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# MIG-BASED METAL ADDITIVE MANUFACTURING SYSTEM

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COLLEGE OF ELECTRICAL AND MECHANICAL ENGINEERING

# DE-41 MTS

# PROJECT REPORT

## MIG-BASED METAL ADDITIVE MANUFACTURING SYSTEM

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# ABSTRACT

This project aims to demonstrate the feasibility of MIG welding for metal additive manufacturing. It was undertaken due to the increasing demand and popularity of additive manufacturing systems, and the great potential for innovation and improvement in the field.

The project has succeeded in designing a three dof system as a base for mig welding. It incorporates two dof on the torch and one dof on the bed. This arrangement has been designed for gasless MIG welding using mild steel. It uses a self-designed wire feeder, operated through a microcontroller and a stepper motor, to drive the wire through a welding torch.

There is a lot of potential for continuation work based on the designed system, which could look to further optimise the design, attempt more complex geometries, and design the system to increase its material capabilities.

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# LIST OF SYMBOLS

**Latin Letters**

° degrees

**Greek Letters**

τ torque

η efficiency

**Acronyms**

F force

m mass

a acceleration due to gravity

W watts

A amperes

V volts

P power

V voltage

I current

r radius

Gpa- Gigapascals

Kg- Kilograms

mm-millimetre

in- inch

N-newtons

Nm-newton metres

Oz- ounce

C- Celsius

MHz- Megahertz

MIG- Metal Inert Gas

CAD- Computer Aided Design

HSLA- High Strength Low Alloy

FEA- Finite Element Analysis

# CHAPTER 1- INTRODUCTION

## 1.1 PROBLEM STATEMENT

The rapid development of additive production technologies, such as 3D printing, is changing the way we design, produce, and manufacture products. A viable alternative to traditional manufacturing methods that may be slow, costly, and reliant on specialized labour has emerged in the form of metal additive production. This project aims to develop a Metal Inert Gas (MIG) based metal additive manufacturing system that is affordable, accessible, and capable of rapid prototyping. Current metal printers are expensive systems and we also aim to minimise the costs associated with them.

Rapid Prototyping and bulk production, for some metal parts, are subject to heavy costs because of the conventional manufacturing process. We can address this problem with the MIG metal additive manufacturing system in which materials and processes are used as little as possible. It may also lead to faster processing times and savings in costs by reducing reliance on specialized labour, also leading to fewer time delays.

Thus, the problems we would be tackling are as follows:

- What would be the design of a three-axis machine that is suitable for welding?
- What would be the heating effects onto such a machine? How can we conduct relevant analysis to mitigate the risks of component failures?
- What is the specific welding equipment that would best suite the project?
- What type of welding would be best suited to this feasibility demonstration?
- Conducting the calculations and procurement of necessary components to ensure they meet the demands of the project.
- How will all the components and equipment be integrated together?
- Ensure the project has minimised cost as we envision such system to be available in developing countries as well.

## 1.2 OBJECTIVES

The main objective of this project is to develop a metal additive manufacturing system that is cost-effective, capable of manufacturing on demand, and accessible. To achieve this objective, the project focuses on the development of a CAD model with a complete bill of materials. We will be conducting relevant analysis using Ansys Workbench. In addition to this, the development of a frame using an OpenBuild design and aluminium extrusions, and the integration of a MIG welding machine to deposit metal in a controlled manner are also targets of the project.

The system will be capable of three degrees of freedom with the use of stepper motors to control the motion of a deposition nozzle and the bed. The result would be a printer designed for MIG welding using mild steel wire.

## 1.3 SCOPE

The project will focus on developing a metal additive manufacturing system that can offer an affordable and accessible alternative to conventional production methods while at the same time being capable of rapid prototyping. The MIG welding system is built on a 3-axis machine with 2 degrees of freedom on the torch and one degree of freedom on the bed. The project involves designing and mounting a printer bed to the frame

## 1.4 SIGNIFICANCE

While this project is a small-scale demonstration, successful implementation of the system would aim to advance the field of manufacturing by introducing advanced manufacturing into the realms of rapid prototyping. This would increase innovation amongst industries by allowing faster product development cycles, which would allow engineers to test iterations of a product at a faster pace. This technology can further help to reduce costs, which would be beneficial to smaller businesses. The costs associated with tooling and setup for various machineries are reduced, along with the material costs, as additive manufacturing require less material than traditional subtractive manufacturing. Being able to manufacture autonomously is a key to extra-terrestrial development, which would require the use of such technologies. An additive metal printer would empower customers by adding advanced alloys to their arsenal to combat harmful practices of businesses, such as planned obsolescence, by giving them the ability to domestically manufacture repairs. In relation, it would combat the rising CO2 emissions by reducing the shipping and travelling emissions.

