some time, we thought to fix it to the lateral arm that moves along the tower of the SCARA robotic arm. At this point, we also just determined that Laser Triangulation was the way to go instead of Photogrammetry. Following this, we had a clear image of what we want to build and innovate on and started working on putting it all together as a standard (.iam) assembly. The catch was still the placement of the 3D scanner, to design it so that it fits in as in if it belongs to be part of a robotic arm, to let it seem natural and not forced. Finally, by the 12th week, we have an assembly drawing.

Figures 3.80 – 3.83 Fyp 1.3

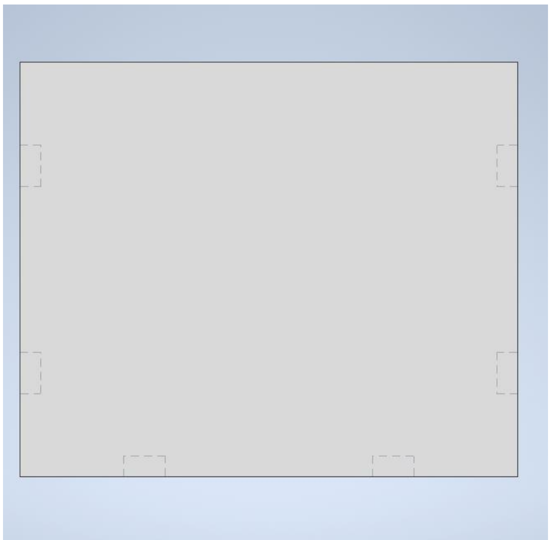




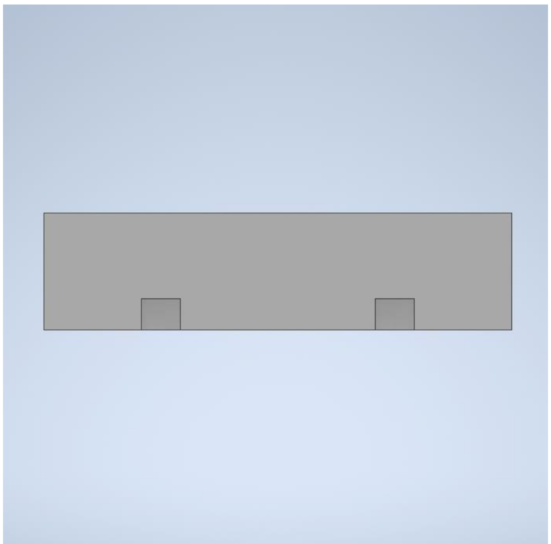
 

As you can see, the drawing Fyp 1.3 shows a 4-axis robotic arm, fitted with an FDM extruder on the wrist, a camera on the lower portion of the upper arm near the elbow, and a laser beam on the side of the upper arm as well, level with the camera. The axes of movement are enabled through rotors. The arms are each about 200mm, allowing a comfortable print area of about 150x150x150mm. The assembly was made up of 8 different parts, involving mostly rotational joints. For this design, the forearm will lift up to unblock the view of the camera, and the laser at the side will rotate out as well. It will reach a position similar to the top right image, and 3DS can be conducted. Although this assembly is decent, it was not complete, and the 3D scanner is still in doubt. There is no explanation yet of how it will be capable of scanning from top to bottom, how does the laser diode rotate out when required. Only by another fortnight, at the penultimate week of the semester, while under the current Movement Control Order (MCO), the assembly was finalised. Its parts as follow: -

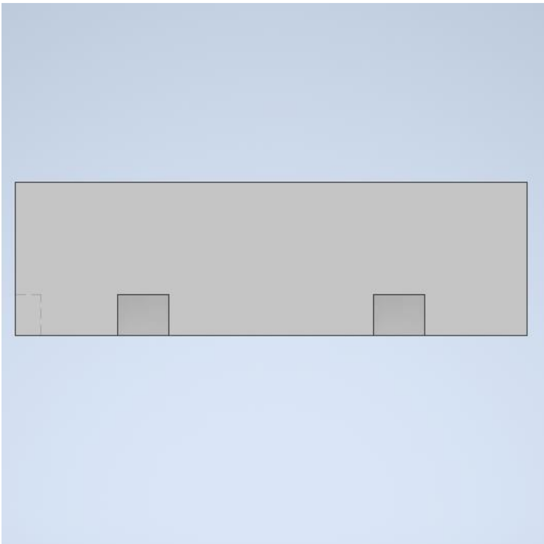
Figures 3.84 – 3.87 Fyp 1.3.1



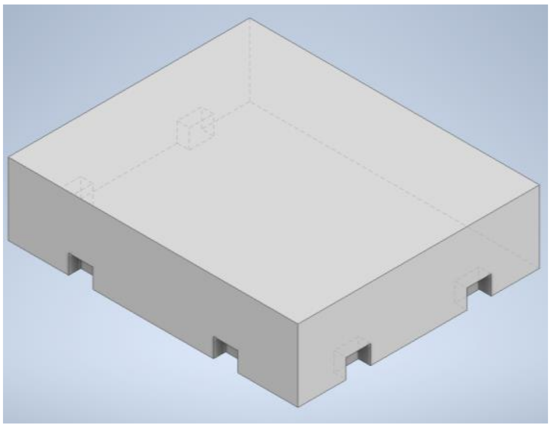
Top view



Front view



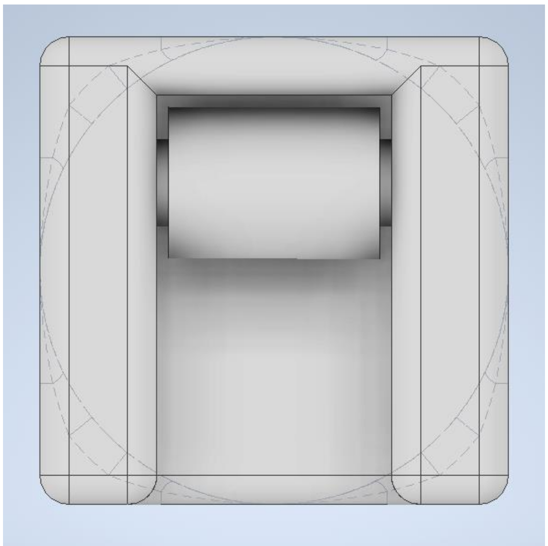
Side view



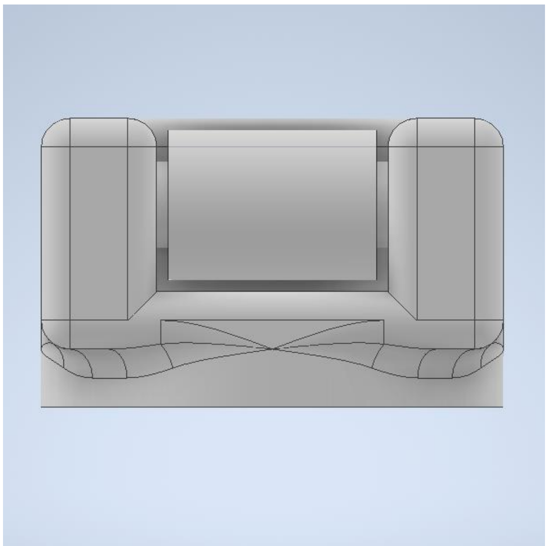
Isometric view

This is the base of the 3D Replicating Robotic Arm. The power source, main chipset will be within this cuboid.

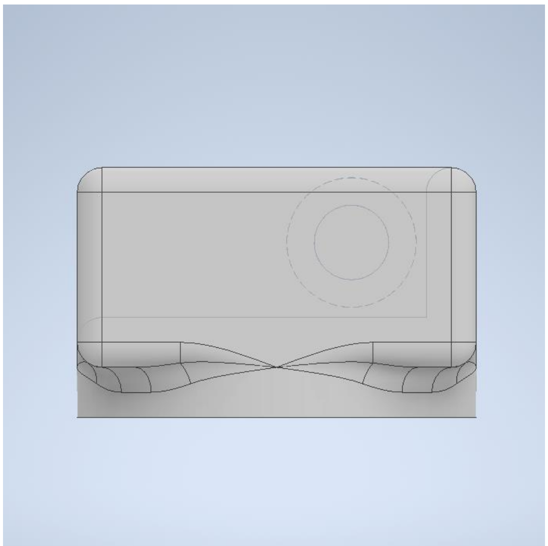
Figures 3.88 – 3.91 Fyp 1.3.2



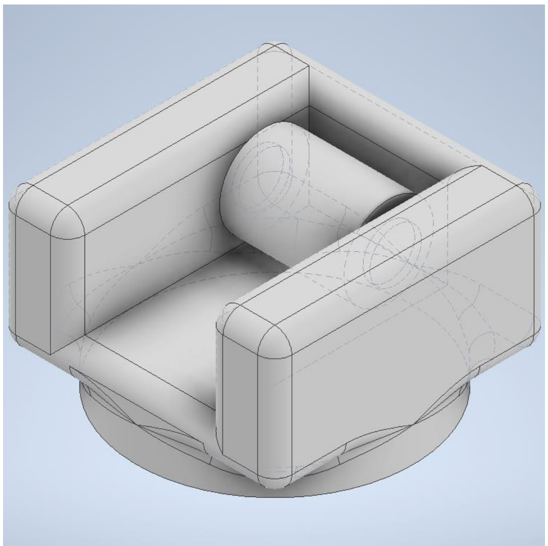
Top view



Front view



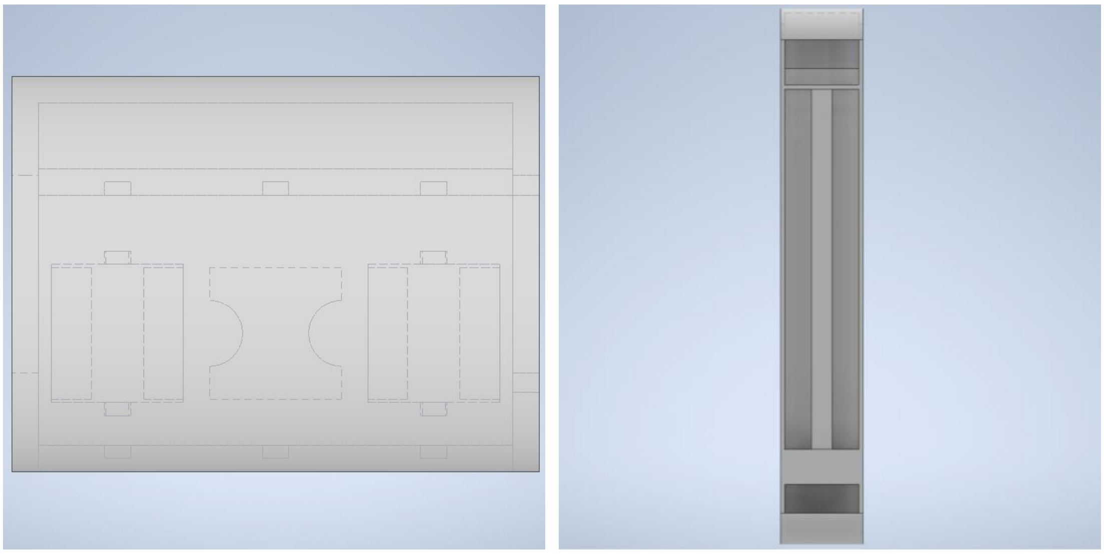
Side view



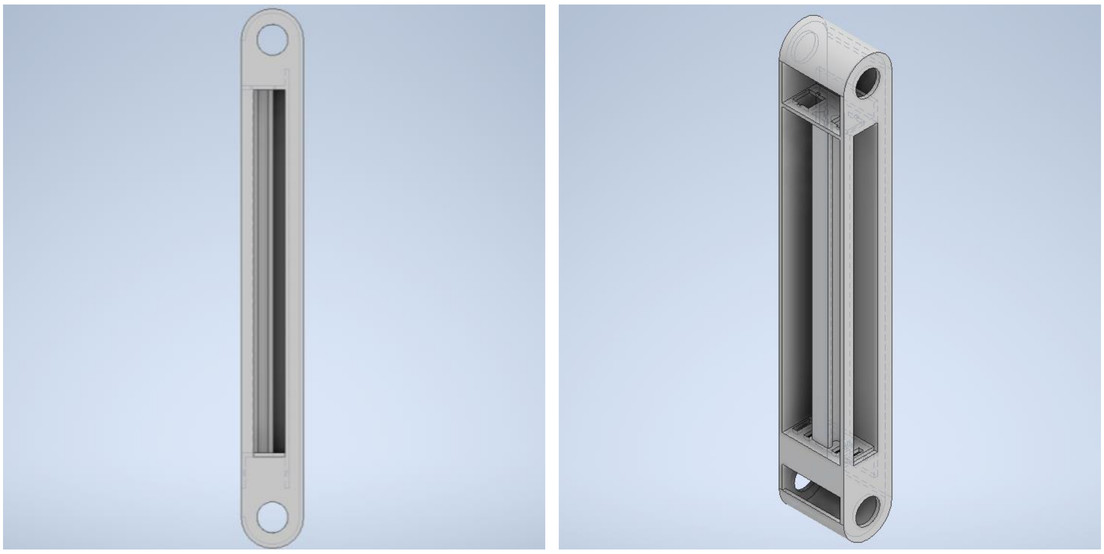
Isometric view

This is the shoulder of which the robotic arm is assembled onto. The shoulder sits on top of the base with a rotational relationship. It has a rotor for the movement of the upper arm.

Figures 3.92 – 3.95 Fyp 1.3.3



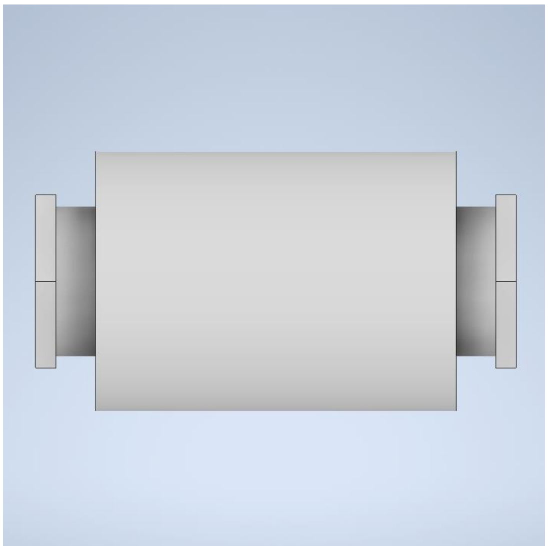
Top view *Front view*



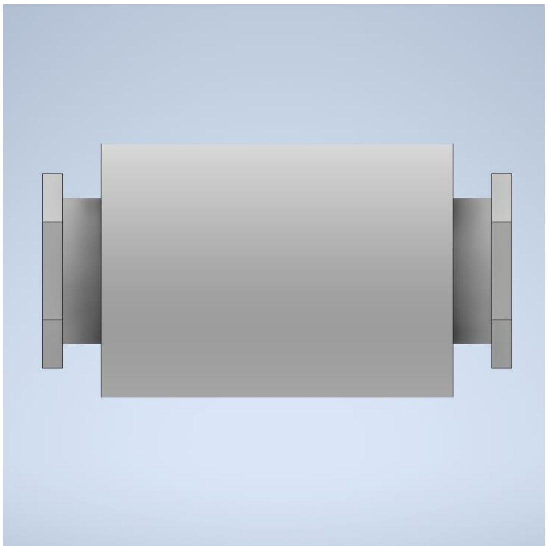
Side view *Isometric view*

This is the upper arm which sits upon the shoulder. It has a rotational relationship with the rotor on the shoulder. Within the upper arm, there is a 175mm metal bar which the camera will travel along. On the right, it is opened to allow movement of the laser diode while scanning is in process. It also contains gaps for drive belts that pull the camera to pass through and 5 slots for rotors, 2 which are axes of the robotic arm, and 3 smaller ones to pull drive belts.

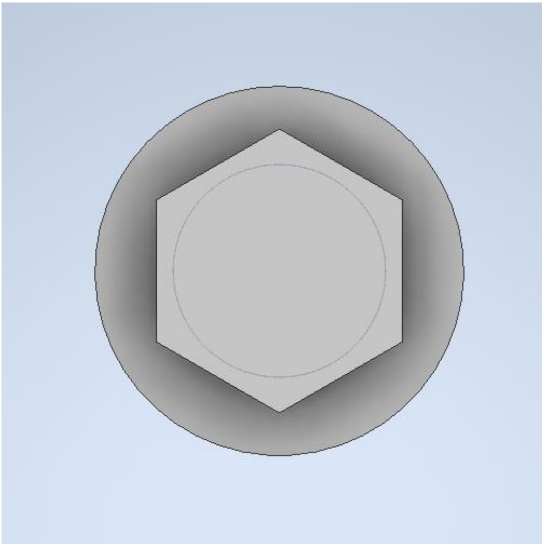
Figures 3.96 – 3.99 Fyp 1.3.4



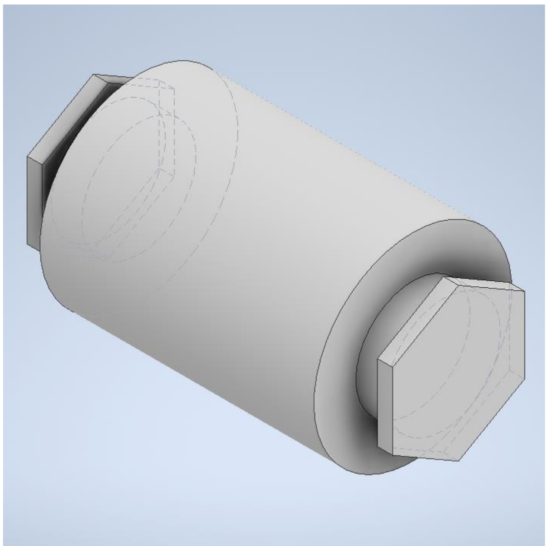
Top view



Front view



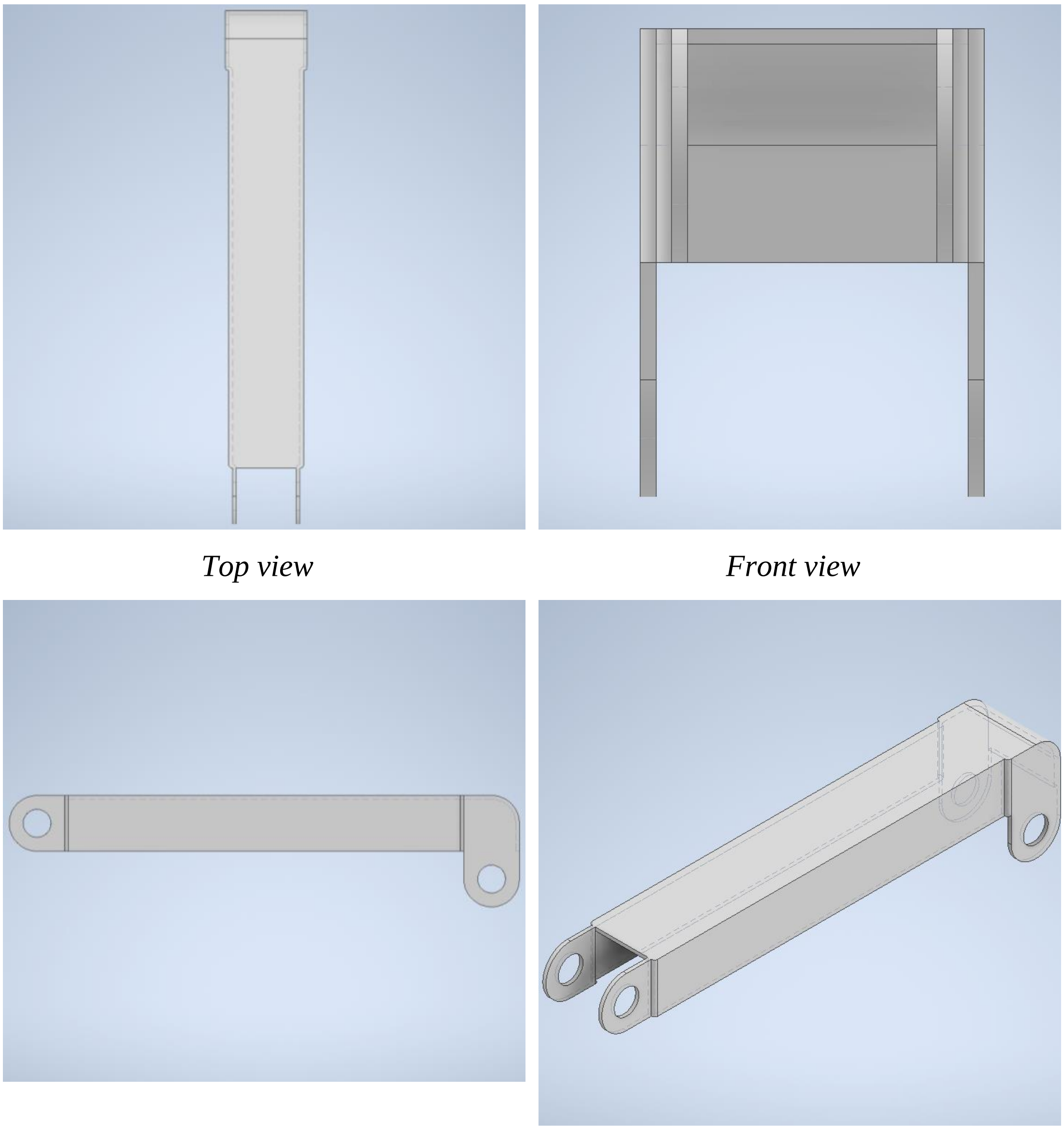
Side view



Isometric view

This is a 48mm long rotor with a diameter of 26mm. It is fixed at the elbow of the robotic arm providing for the movement for the forearm.

Figures 3.100 – 3.103 Fyp 1.3.5

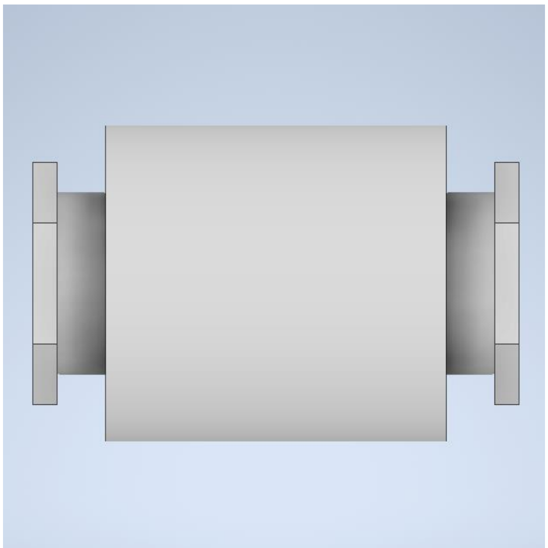


Top view *Front view*

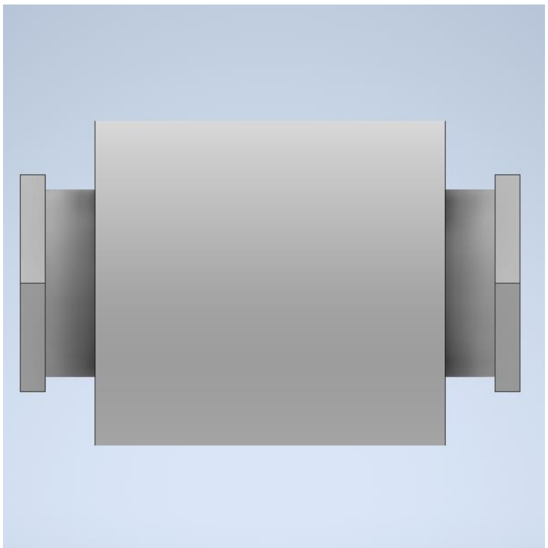
Side view *Isometric view*

This is the forearm. Its movement is enabled by rotor Fyp1.3.4. It has another slot for a rotor at the wrist, for the movement of the FDM extruder.

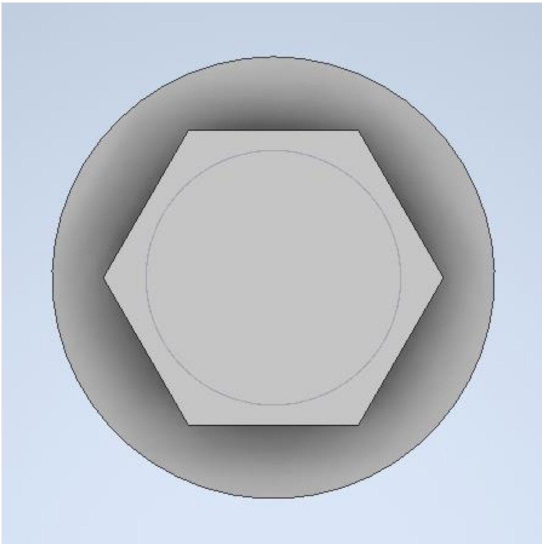
Figures 3.104 – 3.107 Fyp 1.3.6



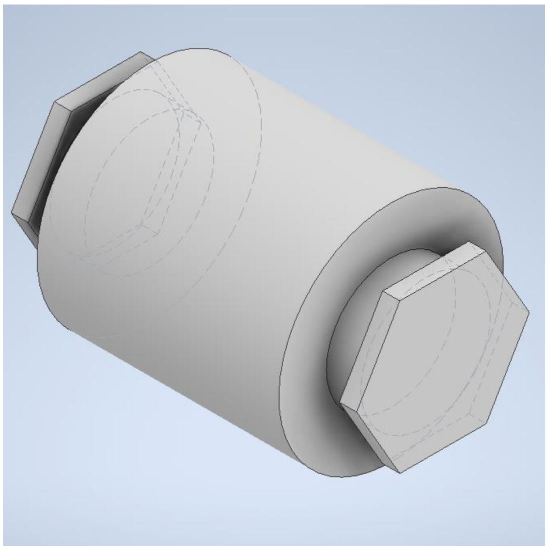
Top view



Front view



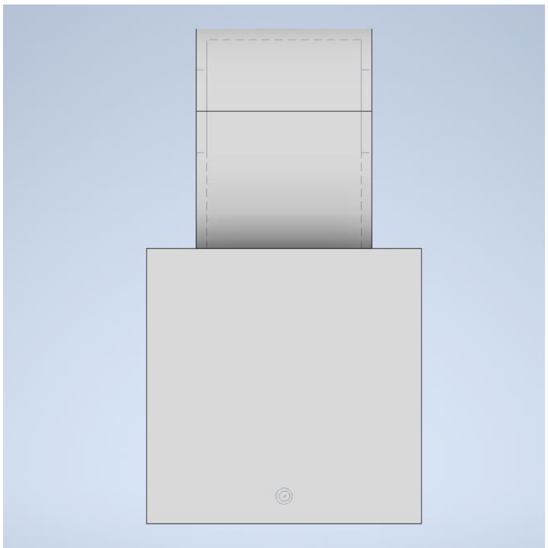
Side view



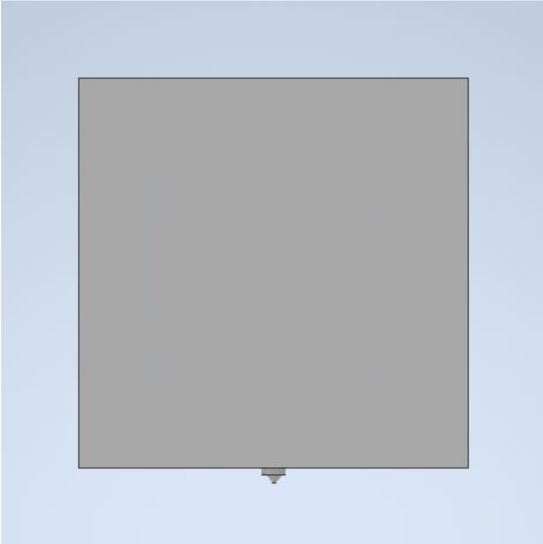
Isometric view

This is a 40mm long rotor with a diameter of 26mm. It is fixed to the forearm at the wrist. It provides movement for the FDM extruder.

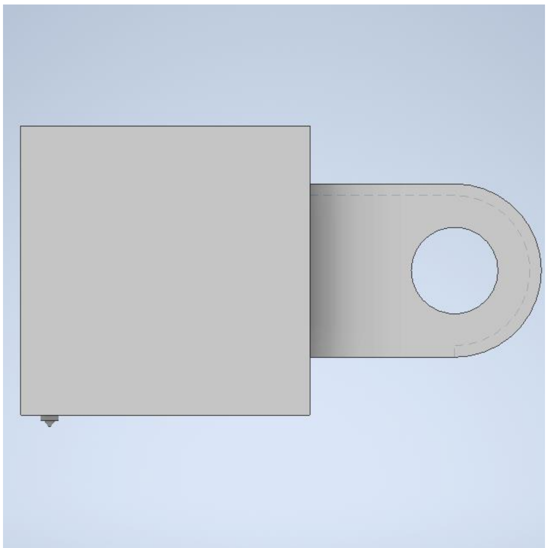
Figures 3.108 – 3.111 Fyp 1.3.7



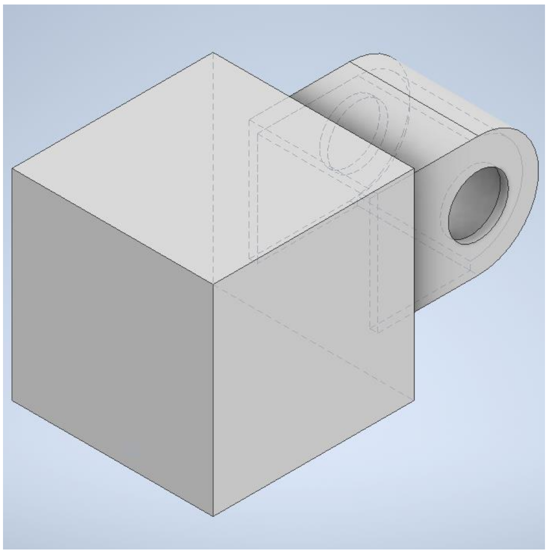
Top view



Front view



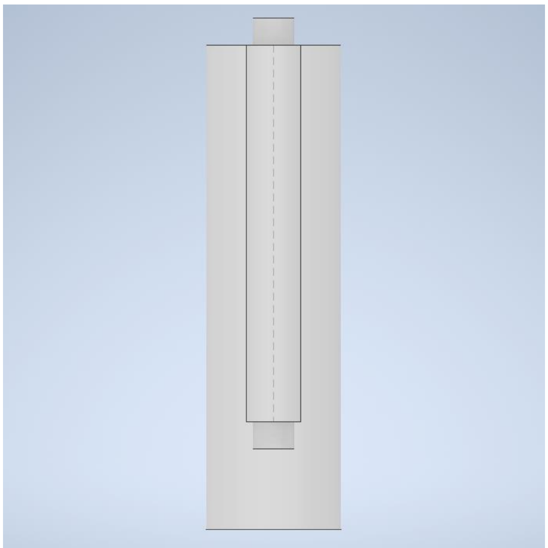
Side view



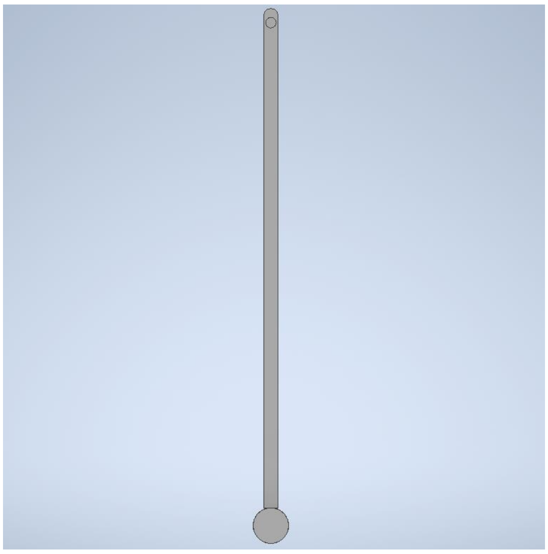
Isometric view

This is the FDM extruder. It is connected to the forearm at the wrist. Its movement is enabled by rotor Fyp 1.3.6.

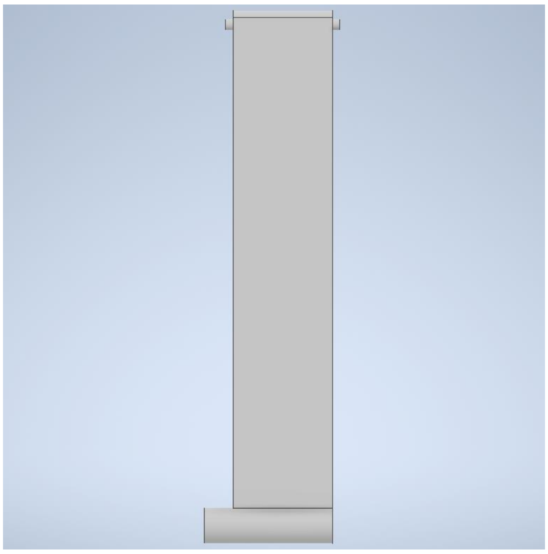
Figures 3.112 – 3.115 Fyp 1.3.8



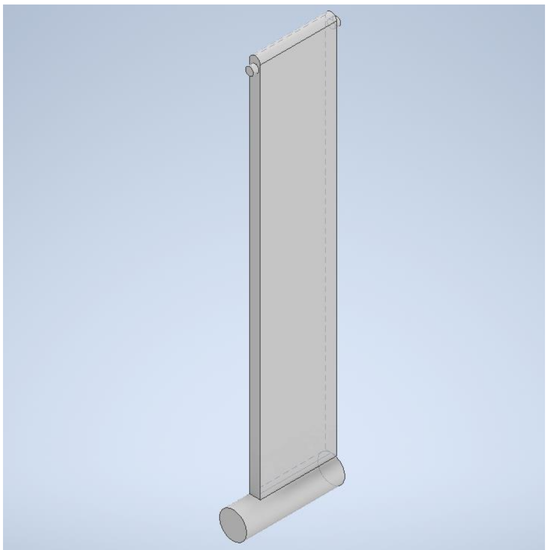
Top view



Front view



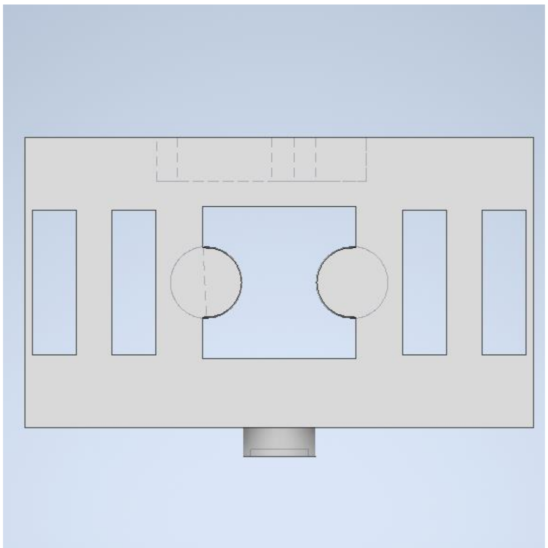
Side view



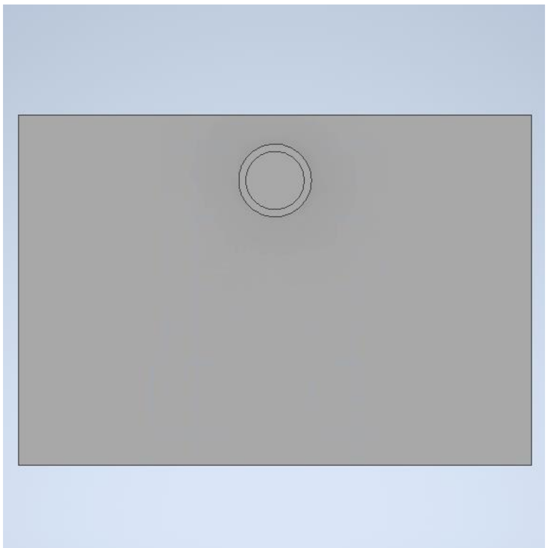
Isometric view

This is a laser diode, which was fixed on Fyp 1.3. It is no longer in use in the new assembly.

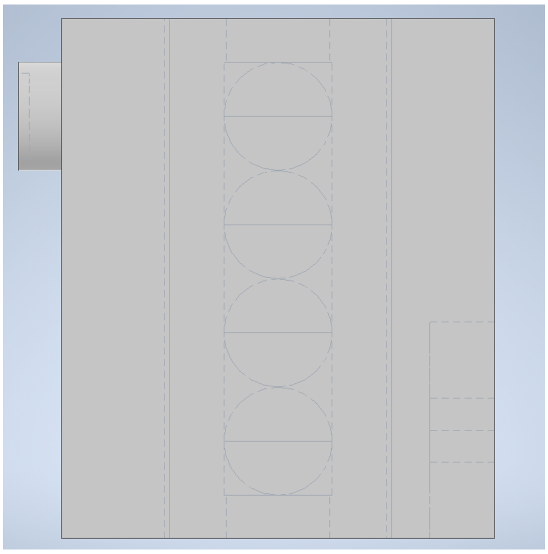
Figures 3.116 – 3.119 Fyp 1.3.9



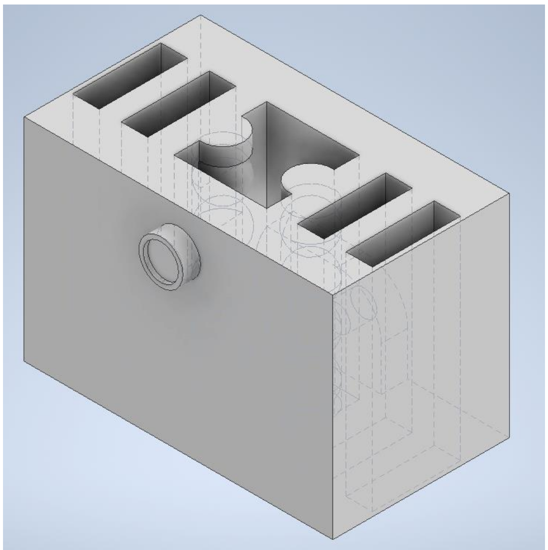
Top view



Front view



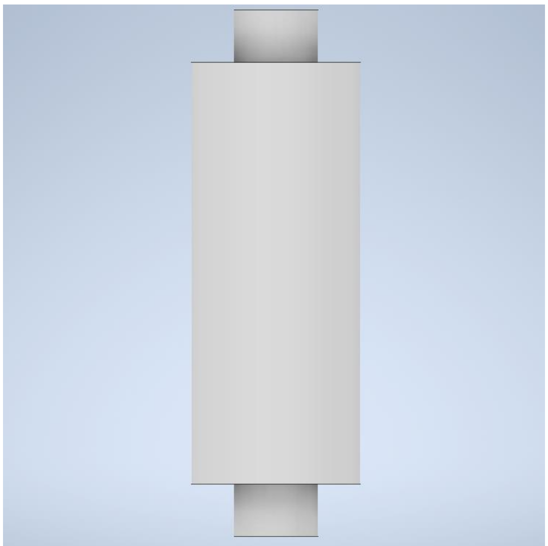
Side view



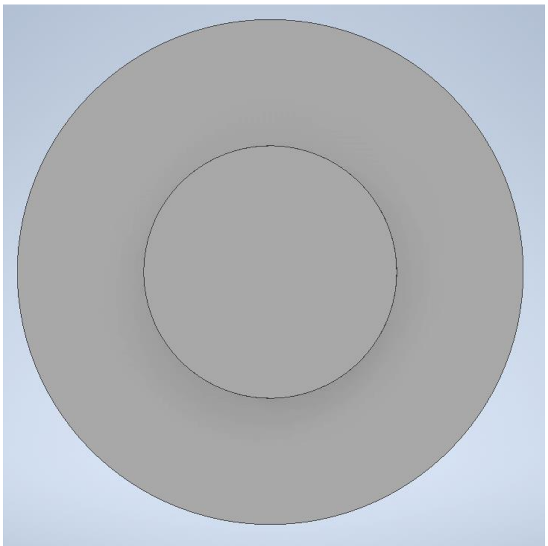
Isometric view

This is the camera. The lens can be seen to be at the top front part of the structure. It moves along vertically the metal bar in the upper arm Fyp 1.3.3. It has 4 ball bearings on the left and right internal side of the structure to ensure smooth movement. Its movement is enabled by the pulling of drive belts by rotors within the upper arm. There is a slot at the back side of the structure for the attachment of the laser diode.