# CHAPTER 2- BACKGROUND AND LITERATURE REVIEW

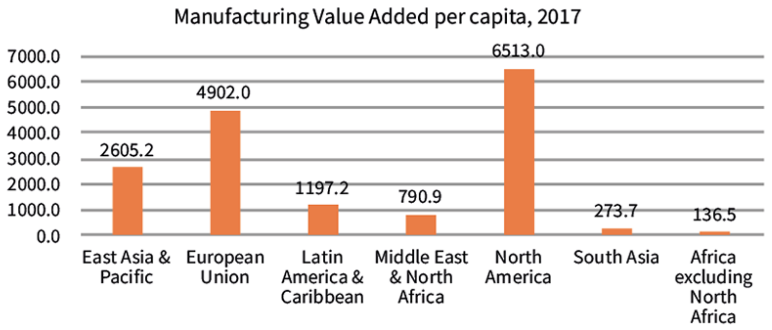
## 2.1 ECONOMICS OF MANUFACTURING

The manufacturing industry of today is highly competitive and fast-paced. With accelerating change in technology, as theorized by Ray Kurzweil, a computer scientist, and futurist, generalized Moore's Law, stating that the speed of technological change is taking place exponentially. He further stated that it will not be a hundred years of technological progress in thenext one hundred years, but rather 20,000 [1]. New products are being pushed out at ever-increasing rates. This drives great pressure on the manufacturing industries to constantly revolutionize and innovate their means of production. Karl Marx, an influential analyst of technical progress claimed in 1848:

"The bourgeoisie cannot exist without constantly revolutionizing the instruments of production, and thereby the relations of production, and with them the whole relations of society. Constant revolutionizing of production, uninterrupted disturbance of all social conditions, everlasting uncertainty and agitation distinguishes the bourgeois epoch from all earlier ones. All fixed, fast-frozen relations, with their train of ancient and venerable prejudices and opinions, are swept away, and all new-formed ones become antiquated before they can ossify. All that is solid melts into air. . . The bourgeoisie, by the rapid improvement of all instruments of production, by the immensely facilitated means of communication, draws all nations, even the most barbarian, into civilization [2]."

A challenge faced by developing countries is that reliance on outdated manufacturing practices and over-reliance on labour has led to a struggle to stay relevant in the fuelling competition [3]. Lack of investment in research resulted in very few indigenous options and the purchasing power of developing countries has made it difficult to import expensive manufacturing equipment. This has widened the gap between developing and developed countries which takes the form of a

**Figure 2: Manufacturing Value Added in Various World Regions, 2017.**



Source: World Development Indicators, World Bank, 2019.

Figure 1 Industrial output of regions per capita [48]

persistent cycle [4].

The fragility of the global supply chain is becoming more obvious with the recent supply shocks fuelled by the COVID-19 pandemic, climate crisis, and The Russian-Ukrainian war. The prices of imports are rising globally, as well as a lack of trade trust. Additional tariffs are being implemented for imports. This puts forward a need to focus on domestic production for countries. This further aligns with the goals of sustainable and clean production as costs and emissions in bringing the products to the market are reduced [5].

By moving more production in-house, an opportunity is presented to rebuild more efficiently by incorporating new methods and technologies. This can be done by using automation, continuous-flow manufacturing, and additive manufacturing procedures [6].

## 2.2 ADVANCED MANUFACTURING TECHNIQUES

Manufacturing converts raw materials into finished products using tools, labour, and machines. With Industry 4.0, there are significant changes to the manufacturing processes. This manufacturing process is becoming increasingly automated and mechanized, with increasing use of robotics, and modern techniques such as additive manufacturing. There is also digitization occurring in the field, with reducing costs and improvements in the implementation of the Internet of Things (IoT). Some key benefits of these changes are:

- Flexibility
- Decentralization
- Individualization, companies can customize production due to rapid prototyping.

less resource usage, techniques such as additive manufacturing reduce the usage of resources and time.

There is a trend towards miniaturization of the manufacturing machinery. This would require less space, which also increases the availability of the machines to a wider audience. There is an increasing trend toward incorporating sensors, actuators, and automation in the industry to reduce labour and increase efficiency, thus leading to less reliance on specialized labour. And this trend is only further accelerating [7].