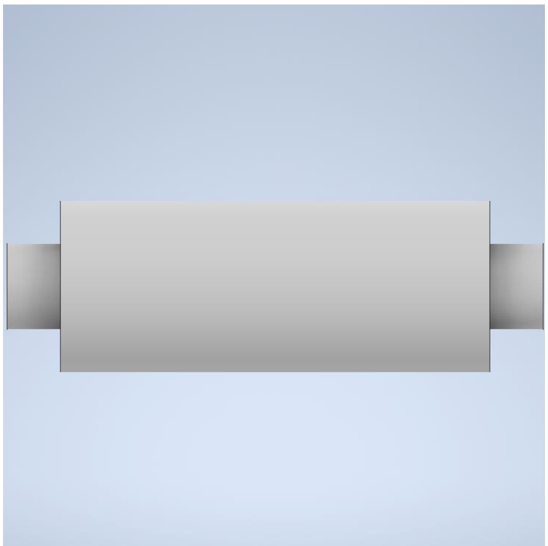
Figures 3.120 – 3.123 Fyp 1.3.10



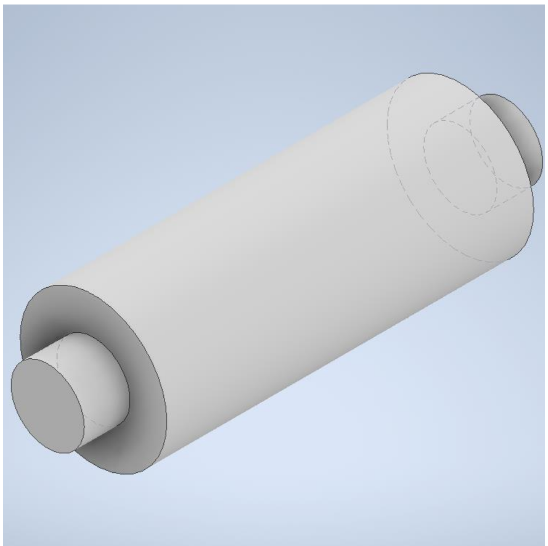
Top view



Front view



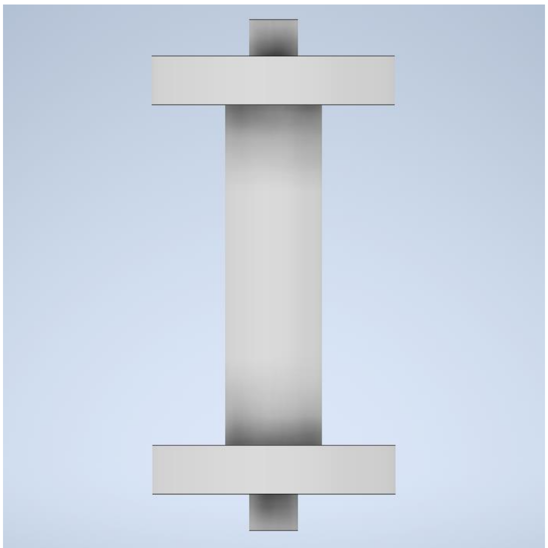
Side view



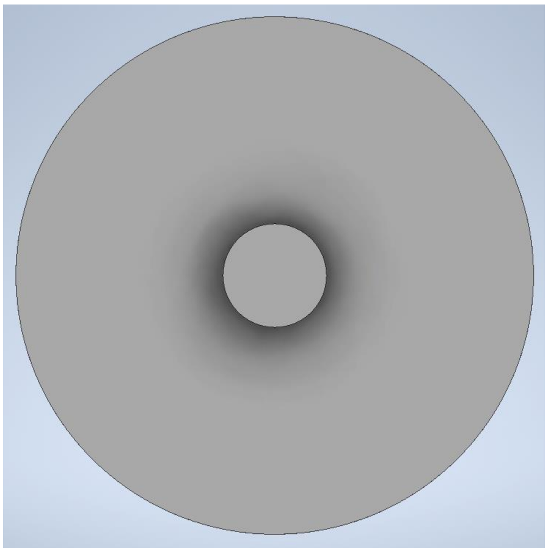
Isometric view

This is a 12.5mm long roller with a diameter of 4mm. There are 2 of these rollers in the upper arm to ensure smooth movement of the drive belts.

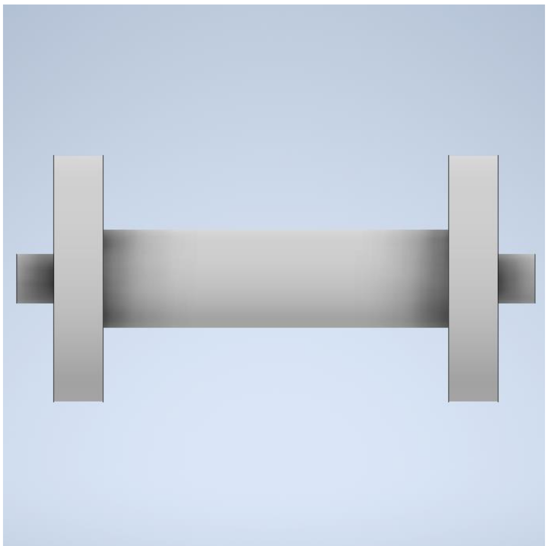
Figures 3.124 – 3.127 Fyp 1.3.11



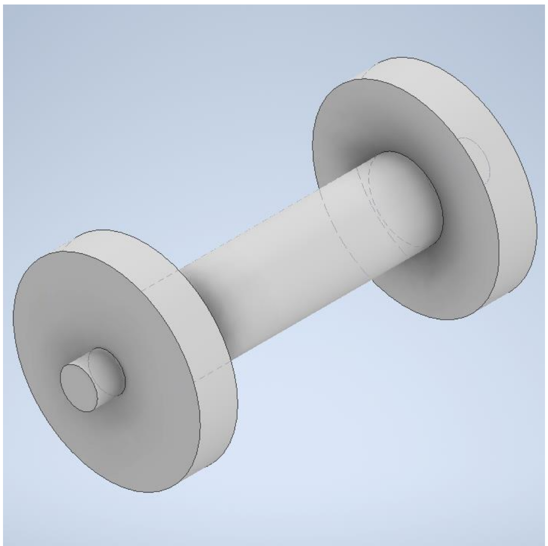
Top view



Front view



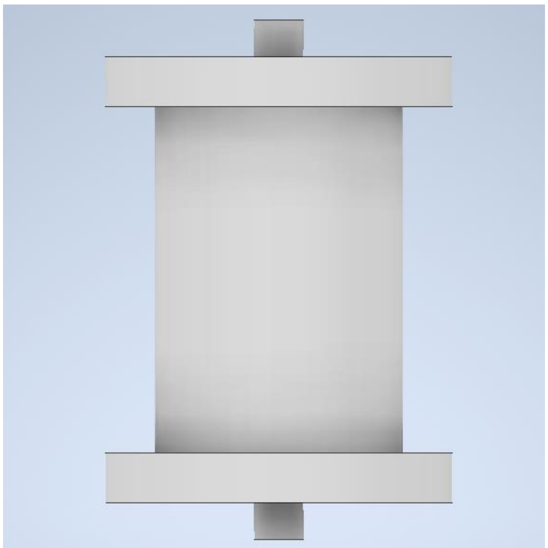
Side view



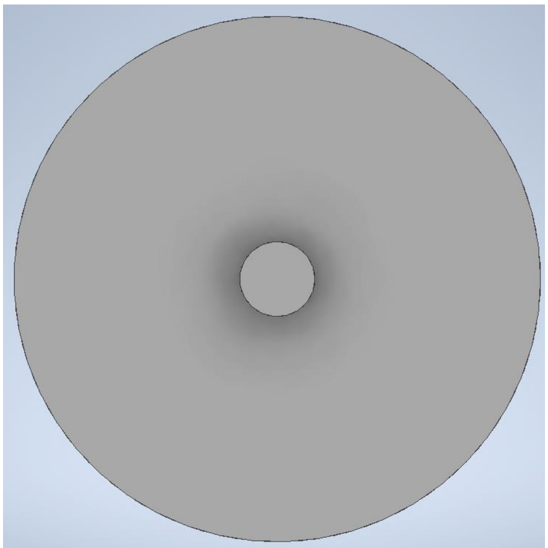
Isometric view

This is a 21mm long gear with a diameter of 10mm.There are 2 of these gears in the upper arm to turn the drive belt and move the camera. The gears turn from the rotations of rotor Fyp 1.3.12

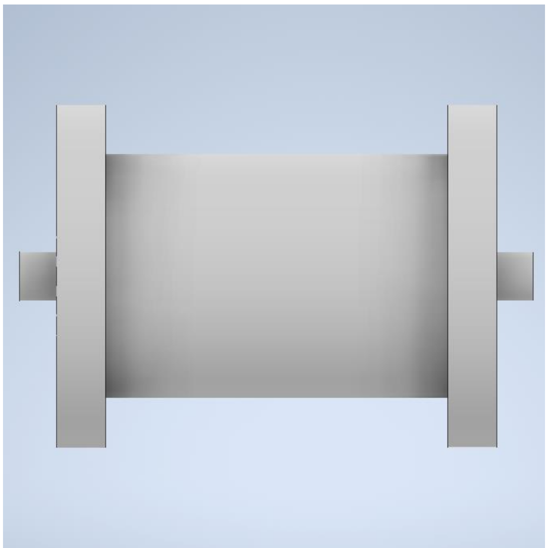
Figures 3.128 – 3.131 Fyp 1.3.12



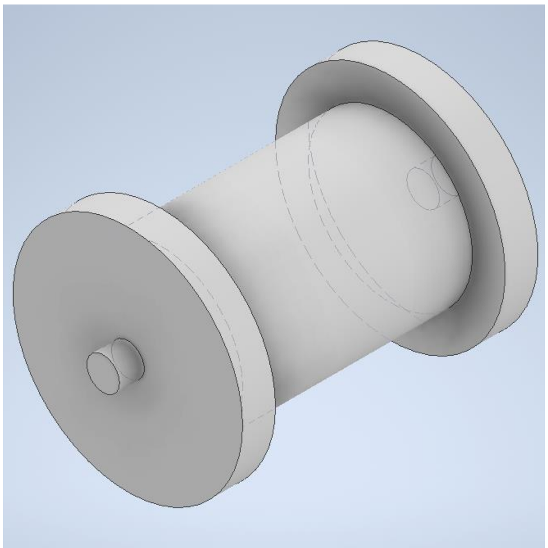
Top view



Front view



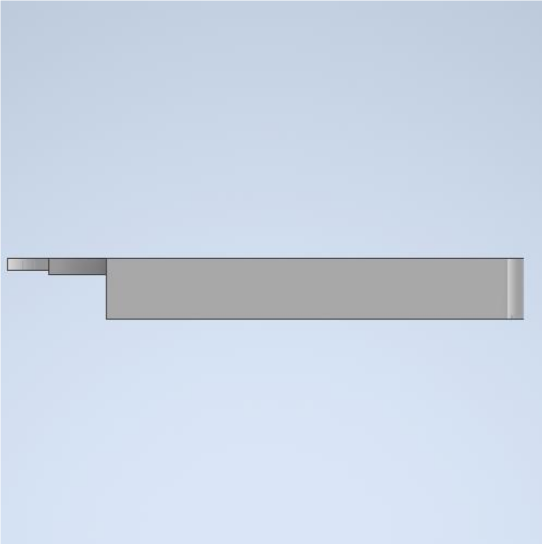
Side view



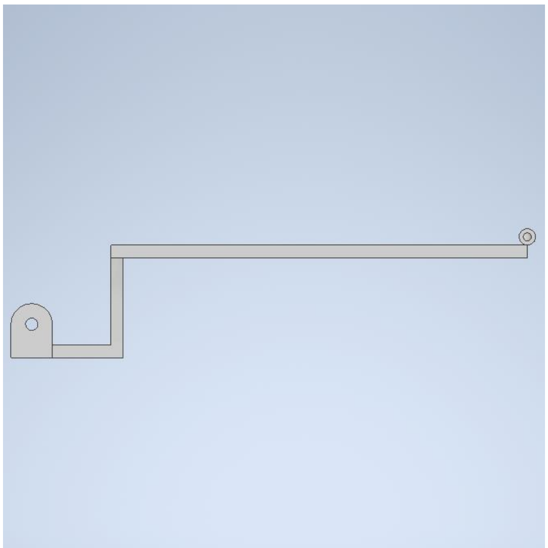
Isometric view

This is a 21mm rotor with a gear diameter of 14mm. It rotates 2 Fyp 1.3.11 gears to pull the drive belt enable movement of the camera.

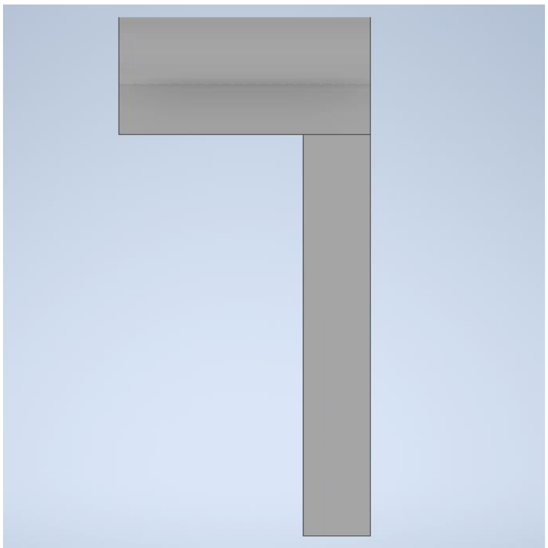
Figures 3.132 – 3.135 Fyp 1.3.13



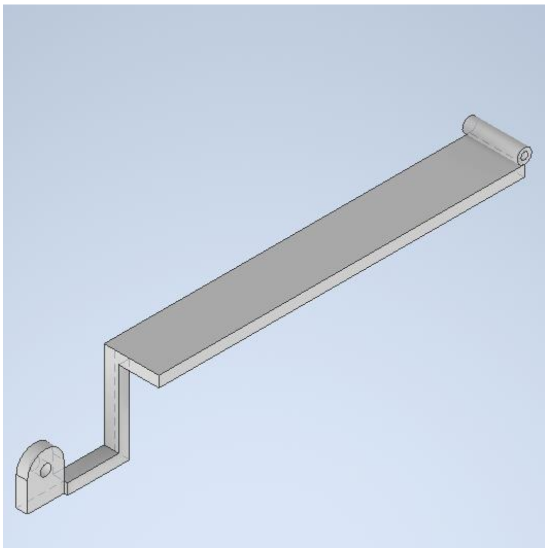
Top view



Front view



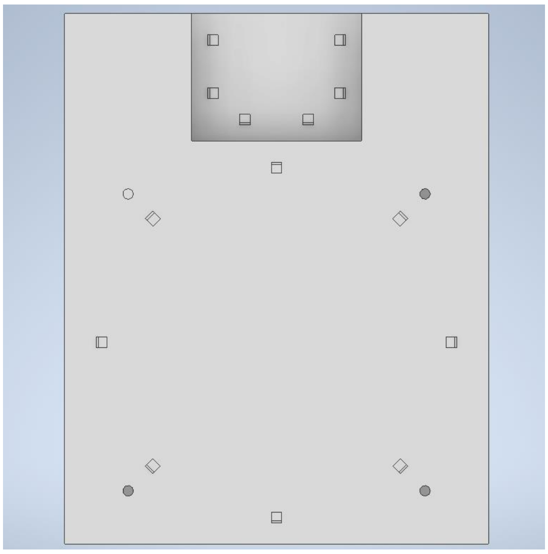
Side view



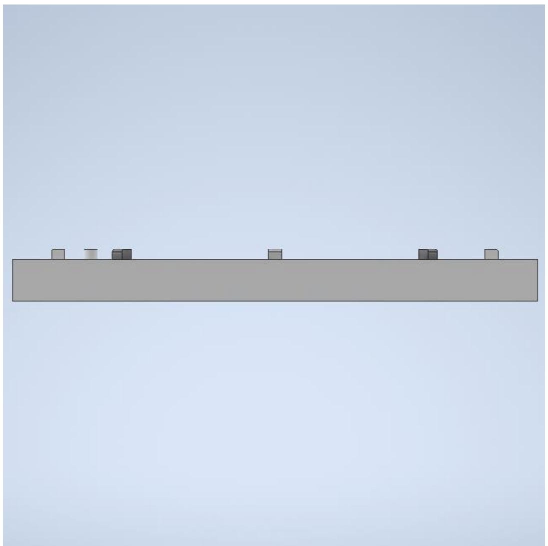
Isometric view

This is the laser diode. It is attached to the back of camera Fyp 1.3.9. It can be folded out when needed for 3DS and folded back when not in use.

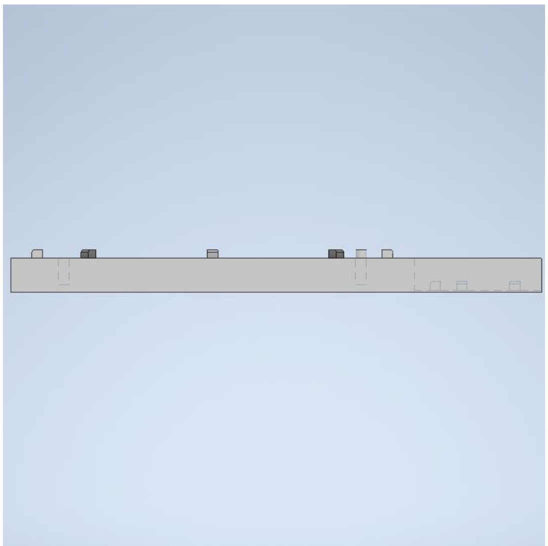
Figures 3.136 – 3.139 Fyp 1.3.14



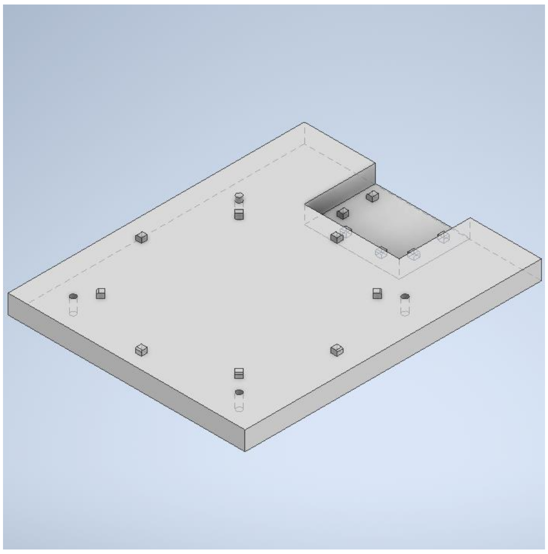
Top view



Front view



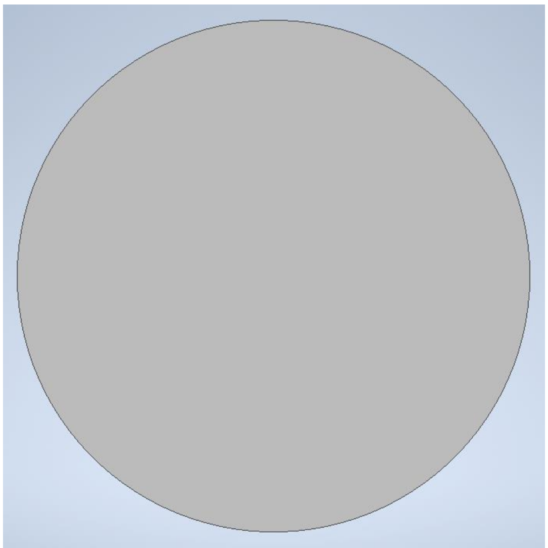
Side view



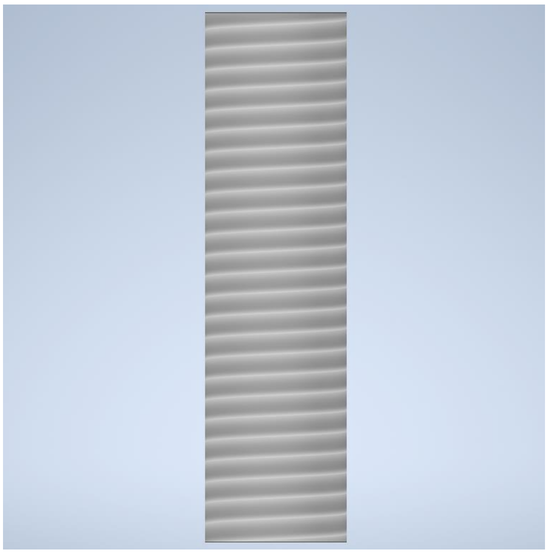
Isometric view

The is the supporting base of the 3D Replicating Robotic Arm. It holds other parts in place to ensure they are the appropriate distance from each other.

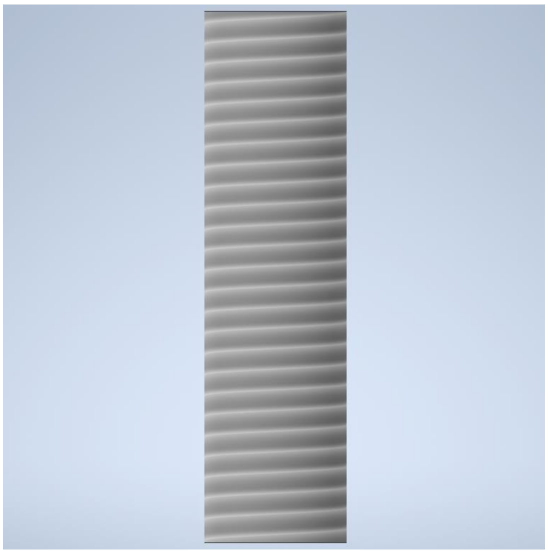
Figures 3.140 – 3.143 Fyp 1.3.15



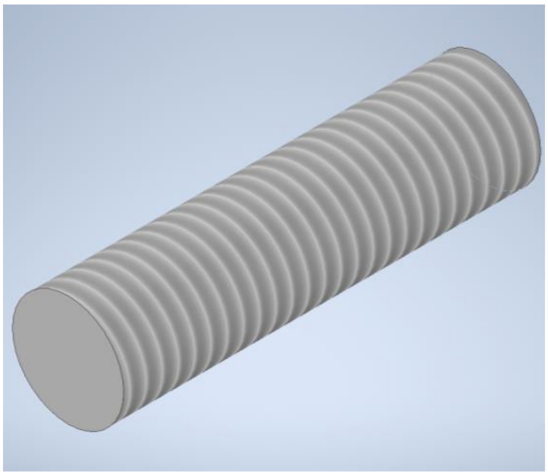
Top view



Front view



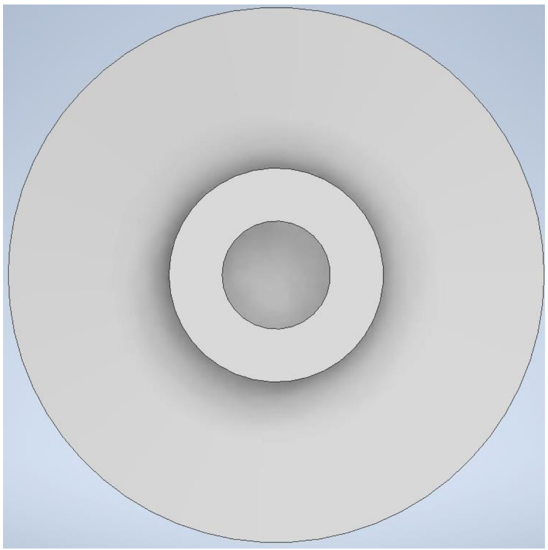
Side view



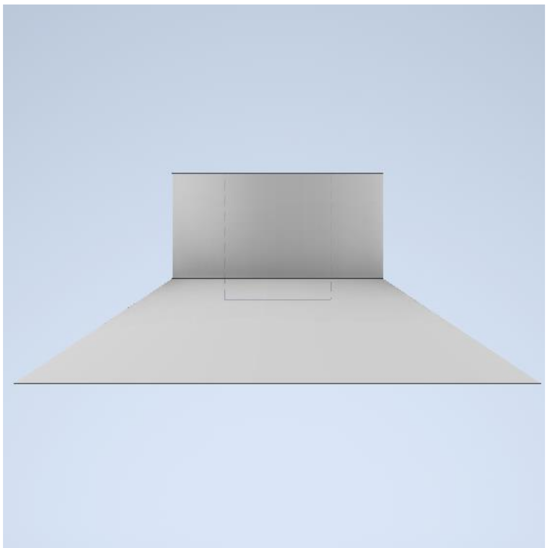
Isometric view

This is a 45mm long M12x1.75 bolt. It is inserted into the supporting base. With rubber stopper Fyp 1.3.16, it allows the FDM print bed Fyp 1.3.17 to be adjustable and well calibrated.

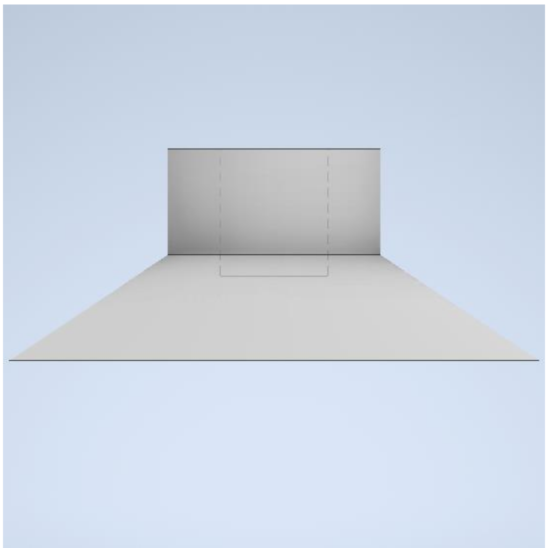
Figures 3.144 – 3.147 Fyp 1.3.16



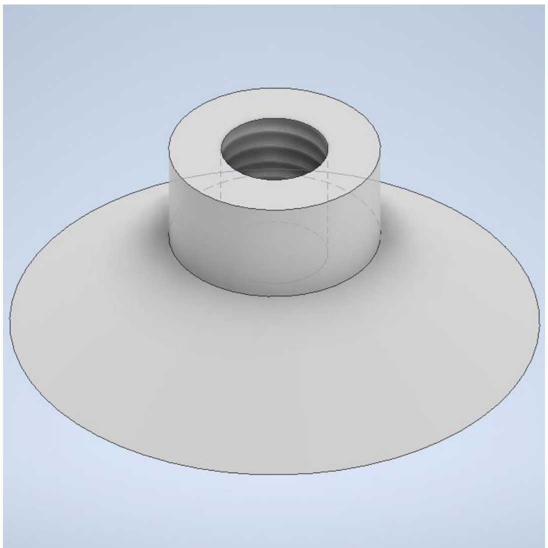
Top view



Front view



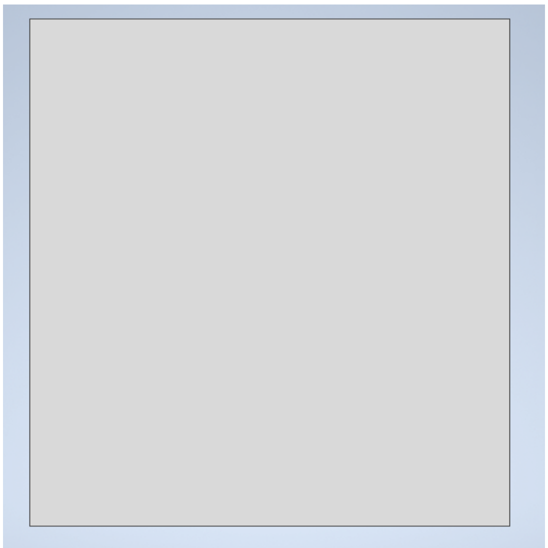
Side view



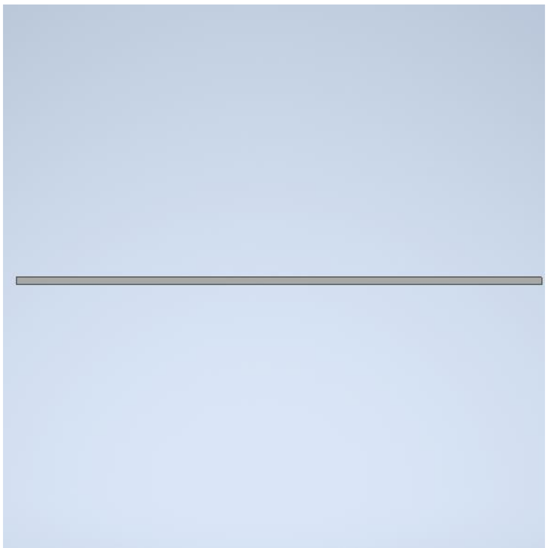
Isometric view

This is a rubber stopper. There are 4 of them, screwed to the M12x1.75 nuts Fyp 1.3.15. These stoppers support the FDM print bed Fyp 1.3.17 and allows for adjustment and calibration to ensure it is straight and flat.

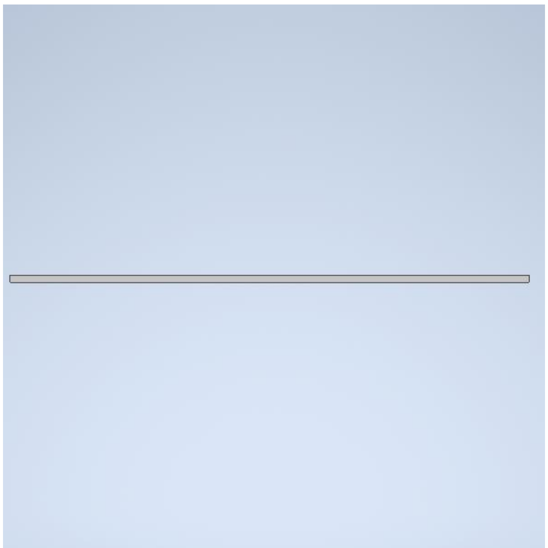
Figures 3.148 – 3.151 Fyp 1.3.17



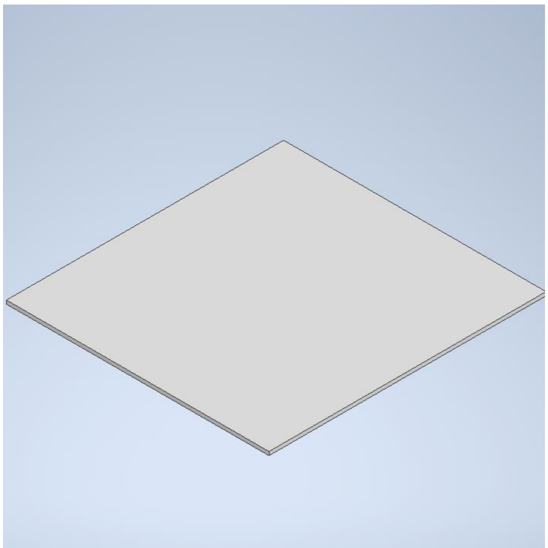
Top view



Front view



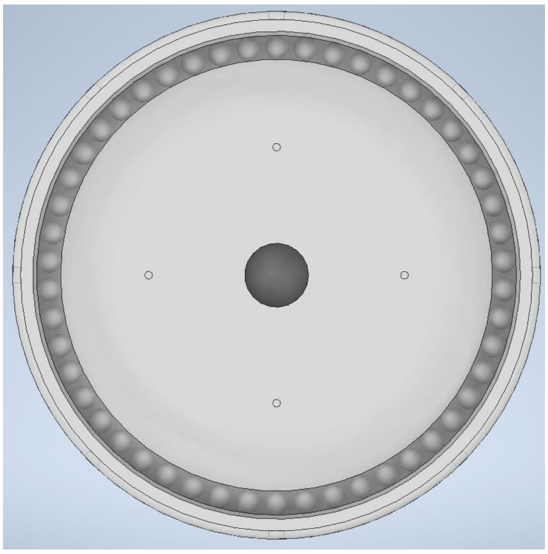
Side view



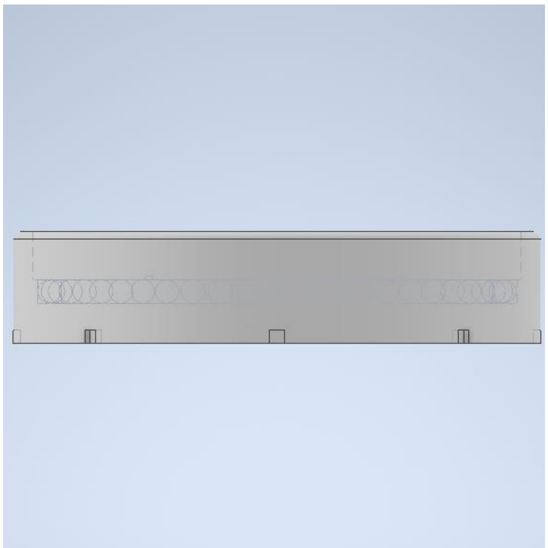
Isometric view

This is the FDM print bed. It is 380x360x5mm. When printing, it is placed on the rubber stoppers Fyp 1.3.16.

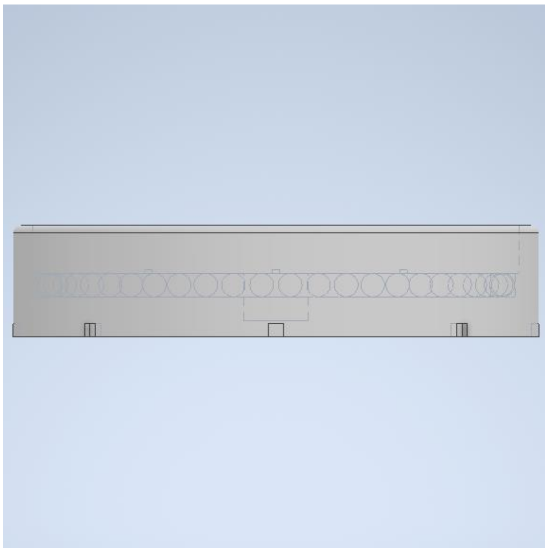
Figures 3.152 – 3.155 Fyp 1.3.18



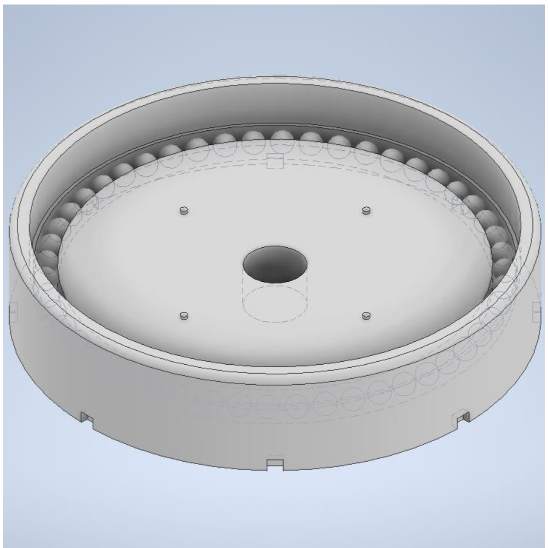
Top view



Front view



Side view

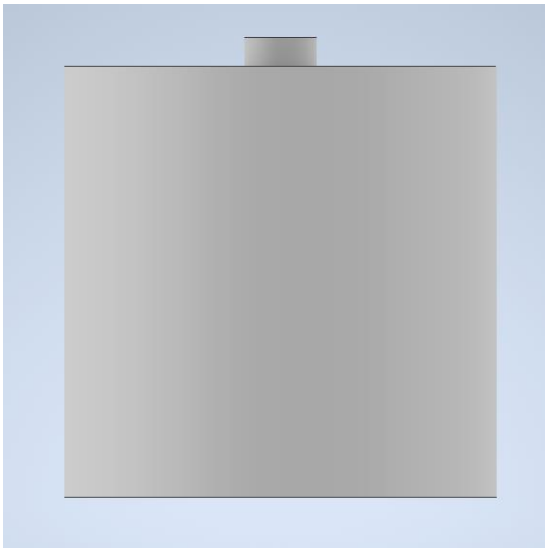


Isometric view

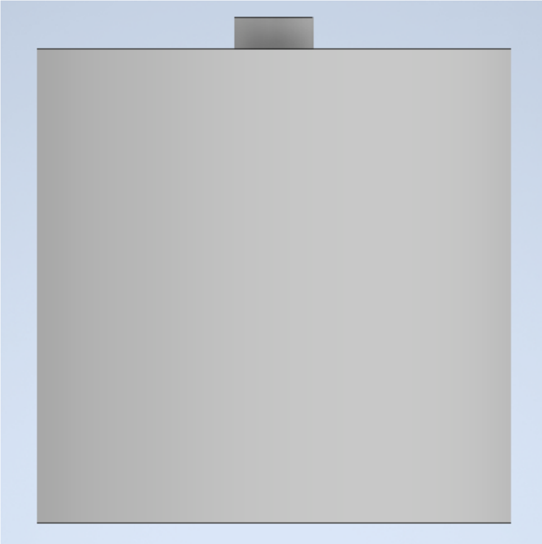
This is the lower part of the turntable to 3DS. It has a hole in the centre to insert a rotor Fyp 1.3.19. Then, spur gears will be fitted in on the 4 knobs and rotor, together it will turn the inner rim of the upper part of the turntable Fyp 1.3.20 which is lined with rubber drive belt, rotating the turntable. There are 50 ball bearings of 15mm diameter to ensure the rotation is as flat and as smooth as possible.

Figures 3.156 – 3.159 Fyp 1.3.19

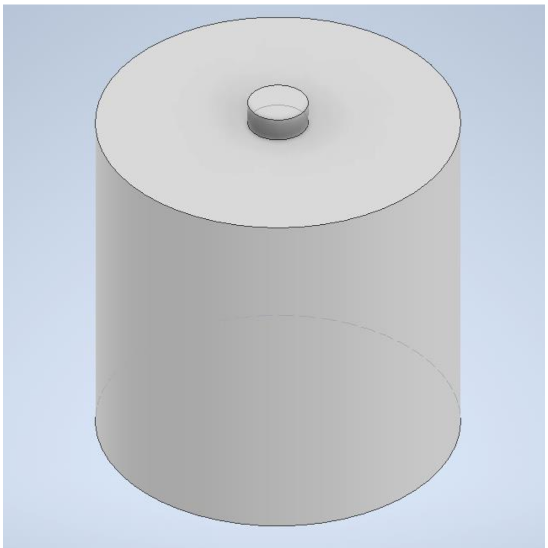
Top view



Front view



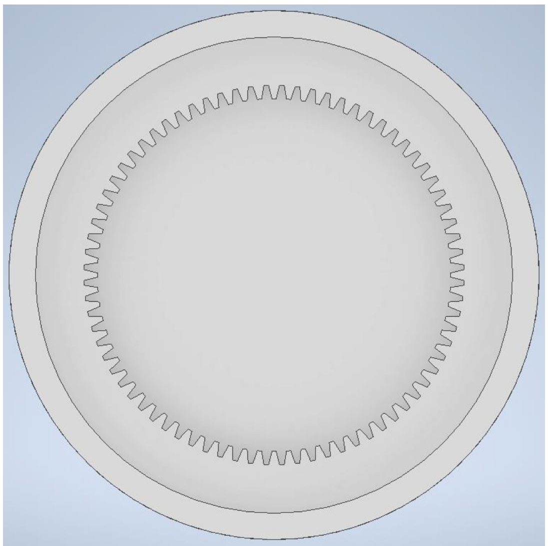
Side view



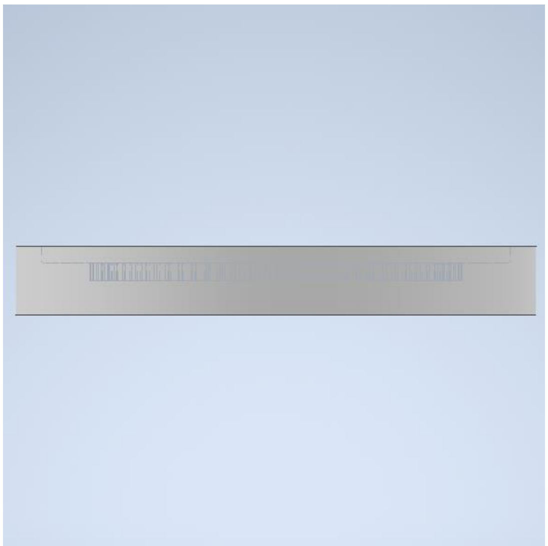
Isometric view

This is 32mm rotor with a dimeter of 30mm. It if fitted in lower part of turntable Fyp 1.3.18. It is the source of rotation of the turntable.