### 2.2.1 INDUSTRY 4.0

The beginning of the industrial revolution was due to progress in technology, there had been a shift in how power was being derived. Humans and animals were being replaced by machinery. This was a phenomenon that spread throughout the globe. Output was being increased exponentially, with traditional jobs being replaced by new jobs [8].

Over the ages, humanity has seen three industrial revolutions. The first Industrial Revolution is said to be around the 1760-1840 period, centred around Great Britain. This led to improved infrastructure and the rise of canals and railway networks. It was characterized by the development of steam power, the production of iron, and the spread of textile manufacturing. There were large changes in the economy due to the invention of the stock exchange. The second industrial revolution was followed by the invention of electrical power, which was then used to operate machinery, further driving down the demford for physical labour. This was centred in the United States, Central Europe, and Japan. This introduced the telegraph, telephones, and the internal combustion engine, which served as the foundation of modern lifestyle. The third industrial revolution gave rise to the Information Age. This led to a transformation in manufacturing, communication, and transportation. Nuclear power was the new energy source during the third industrial revolution. Notable technologies introduced in the third industrial revolution were electronics and computing [9].

Industry 4.0 refers to the ongoing fourth industrial revolution with trends on collaboration and integration through a focus on digital manufacturing. The trademark of this revolution would be the integration of the cyber domain. This revolution promises to bring increased personalization and customization foe consumers, as well as help make an impact on pressing issues such as pollution and climate change [10]. The interconnection of these systems refers to the ability of the system to be able to share data and communicate with other devices and processors within the system by taking data from sensors. The human element should be minimized in decision-making and construction of the system [11]. The system should possess autonomy, which in this case refers to its ability to detect faults and make basic corrective decisions such as restarting the system. These decisions must be made in real time [12]. The rate of adoption of Industry 4.0 is not consistent across the globe due to a lack of roadmaps for the transition as well as present technological gaps. The collaboration between companies and technical experts is important for industries to maintain a competitive edge [13]. A key technology in industry 4.0 is the rise of robotics and co-bots in global factories. This would have tremendous applications and would need the workplace to follow new workplace safety accordingly. All these changes would lead to minimum down-times hence reducing the economic hits to the industry [14].

### 2.2.2 ADDITIVE MANUFACTURING

Rapid prototyping is a revolutionary technology often characterized by industry 4.0. It uses algorithms to transform digital model data into physical 3-dimensional objects, with vast applications in every field. This technology is popularized as 3-d printing generally and additive manufacturing in the industry [15]. Prototyping, experimentation, and piloting are three key strategies for modern business model focusing on agile and resourceful methods to meet the demands of today’s rapidly evolving markets. These technologies have led to the rise in start-ups and helps smaller businesses compete against large established businesses while causing disruption through risk mitigation and increased agility through continuous feedback [16].

### 2.2.2.1 TRENDS IN ADDITIVE MANUFACTURING

Additive manufacturing initially used to build models limited to visualization of products, has now benefited from progress in accuracy, materials development, and technology to now produce models useful for evaluating the Form, Fit and Function of the final product by carrying out tests on highly accurate models. Recently, additive manufacturing has even progressed to directly manufacture the product itself. A digital model is generated through Computer-Aided Design Software (CAD) or through reverse engineering technologies such as optical scanning. The manufacturing is done in thin cross-sections of the model. Models manufactured through this technology are an approximation of the digital model, with the physical model approaching the ideal digital model as the thickness of the cross- section approaches zero [17].

Companies engaging in additive manufacturing system increased from 49 in 2014 to 97 in 2016 [18]. Starting from a valuation of 16.6 million in 2020, it is expected to reach a value of 70.92 million in 2026.

Furthermore, there have been lots of initiatives by groups to quickly adapt such technologies. The BMW group launched the 'Industrialization and Digitization of Additive Manufacturing for Automotive Series Processes' project (IDAM), which has targeted at the production of up to 50,000 components using additive manufacturing technologies.

| | |
|---|---|
| Study Period: | 2018 - 2028 |
| Fastest Growing Market: | Asia Pacific |
| Largest Market: | North America |
| CAGR: | 27.5 % |
| Major Players | |

*Disclaimer: Major Players sorted in no particular order

Figure 2 Market growth forecast [49]

Additionally, there is growing demand for software designs using additive manufacturing. This software is used for the prototyping and printing objects, with growing traction in industries like aerospace, defence, automotive and construction industry [19]