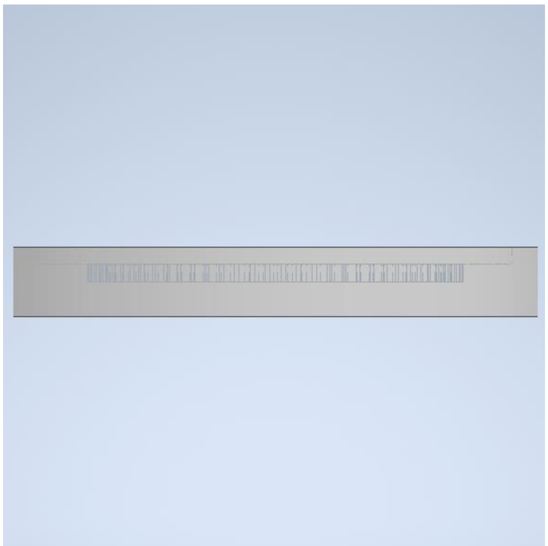
Figures 3.160 – 3.163 Fyp 1.3.20



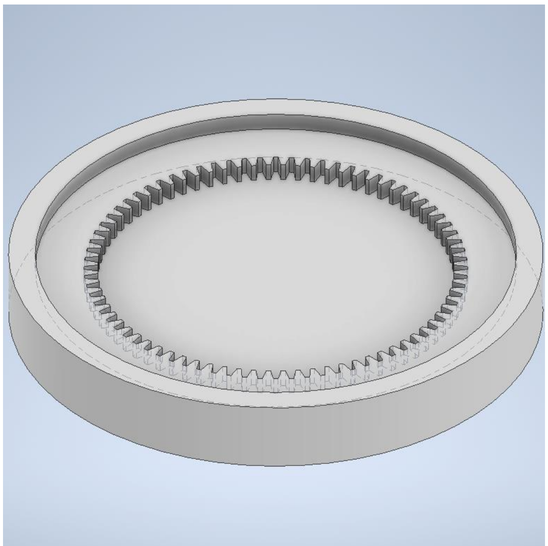
Top view



Front view



Side view

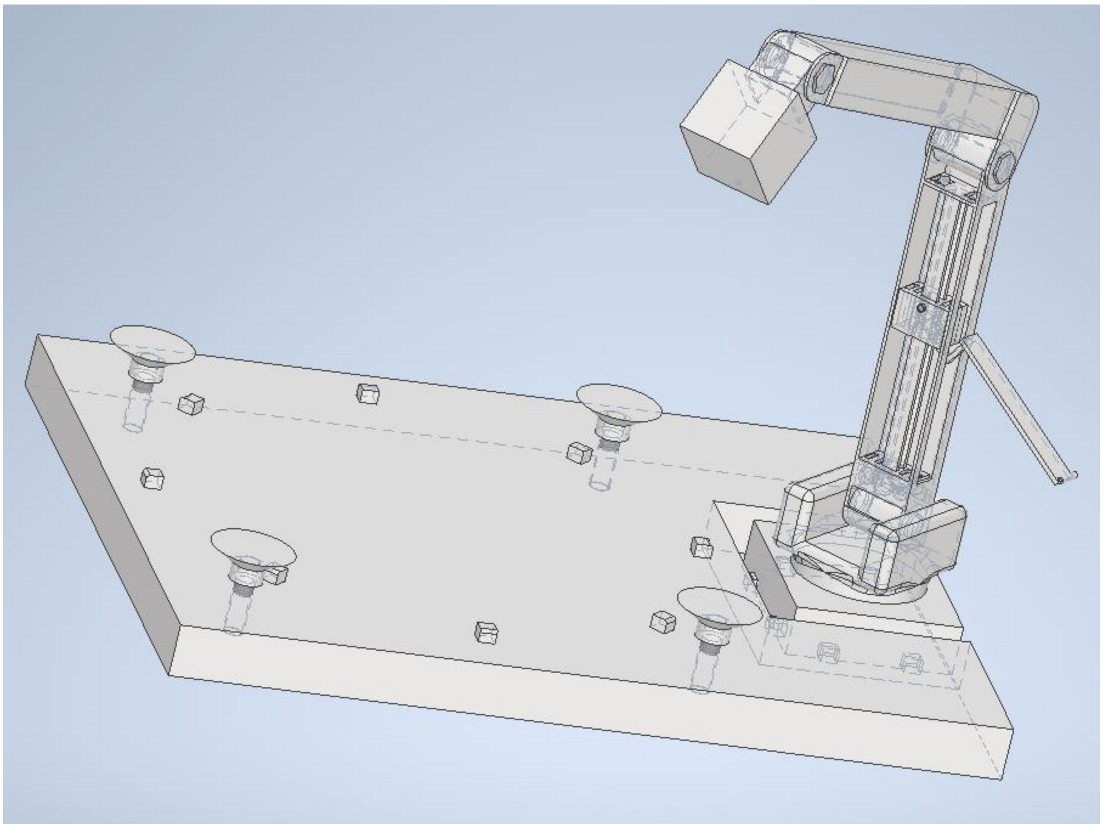


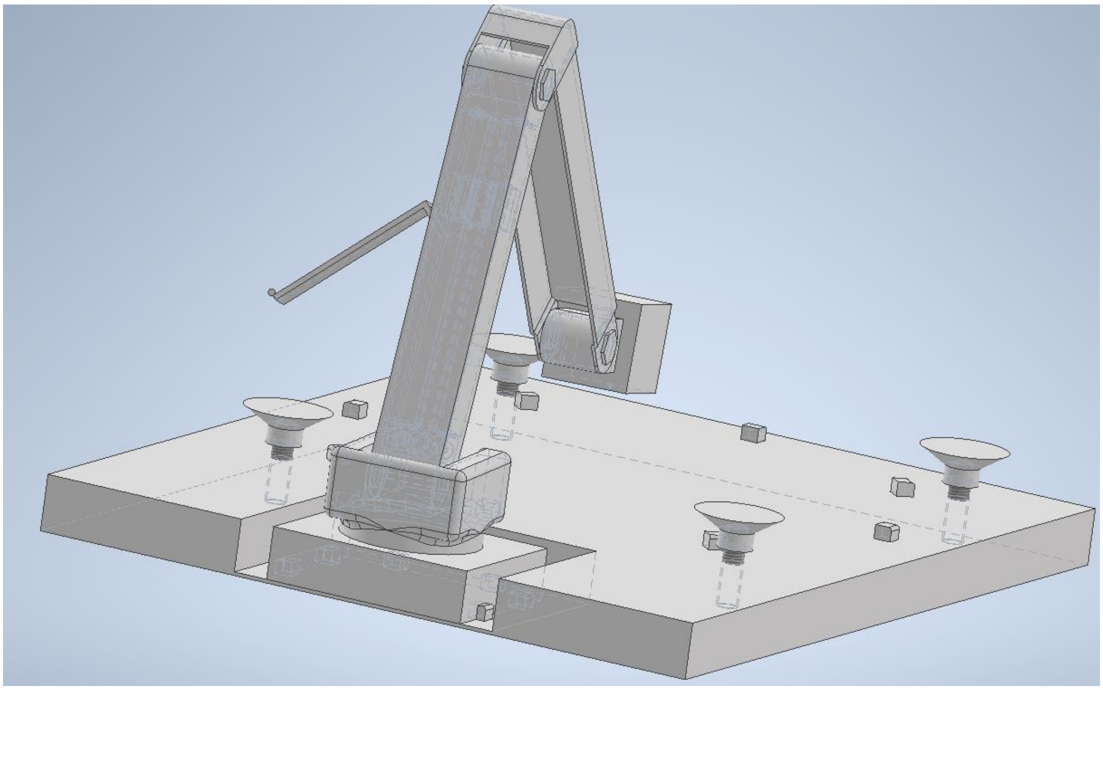
Isometric view

This is the upper part of the turntable. It is fitted on to the lower part of the turntable Fyp 1.3.18 to form the complete turntable for 3DS operations.

With 20 different parts, the 3D Replicating Robotic Arm is built. The full structure takes 3 forms. The first, a neutral mode. This a free form whereby no actual operations are underway.

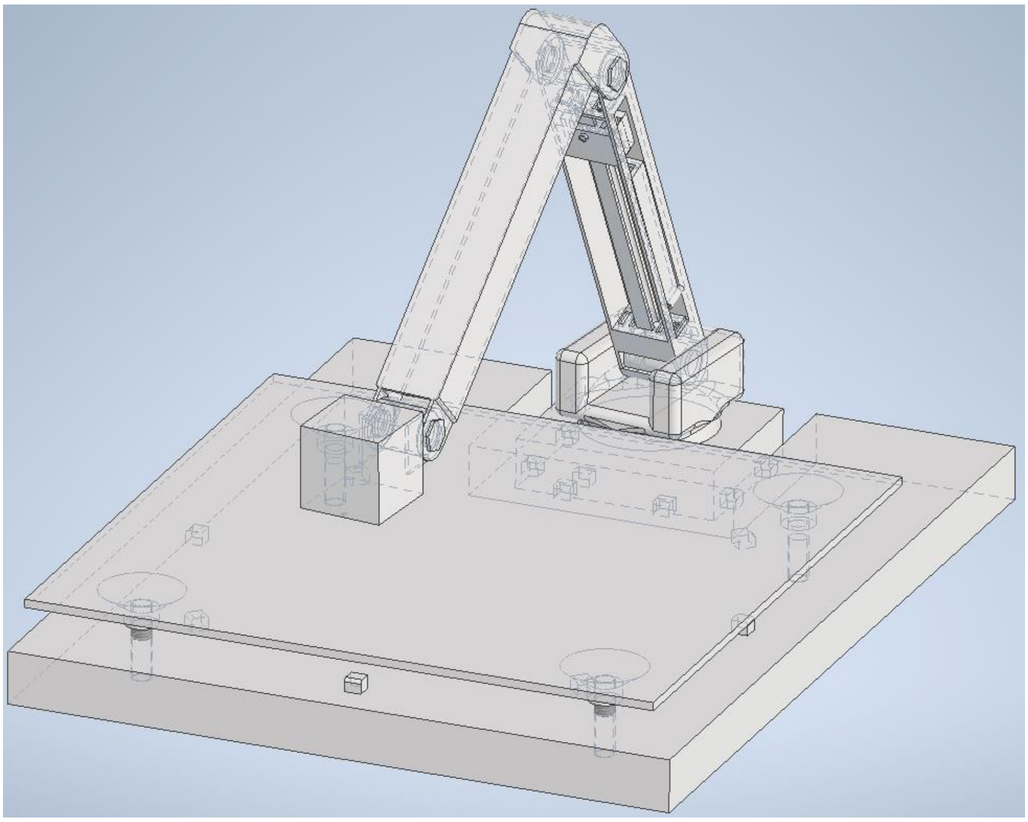
Figures 3.164 – 3.165 Fyp 1.3.N

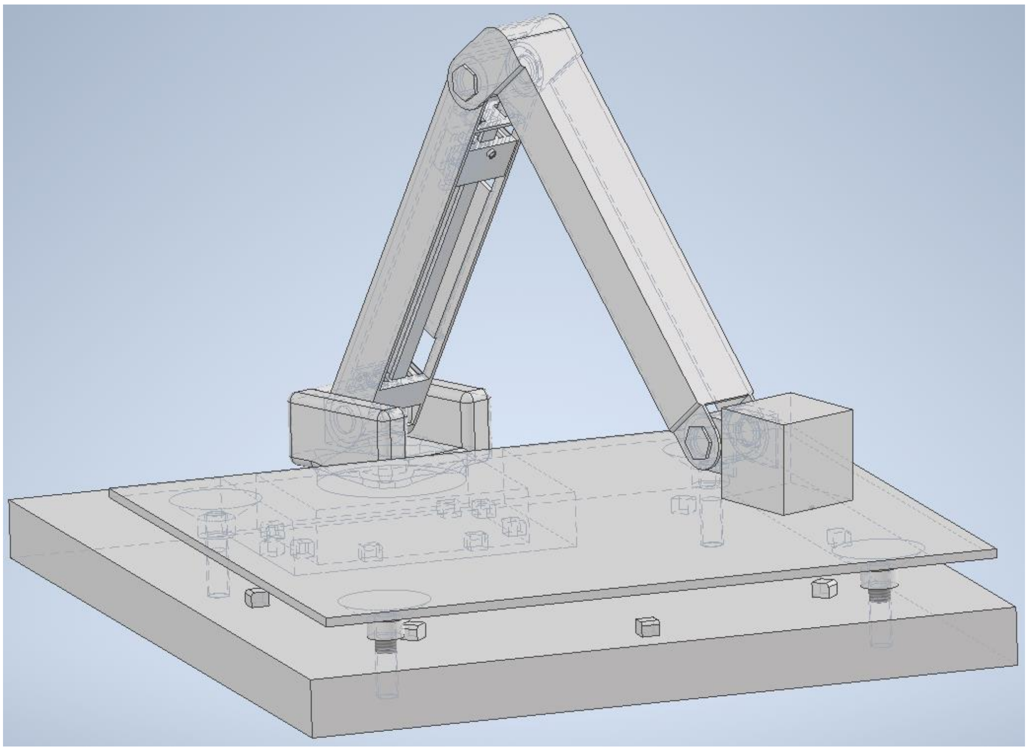




Next, 3DP mode. This is the state of the printer while printing 3D. The position of the camera is locked, the laser diode as well is not extended, while the FDM print bed is in use.

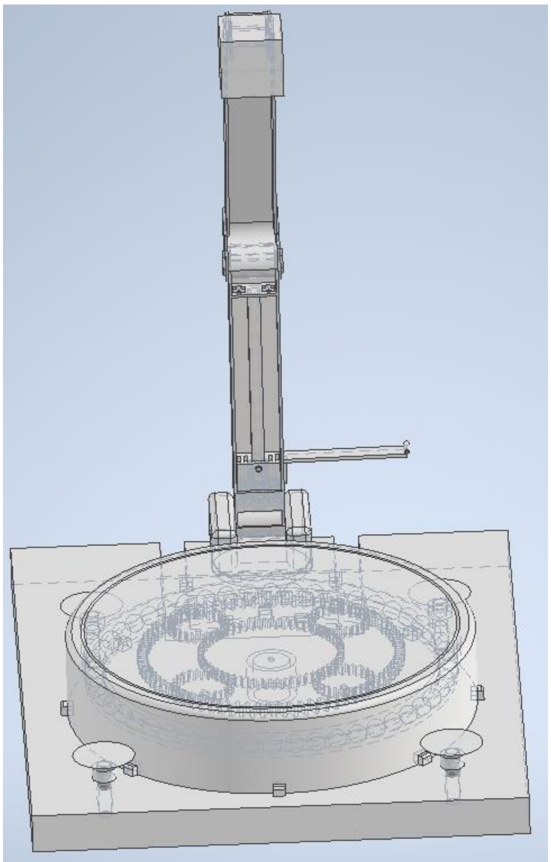
Figures 3.166 – 3.167 Fyp 1.3.P

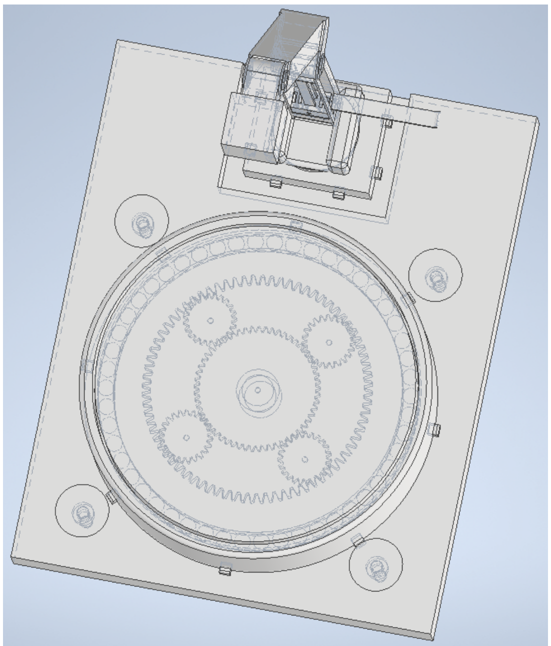


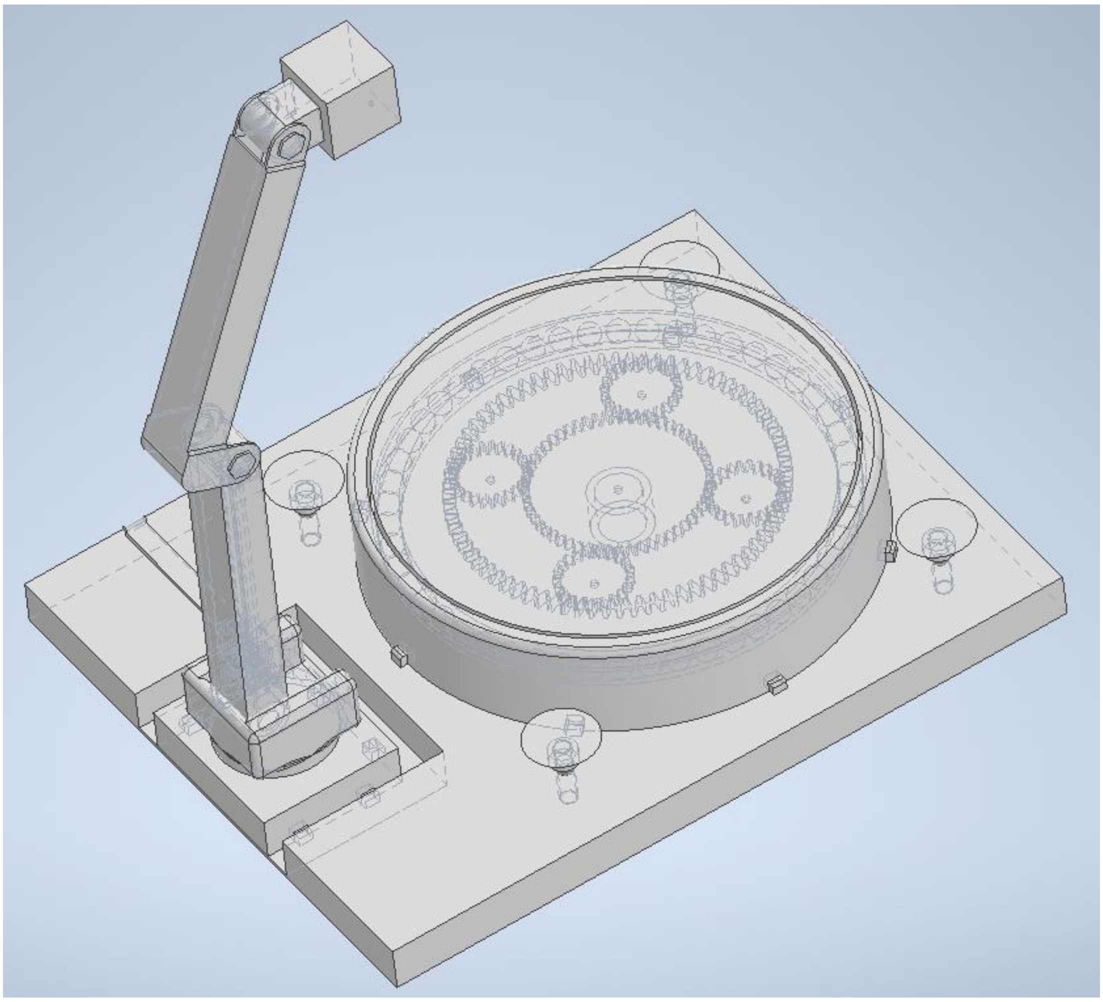


Lastly, 3DS mode. The image below shows the 3D Replicating Robotic Arm ready for 3DS operations. In this form, the forearm is extended and lifted up, while the upper arm is 90˚ upright. The laser diode is fully extended so that it is level with the camera, then, the camera is lowered all the way. If an object were to actually be scanned, the turntable will rotate, and the camera gradually climbs up scanning the object from top to bottom.

Figures 3.168 – 3.170 Fyp 1.3.S

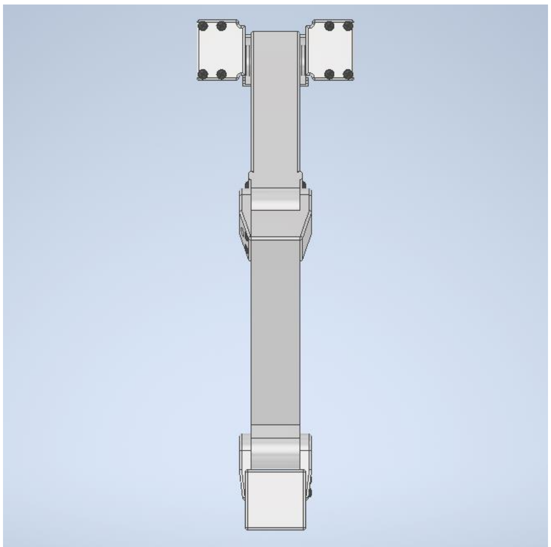




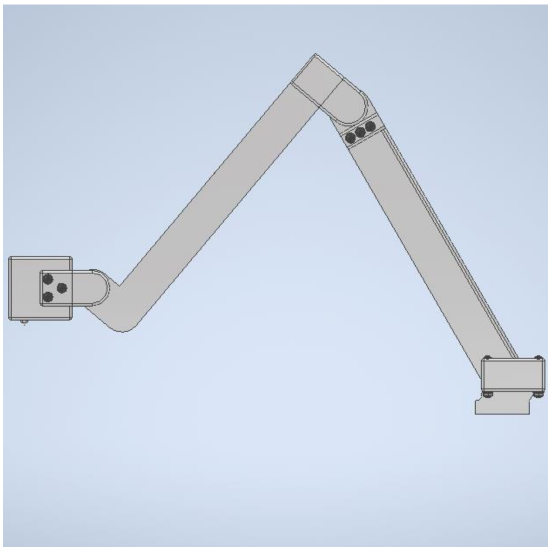


Following the first assembly drawing, a second more refined drawing was made to include more details and ideas. This was drawn during the 15th week, which is the first week of Project 2.

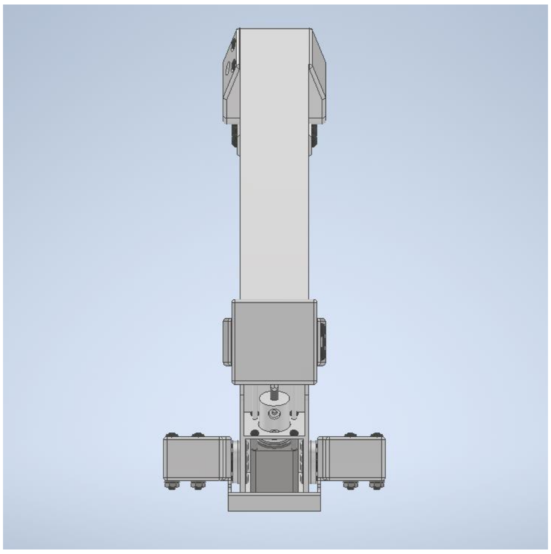
Figures 3.171 – 3.175 Fyp 1.4



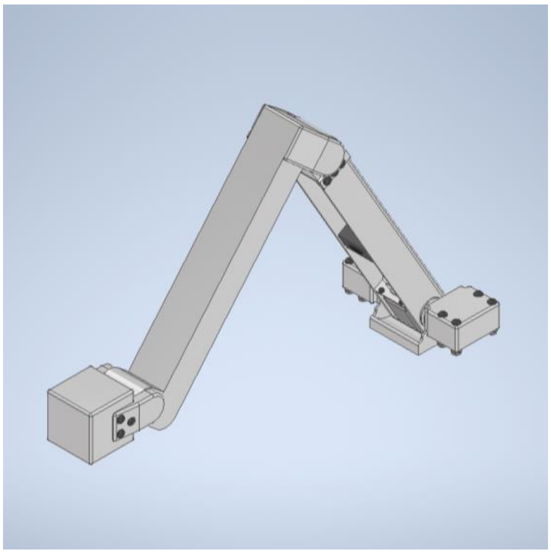
Top view



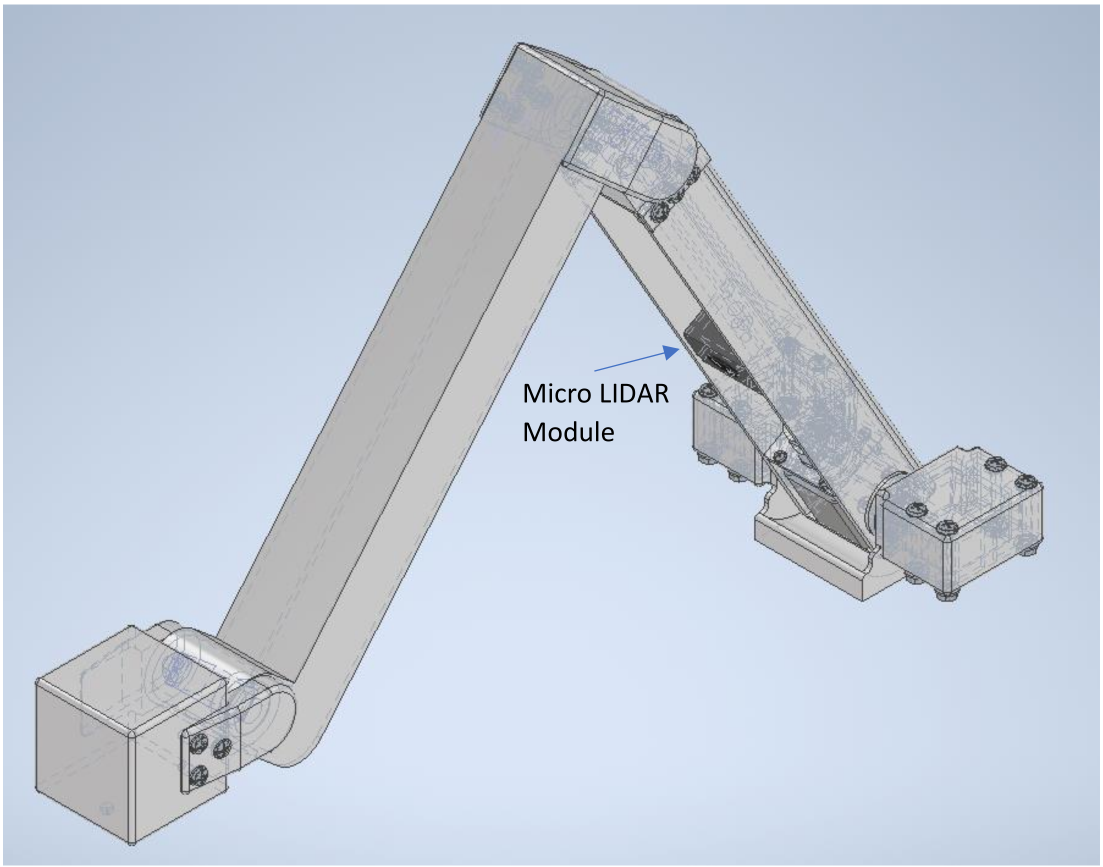
Front view



Side view



Isometric view

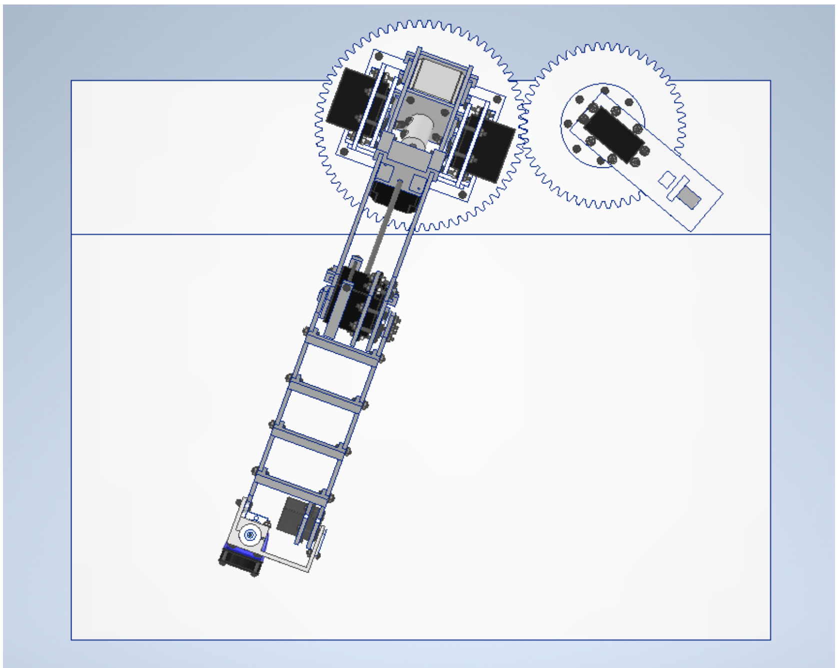


Isometric view with hidden edges

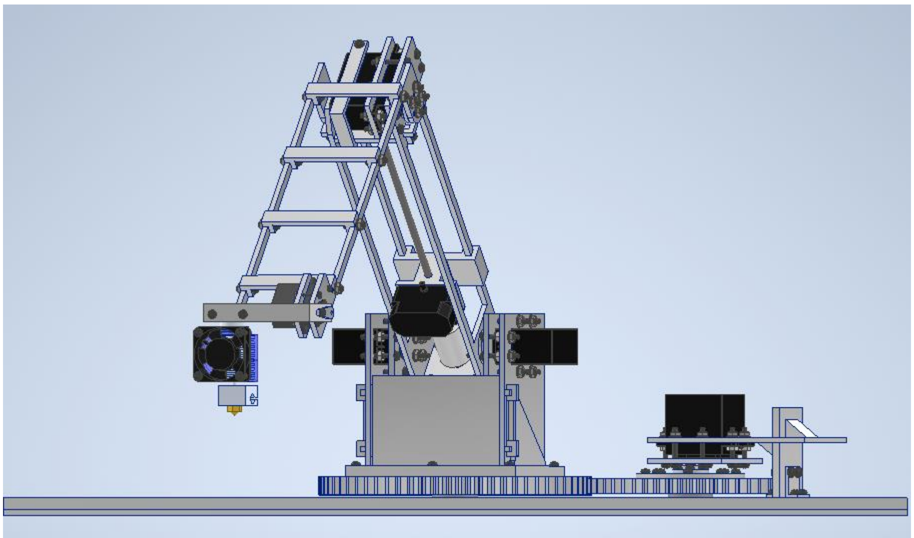
This drawing features the TFMini Plus Micro LIDAR Module, which would eventually end up being equipped on our final product. The micro LIDAR module moves vertically along a threaded rod, which is being rotated by a stepper motor. The robotic arm is powered by 4 motors, respectively 2 motors for the upper arm, 1 motor for the forearm, and 1 motor at the wrist for the extruder. The drawing also features more detailed joints between the parts with the use of bolted connections. This drawing involved 23 parts and 10 bolted connections in total. However, this drawing was not fully completed as inspiration struck for another concept to be tried and drawn.

We found the need to design the robotic arm whereby its part can be easily mass manufactured, as there is a substantial market for such robotic arms. Often sold as robotic arm kits or DIY robotic arms, the parts are often flat, in sheets, and are slotted or bolted together. It took close to 3 weeks to complete this new design.

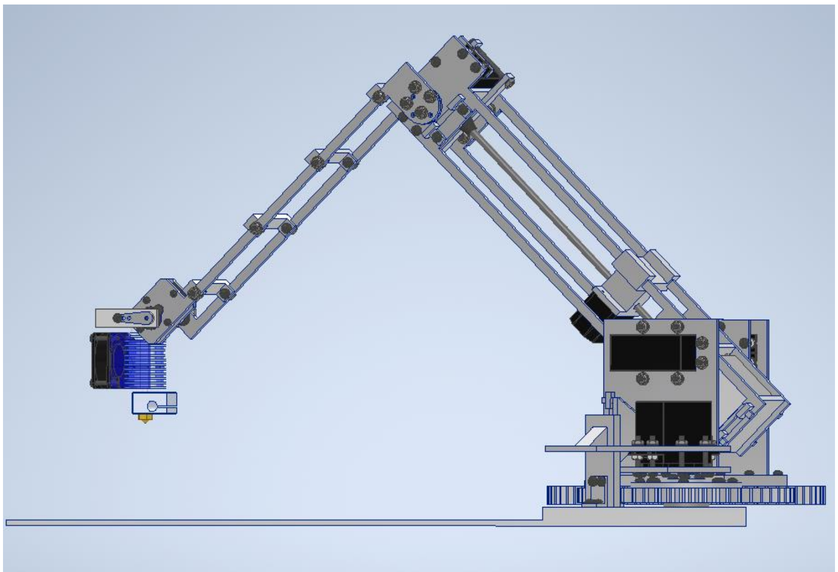
Figures 3.176 – 3.179 Fyp draft

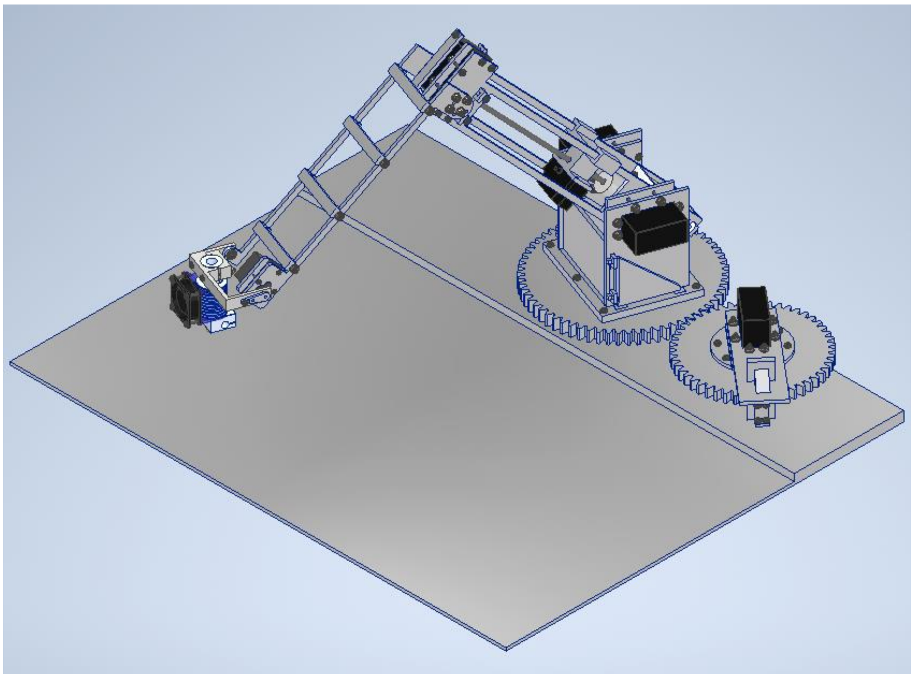


Top view



Front view

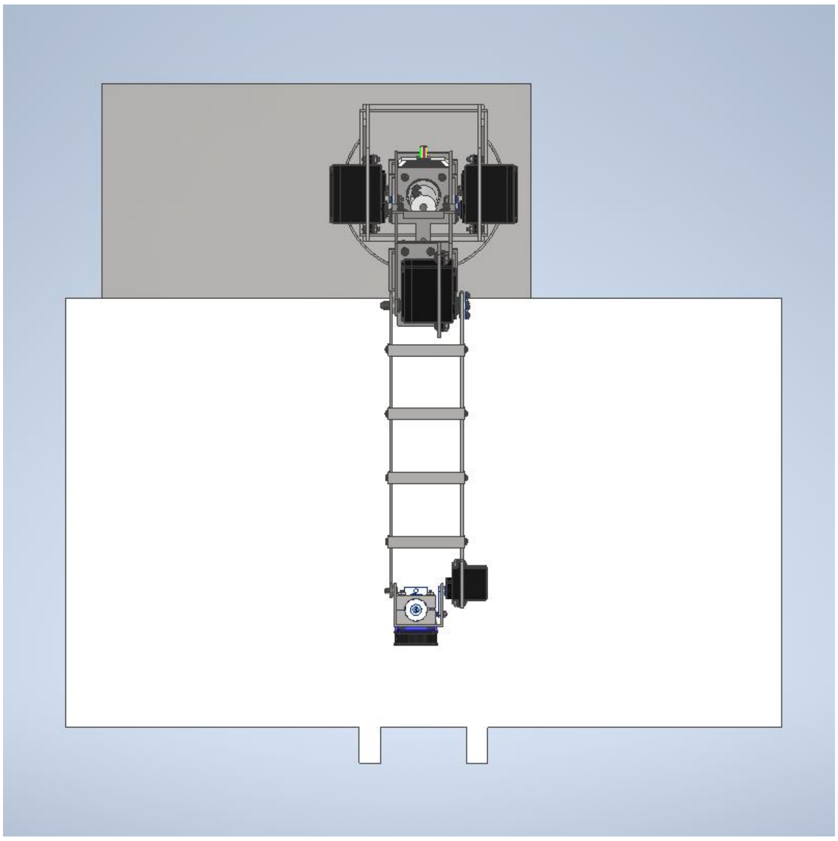

Side view


Isometric view

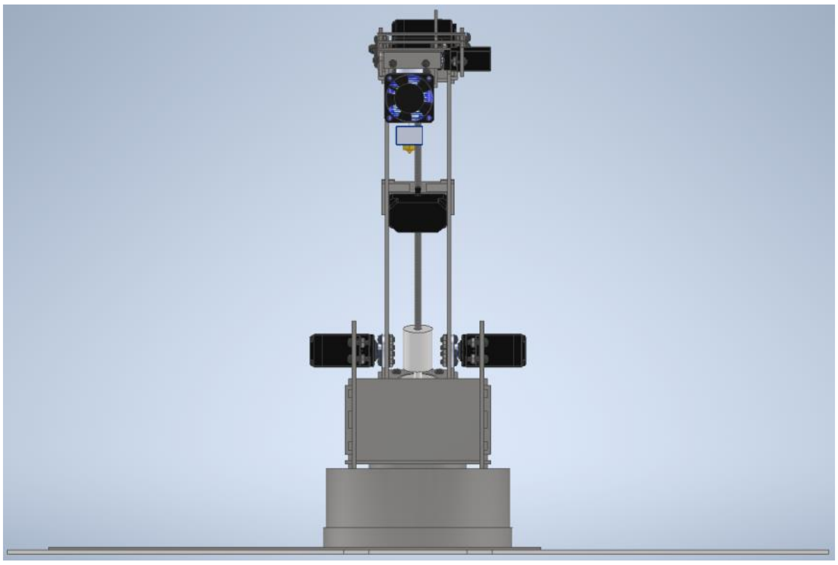
This drawing was named *Fyp draft* when completed, with the intent that it will be proposed and successfully produced. In the assembly, it consists of 43 different types of parts, a set of spur gears, 2 single row ball bearings, 1 clevis pin connection, and 24 bolted connections. In total, there are about 200 relationships between the parts, motors, gears, bearings, pin, bolts, and nuts. Out of all 43 parts, only 3 parts may require welding to be produced. Each part was also accurately assigned material to obtain physical properties such as mass for power and torque calculations. It was estimated to weigh just under 5kg. It also featured FDM extruder, various stepper motors and servo motors, all with accurate dimensions, tolerance +- 1mm.

The drawing was brought to several engineering, machinery, and sheet metal factories / companies for discussion and obtain quotation. This led to some modification towards *Fyp draft*, which were also the final modifications of the project design.

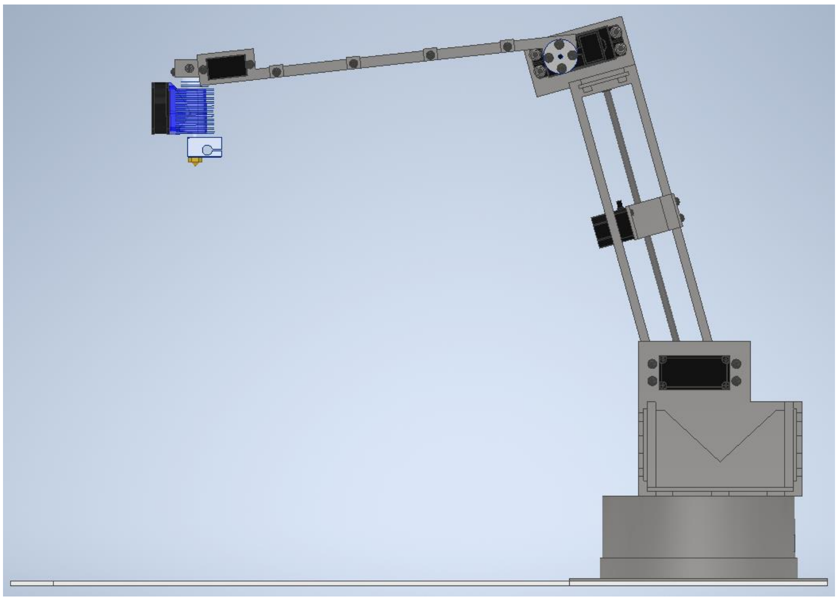
Figures 3.180 – 3.183 Fyp draft (revised)

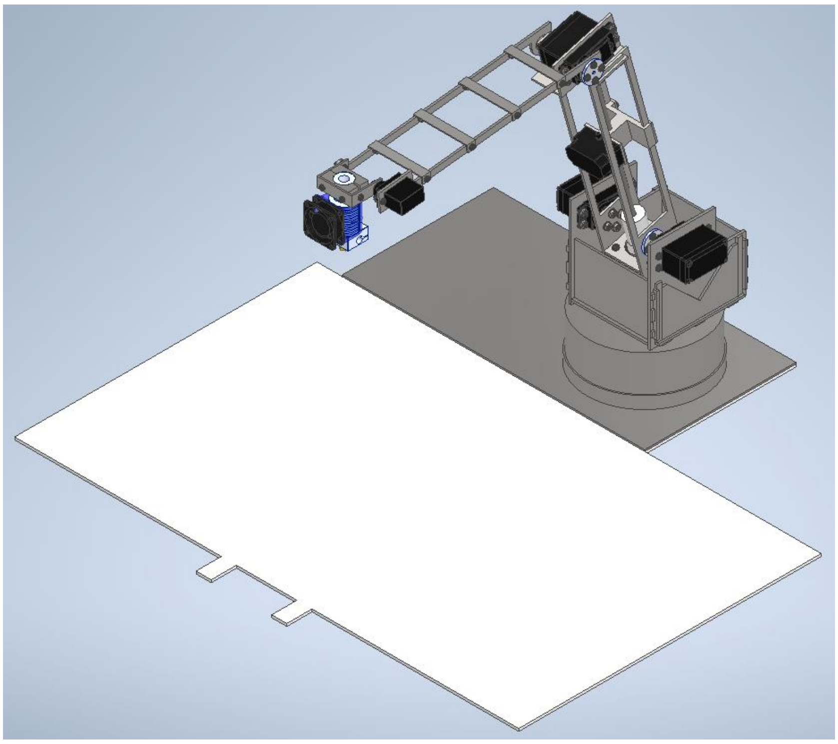


Top view



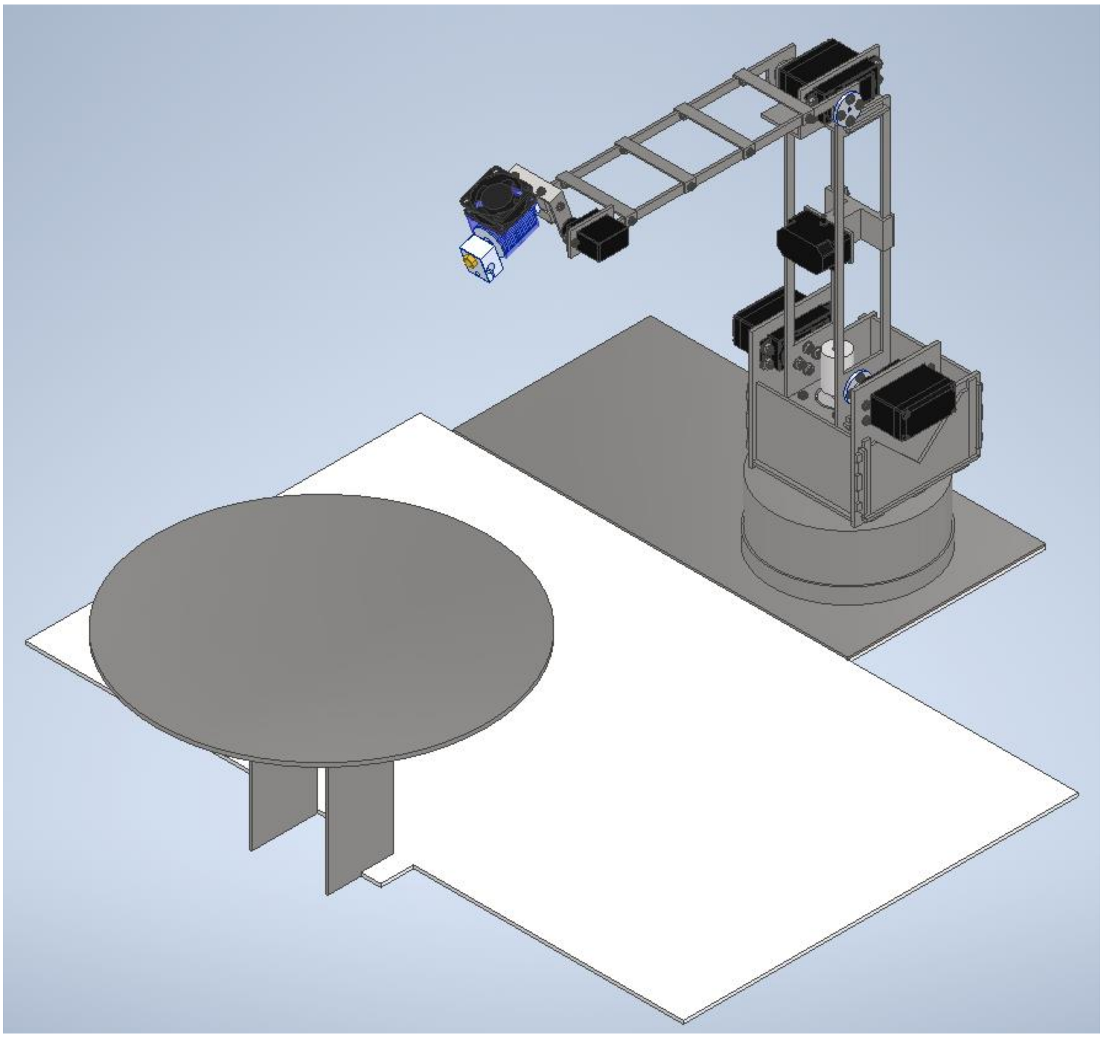
Front view

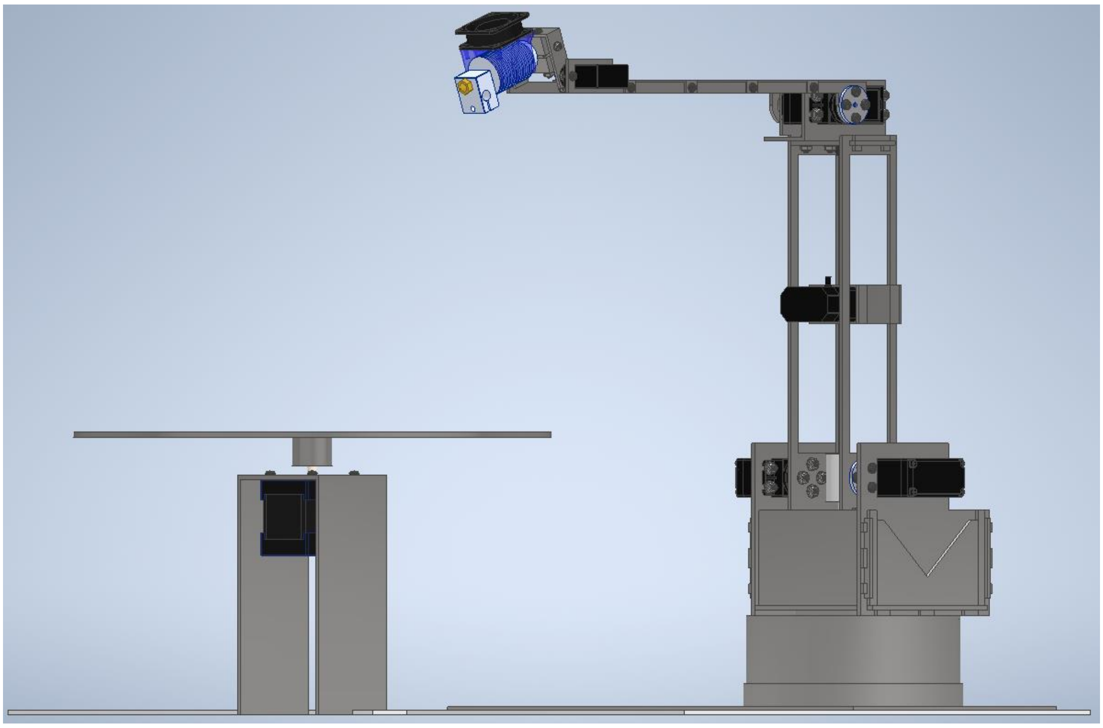

Side view


Isometric view

The modifications were made mainly to increase material efficiency while preserving structural integrity of the robotic arm. We removed the need for gears, and instead, strengthen the shoulder with a cylindrical cover. The size of the platform was also adjusted. The arm is made out of aluminium and mild steel, wherever suitable. A simple turntable was also added, which would fit in between the two protruding parts of the rectangular platform. Following *Figures 3.184 – 3.185* shows *Fyp draft (revised)* with turntable attached.

Figures 3.184 – 3.185 Fyp draft (revised) turntable attached





Following is a part list of the *Fyp draft (revised)*. Refer to attachment for technical drawings.

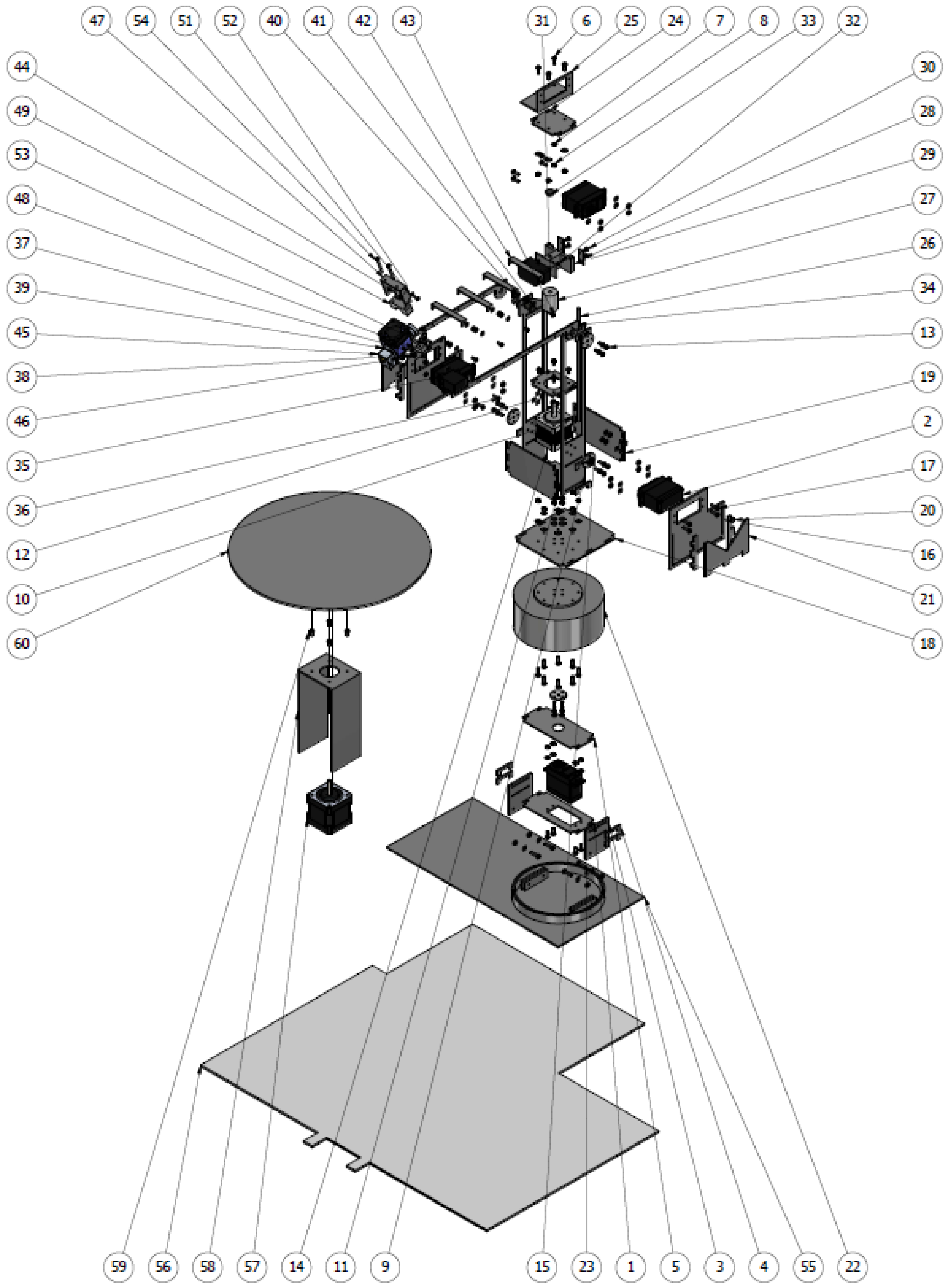


Figure 3.186 Exploded view

No.	Qty.	Item
1	1	servo holder base
2	4	MG996R Servo
3	2	base stand
4	10	lock
5	1	servo holder base upper

6	22	ISO 7045 - M3 x 8 - 4.8 - H
7	44	ISO 7089 - 3
8	44	ISO 4032 - M3(4)
9	1	upper arm L
10	1	NEMA 14 Stepper Motor 34mm
11	1	upper arm base
12	1	upper arm stepper motor support
13	8	ISO 7045 - M3 x 5 - 4.8 - H
14	1	upper arm R
15	4	25t round servo horn
16	2	shoulder
17	17	ISO 7045 - M3 x 10 - 4.8 - H
18	1	shoulder base
19	2	shoulder vertical support
20	4	shoulder vertical support lock
21	2	shoulder base lock
22	1	shoulder cover
23	8	ISO 7045 - M3 x 12 - 4.8 - H
24	1	upper arm support upper
25	1	elbow base
26	1	M5 x 0.8 bolt 170mm
27	1	M5 shaft coupler
28	2	LIDAR holder lock
29	1	LIDAR holder
30	4	ISO 7045 - M2.5 x 4 - 4.8 - H
31	1	TFMini Plus micro LIDAR module
32	2	ISO 7045 - M2 x 4 - 4.8 - H
33	1	bolt holder
34	1	forearm L
35	1	MG90S micro servo
36	2	ISO 7045 - M2.5 x 8 - 4.8 - H
37	12	ISO 7089 - 2.5
38	12	ISO 4032 - M2.5(4)
39	1	forearm R
40	1	ISO 7089 - 6
41	1	ISO 2341 - B - 6 x 12
42	4	forearm support
43	8	ISO 7045 - M2.5 x 6 - 4.8 - H
44	1	21t straight servo horn
45	1	E3D V6 direct extruder
46	1	ISO 7089 - 4
47	1	hand
48	1	extruder holder 1
49	1	extruder holder 2
50	1	ISO 7045 - M2 x 6 - 4.8 - H
51	1	ISO 7089 - 2
52	1	ISO 4032 - M2(4)
53	1	ISO 2341 - B - 4 x 8
54	2	ISO 7045 - M2.5 x 25 - 4.8 - H
55	1	base
56	1	platform
57	1	NEMA 17 stepper motor 40mm
58	1	stepper motor holder
59	4	ISO 7045 - M3 x 6 - 4.8 - H
60	1	turntable

Table 3.9 Parts lists

3.7. MATERIAL SELECTION & BUDGET

While hours and days were poured in to achieve the final design, several other decisive choices were made. These included starting to search for materials for the project. Regarding the build of the robotic arm, we refer to the table below.

Metal	Mild/carbon steel	Stainless steel	Aluminium
Cost	Low	High	High
Weight	High	High	Low
Strength	High	High	Low
Ductility	Low for carbon, medium for mild	High	High

Table 3.10 Metal properties

Based on that, aluminium was chosen as the main material of the robotic arm. This is because it is a light-weight alloy with good strength, high flexibility, and outstanding thermal properties. Due to its remarkable mechanical properties, it serves multiple industries, including biomedical, automotive, and aerospace. Besides that, its easily moulded and used for functional parts that require stiffness, low weight, high strength, and high accuracy. It is also corrosion resistant and is ideal for outdoor applications. Furthermore, the strength of aluminium at low temperature show increased tensile strength as temperatures drop and has a melting point of -933.47K (660.32˚C). Besides that, mild steel was also used to produce certain parts of the robotic arm which requires high strength.

For 3DS, we purchased the TFMini Plus Micro LIDAR Module. It is a versatile and compact micro LIDAR module that comes with a humble price of RM193.37. Whereas for FDM extruder, we got a E3D V6 Hot End Extruder and a Metal Bowden Extruder Kit, which altogether costed RM76.84. For print filament, we decided on ABS plastic. The robotic arm is powered by MG90s micro servo motors and MG996R servo motors, both are from TowerPro, well known for their low prices. Last but not least, the chipsets which controls the project, are Arduino Pro Micro and Mega.

Figure 3.187 MG90S Micro Servo Motor

Figure 3.188 MG996R Servo Motor

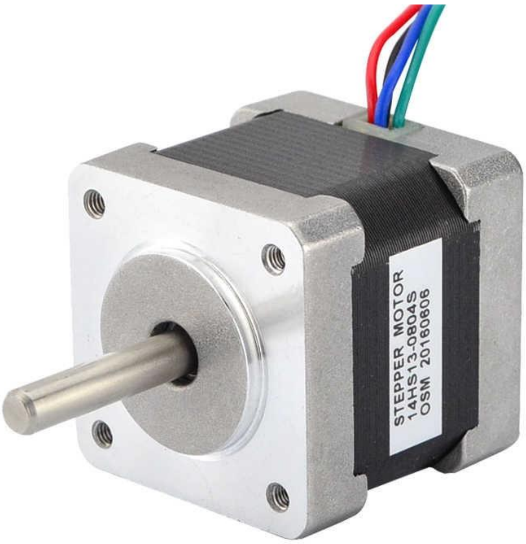


Figure 3.189 NEMA 14 Stepper Motor 34mm

Figure 3.190 25t round servo horn

Figure 3.191 M5 shaft coupler

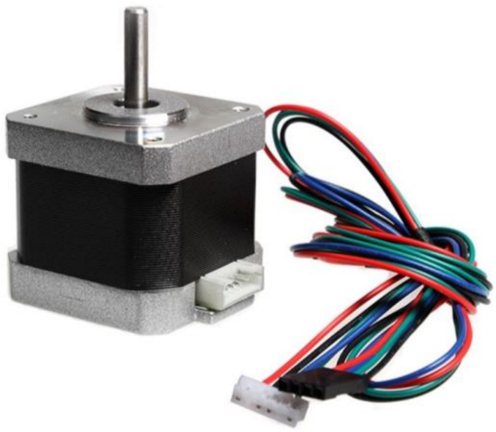


Figure 3.192 NEMA 17 stepper motor 40mm

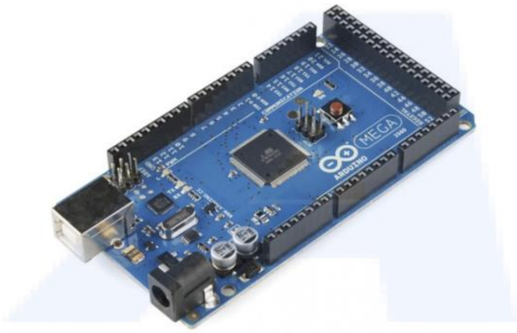


Figure 3.193 Arduino Mega   *Figure 3.194 TFMini Plus Micro LIDAR Module*

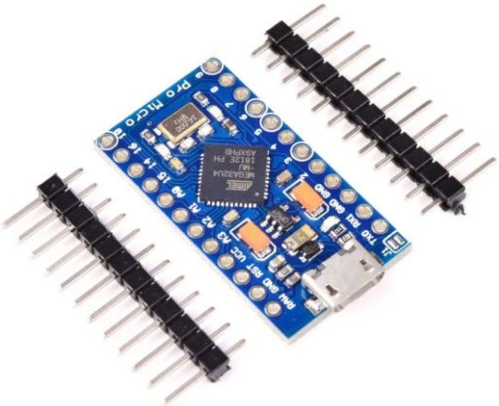


Figure 3.195 Arduino Pro Micro   *Figure 3.196 E3D V6 Hot End Extruder*

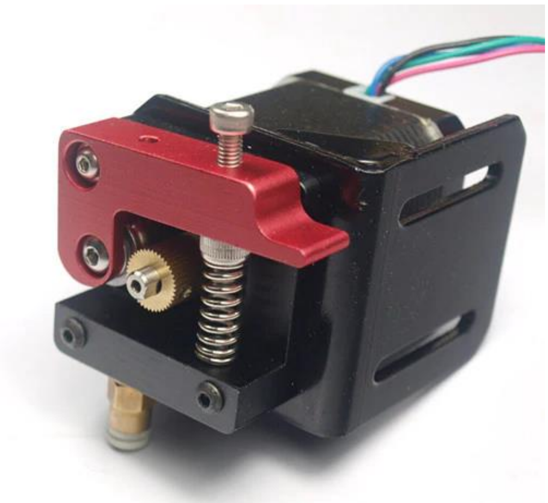


Figure 3.197 Metal Bowden Extruder

Below is a table of the expenses.

Item	Price (RM)	Quantity	Shipping Fee (RM)	Total
MG90S Micro Servo Motor	6.50	2	5.00	18.00
MG996R Servo Motor	15.90	6	5.04	100.44
TFMini Plus Micro LIDAR Module	188.17	1	5.20	193.37
E3D V6 Hot End Extruder	28.14	1	5.20	33.34
Metal Bowden Extruder Kit	40.00	1	3.50	43.50
NEMA 14 Stepper Motor 34mm	29.31	1	5.20	34.51
NEMA 17 stepper motor 40mm	19.00	2	-	38.00
25t round servo horn	2.20	5	5.20	16.20
M5 shaft coupler	5.90	1	3.50	9.40
Arduino chipset & consultation	450.00	1	-	450.00
Nuts and bolts	36.60	-	-	36.60
Robotic arm parts	1200.00	1 set	-	1200.00
Grand Total				2173.36

Table 3.11 Expenses

Overall, we are glad were able to complete the project within our estimated budget, which was RM2200.00.

3.8. PROJECT PRODUCTION & ASSSEMBLY

With our proposal and project design set, we approached several engineering/machining/metal fabrication companies and factories to produce the parts we designed for our robotic arm. We found these companies/factories mainly through recommendation of friends and seniors, as well as from search online. Based on the ratings and reviews of the companies/factories we found on google, we sent out emails requesting for a quotation. Then, we considered our options in aspects of duration required, price, and material used for the parts. We decided to produce our robotic arm parts at a sheet metal fabrication company which offered the service at RM1200.00. The production of parts took about 25 days.

The following are the images of the robotic arm parts during trial to confirm the material and tolerance during production.

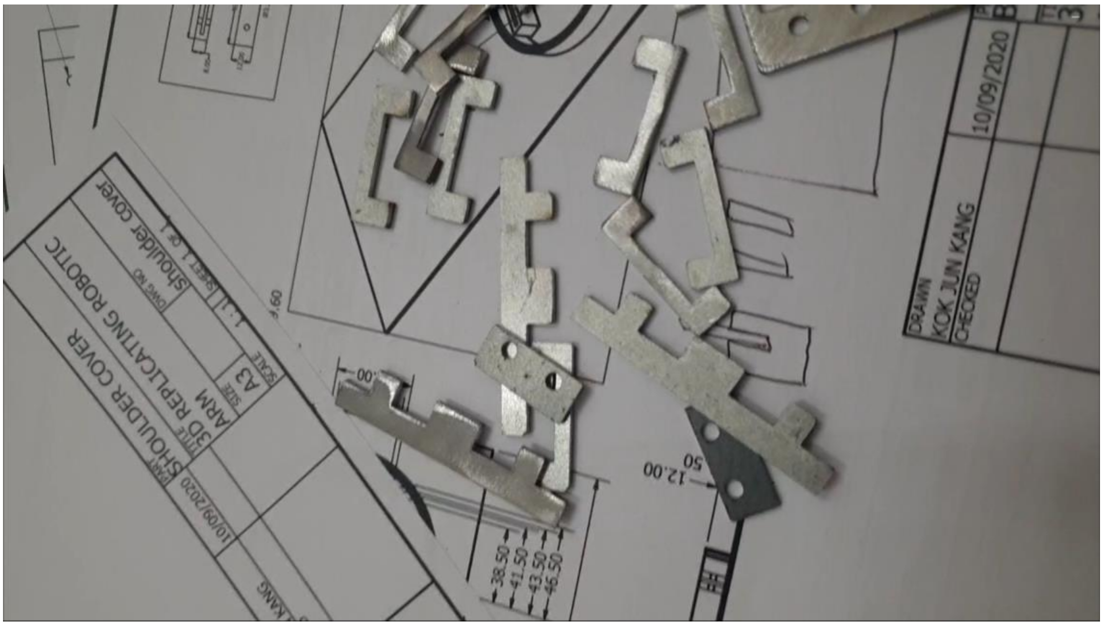
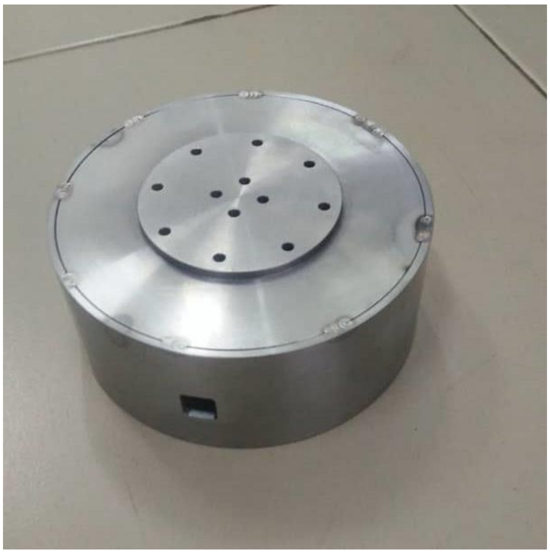


Figure 3.198 First batch of small parts produced

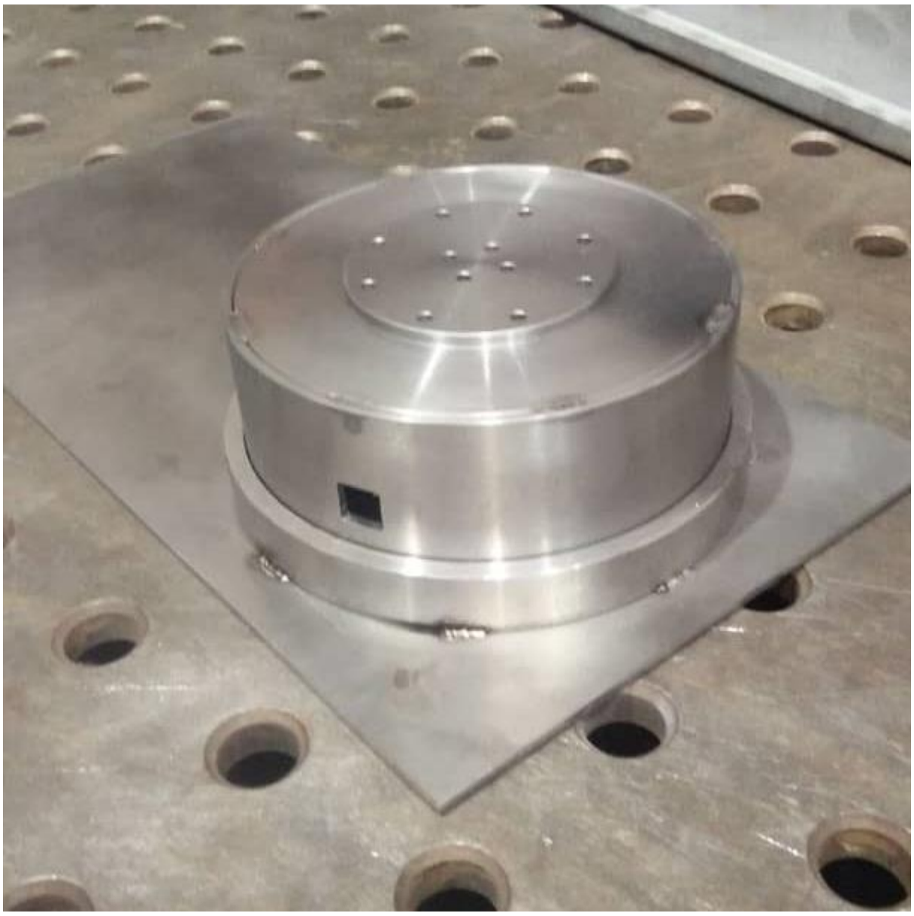
Figure 3.199 Testing of parts using chrome plated mild steel

It was decided that most parts will be made out of aluminium while a few parts experiencing high stress involved in the shoulder and base will be made out of mild steel. The following are pictures of the parts being produced.

Figures 3.200 – 3.202 Welded parts



Base *Shoulder cover*



Shoulder cover fitted onto the base

Figure 3.203 shows completed parts being packaged to be brought back for assembly.

Figure 3.203 Completed parts

The assembly process roughly 27 hours, spent across a period of 3 days. Filing and sanding were required to ensure the parts can be put together neatly without damage. The tools used for the assembly process were Phillips head screwdriver, needle nose plier, combination plier, metal file, rubber hammer, brush, and sandpapers with grit ranging from 200 to 1000.

Figure 3.204 Packaged parts

Figure 3.205 Unpacking the parts

Figure 3.206 Assembling during the first day

Figure 3.206 shows the assembling process during the first day. The image shows the upper arm being slotted in with a stepper motor.

Figure 3.207 Assembling during the second day

On the second day, the workspace has visibly gotten much messier with tools lying around. More parts have been assembled together. Most of the stepper motors and servo motors have been bolted in place by this point.

Figure 3.208 Assembling during the third day

Figure 3.208 shows the robotic arm taking shape as it is almost fully assembled. The turntable can also be seen on the bottom left of the image. Lubricant was sprayed onto moving parts to reduce friction and prevent corrosion.

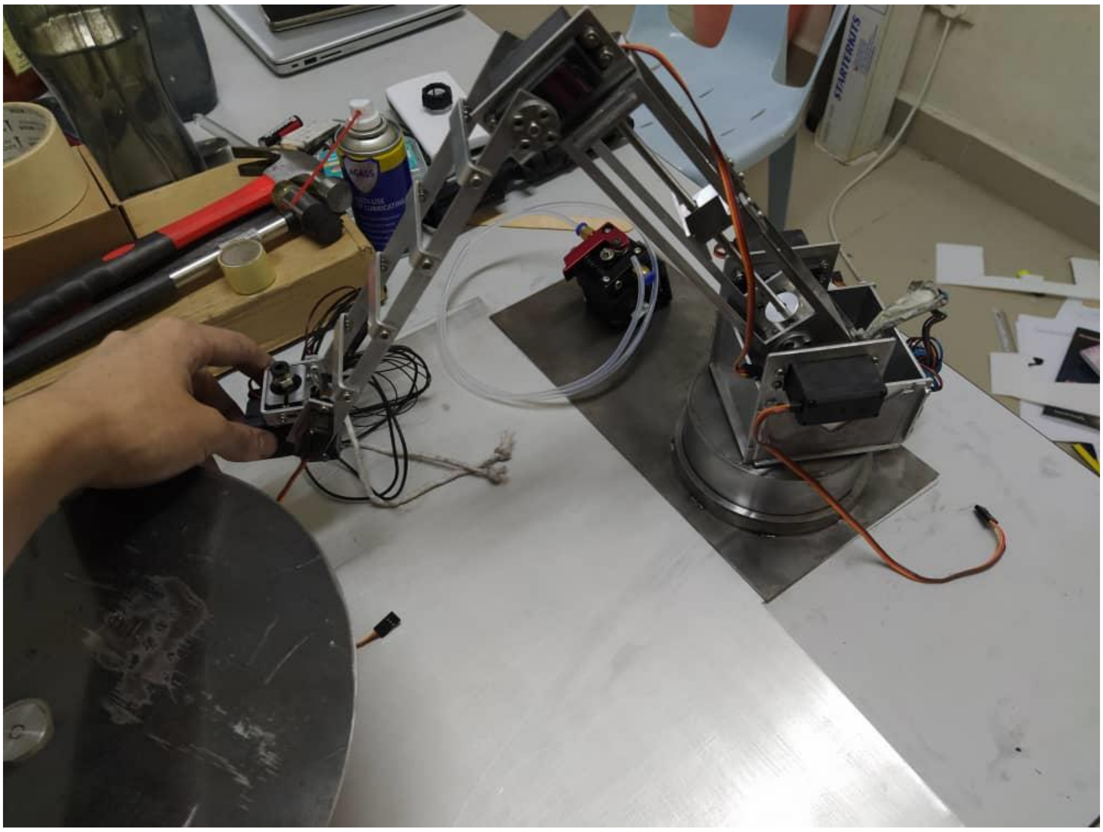


Figure 3.209 Testing of arm movement

Figure 3.209 shows the robotic arm almost fully assembled and its joints being rotated to check if the movements are smooth and motor rotations are within range. At the base, the shoulder was to be not parallel to the base and caused the arm to tilt while turning. This was rectified by disassembling relevant parts for filing and sanding, then reassembled with care.

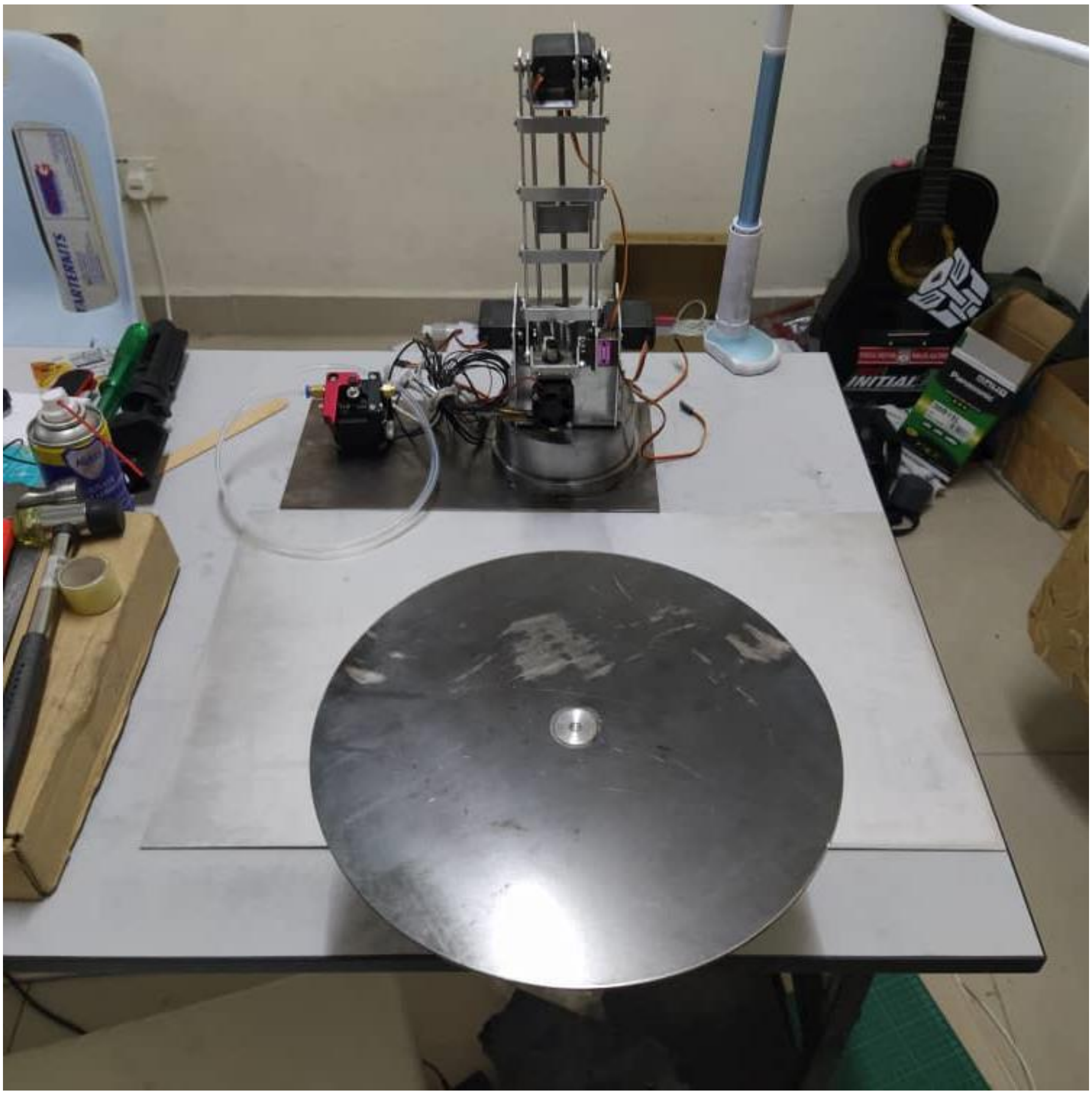


Figure 3.210 Complete assembly

Figure 3.210 shows the assembled robotic arm with turntable attached from the front. Words cannot express the excitement of our research and imagination coming to life. This was then lightly coated with light grey spray paint to prevent rusting, as well as making the arm neater and more aesthetically pleasing.

After a day of drying, we brought the project to an electronics programmer for consultancy and guidance for the coding process. Finally, the project is complete.

CHAPTER 4

RESULTS

4.1. INTRODUCTION

This chapter describes the findings of our research, based on the research objectives and questions, and explains in detail the operation of the 3D Replicating Robotic Arm.

4.2. PROJECT OPERATION

The device has 2 modes, which are for 3DP and 3DS. This in enabled by 4 main chipsets, the robotic arm, micro LiDAR module, and FDM extruder is each controlled by a chipset, and another general chipset controls which chipsets are being operated. During the 3DP mode, the micro LiDAR module will be locked to the centre of the forearm to act as a support, whereas during 3DS mode, the robotic arm's movement will be locked. The micro LiDAR module is programmed to record its distance between it and the scanned object in a manner a written Arduino code is able to interpret it as point cloud data. Whereas the robotic arm is programmed to execute G-code written for 3DP. The FDM extruder runs on a code package downloaded online for our E3D V6 HotEnd. It is programmed to extrude 1.75mm ABS plastic filament through a 0.4mm nozzle. Following are operational instructions.

General

1. Plug in the device and turn it on.
2. Run calibration process. This is to ensure 3DP and 3DS results are precise and accurate. Make sure that the 3D Replicating Robotic Arm is placed on a flat surface.

3. When not in use, properly switch off the device before unplugging. Improper shut down may damage the device.

3D Scanning Process

1. Place the detachable turntable within the slot on the 3DP platform.
2. Place the object to be scanned on the centre of the turntable. For best result, scan in a well-lit area. Shiny/reflective/translucent/through holes objects are not advised. Maximum scanning height is 140mm.
3. Start the 3DS process. The turntable will rotate the object gradually while the micro LiDAR module detects the distance between it and the scanned object. After every rotation, the micro LiDAR module will move up by a certain distance and continue the detect the distance of the object at that height. During this process, do not move the object or device, or scan results will not be desirable.
4. When the scan is complete, the micro LiDAR module will return to the centre of the forearm and the turntable to stop rotating. You may now remove the scanned object and turntable.
5. Remove the micro SD card from the micro LiDAR module’s microcontroller and connect it into a computer.
6. Run Arduino code to interpret the data on the micro SD card into point cloud data. Save this point cloud file.
7. Run MeshLab and import the saved point cloud file. Export this point cloud as a 3D mesh e.g., STL format.
8. 3D mesh of object is now obtained. You may edit the 3D mesh using CAD software such as Autodesk Inventor.

3D Printing Process

1. Run MakerBot Print. This is a 3DP slicer programme developed by MakerBot. The 3D Replicating Robotic Arm has been integrated with this software. Import a 3D mesh file to 3D print e.g., the 3D mesh obtained from 3DS.
2. You may edit how to print your object from here. You may also rescale your object size.

3. Simulate the 3DP process.
4. If satisfied, generate G-code. Copy this G-code on a micro SD card, then insert it into the microcontroller of the robotic arm.
5. The robotic arm will now run the code and 3D print objects accordingly. Do not interfere during the robotic arm during this time as it will affect the print quality.
6. 3D print of 3D mesh is now produced.

4.3. RESEARCH FINDINGS

As a whole, we are successful at building a robotic arm equipped with 3DP and 3DS features. Besides that, compared to other 3D printers and 3D scanners in the market, our device is considerably lightweight. Furthermore, we also managed to complete the project within our estimated budget, proving reasonably affordable to be manufactured as a commercial product. Moreover, the robotic arm is material efficient and an assembly of sheet parts which are relatively easy to produce in a short amount of time.

However, despite many efforts and attempts, we are unable achieve a fully operational device that could compete against any decent 3D printer or 3D scanner. The device tends to freeze during operation, or the movements of the arm may slow down unexpectedly. This has caused uneven extrusion of filament while printing, as the extrusion of filament does not slow down with the unexpected movement of the arm. This in turn may jam up the extruder, which would then require disassembling for cleaning. To date, we are only able to print simple shapes and designs, all models with high details such as cartoon figurines, are off limits. This is speculated to be caused by lack of processing power of the chipset. Certain CAD files are too dense when converted to G-code for the chipset to process and execute smoothly. 3DS on the other hand does not experience programming issues, but mechanical issues. The vertical movement of the micro LiDAR module along the upper arm relies heavily on the threaded bolt and support beams of the upper arm. Any bending done to the beams and bolt will prevent the micro LiDAR module from moving smoothly, thus affecting 3DS accuracy. Such in this case, the beam was most probably bent during the assembly of the robotic arm and caused alignment issues for the movement of the micro LiDAR module.

Therefore, there is much improvement that can be done to this device for a smother operation. A chipset with higher computing power and storage is needed to ensure the robotic arm is always in control. Besides that, the extruder should be programmed to directly correspond with the speed of the robotic arm so that filament is not wrongly extruded. Next, the upper arm needs to be modified for a stronger structure, or be made out of stronger and stiffer material, such as mild steel and stainless steel instead of aluminium which is ductile and bends more easily.

From this research, we are able to determine that robotic arms are definitely a feasible way to making 3D printers, as they are used for many other purposes which require high accuracy and repeatability. A robotic arm would also work best with an FDM Bowden extruder and LiDAR module for 3DP and 3DS features, as they are most affordable, easy to operate, and easy to maintain. As mentioned, the bending of the upper arm has affected the 3DS on our device, thus, future attempts should explore other designs and alternatives on how to mount a 3DS system onto a robotic arm.

4.4. CONCLUSION

Overall, we are able to achieve the objectives of our research to a certain degree, as well as answer most of the questions of this research. Due to the complexity and cost of this project, we are unable to perfect the device within the allocated time and agreed budget cap. This does not mean that our research is not complete or fruitful, but demonstrates the depths of 3DP, 3DS, and robotic arm technologies, and that this may serve as a helpful reference to future research in this field.

CHAPTER 5

DISCUSSION & CONCLUSION

5.1. INTRODUCTION

We have come to the final chapter in this report, the end of this project, stretched across a period of 2 semesters. Here, we will take a short recap of the entire project, with all its contents and aspects of research, to be discussed in general and concluded. A year's work, backed by 30 months of diploma studies, boils down to this.

5.2. DISCUSSION

There is no doubt that 3DP, 3DS, and robotic arm are remarkable technologies that are still experiencing mass growth and improvement today. However, to put them together as one has not been a subject of success, nor popular topic of research. Although, time and time again, history demonstrates that inventions combine to make better products. The best example would be the mobile phone. A combination of television, telephone, camera, microphone, compass, radio, and the lists continues on individual inventions that enable the smartphone to do what it does today. Robotic arms have been tried to be innovated in all sorts of ways, and it should with 3DP and 3DS. The importance and potential of 3DP and 3DS, especially in manufacturing, education, and research sectors almost guarantees the innovation of robotic arm with such technologies to be a success. This is shown when robotic arm with 3DP features garnered exceptional response on fund raisers online. Therefore, there is a need to build on those products and enhance their abilities even more.