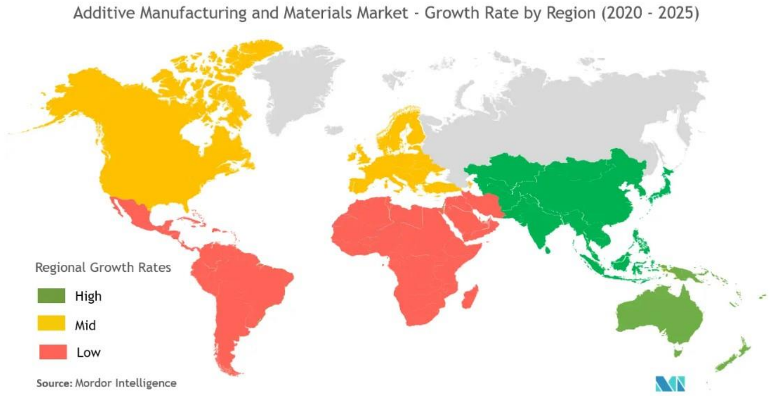


Figure 3 Regional growth forecast [49]

A positive point in developing such technologies locally for deployment in South-East Asian region is the strong growth possibility. Rapid industrialization and immature manufacturing practices have left a potential for implementation of advanced manufacturing in such countries.

### 2.2.2.2 IMPACT OF ADDITIVE MANUFACTURING

Additive manufacturing has various applications with potential to revolutionize the industry. There are rising demands following the decreasing costs of implementing additive manufacturing systems. The costs of additive manufacturing initially limited them to large industrial fields, but recently have started to show up in schools, homes, and other accessible places. This can be credited to the expiration of patents protecting the capitalization of the technology, with now multiple manufacturers working towards producing such systems [20]. There is a demand for metal-based additive manufacturing due to the ability of AM to fabricate complex titanium alloys used in air crafts. Rising demand in the Medical Industry can also be seen where complex anatomical parts are needed from scanned data. Further demand is for medical education where surgical practice can be planned and taught on manufactured models. Architectural fields have also seen its applications with prototypes of complex structures enable architects to analyse their designs quickly [21].

Such technology has opened opportunities for customized products, in accordance with Industry 4.0. This has become especially practical with additive manufacturing as the customized designs have their data saved and can lead to quick replacement, or even modify the design as per requirement. This also can open up new business models and for business growth and innovation. There is an increased viability of prototyping and testing models. Not only can the models be initially tested in simulations before generating the STL file, but additionally, the physical model can be tested before being deployed into the market, and hence, quick design innovations can be employed. Hence all potential risks and defects are measured before releasing the product into the market. The use of AM also optimizes the cost of the supply chain through virtual inventory. In traditional manufacturing systems, inventory holding often leads to an increase in the final cost of the product. How- ever, with AM, the inventory is stored digitally in the form of a 3D CAD file, which eliminates the need for vendors and enhances the efficiency of the supply chain by reducing lead time, inventory costs, and production time. Additionally, AM offers cost savings through reduced material wastage and streamlined production processes. The costs associated with tooling, moulds, and jigs are minimized, making it a cost-effective solution to produce low-volume and customized products [22]. It can serve as a key tool for combating the climate crisis. Using the 10-R of production, such as remanufacturing. This can help reduce the carbon footprint and help reduce global warming and thus assist businesses to achieve sustainability goals [23]

#### 2.2.2.3 CHALLENGES OF ADDITIVE MANUFACTURING

While additive manufacturing does have extensive advantages, it also faces several challenges that need to be addressed. Some of these include limitations in part size, uneven extrusion, misaligned layers, gaps in top layers and limitations in materials. Additive manufacturing is limited in size to the maximum size that the system is designed to handle. It cannot work on larger models without scaling the system. Additive manufacturing also did not have the time to adopt the variety of materials that traditional manufacturing can use to fabricate a product. Currently, work is being carried out to develop new advanced materials for use in additive manufacturing, but the options are limited now. One of the major issues with AM components is the formation of voids between layers, which weakens the mechanical performance. The build volume is also limited, and large parts need to be divided into smaller parts, which is time-consuming and can affect the strength of the assembly [24]. Another challenge in home 3-d printers is the regulation of such technology. A challenge here is to control the manufacture of illegal technologies such as weaponry, while a challenge in the medical industry is to make the system compliant with Food and Drug Administration safety standards [21]. Parts made using Fused Deposition Modelling (FDM) also have problems with anisotropy where the microstructures and mechanical properties are not uniform across all directions. Typically, in FDM, the build direction has different properties than the other two axes due to the layering procedure changing properties[25], [26].