The 3D Replicating Robotic Arm serves as a prototype for such a product. Although not perfect, it is the basis and reference for realisation of this concept of robotic arm with 3DP and 3DS features. It should be continued to be researched on to further develops this idea and product to make it fully functional and commercialised. Although imperfect at the current stage, it stills shows great potential, with closely supervised operation, we are already able to replicate simple objects such as a small container. The current issue with the computing ability and design of the upper arm are solvable and should be tackled accordingly. By providing enough computing power to the robotic arm and smoothening the movement of the micro LiDAR module, the project will be one step closer to realising this concept.

5.3. CONCLUSION

To conclude, engineering has always been and always be about applying science and mathematics into daily life, fabricating sophisticated devices to make life easier, more enjoyable, and more efficient. In this project, we plan to do nothing less than that, combining 3DP, 3DS and robotic arm technologies to produce one device that does it all.

Over the course of this project, we discussed the technologies from various standpoints, especially in technical, economical, and legal perspectives. As engineering students, technicality is pivot. However, they never work without the support of the other two, cost and quality, after all, we live in a capitalist world of supply and demand. To determine the balance between cost and quality is key, to minimalise cost but not compromise quality, in order for the project to be successful.

Through this project, we hope to contribute to efforts of making Malaysia a harmonious developed nation whereby citizens are focused and well aware of the developments of STEM, as we progress into the 4th industrial revolution and the era of the Internet of Things. We sternly believe in our product, the 3D Replicating Robotic Arm, in its capability to resolve issues that are in current 3D replicating devices, and in its potential that one day, devices with similar functions to our 3D Replicating Robotic Arm will become the norm, the standard, the baseline of robotic arms, 3D printers and devices alike. We hope people after us will take inspiration from this project and bring this concept to even greater heights.

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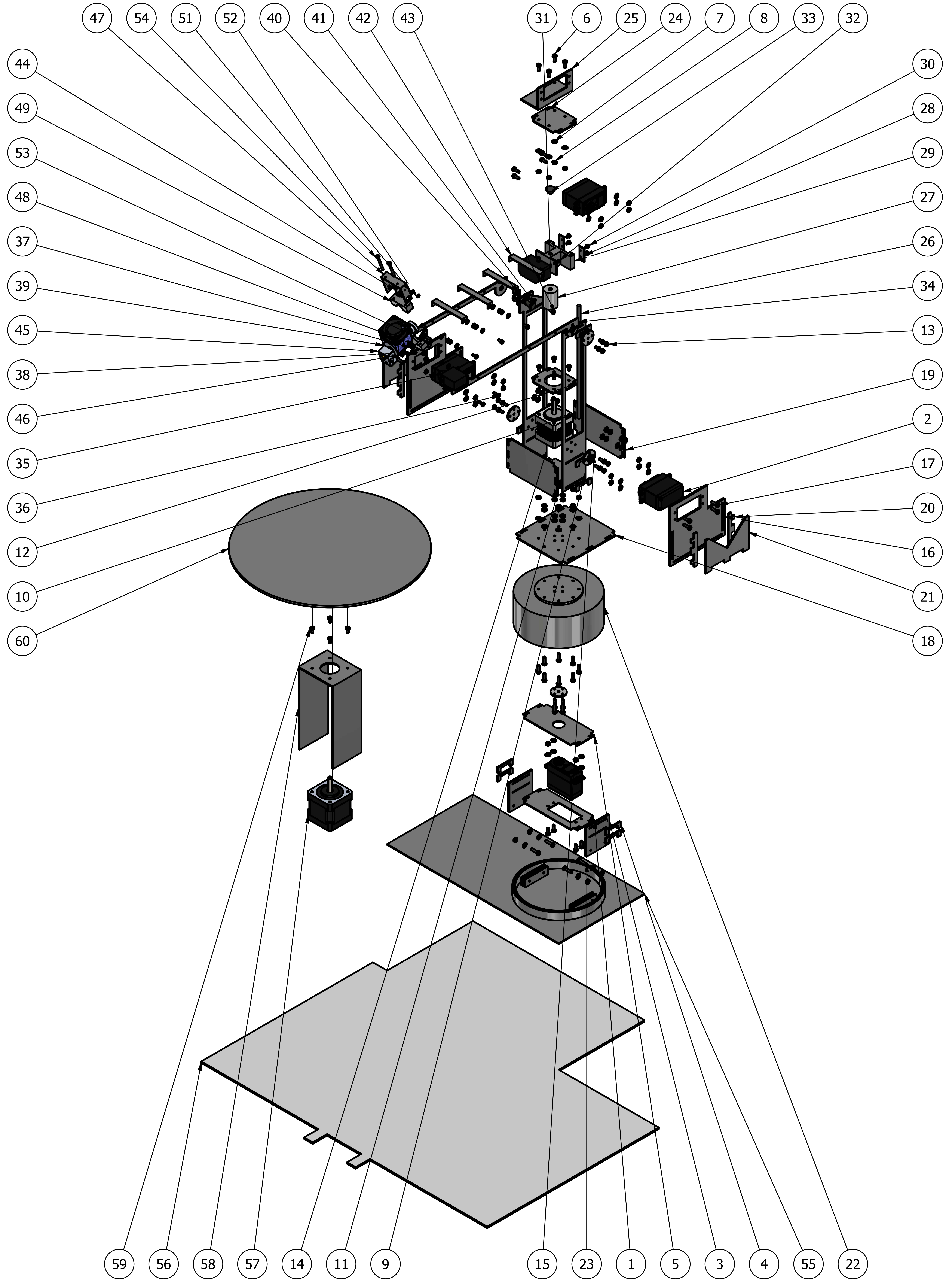
APPENDICES

APPENDIX A

GANTT CHART

No.	Week / Activity	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	Project Planning														
2	Project Designing														
3	Project Production														
4	Project Assembling														
5	Project Implementation														
6	Project Testing														
7	END														

APPENDIX B



DRAWN KOK JUN KANG	10/09/2020	PART EXPLODED VIEW	
CHECKED		TITLE 3D REPLICATING ROBOTIC ARM	
		SIZE A2	DWG NO exploded
		SCALE 1 / 4	SHEET 1 OF 1

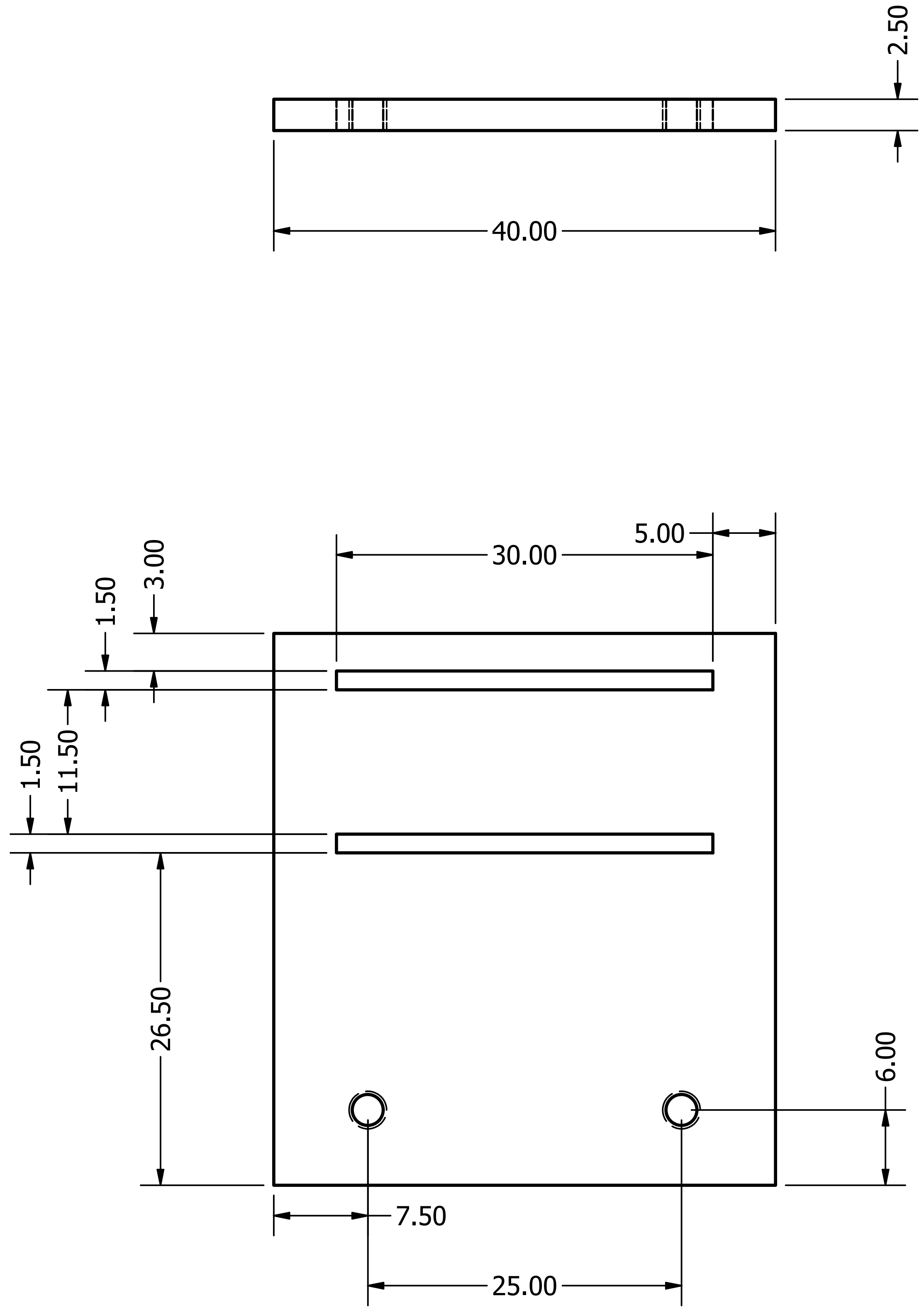
PRODUCED BY AN AUTODESK STUDENT VERSION
PRODUCED BY AN AUTODESK STUDENT VERSION
PRODUCED BY AN AUTODESK STUDENT VERSION

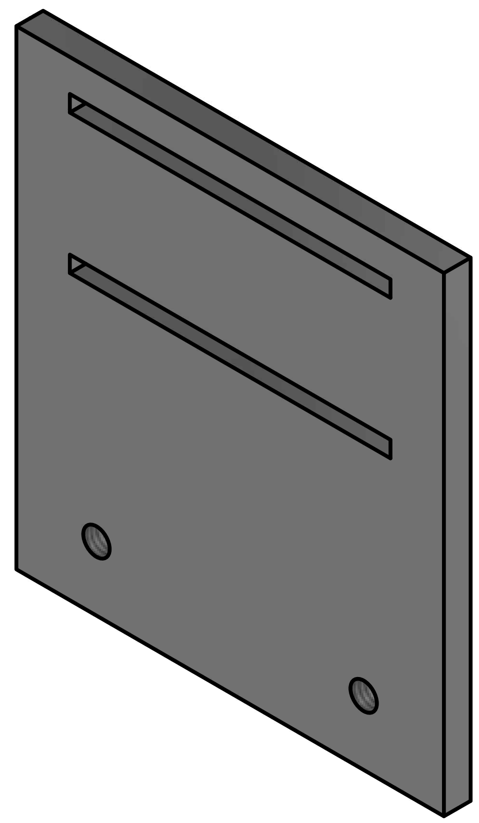
PARTS LIST

ITEM	QTY	PART NUMBER	DESCRIPTION
1	1	servo holder base	
2	4	MG996R Servo	
3	2	base stand	
4	10	lock	
5	1	servo holder base upper	
6	22	ISO 7045 - M3 x 8 - 4.8 - H	Pan head screw with type H cross recess - product grade A
7	44	ISO 7089 - 3	Plain washers - Normal series - Product grade A
8	44	ISO 4032 - M3(4)	Hexagon nuts, style 1 - Product grades A and B
9	1	upper arm L	
10	1	Nema 14 Stepper Motor Dimensions 34mm 1.8 Degree	
11	1	upper arm base	
12	1	upper arm stepper motor support	
13	8	ISO 7045 - M3 x 5 - 4.8 - H	Pan head screw with type H cross recess - product grade A
14	1	upper arm R	
15	4	25t round servo horn	
16	2	shoulder	
17	17	ISO 7045 - M3 x 10 - 4.8 - H	Pan head screw with type H cross recess - product grade A
18	1	shoulder base	
19	2	shoulder vertical support	
20	4	shoulder vertical support lock	
21	2	shoulder base lock	
22	1	shoulder cover	
23	8	ISO 7045 - M3 x 12 - 4.8 - H	Pan head screw with type H cross recess - product grade A
24	1	upper arm support upper	
25	1	elbow base	
26	1	M5 x 0.8 bolt 170mm	
27	1	M5 shaft coupler	
28	2	LIDAR holder lock	
29	1	LIDAR holder	
30	4	ISO 7045 - M2.5 x 4 - 4.8 - H	Pan head screw with type H cross recess - product grade A
31	1	TFMini Plus micro LIDAR module	
32	2	ISO 7045 - M2 x 4 - 4.8 - H	Pan head screw with type H cross recess - product grade A
33	1	bolt holder	
34	1	forearm L	
35	1	MG90S micro servo	
36	2	ISO 7045 - M2.5 x 8 - 4.8 - H	Pan head screw with type H cross recess - product grade A
37	12	ISO 7089 - 2.5	Plain washers - Normal series - Product grade A
38	12	ISO 4032 - M2.5(4)	Hexagon nuts, style 1 - Product grades A and B
39	1	forearm R	
40	1	ISO 7089 - 6	Plain washers - Normal series - Product grade A
41	1	ISO 2341 - B - 6 x 12	Clevis pins with head
42	4	forearm support	
43	8	ISO 7045 - M2.5 x 6 - 4.8 - H	Pan head screw with type H cross recess - product grade A
44	1	21t straight servo horn	
45	1	E3D V6 direct extruder	
46	1	ISO 7089 - 4	Plain washers - Normal series - Product grade A
47	1	hand	
48	1	extruder holder 1	
49	1	extruder holder 2	
50	1	ISO 7045 - M2 x 6 - 4.8 - H	Pan head screw with type H cross recess - product grade A
51	1	ISO 7089 - 2	Plain washers - Normal series - Product grade A
52	1	ISO 4032 - M2(4)	Hexagon nuts, style 1 - Product grades A and B
53	1	ISO 2341 - B - 4 x 8	Clevis pins with head
54	2	ISO 7045 - M2.5 x 25 - 4.8 - H	Pan head screw with type H cross recess - product grade A
55	1	base	
56	1	platform	
57	1	NEMA 17 stepper motor 40mm	
58	1	stepper motor holder	
59	4	ISO 7045 - M3 x 6 - 4.8 - H	Pan head screw with type H cross recess - product grade A
60	1	turntable	

DRAWN KOK JUN KANG	10/09/2020	PART EXPLODED VIEW	
CHECKED		TITLE 3D REPLICATING ROBOTIC ARM	
		SIZE A2	DWG NO parts list
		SCALE	SHEET 1 OF 1

PRODUCED BY AN AUTODESK STUDENT VERSION

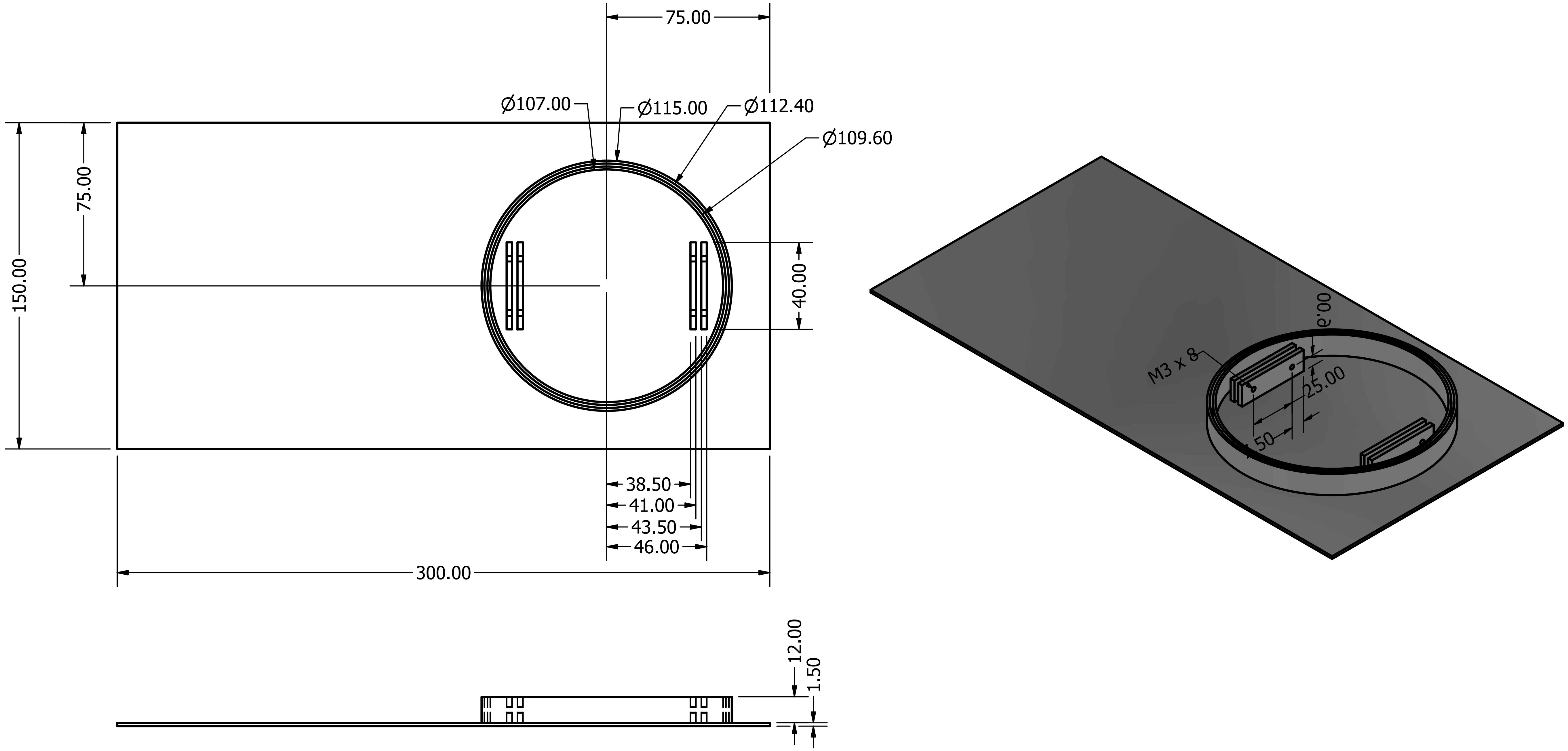




DRAWN		PART
KOK JUN KANG	10/09/2020	BASE STAND
CHECKED		TITLE
		3D REPLICATING ROBOTIC ARM

SIZE		DWG NO
A3		base stand
SCALE 2 : 1		SHEET 1 OF 1

PRODUCED BY AN AUTODESK STUDENT VERSION
PRODUCED BY AN AUTODESK STUDENT VERSION
PRODUCED BY AN AUTODESK STUDENT VERSION



DRAWN
KOK JUN KANG
10/09/2020
CHECKED

PART
BASE

TITLE
3D REPLICATING ROBOTIC ARM

SIZE
A3

DWG NO
base

SCALE 1 / 2

SHEET 1 OF 1

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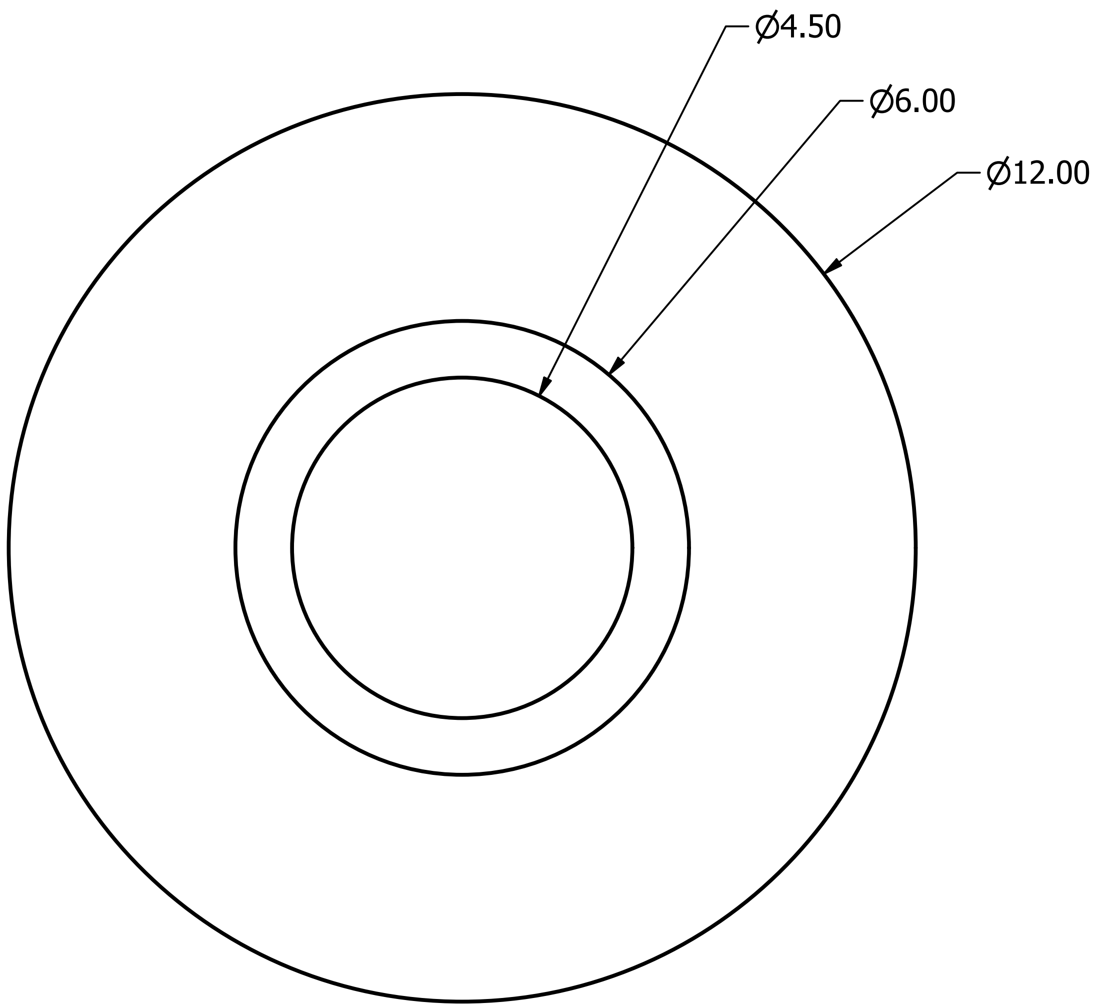
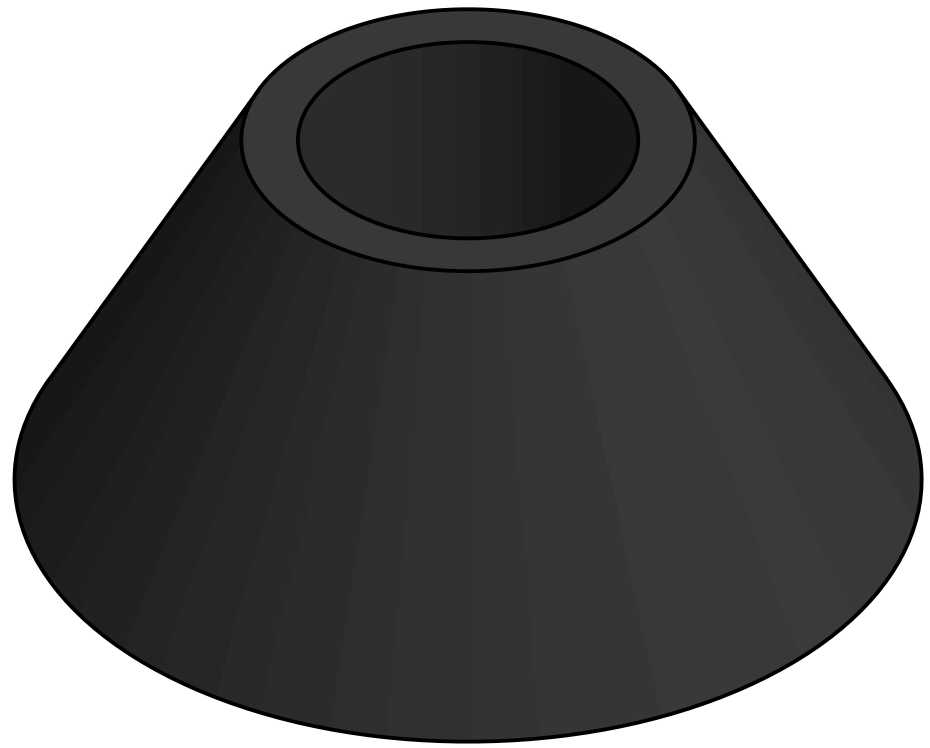
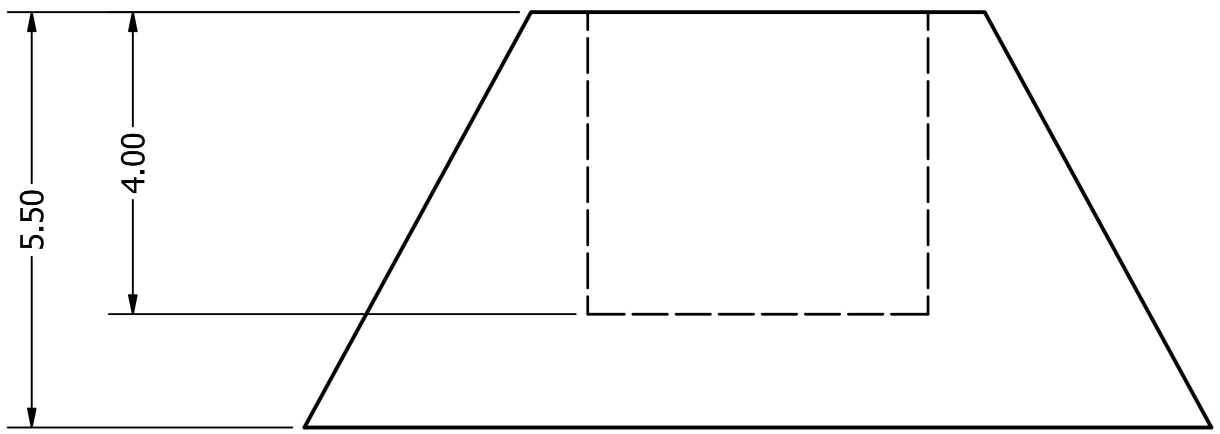
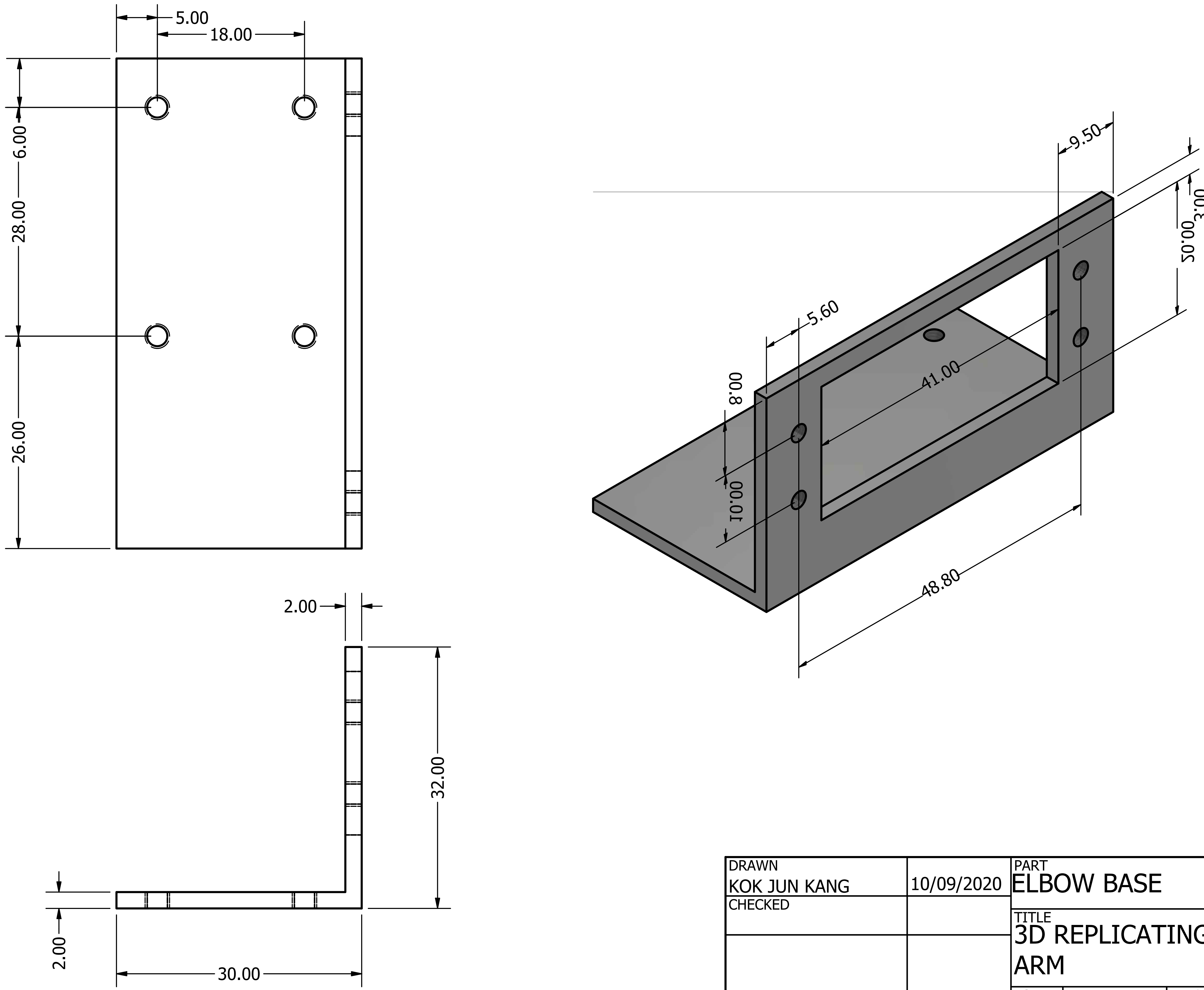


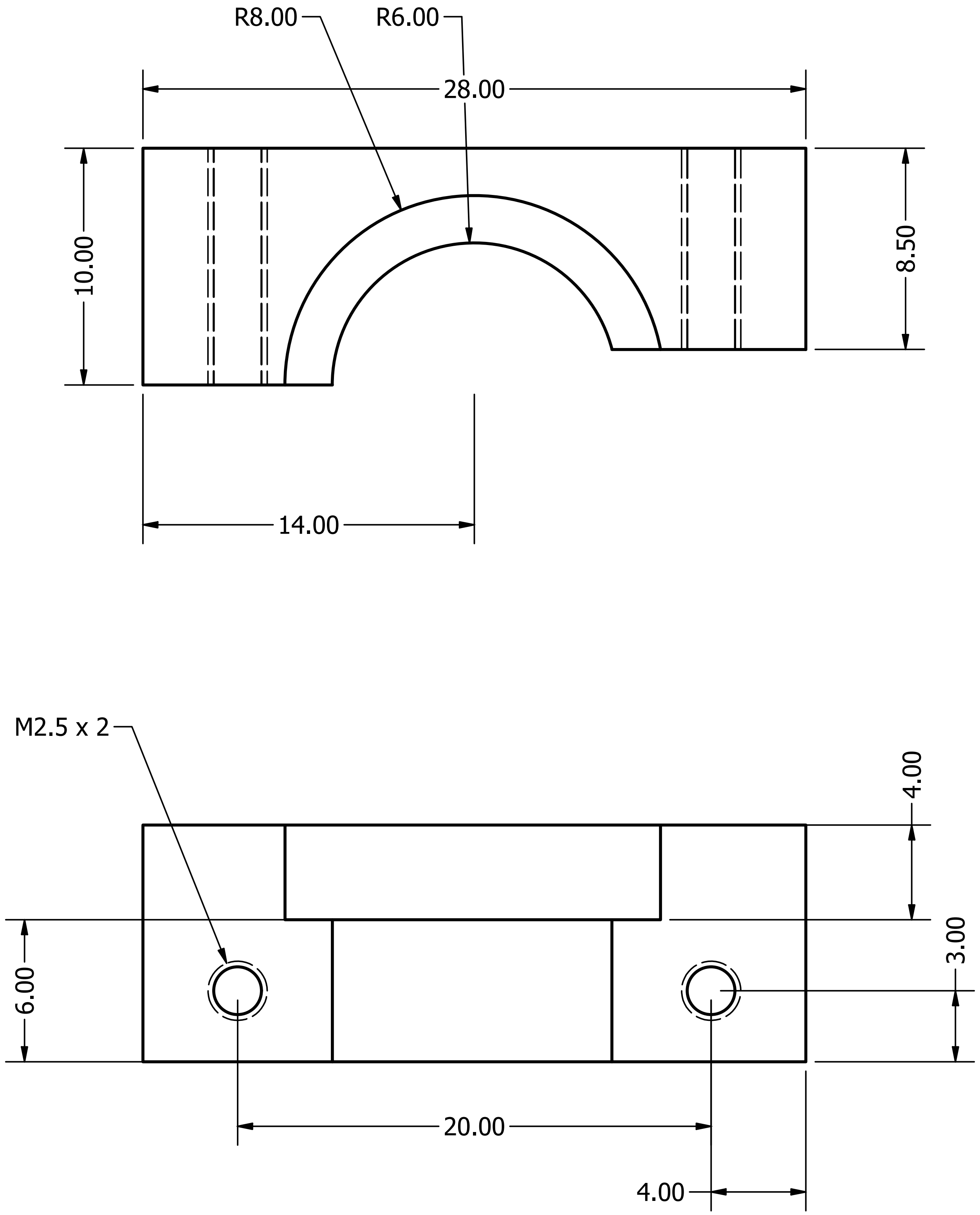


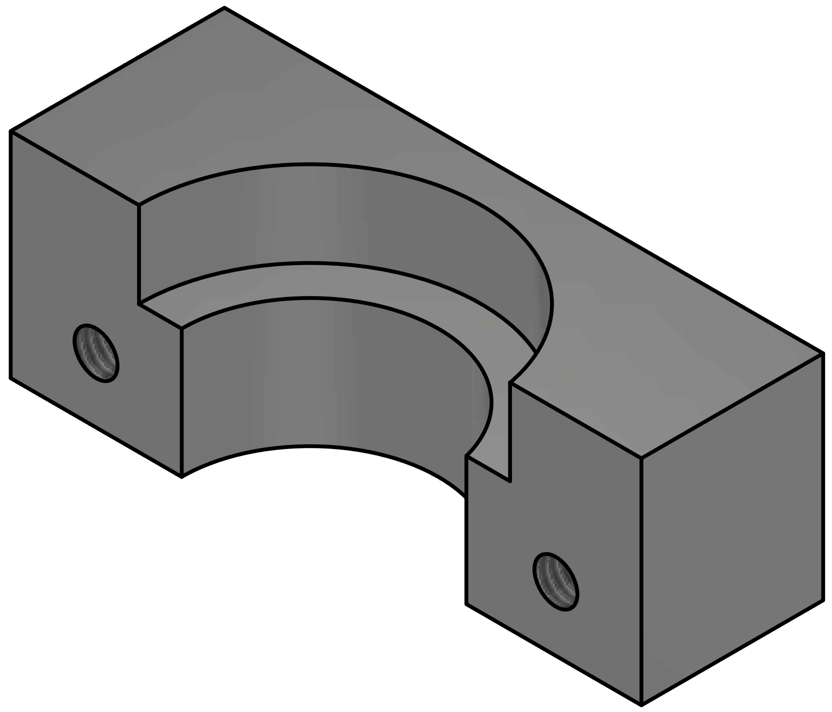


DRAWN KOK JUN KANG	10/09/2020	PART BOLT HOLDER (RUBBER)
CHECKED		TITLE 3D REPLICATING ROBOTIC ARM
		SIZE A3 — DWG NO base
		SCALE 10 : 1 — SHEET 1 OF 1

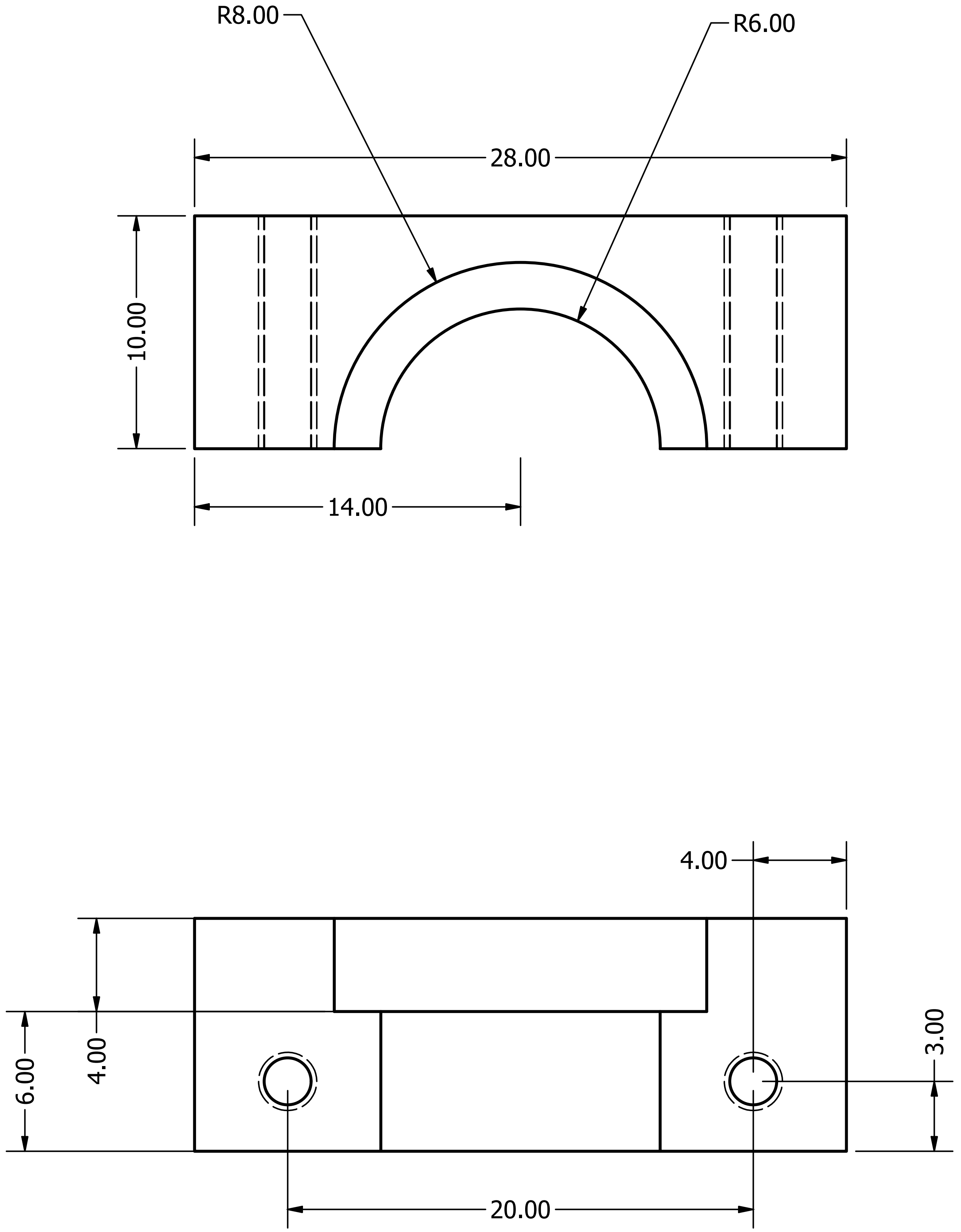


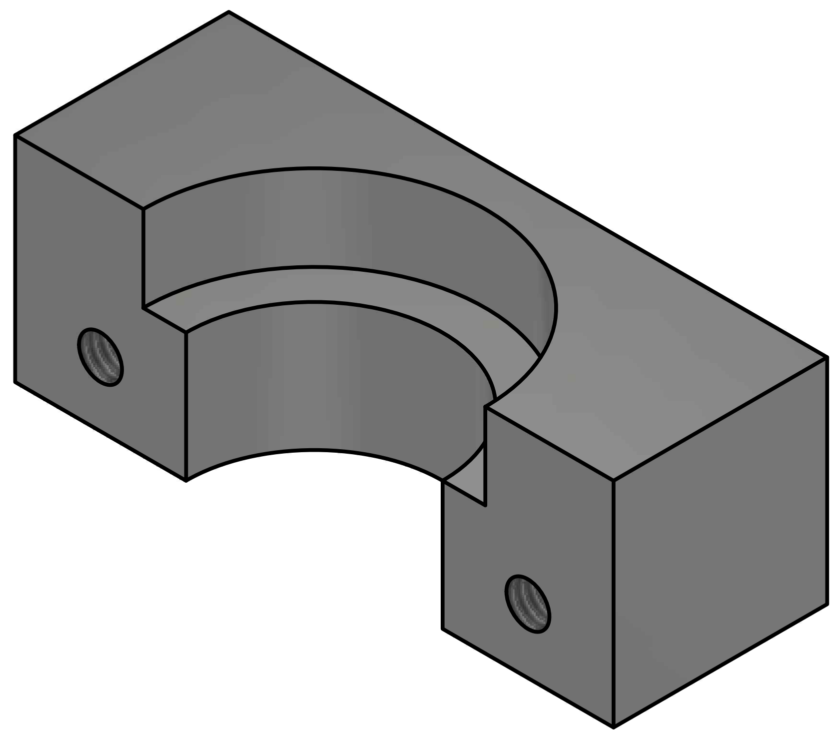
DRAWN KOK JUN KANG	10/09/2020	PART ELBOW BASE	
CHECKED		TITLE 3D REPLICATING ROBOTIC ARM	
		SIZE A3	DWG NO bolt holder
		SCALE 2 : 1	SHEET 1 OF 1



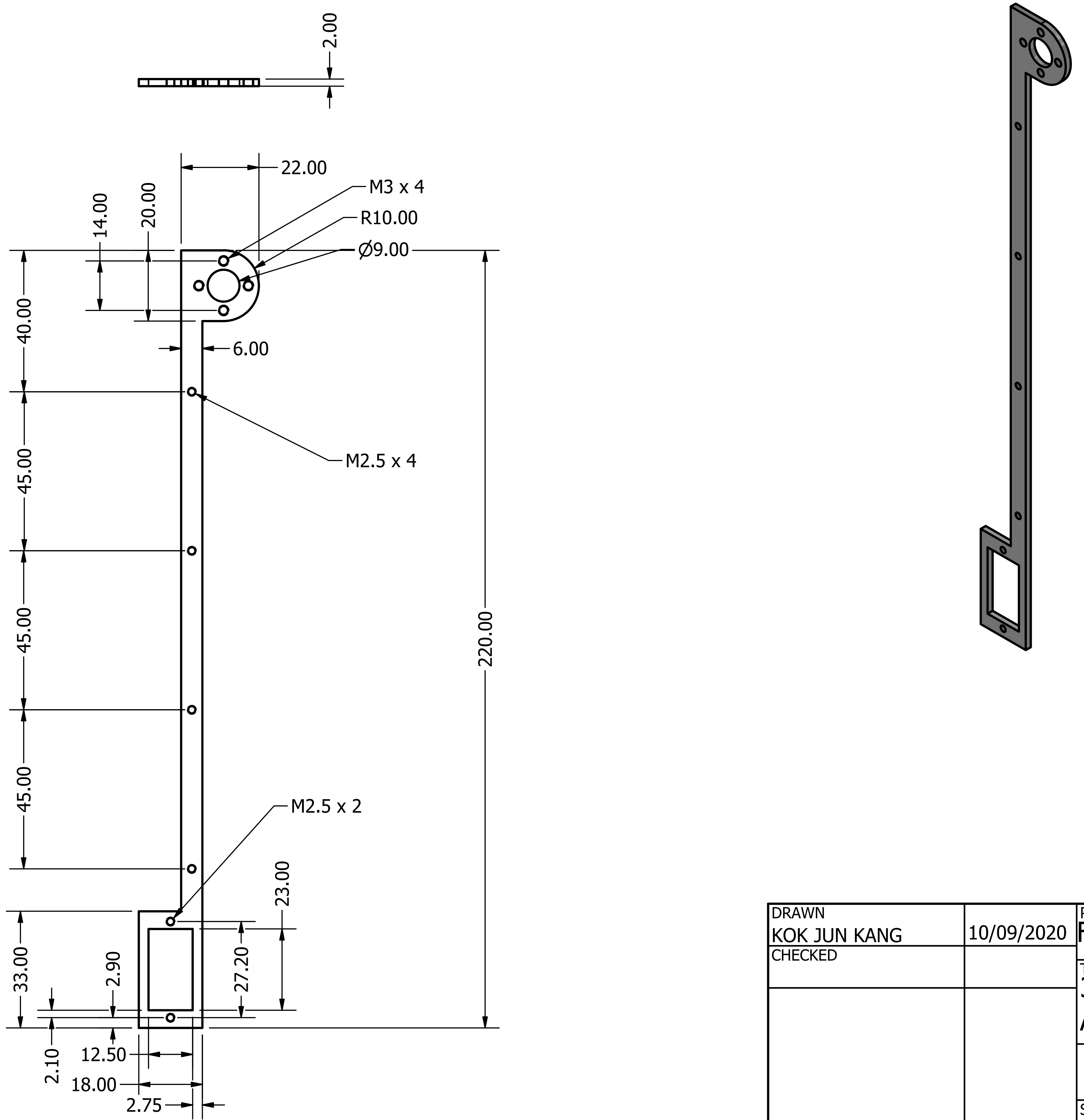


DRAWN KOK JUN KANG	10/09/2020	PART EXTRUDER HOLDER 1	
CHECKED		TITLE 3D REPLICATING ROBOTIC ARM	
		SIZE A3	DWG NO elbow base
		SCALE 4 : 1	SHEET 1 OF 1

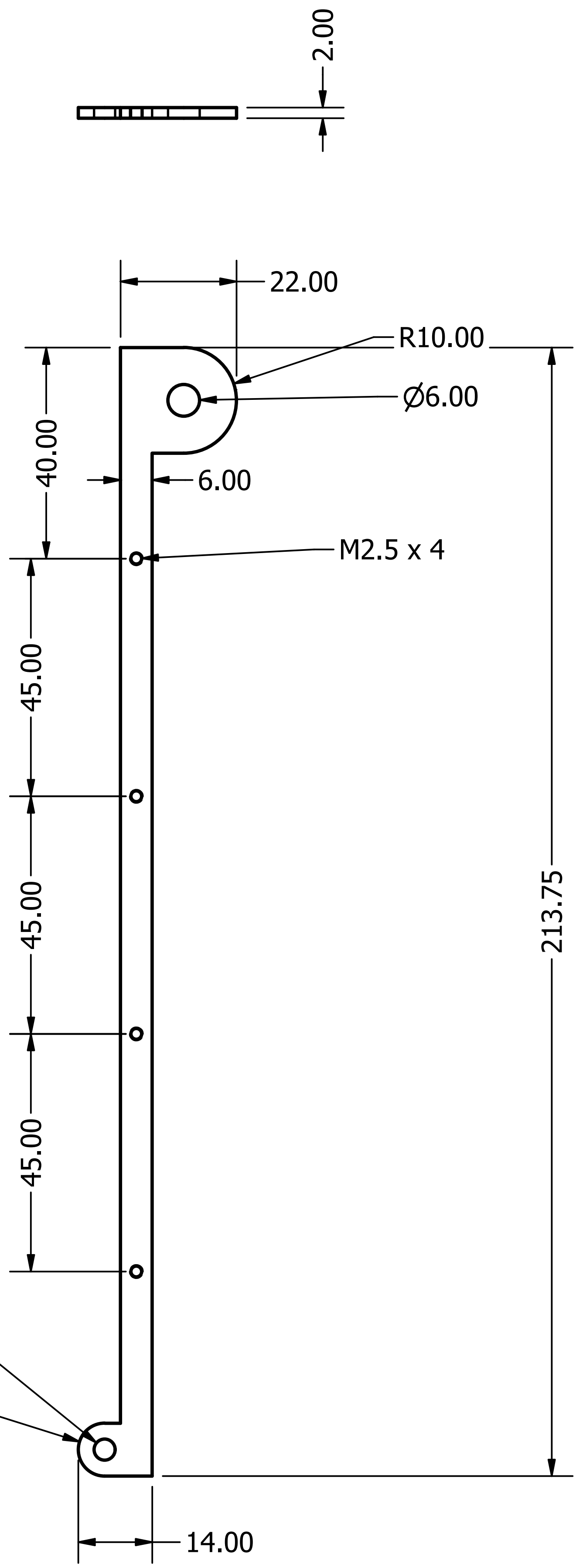


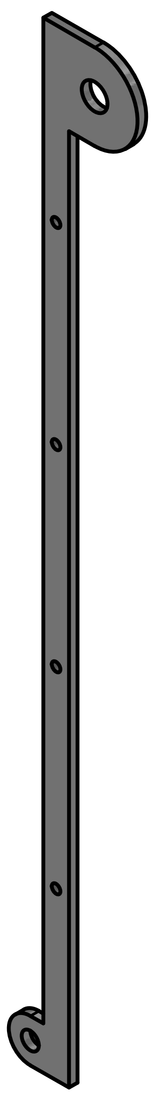


DRAWN KOK JUN KANG	10/09/2020	PART EXTRUDER HOLDER 2	
CHECKED		TITLE 3D REPLICATING ROBOTIC ARM	
		SIZE A3	DWG NO extruder holder 1
		SCALE 4 : 1	SHEET 1 OF 1

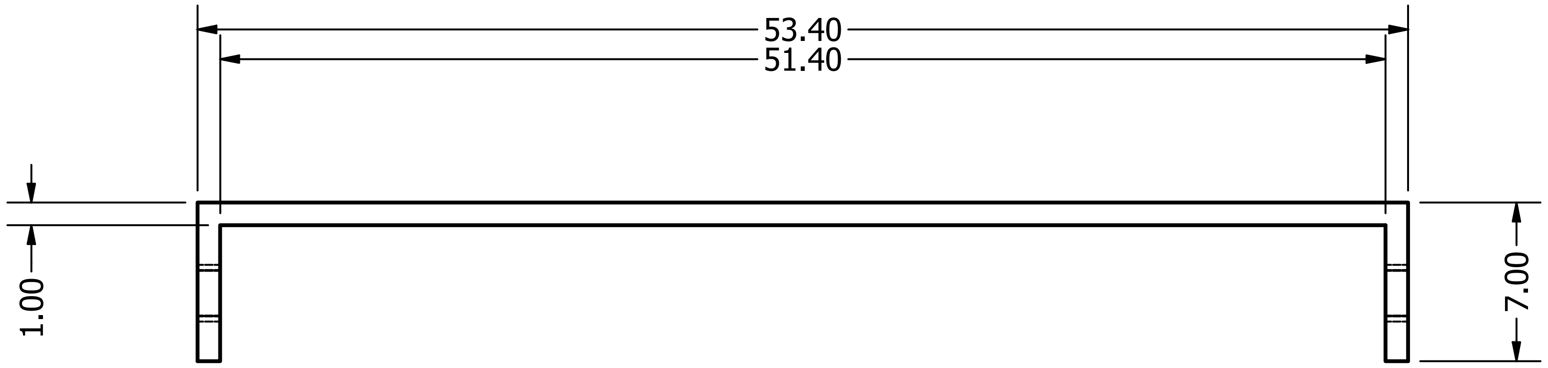


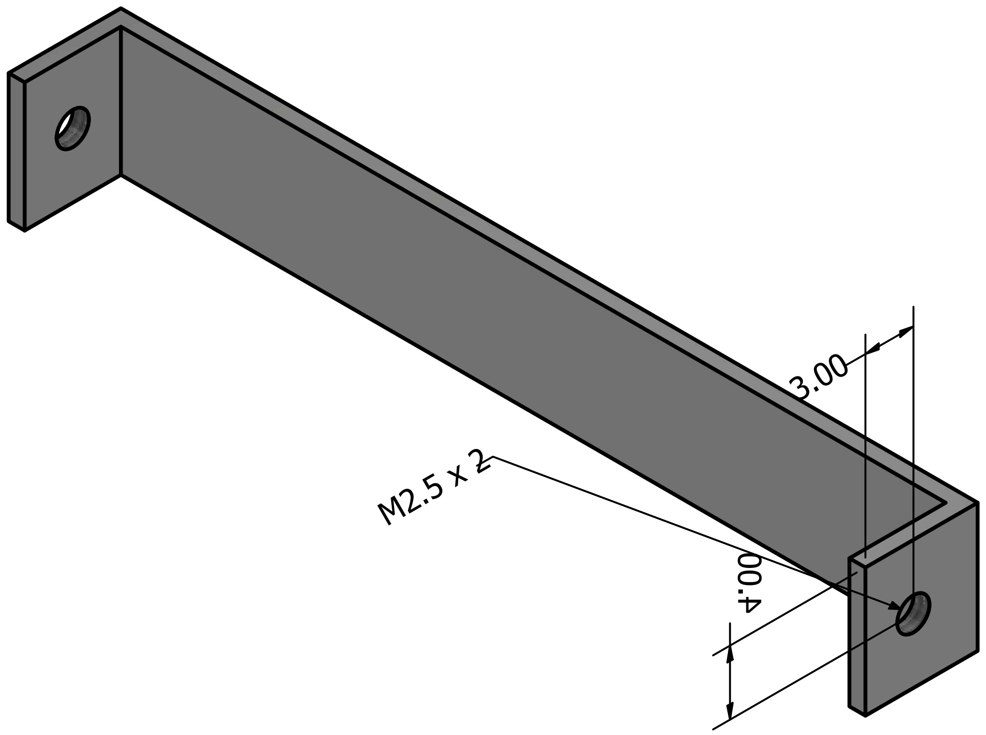
DRAWN		PART
KOK JUN KANG	10/09/2020	FOREARM L
CHECKED		TITLE 3D REPLICATING ROBOTIC ARM
		SIZE A3 / DWG NO forearm L
		SCALE .8 / SHEET 1 OF 1





DRAWN KOK JUN KANG	10/09/2020	PART FOREARM R	
CHECKED		TITLE 3D REPLICATING ROBOTIC ARM	
		SIZE A3	DWG NO forearm R
		SCALE .8	SHEET 1 OF 1





DRAWN KOK JUN KANG	10/09/2020	PART FOREARM SUPPORT	
CHECKED		TITLE 3D REPLICATING ROBOTIC ARM	
		SIZE A3	DWG NO forearm R
		SCALE 3 : 1	SHEET 1 OF 1

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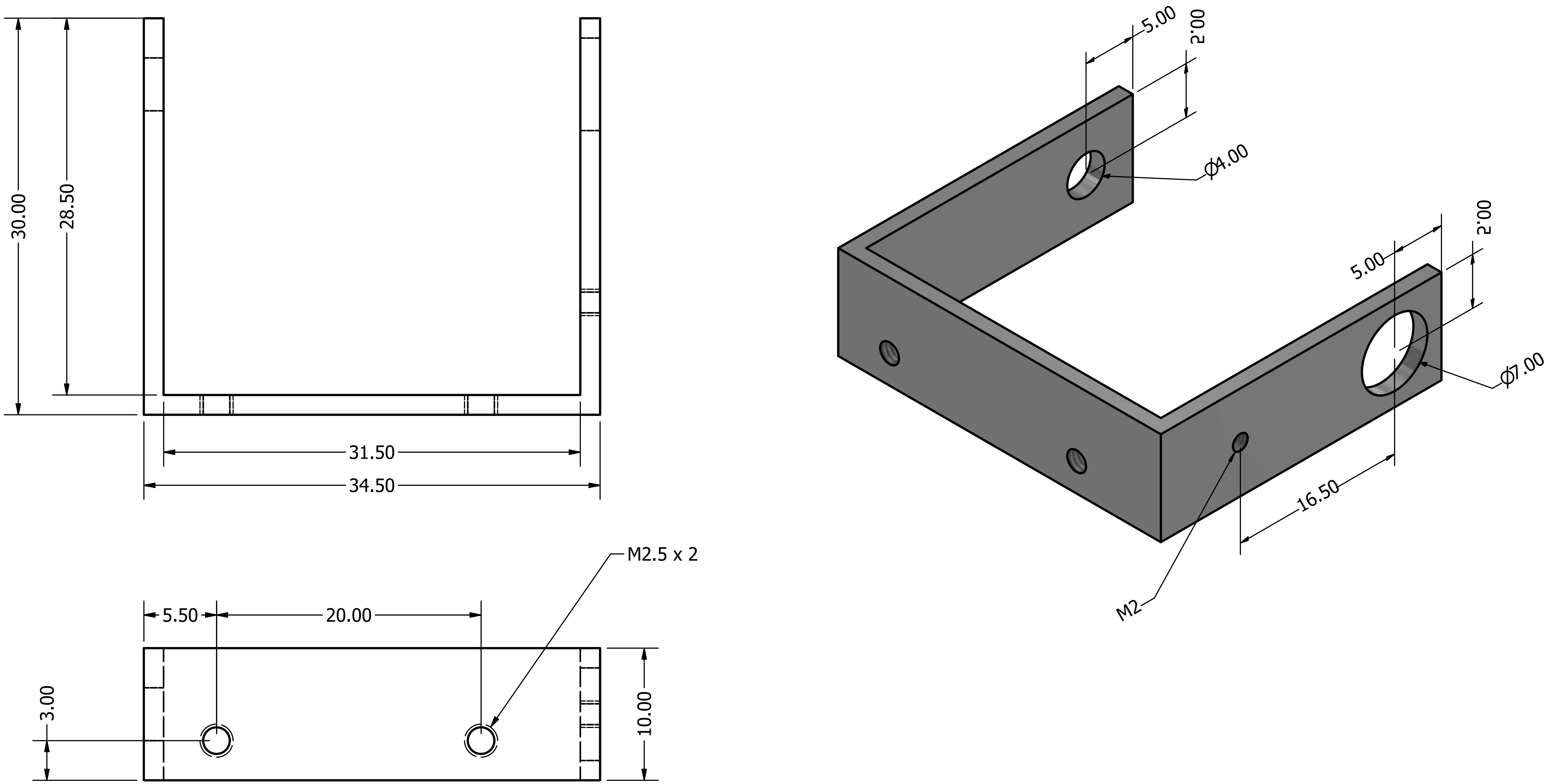
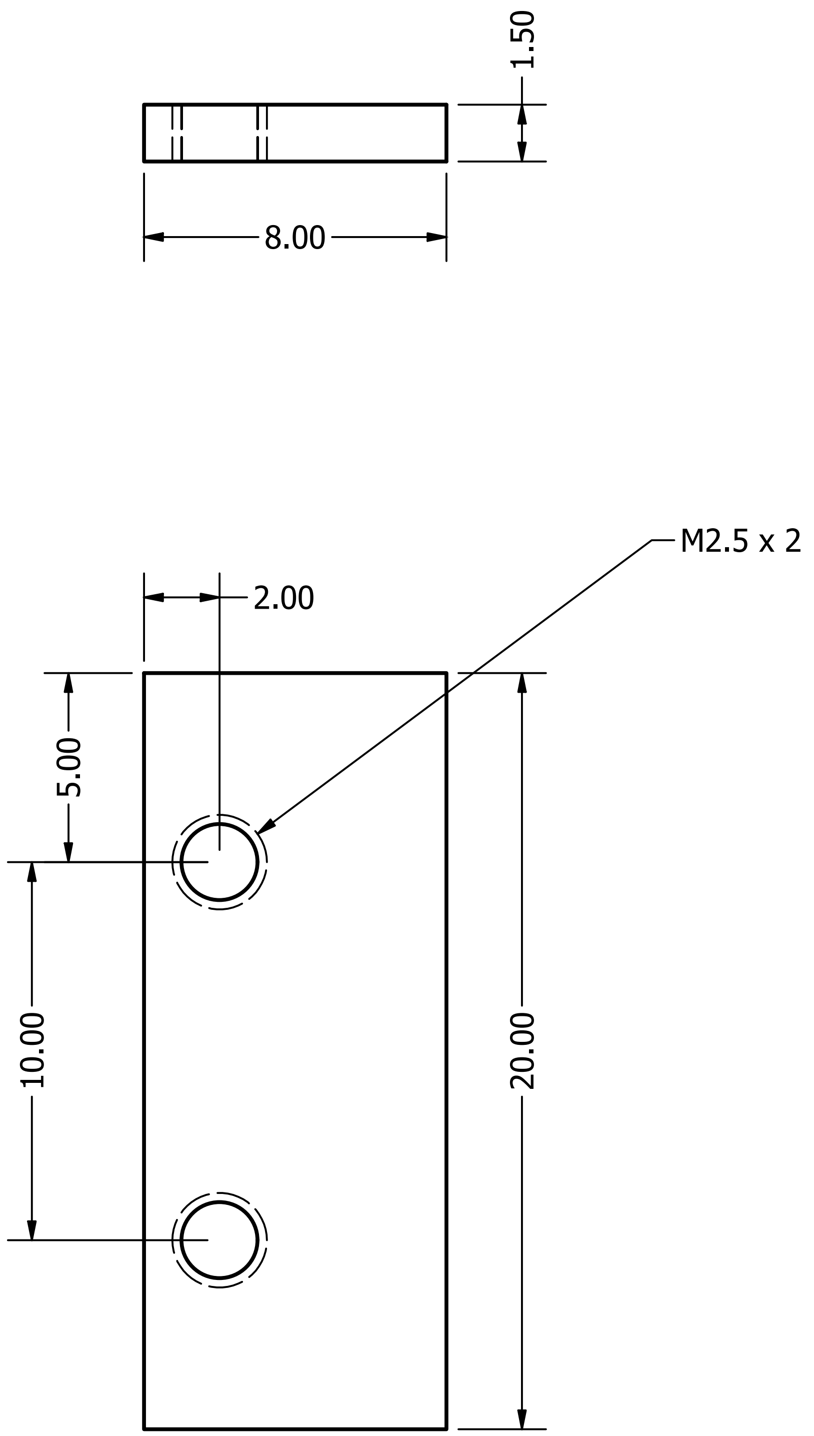
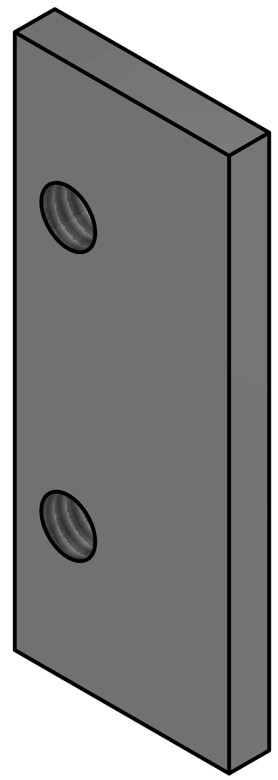
PRODUCED BY AN AUTODESK STUDENT VERSION



DRAWN KOK JUN KANG	10/09/2020	PART HAND	
CHECKED		TITLE 3D REPLICATING ROBOTIC ARM	
		SIZE A3	DWG NO forearm support
		SCALE 3 : 1	SHEET 1 OF 1





DRAWN KOK JUN KANG	10/09/2020	PART LIDAR HOLDER LOCK
CHECKED		TITLE 3D REPLICATING ROBOTIC ARM
		SIZE A3
		DWG NO hand
		SCALE 5 : 1
		SHEET 1 OF 1

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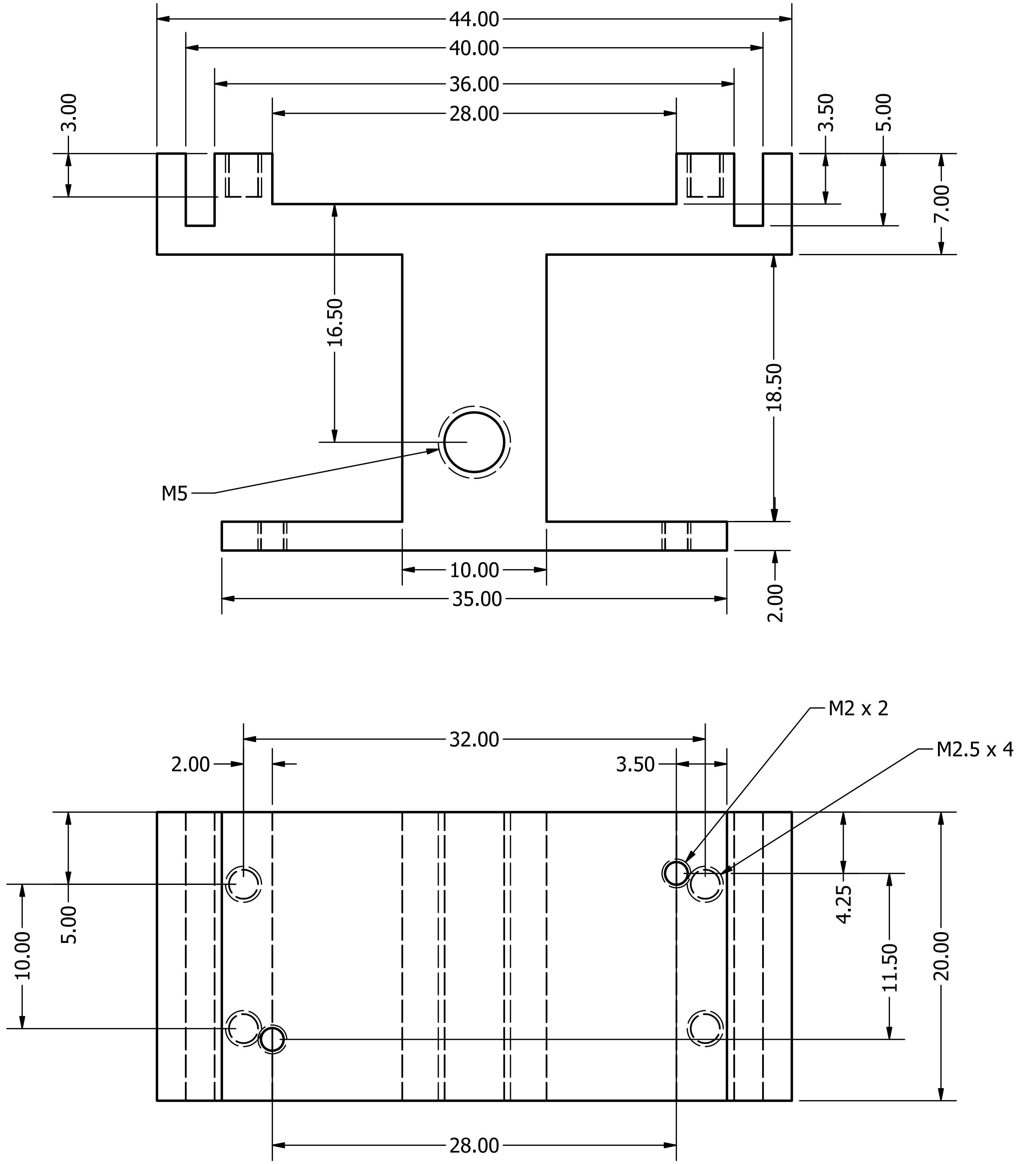
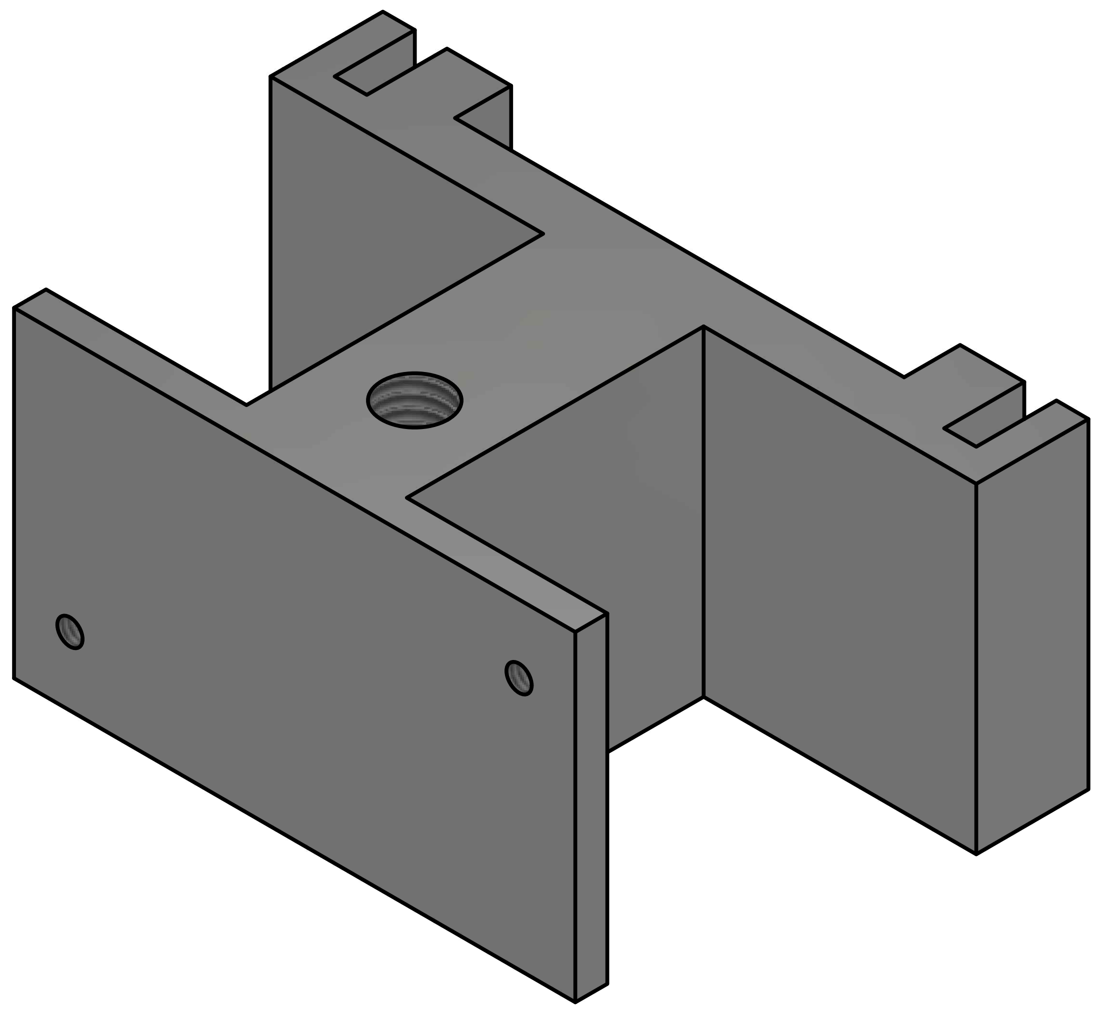
PRODUCED BY AN AUTODESK STUDENT VERSION





DRAWN		PART
KOK JUN KANG	10/09/2020	LIDAR HOLDER
CHECKED		TITLE 3D REPLICATING ROBOTIC ARM
		SIZE A3 / DWG NO LIDAR holder
		SCALE 3 : 1 / SHEET 1 OF 1

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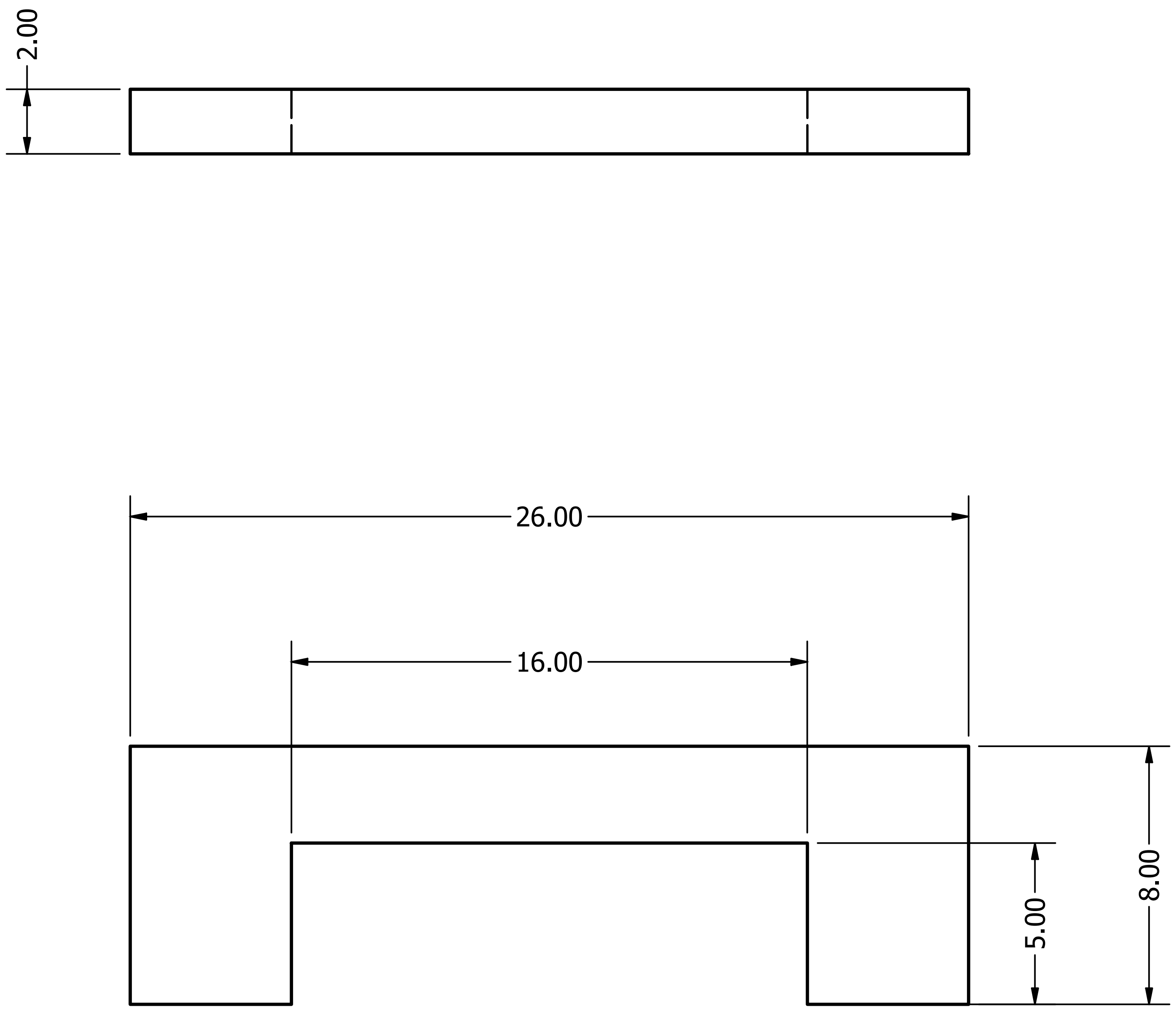
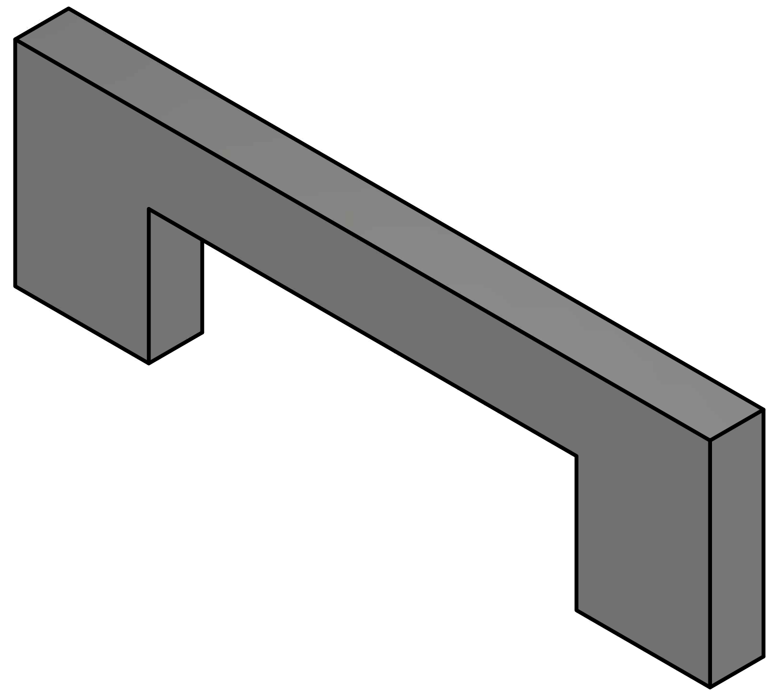
PRODUCED BY AN AUTODESK STUDENT VERSION





DRAWN KOK JUN KANG	10/09/2020	PART LOCK	
CHECKED		TITLE 3D REPLICATING ROBOTIC ARM	
SIZE A3		DWG NO LIDAR holder	
SCALE	5 : 1	SHEET 1 OF 1	

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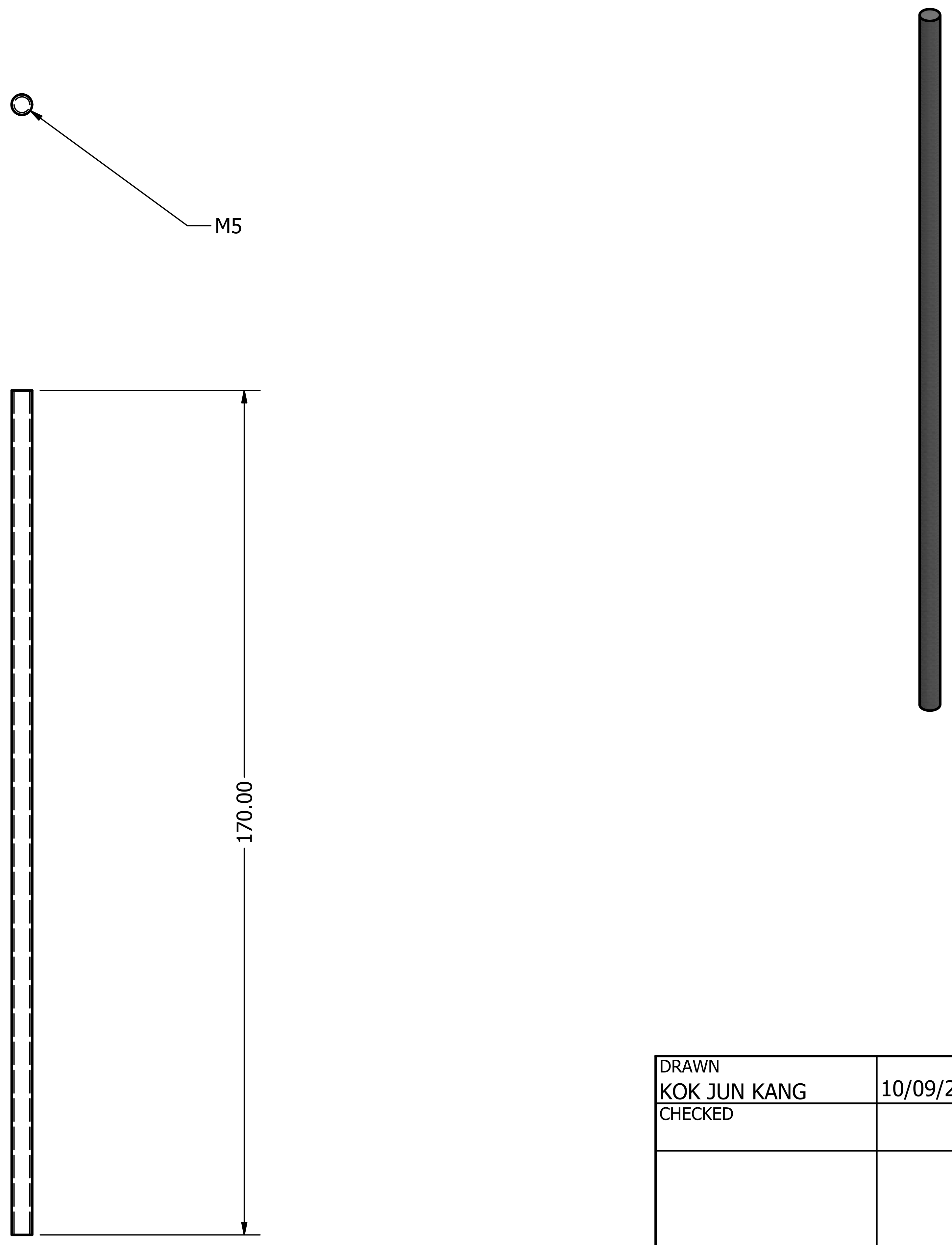
PRODUCED BY AN AUTODESK STUDENT VERSION



DRAWN KOK JUN KANG	10/09/2020	PART M5 x 0.8 BOLT 170mm	
CHECKED		TITLE 3D REPLICATING ROBOTIC ARM	
		SIZE A3	DWG NO lock
		SCALE 1 : 1	SHEET 1 OF 1