## 2.3 MIG-BASED METAL ADDITIVE MANUFACTURING

### 2.3.1 METAL ADDITIVE MANUFACTURING

In the previous section, we talked about a major limitation of additive manufacturing the lack of a wide range of manufacturing materials. With metals being a critical aspect of the modern industrial economy, it comes without question that additive manufacturing technologies would focus their research on metal manufacturing. The market value for metal additive manufacturing was estimated at around 2631 million USD in 2021 with the projections being 14094.5 million USD by 2031 [27].

Among the prevalent methods for metal additive manufacturing, Powder Bed Fusion (PBF) and Direct Energy Deposition (DED) are two notable techniques [28]. PBF involves the selective melting of powder particles, commencing with the distribution of a fine metal powder layer on a construction platform. A laser or electron beam is employed to selectively melt the powder particles, based on the STL files created during the design phase and subsequently converted into printer code. The melting process results in the formation of the prototype's layers, with the construction platform adjusting to accommodate subsequent layers. PBF has two sub-categories: Selective Laser Melting (SLM) and Electron Beam Melting (EBM), which utilize laser and electron beams, respectively. Another PBF method is Selective Laser Sintering (SLS), where powder particles are heated to a high temperature, forming porous layers of bonded particles instead of melting [29].

DED, on the other hand, is a metal additive printing technique that employs a laser or electron beam to melt wire or powder feedstock as it is deposited onto a substrate. The process starts with a nozzle positioned near the substrate, and a laser beam is used to melt the metal wire or powder, which is then deposited onto the substrate through the nozzle. The nozzle follows a pre-determined pattern to construct the 3D structure layer by layer. DED can rapidly produce large parts and has the potential to utilize a broader range of materials compared to PBF, including metals that are challenging to melt using conventional manufacturing methods. However, DED's drawback is the decrease in precision and resolution. Generally, PBF is more suitable for creating high-quality, intricate parts with fine details, while DED is better suited for quickly producing larger parts and adding material to existing structures.

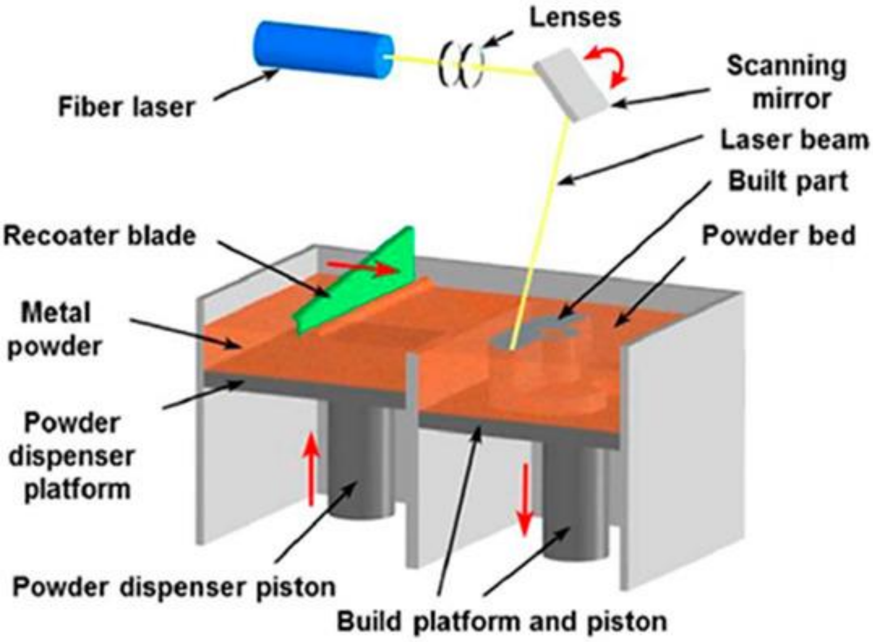


Figure 4 Depiction of Powder Bed Fusion (PBF) [50]

Metal Additive Manufacturing (AM) is gaining traction across government, industry, and academic sectors. Its application is especially valuable in the aerospace field, where it enables part consolidation, the utilization of innovative alloys and multi-material components, and internal complexity that boosts performance. Consequently, many aerospace components have experienced enhanced performance, cost reduction, and shorter production times. The aerospace industry's adoption of AM has led to the establishment of specialized companies and equipment manufacturers concentrating on this technology. Aerospace parts, including thrusters, heat exchangers, rocket nozzles, antenna components, and structural elements, are now being fabricated using AM. Nevertheless, challenges persist in the realm of AM, such as post-processing, design allowances, qualification, repeatability, and accurate cost assessment [30].

### 2.3.2 MIG WELDING

Welding involves the union of two metals by heating them to their melting points, creating a weld pool, and applying pressure or a combination of both to merge them. There are several welding methods, such as arc welding, laser welding, and friction welding, among others. Metal Inert Gas (MIG) welding stands out as a versatile technique, suitable for both thin sheet and thick section components, making it a popular choice in the field. [31].

Arc Welding: Arc welding is the process of joining metals using an electric arc to create heat. The heat melts the metal and creates a bond between the two pieces. This process is widely used in construction, fabrication, and repair work.

Gas Welding: Gas welding is a process that utilizes a torch to heat the metal and a separate filler rod to join the two pieces. The torch creates a flame that melts the metal, and the filler rod is added to create a bond between the two pieces.

Resistance Welding: Resistance welding applies pressure and heat to the metal, creating a strong bond. This process is widely used in the automotive and aerospace industries.

TIG welding: TIG welding, an acronym for Tungsten Inert Gas welding, is also referred to as gas tungsten arc welding (GTAW). This welding method utilizes an electric arc to generate heat. Primarily, TIG welding is employed for joining thin sections of stainless steel and non-ferrous metals like aluminium, magnesium, and copper alloys [32]..

MIG welding: Also known as gas metal arc welding (GMAW). It involves an electric arc that is formed between a continuous solid wire electrode and the workpiece. The wire electrode serves as both the heat source and the filler metal for the weld joint. The arc and the weld pool are protected from atmospheric contamination by a shielding gas that flows through a nozzle surrounding the wire.

MIG welding requires a direct current positive electrode (DCEP) or reverse polarity. The wire diameter and feed speed determine the welding current. The wire can be either solid or cored, depending on the material and application. The shielding gas can be either inert (such as argon or helium) or active (such as carbon dioxide or argon-carbon dioxide mixtures).

MIG welding can be performed manually, mechanized, or automatically. In manual MIG welding, the welder controls the travel speed and wire position, while the wire feed rate and arc length are controlled through the power source. In mechanized MIG welding, the welder may adjust some parameters during welding, but the travel speed and wire position are controlled by a machine. In automatic MIG welding, no manual intervention is needed during welding and the parameters cannot be changed during welding.

MIG welding has many advantages over other welding processes. It can weld a wide range of metals and alloys with high quality and low distortion. It has low operator skill requirements and can be easily automated. It also has some disadvantages, such as high equipment cost, high heat input, spatter generation, and shielding gas requirement [33].

#### 2.3.2.1 WELDING PROCESS

A solid wire electrode is constantly fed through a wire feeder into a puddle of weld. A welding gun is used to generate the weld pool. In gassed MIG welding, the gun is also used to provide the shielding gas that prevents contamination of the weld pool. The base materials melt together to form what is called a join.

MIG/MAG welding is a versatile technology that may be utilised for both thin sheet and thick section components. An arc is formed between the workpiece and the end of a wire electrode to form a weld pool. The wire serves as a heat source and filler metal for the welding joint via the arc at the wire tip. To feed the wire, a copper contact tube (contact tip) is employed, which carries welding current into the wire. To protect the weld pool from the atmosphere, a shielding gas is provided through a nozzle around the wire. The shielding gas used is determined by the application and the material being welded. A motor drive feeds the wire from a reel, and the welder moves the wire as it is fed. The wire is supplied from a reel via a motor drive, and the welder moves the wire as it is fed.

The wire is normally positively charged and connected to a power source that supplies a constant voltage to allow the process to function. Because the wire burn-off rate will attain equilibrium with the feed speed, the welding current is determined by the wire diameter (typically between 0.6 and 1.6mm) and wire feed speed. Metal transfer can be accomplished in three ways:

- Short-circuiting
- Droplet
- Pulsed

While spray metal transfer is only employed with high welding currents, short-circuiting, and pulsed metal transfer are used for low-current operation. The molten metal that is developing on the wire's tip is transmitted by short-circuiting or "dipping" the wire into the weld pool. Setting a low voltage is how this is done; for a wire with a diameter of 1.2mm, the arc voltage ranges from 17v (100a) to 22v (200a). To minimize spatter, care must be taken when adjusting the voltage and inductance in relation to the wire feed speed. The surge in current that happens when the wire dips into the weld pool can be controlled using inductance.