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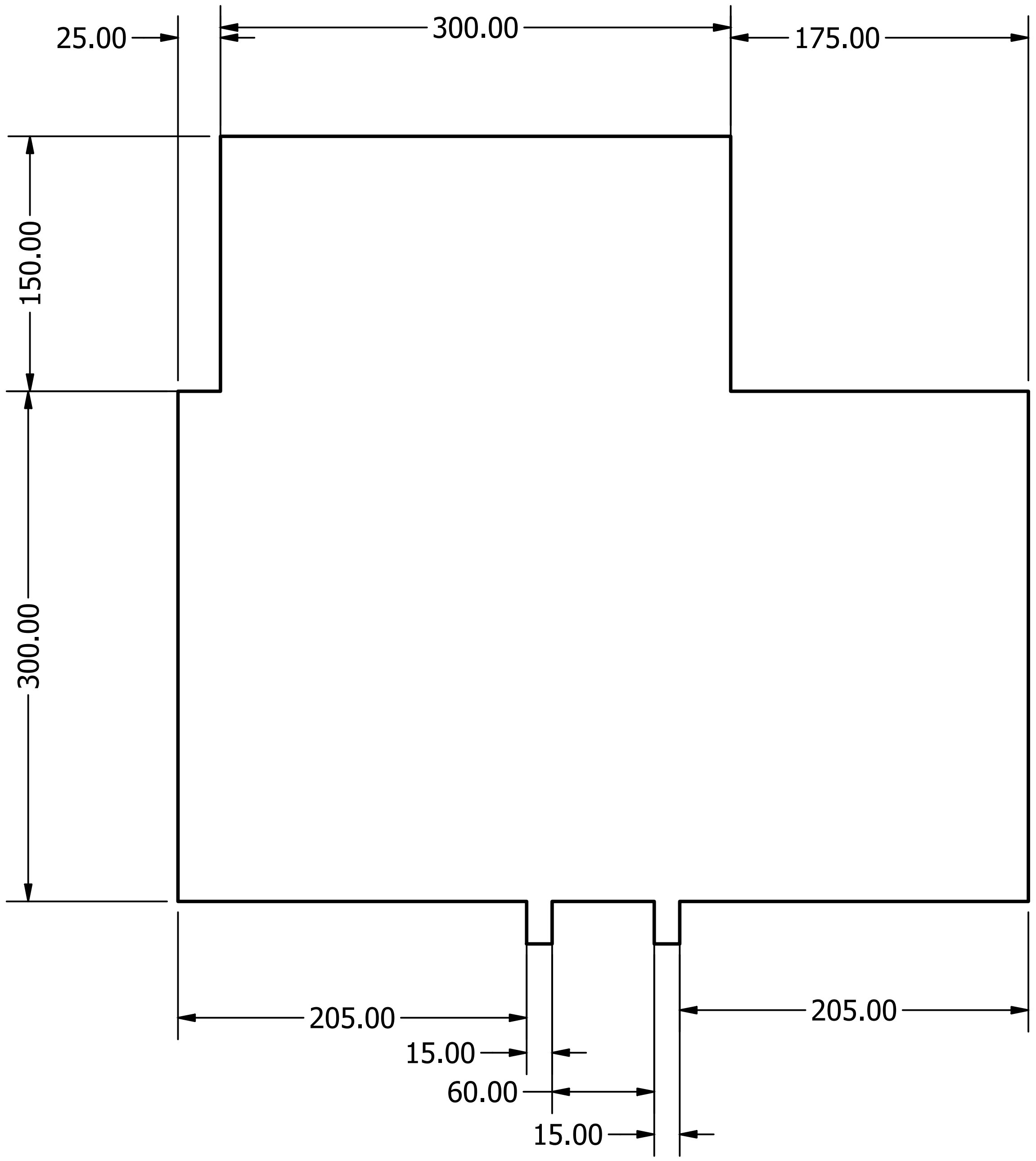
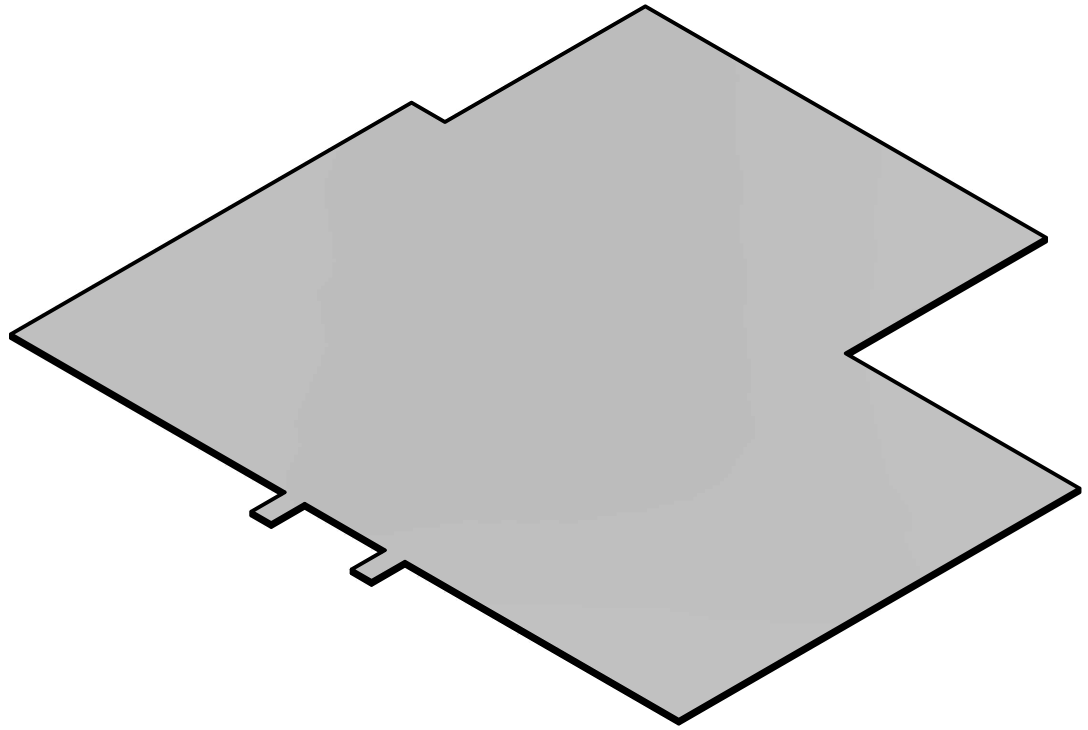
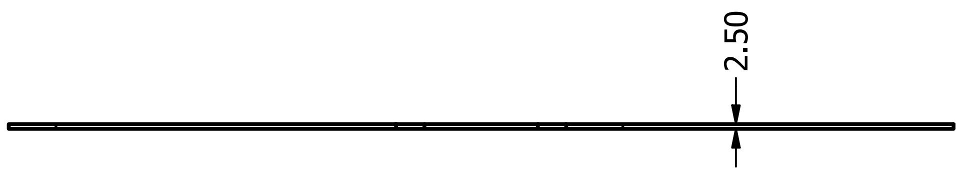
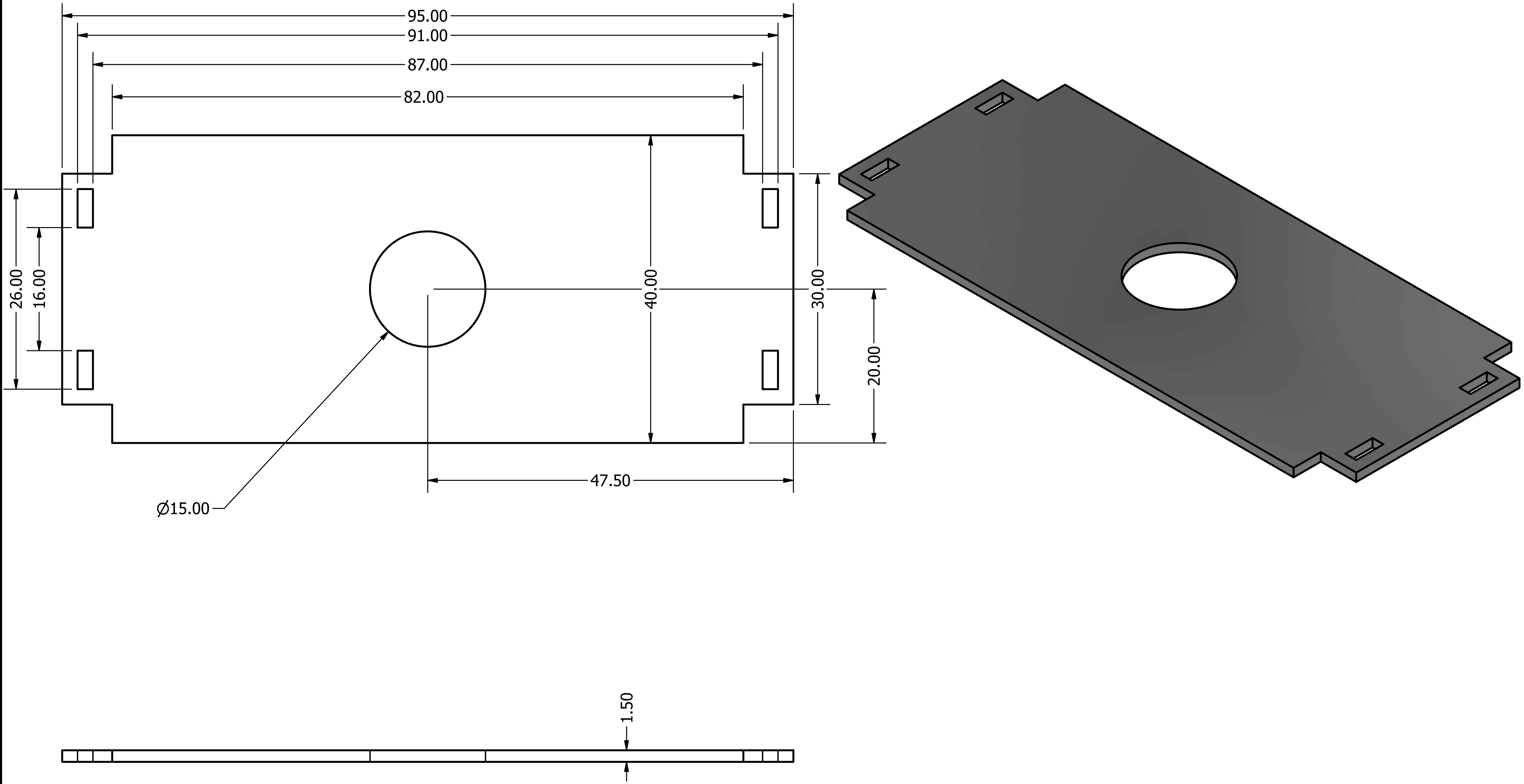
PRODUCED BY AN AUTODESK STUDENT VERSION



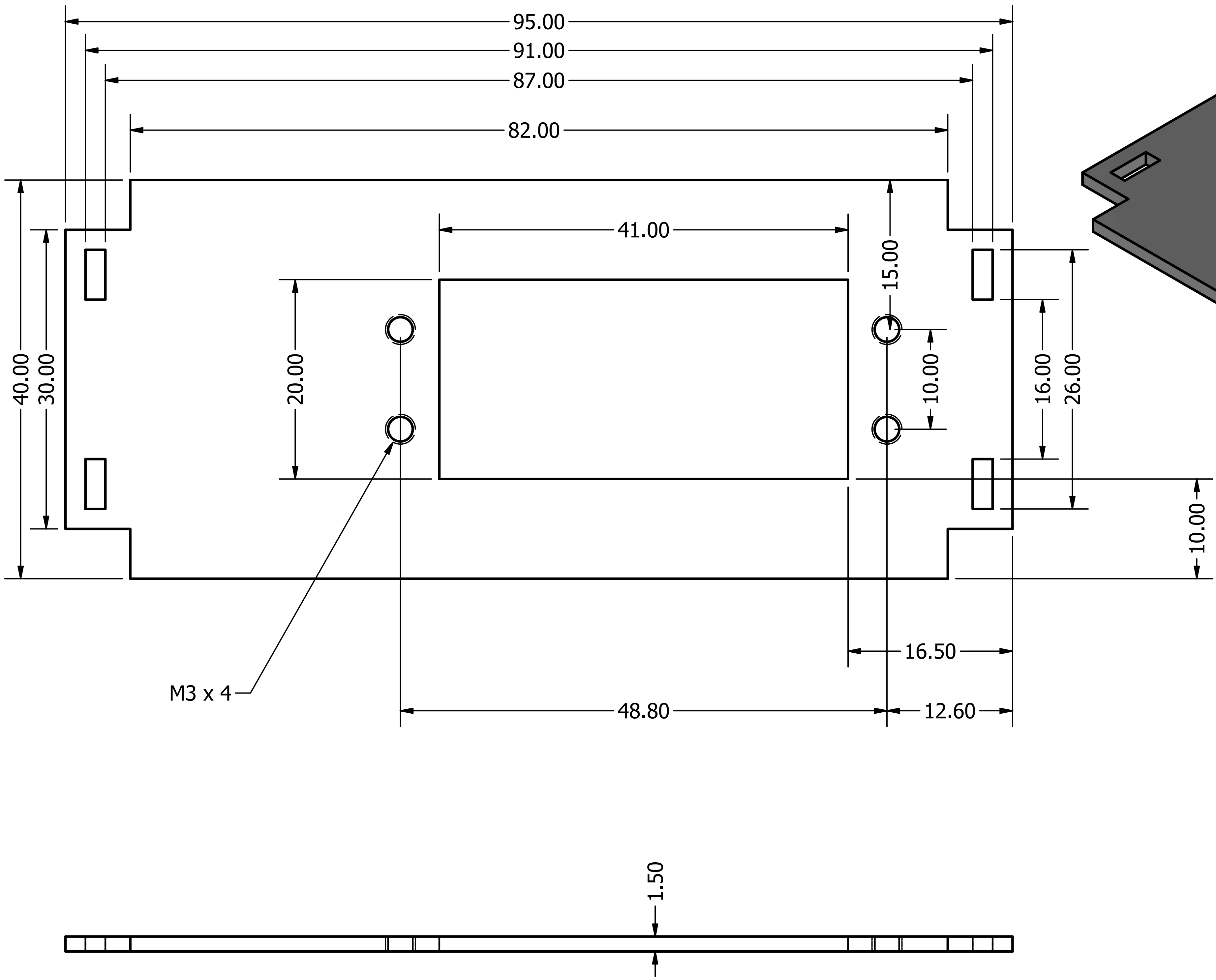


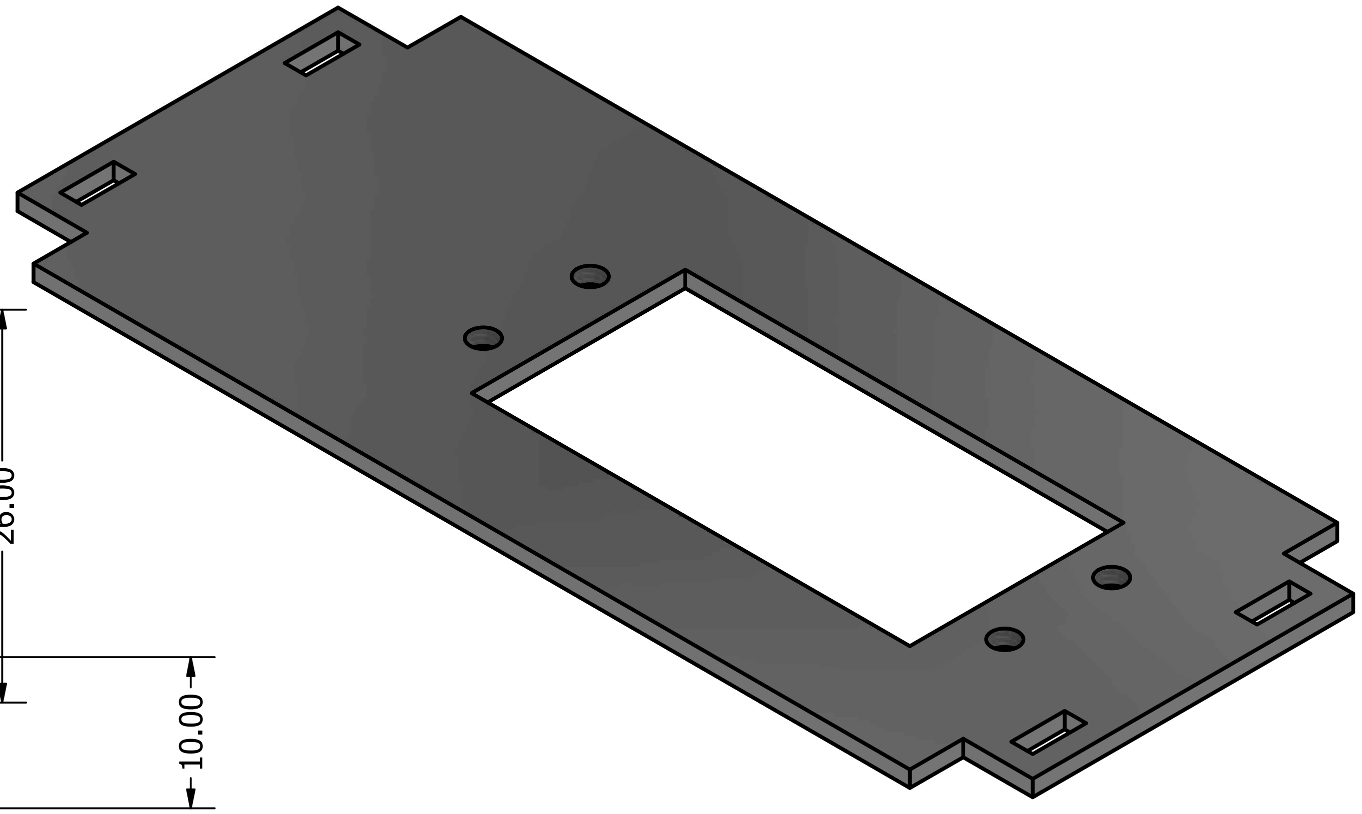


DRAWN KOK JUN KANG	10/09/2020	PART PLATFORM (PLASTIC)	
CHECKED		TITLE 3D REPLICATING ROBOTIC ARM	
		SIZE A3	DWG NO platform
		SCALE 1 / 4	SHEET 1 OF 1



DRAWN KOK JUN KANG	10/09/2020	PART SERVO HOLDER BASE UPPER
CHECKED		TITLE 3D REPLICATING ROBOTIC ARM
		SIZE A3 — DWG NO servo holder base u
		SCALE 2 : 1 — SHEET 1 OF 1





DRAWN KOK JUN KANG	10/09/2020	PART SERVO HOLDER BASE	
CHECKED		TITLE 3D REPLICATING ROBOTIC ARM	
		SIZE A3	DWG NO servo holder base
		SCALE 2 : 1	SHEET 1 OF 1

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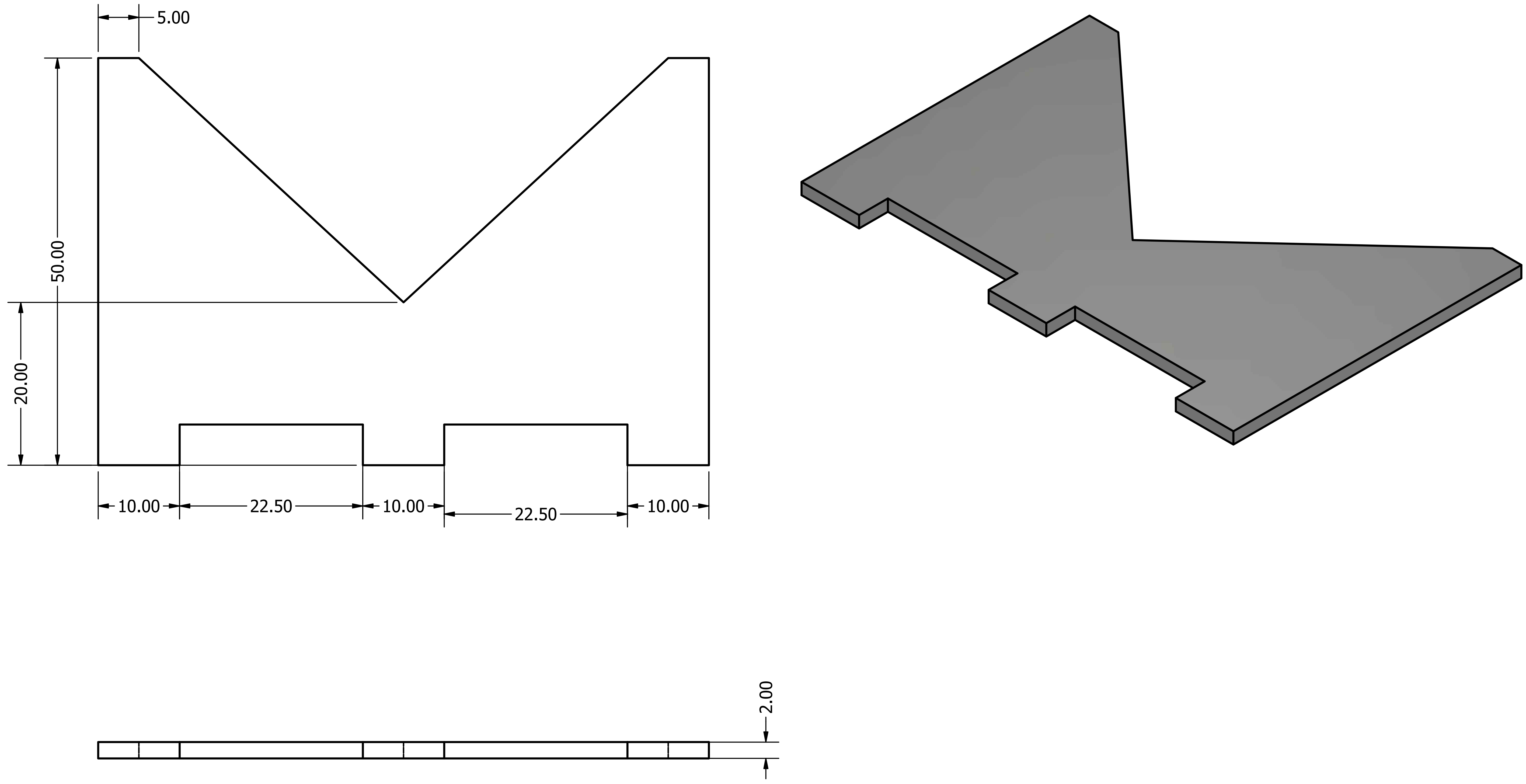
PRODUCED BY AN AUTODESK STUDENT VERSION



DRAWN KOK JUN KANG	10/09/2020	PART SHOULDER BASE LOCK
CHECKED		TITLE 3D REPLICATING ROBOTIC ARM
		SIZE: A3 · DWG NO: shoulder base lock
		SCALE 2 : 1 · SHEET 1 OF 1

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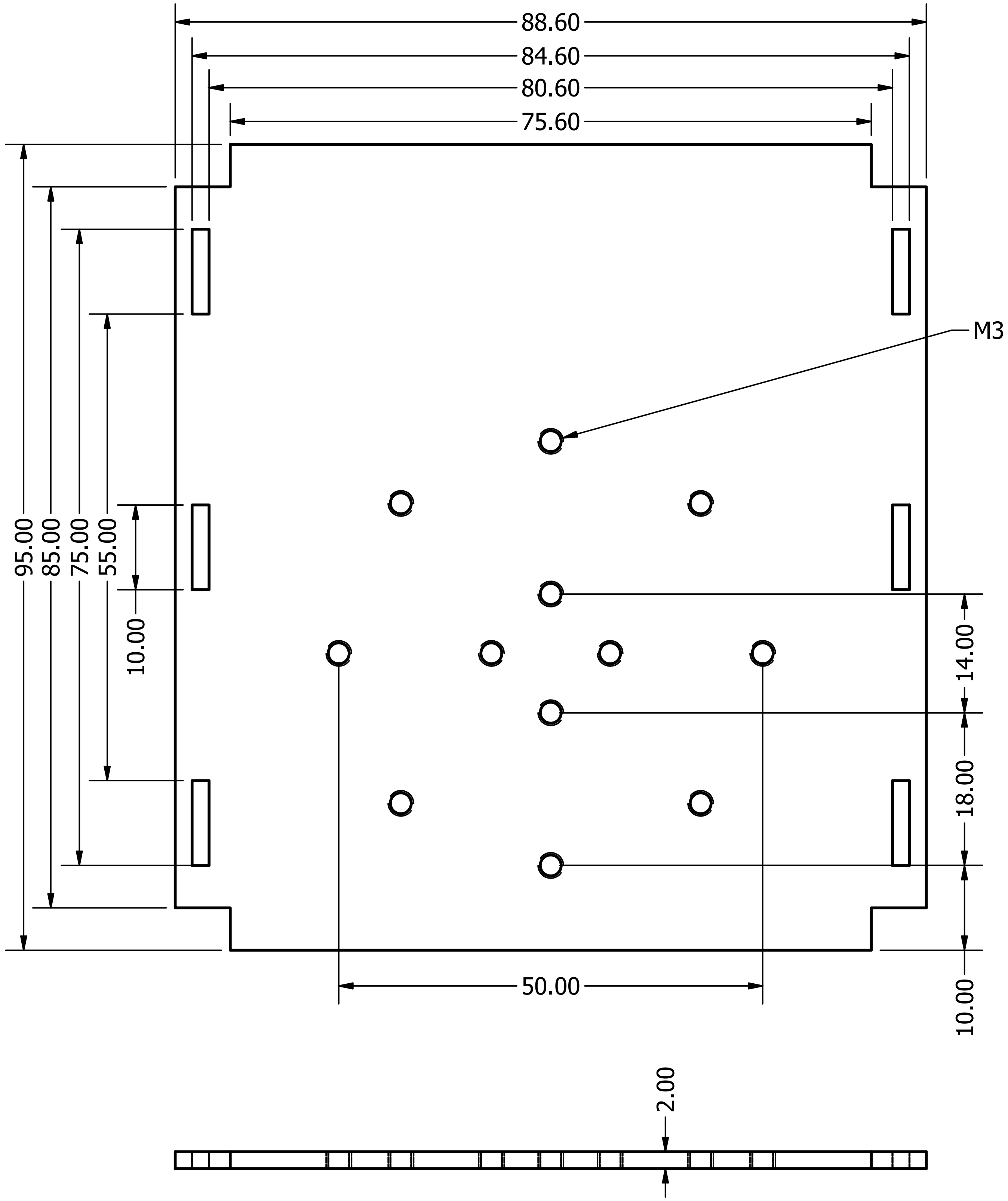

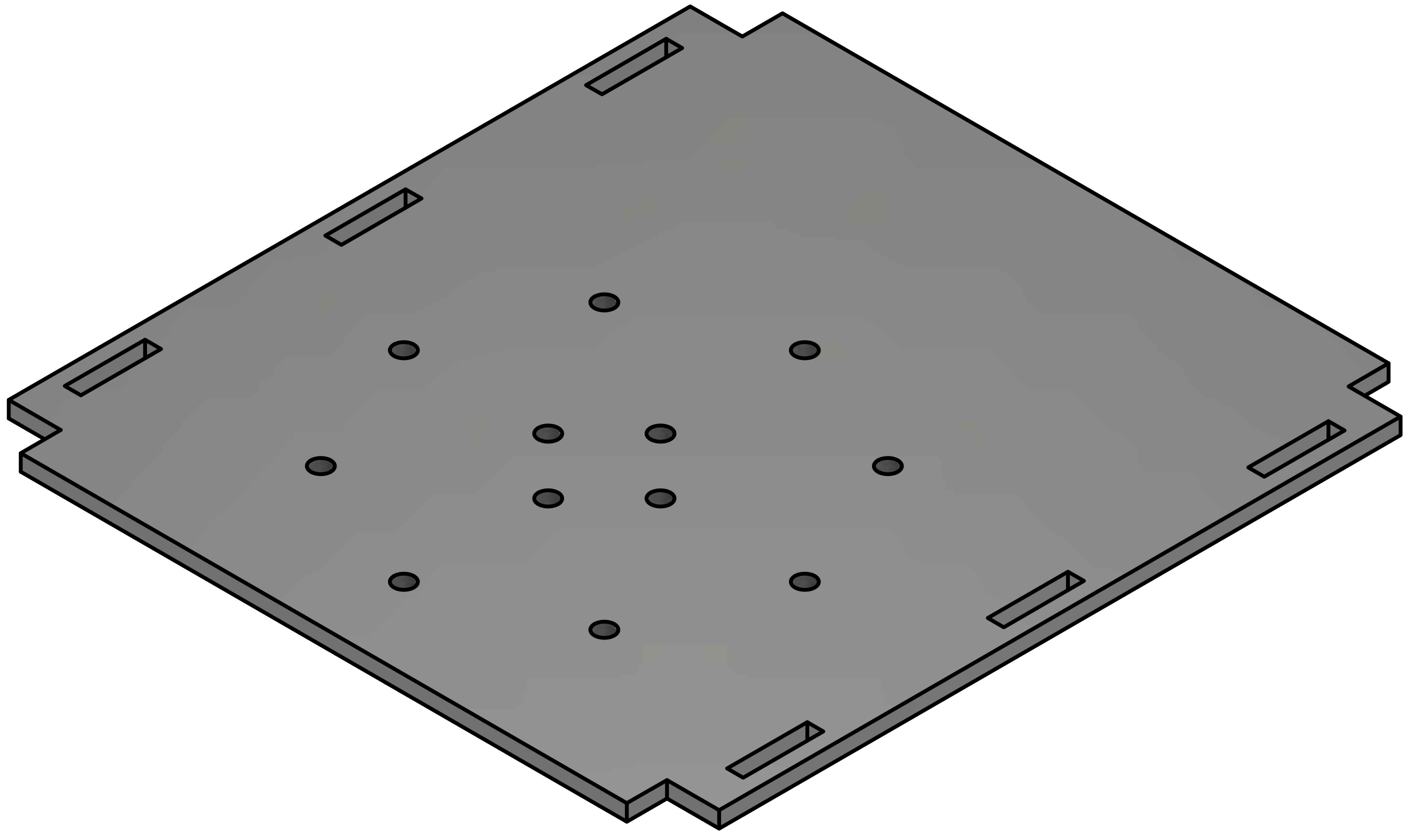

DRAWN KOK JUN KANG	10/09/2020	PART SHOULDER BASE	
CHECKED		TITLE 3D REPLICATING ROBOTIC ARM	
		SIZE A3	DWG NO shoulder base
		SCALE 1.5	SHEET 1 OF 1

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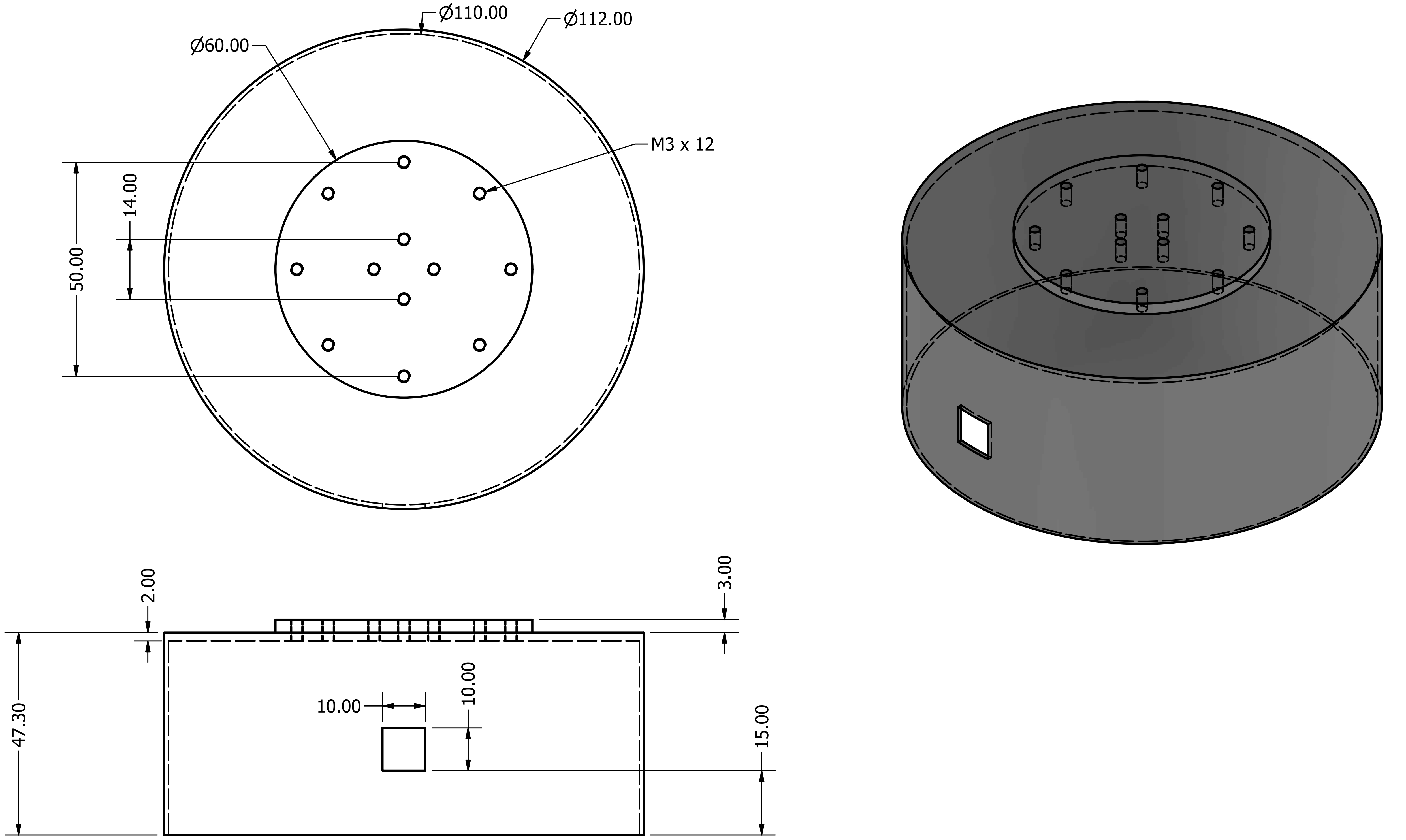
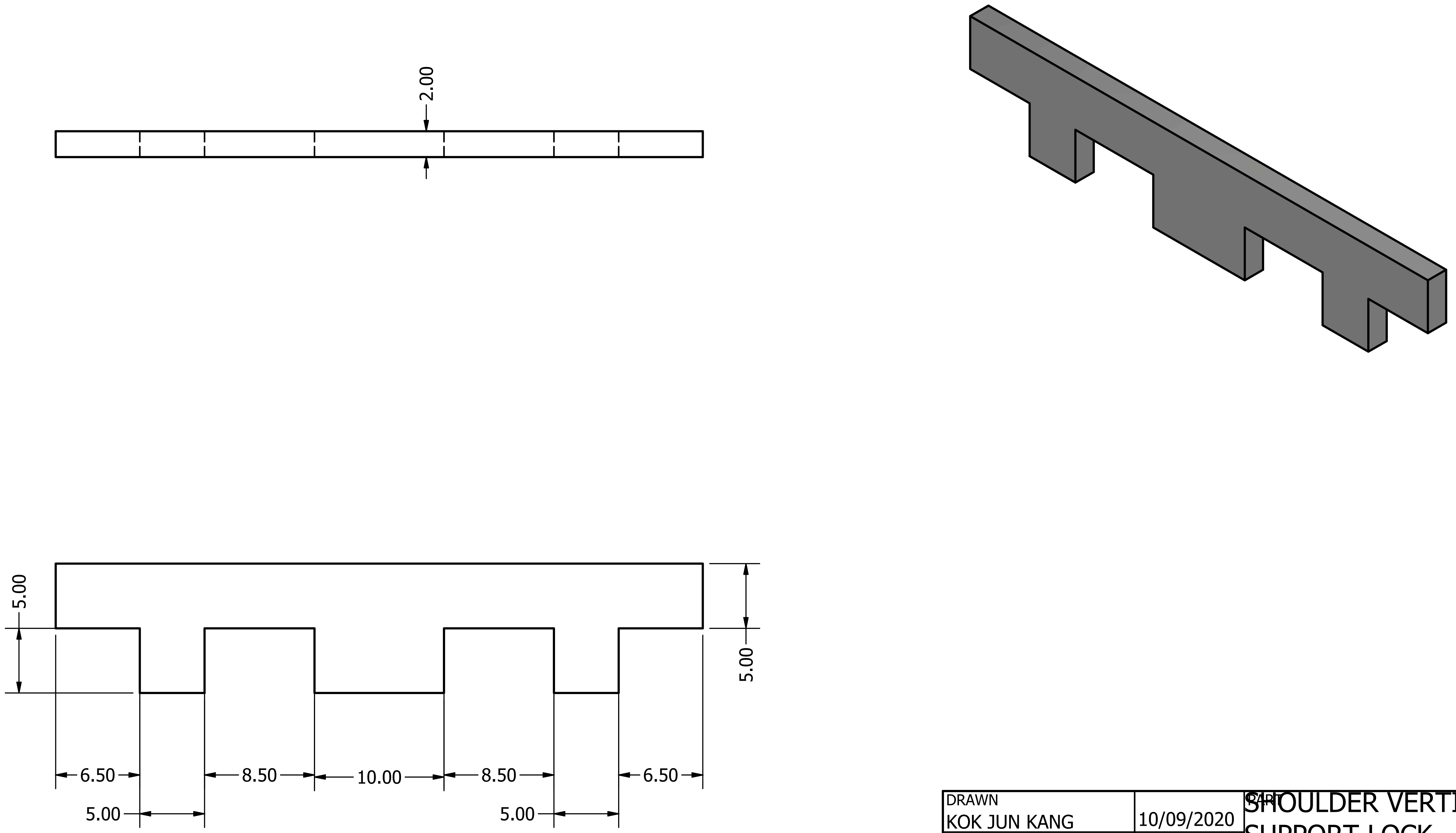


DRAWN KOK JUN KANG	10/09/2020	PART SHOULDER COVER	
CHECKED		TITLE 3D REPLICATING ROBOTIC ARM	
		SIZE A3	DWG NO shoulder cover
		SCALE 1 : 1	SHEET 1 OF 1



DRAWN KOK JUN KANG	10/09/2020	PART SHOULDER VERTICAL SUPPORT LOCK
CHECKED		TITLE 3D REPLICATING ROBOTIC ARM
		SIZE A3 · DWG NO shoulder cover
		SCALE 3 : 1 · SHEET 1 OF 1