To prevent the wire from making contact, a much greater voltage is required for droplet or spray transfer. Droplets are not forcibly pushed across the arc below a certain minimum current level or threshold. The open arc could be stabilized using the pulsed mode at low current levels.

There are two methods of MIG welding: gas welding and gasless welding. Gas welding is used in situations where the cosmetics of the weld are an issue. It forms a cleaner weld on a more expensive setup. Gasless welding is a more cost-saving approach, and can also be used in harsher environments, such as outdoors.

The shielding gas has the following additional functions:

- Ensures the smooth transfer of molten droplets.
- Creates an uncontaminated weld pool.
- Forms an arc plasma.

Mixtures of argon, oxygen, and carbon dioxide are used as general-purpose shielding gases for MIG welding, and helium may be added to gas mixes. For the various materials, the following gases are typically used:

For a deeper, less-spatter weld on mild steel, argon, and carbon dioxide (AR/CO2) gas**.**

For MIG welding aluminium, pure argon (AR) gas for a shallower, thicker weld **[34].**

#### 2.3.2.2 WELDING EQUIPMENT

Since we are going to be manipulating a MIG welder, we need an analysis of the working of the welding equipment. A MIG welding system typically consists of:

- A power sources.
- A wire feed system
- Gun/Torch

A DC power source is commonly utilized for MIG operation. Based on the relationship between voltage and welding current, this source is known as a flat or constant voltage characteristic power supply. MIG welding current is influenced by the wire feed rate, while the arc length is affected by the power source voltage level (also called open circuit voltage). The wire feed rate, current pick-up at the contact tip, and distance from the gun to the workpiece are all automatically adjusted, as is the wire burn-off rate. For example, if the arc momentarily shortens, the arc voltage will decrease, and the welding current will temporarily increase to burn back the wire and maintain the pre-set arc length. The opposite will occur to compensate for a momentary arc extension.

There are two types of welding guns: "air"-cooled and "water"-cooled. "Air"-cooled guns have a limited current carrying capacity, as they rely on the shielding gas flowing through the body to keep the nozzle cool. These are suitable for light-duty applications. Water-cooled guns are preferred for high current levels, particularly at high-duty cycles, although "air-cooled" guns with current ratings up to 500 A are available.

Welding current is delivered to the wire through a contact tip with a bore slightly larger than the wire diameter. For example, a 1.2-mm-diameter wire has a contact tip bore diameter of approximately 1.4 to 1.5mm. Tips should be inspected regularly and replaced as soon as excessive wear is detected, as an overly large bore diameter hinders current pick-up. Copper alloy contact tips with chromium and zirconium additives, which are harder than pure copper, have a longer lifespan, especially when using spray and pulsed modes. The typical traditional wire feeding system consists of a pair of rollers, one of which contains grooves and the other of which is flat. Too much roll pressure will cause the wire to bend and have a poor current pickup at the contact tip. With copper-coated wires, using knurled rolls or applying excessive roll pressure increases the chance that the coating may flake off, accumulating copper at the contact tip. Dual-drive systems should be used to feed soft wires, such as aluminium, to prevent the soft wire from being deformed.

Using a push-pull method, tiny aluminium wires, 1mm and smaller, may be fed more consistently. A second set of rolls is included in the welding gun at this point, which makes it much easier to draw the wire through the conduit. The bigger gun under this technique is a drawback. A tiny spool that is directly attached to the cannon can be used to feed small wires as well. The increased size, the awkwardness of the gun, and greater wire cost are drawbacks to this [35].

# CHAPTER 3- METHODOLOGY

## 3.1 HARDWARE COMPONENTS

### 3.1.1 2040 ALUMINIUM V-SLOT EXTRUSIONS

We have chosen 2040 aluminium V-Slot Extrusions because of their excellent mechanical features, including high strength, strong corrosion resistance, and high thermal conductivity, these extrusions include a V-shaped slot on one or more sides, allowing for easy installation of components such as motors, linear rails, and other accessories.

We chose to use 2040 aluminium V-Slot Extrusions in our project to construct a 3-axis machine for additive manufacturing utilising MIG welding. The use of V-slot extrusions will provide our machine with a sturdy and precise framework, which is critical for attaining accurate and consistent outcomes in additive manufacturing [36].

The V-shaped slot on the extrusions is a useful feature that allows us to quickly place linear rails on the machine. Linear rails are used by us for the movement of axes in our three axes machine.