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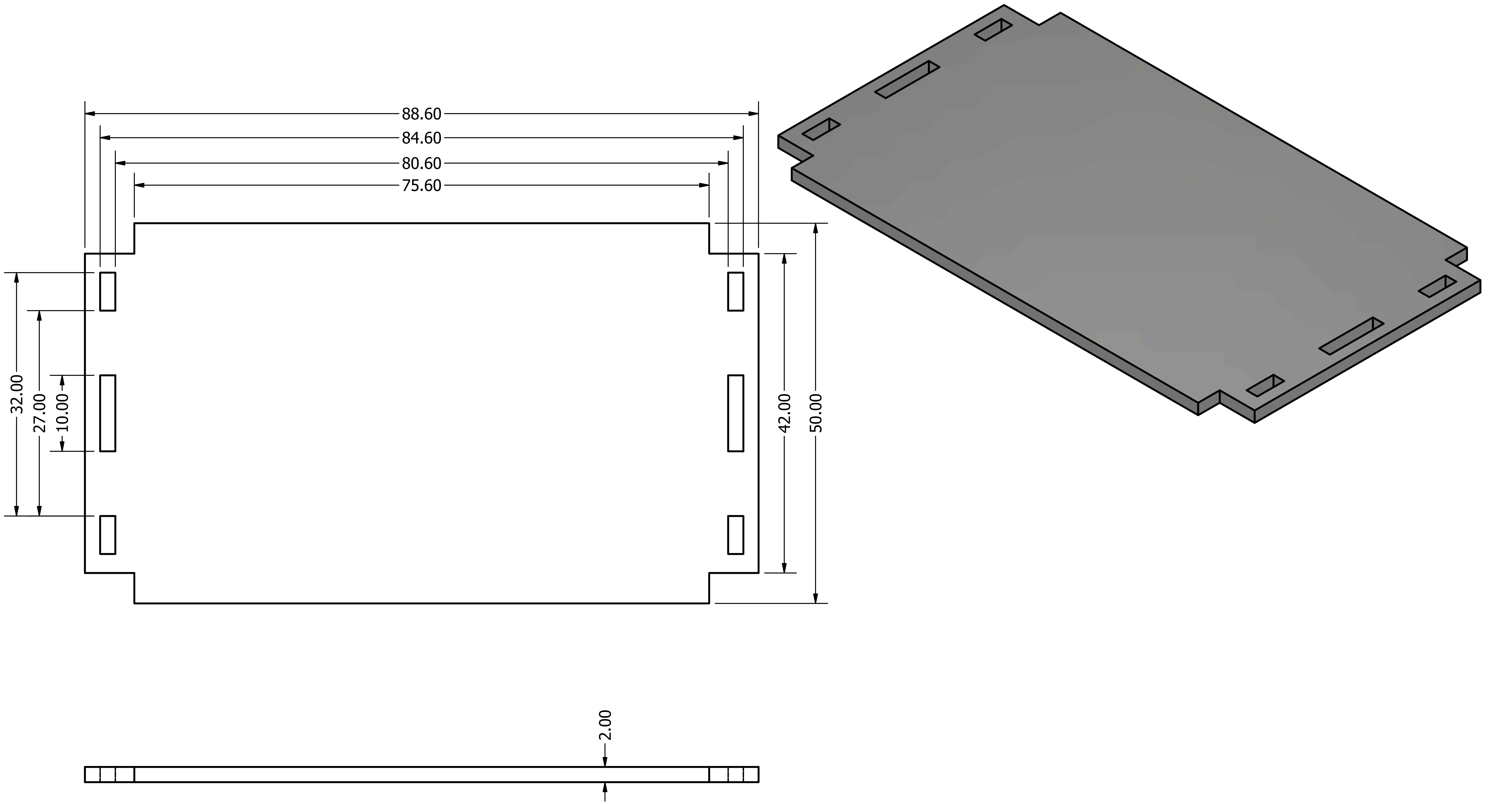
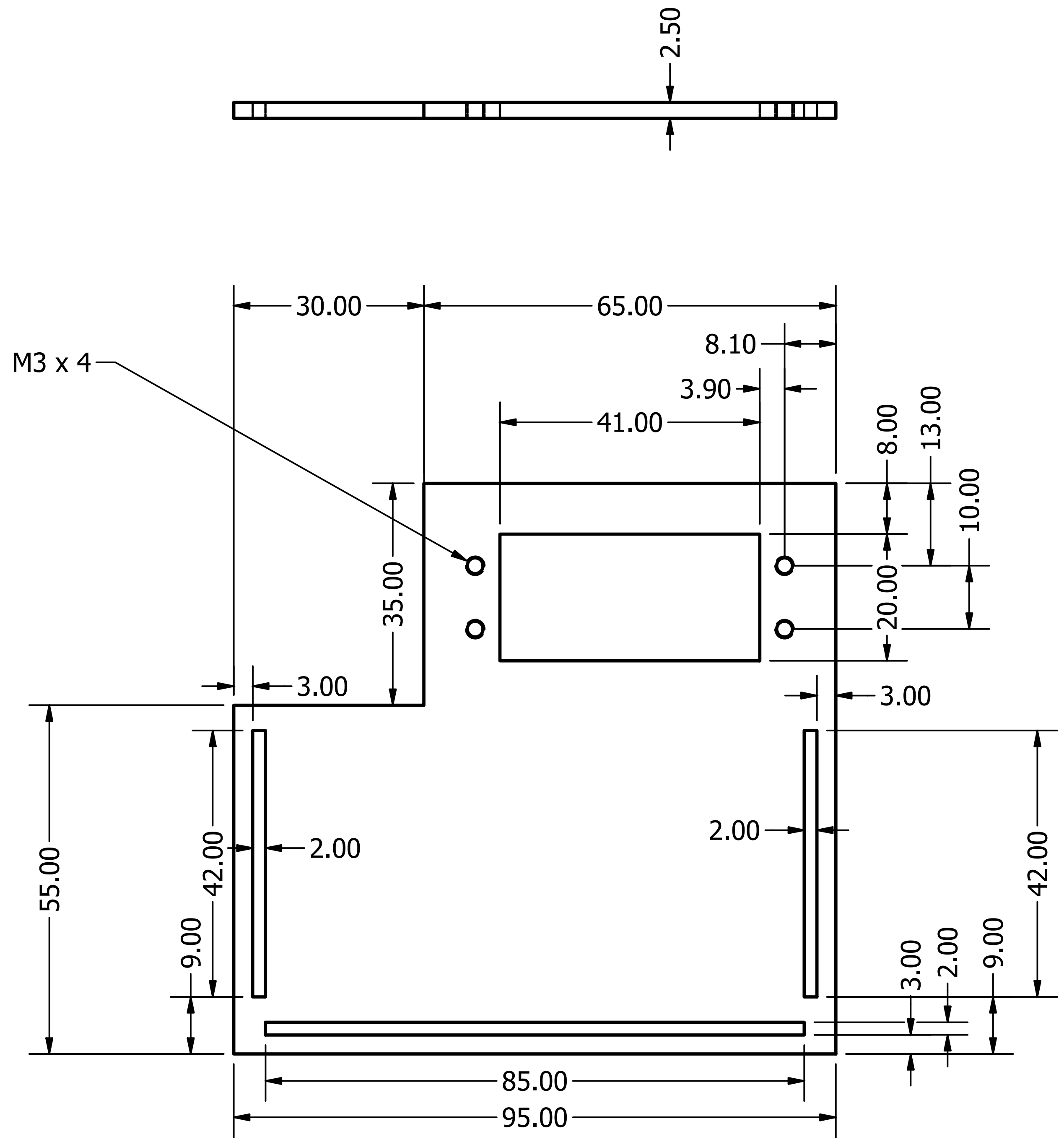
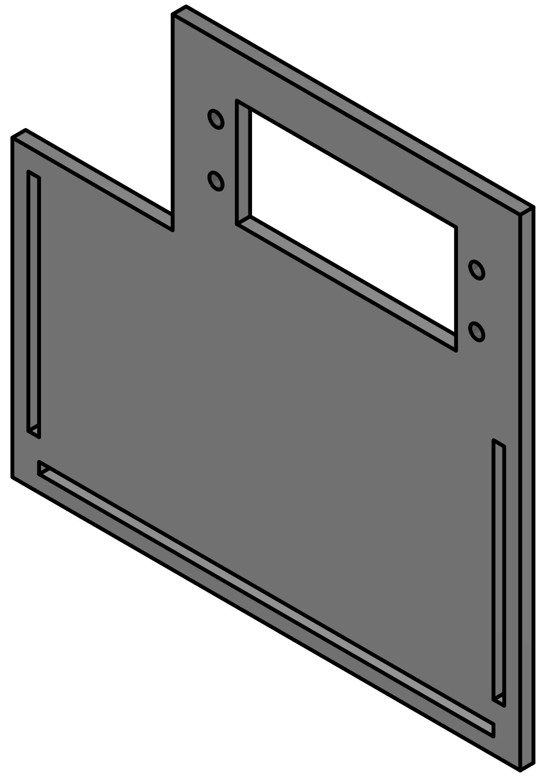
PRODUCED BY AN AUTODESK STUDENT VERSION

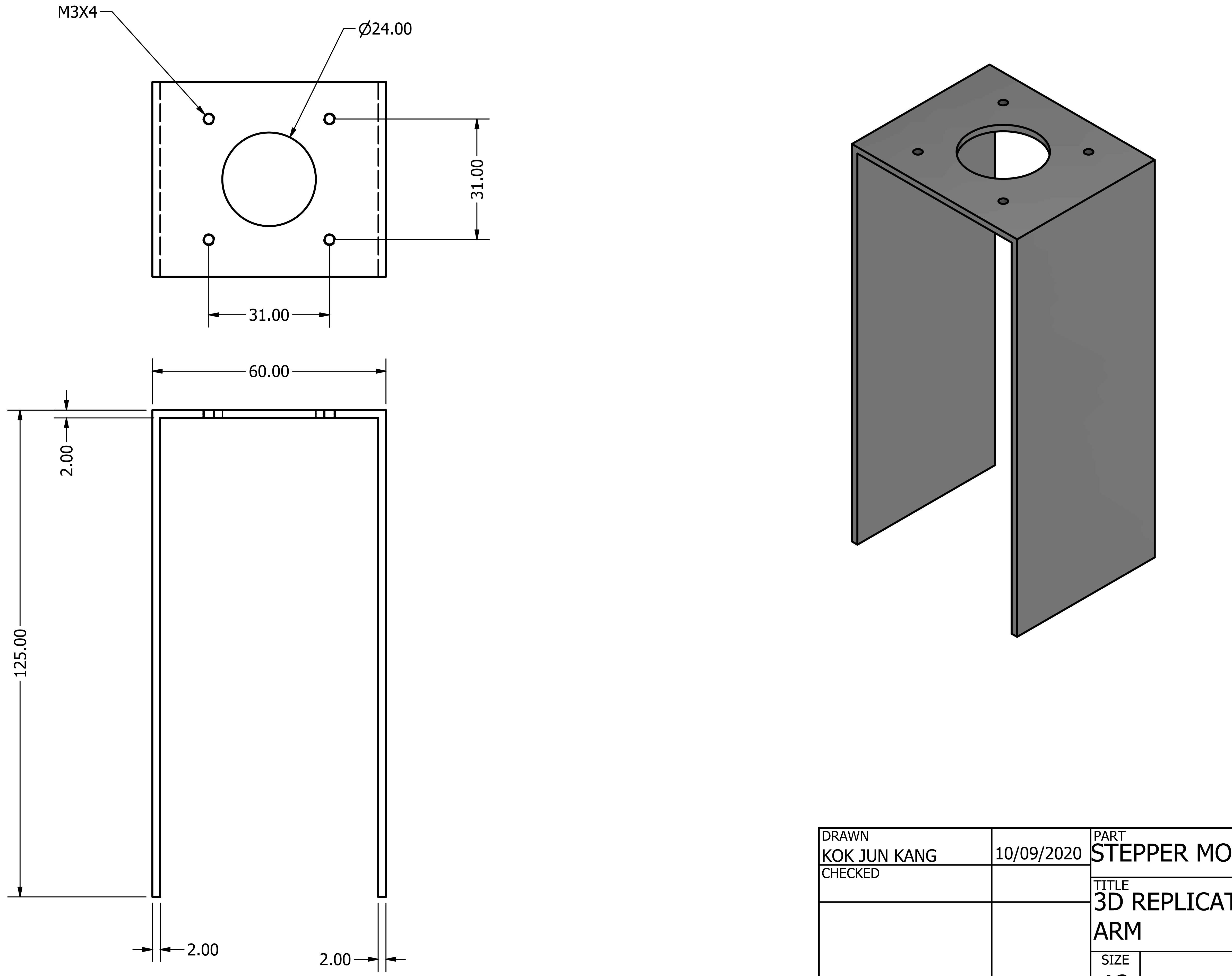


DRAWN KOK JUN KANG	10/09/2020	PART SHOULDER VERTICAL SUPPORT	
CHECKED		TITLE 3D REPLICATING ROBOTIC ARM	
		SIZE A3	DWG NO shoulder vertical su
		SCALE 2 : 1	SHEET 1 OF 1

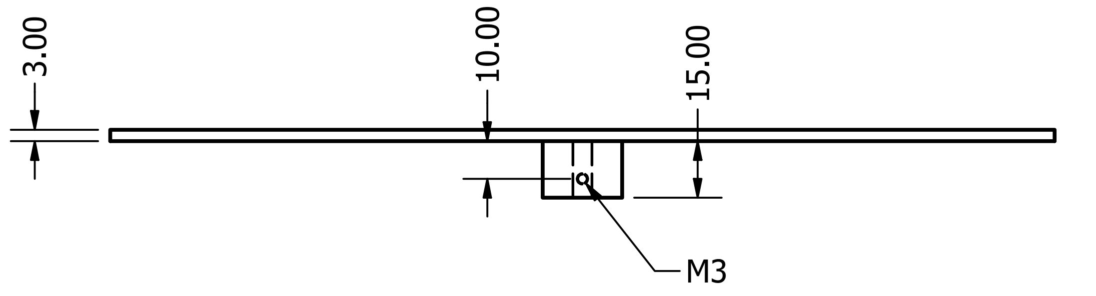


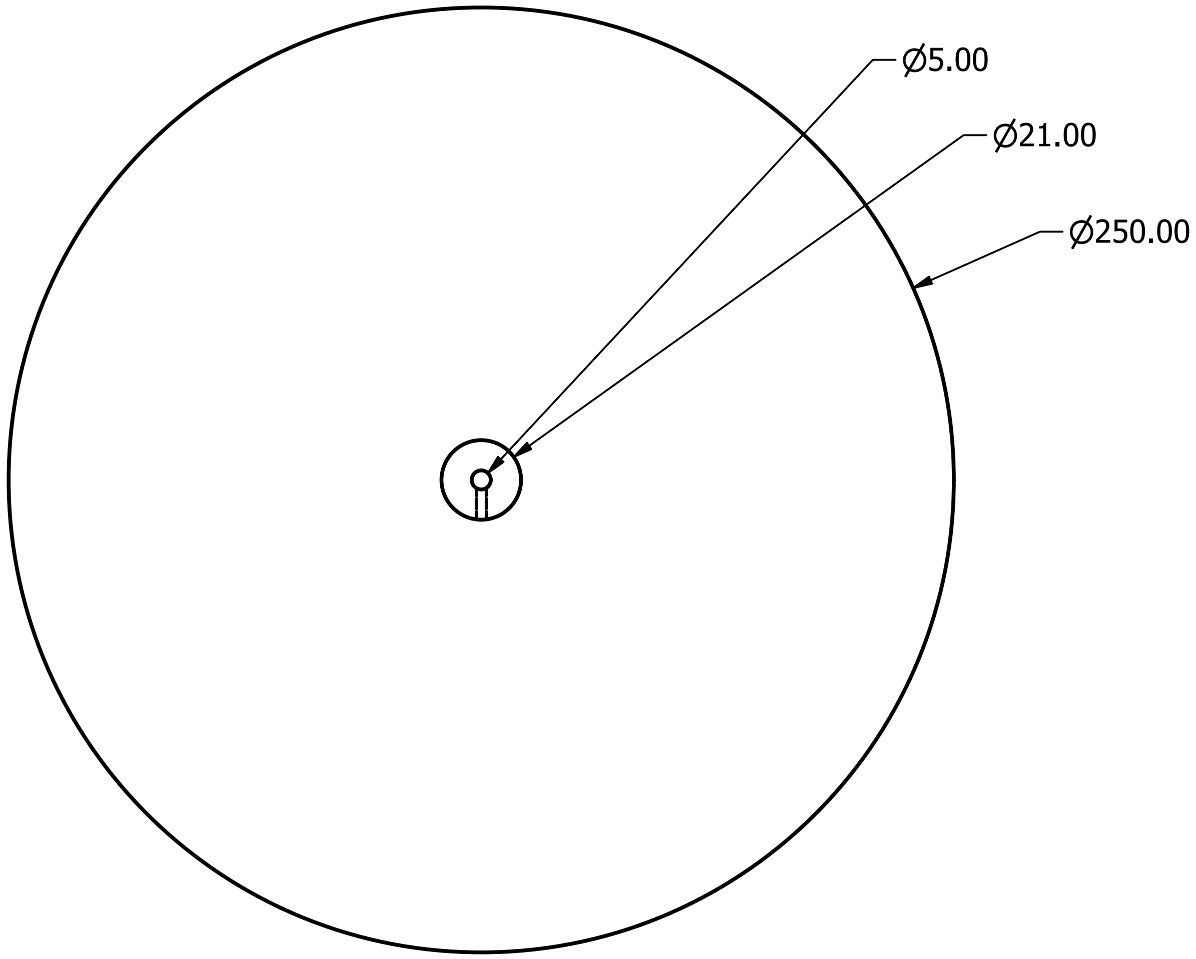


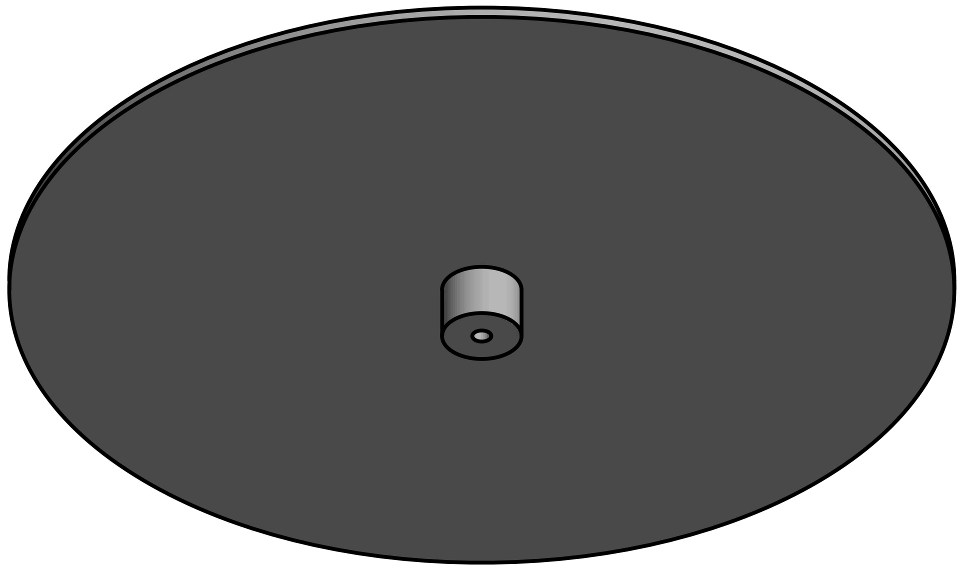
DRAWN		PART
KOK JUN KANG	10/09/2020	SHOULDER
CHECKED		TITLE 3D REPLICATING ROBOTIC ARM
		SIZE A3 / DWG NO shoulder
		SCALE 1 : 1 / SHEET 1 OF 1



DRAWN KOK JUN KANG	10/09/2020	PART STEPPER MOTOR HOLDER	
CHECKED		TITLE 3D REPLICATING ROBOTIC ARM	
		SIZE A3	DWG NO stepper motor holde
		SCALE 1 : 1	SHEET 1 OF 1







DRAWN KOK JUN KANG	10/09/2020	PART TURNTABLE	
CHECKED		TITLE 3D REPLICATING ROBOTIC ARM	
		SIZE A3	DWG NO turntable
		SCALE 1 / 2	SHEET 1 OF 1

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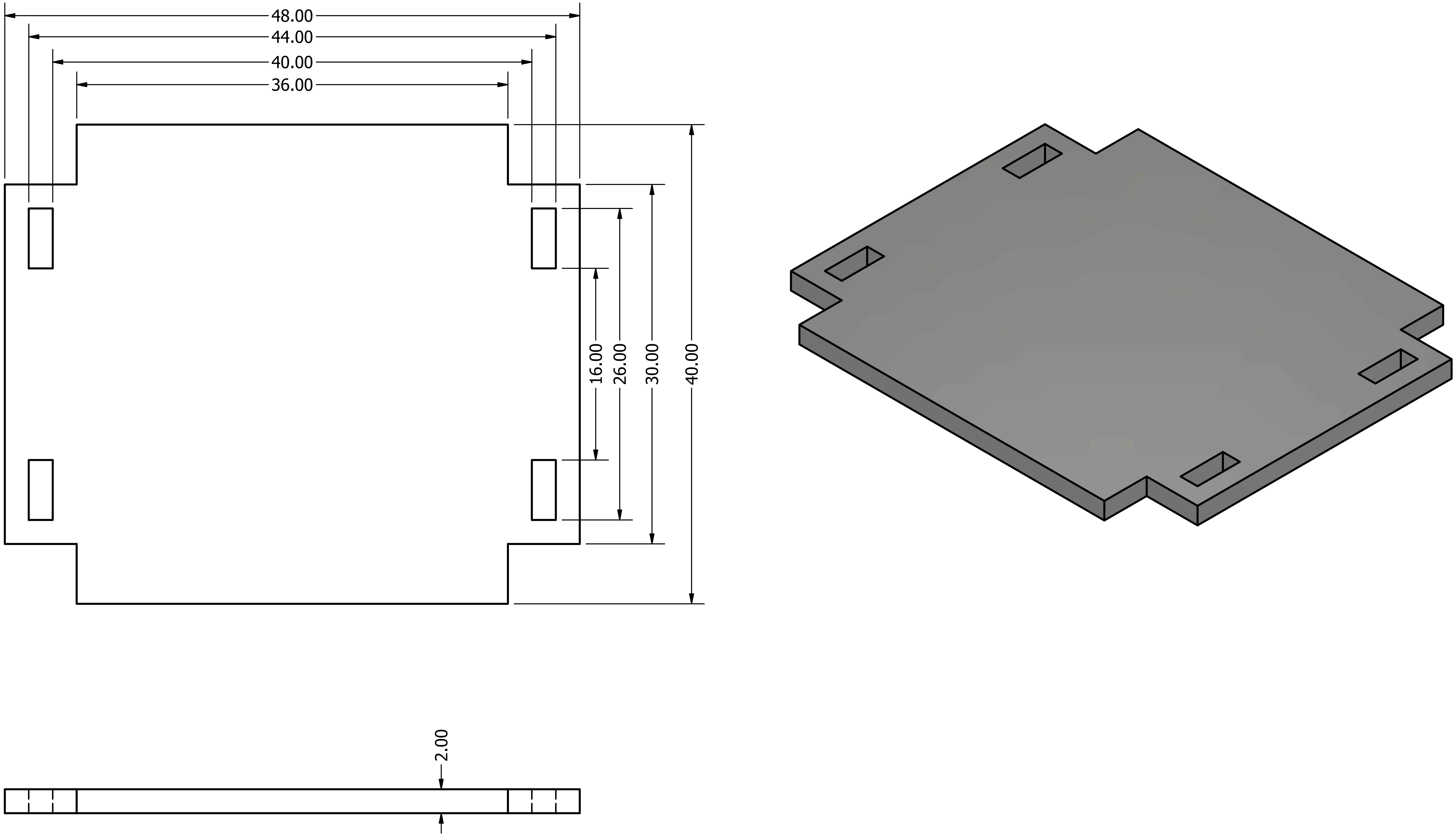

DRAWN KOK JUN KANG	10/09/2020	PART UPPER ARM BASE
CHECKED		TITLE 3D REPLICATING ROBOTIC ARM
		SIZE A3 — DWG NO shoulder
		SCALE 3 : 1 — SHEET 1 OF 1

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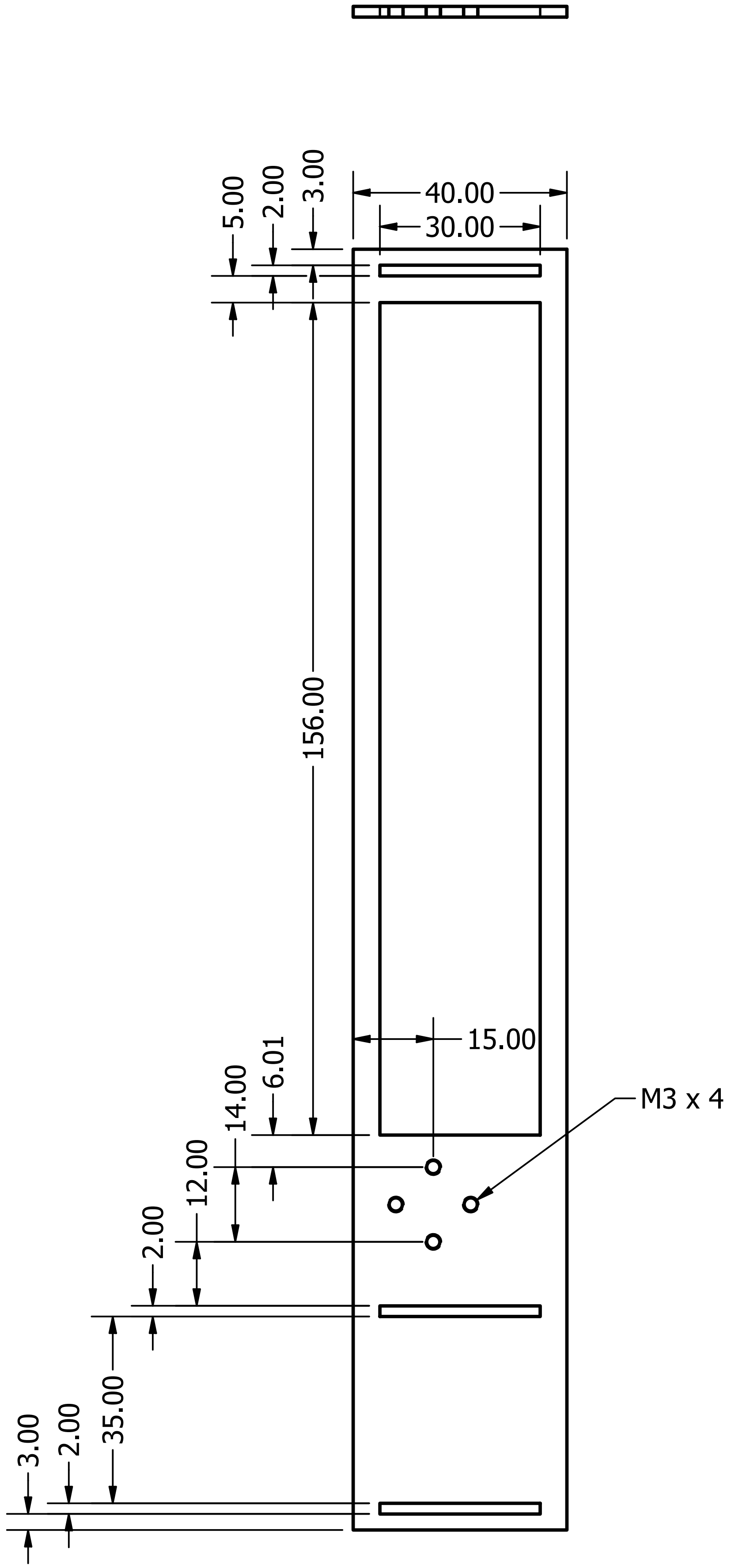
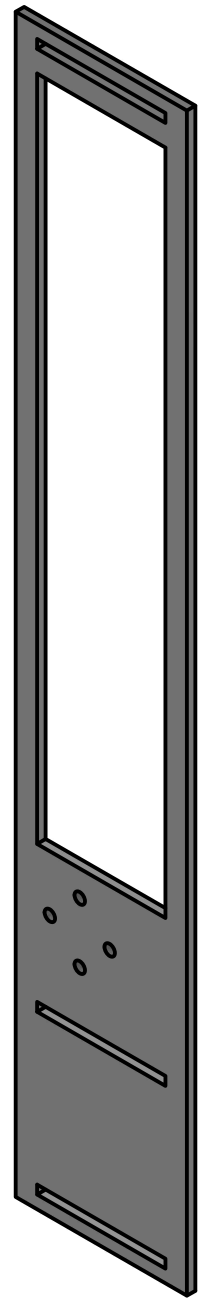
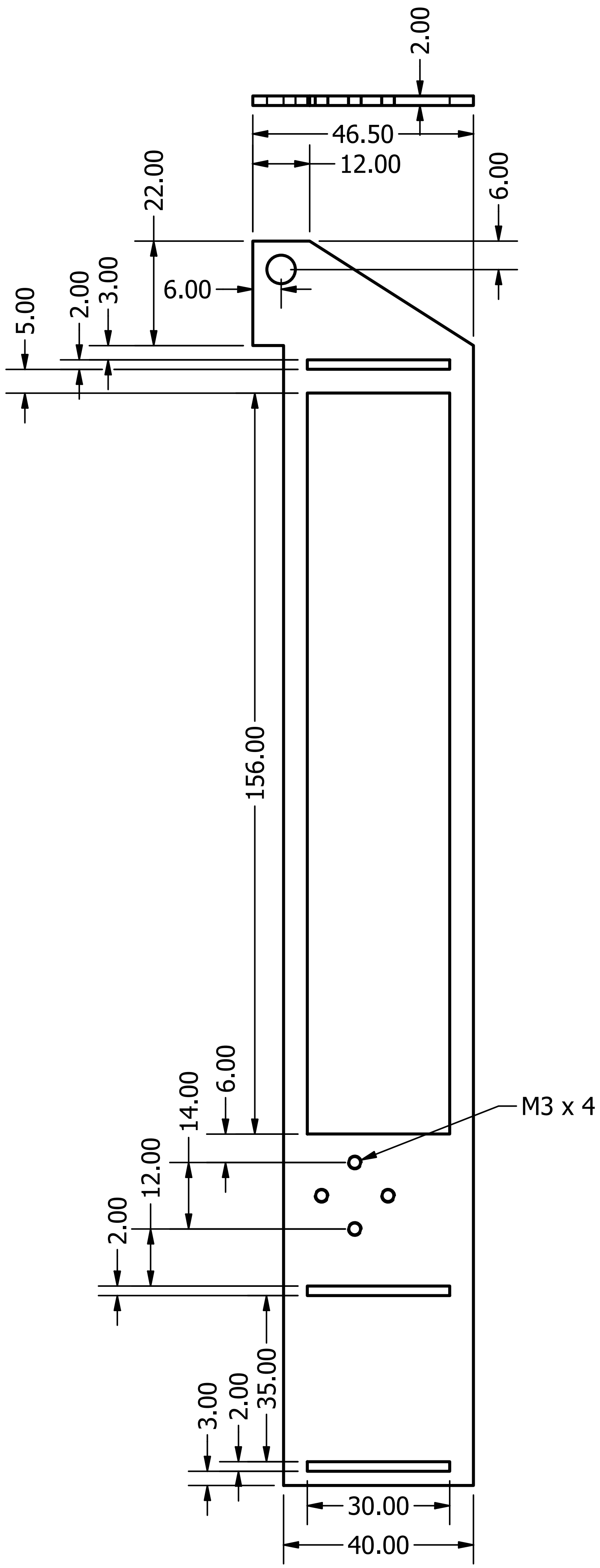
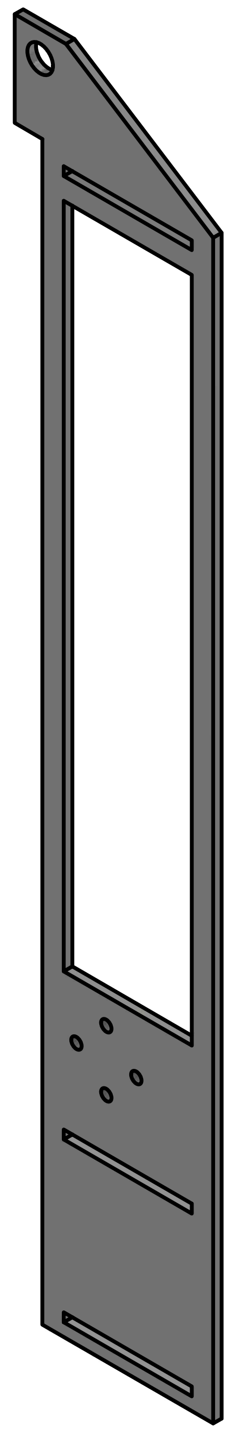
PRODUCED BY AN AUTODESK STUDENT VERSION



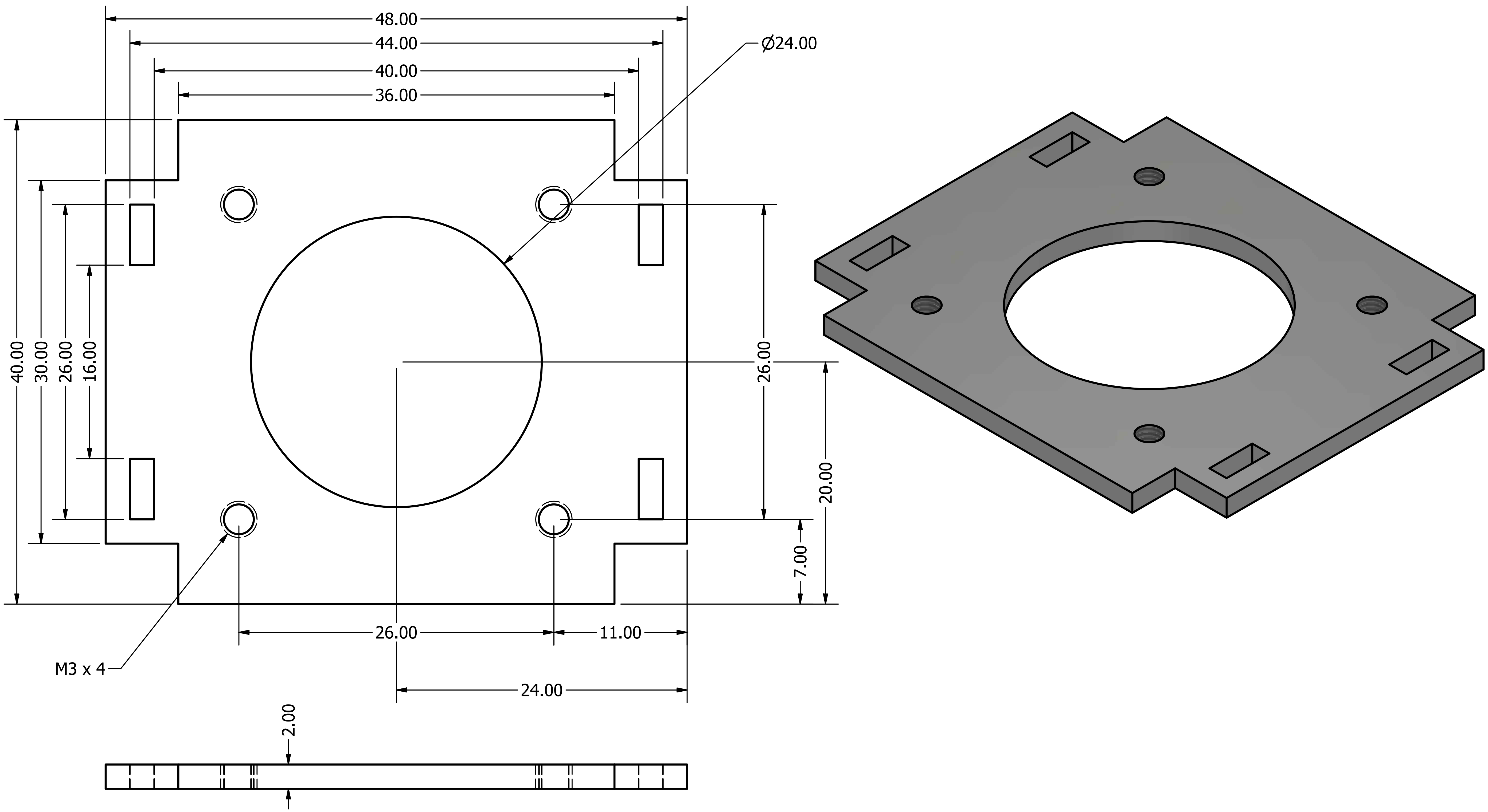


DRAWN KOK JUN KANG	10/09/2020	PART UPPER ARM L
CHECKED		TITLE 3D REPLICATING ROBOTIC ARM
		SIZE A3	DWG NO upper arm L
		SCALE .8	SHEET 1 OF 1





DRAWN KOK JUN KANG	10/09/2020	PART UPPER ARM R	
CHECKED		TITLE 3D REPLICATING ROBOTIC ARM	
		SIZE A3	DWG NO upper arm L
		SCALE .8	SHEET 1 OF 1



DRAWN KOK JUN KANG	10/09/2020	PART UPPER ARM STEPPER MOTOR SUPPORT	
CHECKED		TITLE 3D REPLICATING ROBOTIC ARM	
		SIZE A3	DWG NO upper arm R
		SCALE 3 : 1	SHEET 1 OF 1

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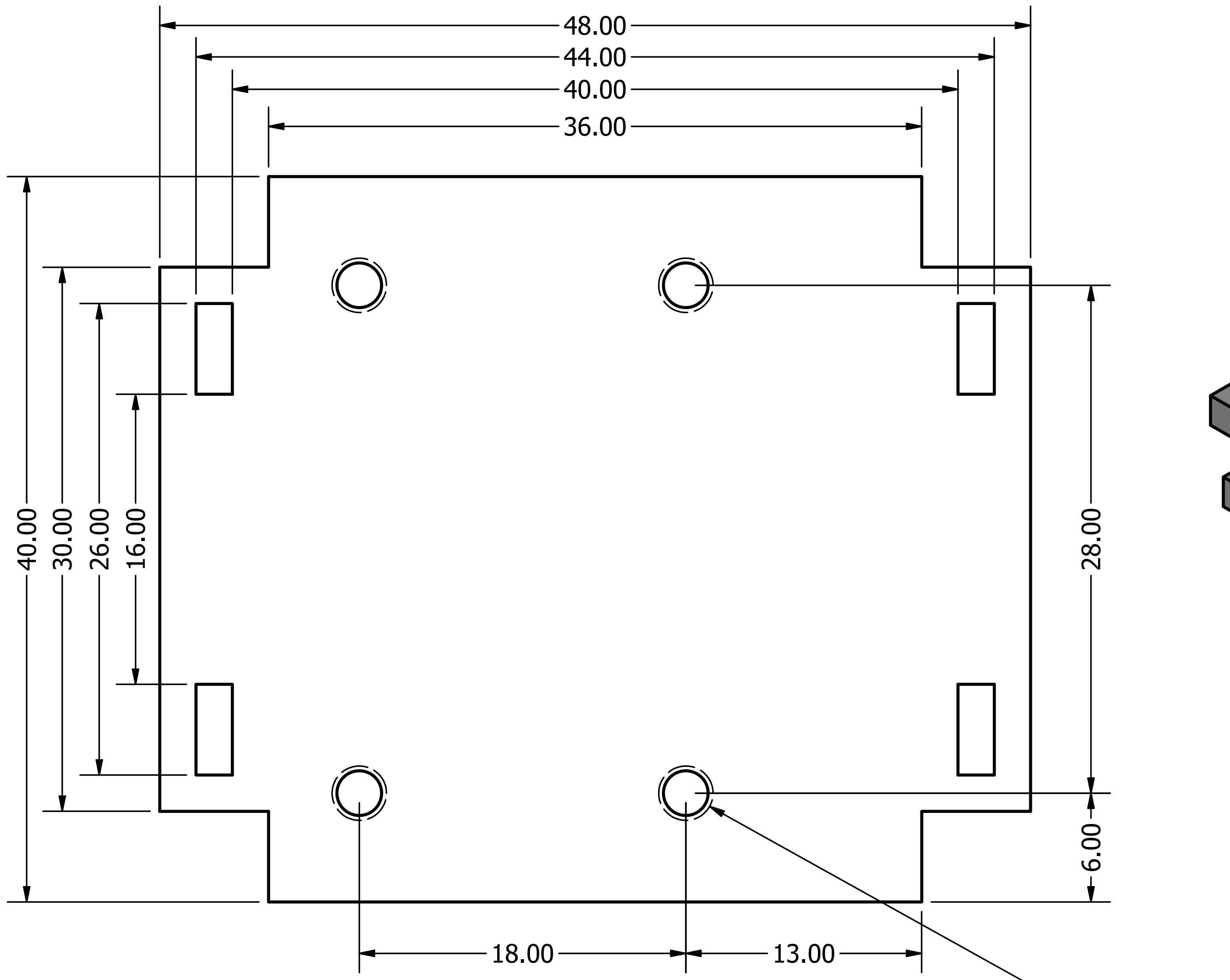
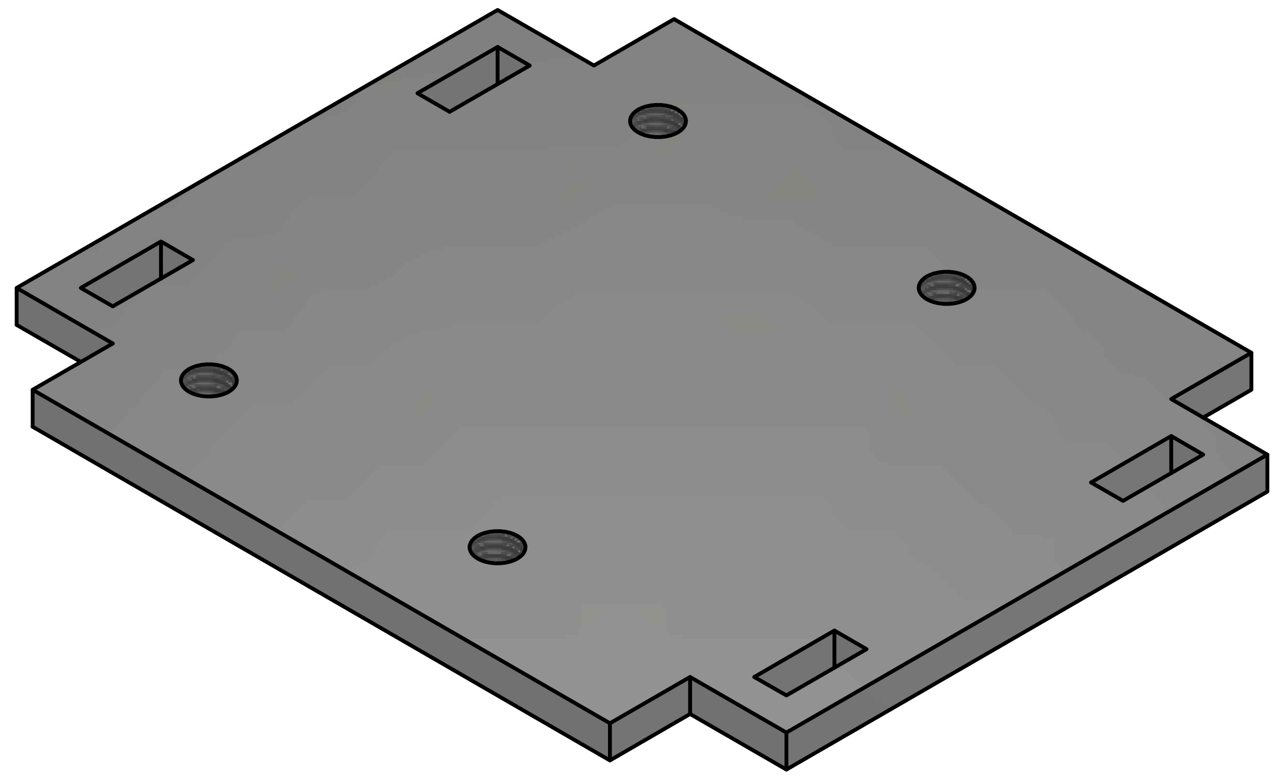
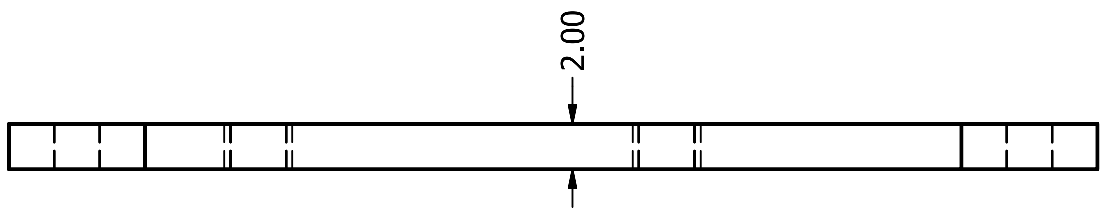
PRODUCED BY AN AUTODESK STUDENT VERSION







DRAWN KOK JUN KANG	10/09/2020	PART UPPER ARM SUPPORT UPPER
CHECKED		TITLE 3D REPLICATING ROBOTIC ARM
		SIZE A3 / DWG NO upper arm support
		SCALE 3 : 1 / SHEET 1 OF 1