Another notable benefit of adopting 2040 aluminium V-slot extrusions is their light weight. This characteristic allows us to design a machine that is easy to move and transfer, which is useful for the portability and storage of the system.

One of the most significant advantages of employing 2040 aluminium V-slot extrusions is their high degree of customization. They are cut to varied lengths and shapes, allowing design versatility. This ability to customise is especially important for our project because we will need to adjust the machine's design to our iterative design process [37].

### 3.1.2 LINEAR RAILS

Linear rails are made up of a rail and a carriage that rides along it, giving stable and precise movement. CNC machines, 3D printers, and other industrial gear frequently use linear rails. We employed linear rails on our 3-axis system. In the additive manufacturing process, linear rails will be important in producing high-precision and consistent output.

The capacity of linear rails to deliver stable and accurate movement is one of their major features. This functionality is very critical in our project since effective material depositing requires precise control of the welding head's movement. Linear rails are also capable of withstanding huge loads and fast speeds, which is required for high-speed movements.

Linear rails also offer smooth and silent operation, which is useful if the machine is in a shared workspace. The smooth operation of the rails will limit the possibility of vibration-induced mistakes and noise, which can degrade the quality of the additive manufacturing process.

Another key benefit of employing linear rails is their great repeatability, which enables consistent and precise results over lengthy periods of time. This quality is critical in our project, where the machine must sustain accurate movement for extended periods of time to deliver consistent results [38].

### 3.1.3 WELDING PLANT

#### 3.1.3.1 OTC TRA-305 POWER SOURCE

The OTC TRA-350 is a MIG welding power source that is extensively used in industrial settings. It is a highly adaptable machine that can handle everything from heavy-duty industrial welding to delicate precision welding.

A welding power source, such as the OTC TRA-350, is a component of a welding system that delivers the electrical energy needed to make a weld junction between two or more metal parts. It is the heart of a welding system, generating the electrical current and voltage required to melt the welding wire and fuse the metal pieces together.

One of the major benefits of employing the OTC TRA-350 MIG welding equipment is its ability to consistently produce high-quality welds. This is critical in additive manufacturing with MIG welding because we need precise control over welding parameters like voltage, amperage, and wire feed speed to precisely deposit the material [39].

#### 3.1.3.2 WIRE FEEDER

In MIG and TIG welding, a wire feeder is a device that feeds the welding wire into the welding torch. In our project, we will build our own wire feeder to work with the OTC TRA-

350 welding power supply.

The wire feeder controls the rate at which the welding wire is fed into the torch. This, in turn, has an impact on the weld's quality and consistency. Typically, the wire feeder is linked to the welding power supply.

Wire feeders come in a variety of configurations, including motorised and manual feeders. Manual wire feeders need the user to physically push the wire into the torch, whereas motorised wire feeders use a motor to drive the wire.

With our project, we plan to create a motorised wire feeder that will work with the OTC TRA-350 welding power supply.

#### 3.1.3.3 WELDING TORCH

A welding torch is a tool that delivers heat and electricity to the welding region. It also holds and feeds the welding wire into the weld pool. A cable connects the torch to the welding power source, which produces the necessary electrical current to generate the heat required for welding.

We will need to select the suitable MIG welding torch for our project to ensure that it is compatible with the OTC TRA-350 welding power source and can withstand the thickness of the metal we will be welding.

Figure 5 The components within the MIG welding gun

The MIG welding torch is made up of three parts: a handle, a trigger, and a nozzle. The handle is normally composed of heat-resistant material and is designed to give the operator a secure grip. The wire feed is controlled by the trigger, which allows the operator to adjust the speed at which the welding wire is supplied into the weld pool. The shielding gas is directed by the nozzle to protect the weld from atmospheric contamination.

## 3.2 ELECTRONICS COMPONENTS

### 3.2.1 POWER SUPPLY

The power supply oversees supplying the necessary electrical power to the system's numerous components. It must meet the voltage and current demands of stepper motors, stepper drivers, and other electronic components. The selection of a suitable power supply is dependent on variables such as efficiency, dependability, and compatibility with the voltage parameters of the system. We have chosen a 24-V power supply after accounting for the power requirements of the system.

Figure 6 24V POWER SUPPLY [40]

### 3.2.2 NEMA23HS STEPPER MOTORS

To regulate the movement of the MIG welding torch and the positioning of the workpiece, NEMA23HS stepper motors are used. Because of their high torque and fine control, these motors are ideal for creating accurate and repeatable motion.

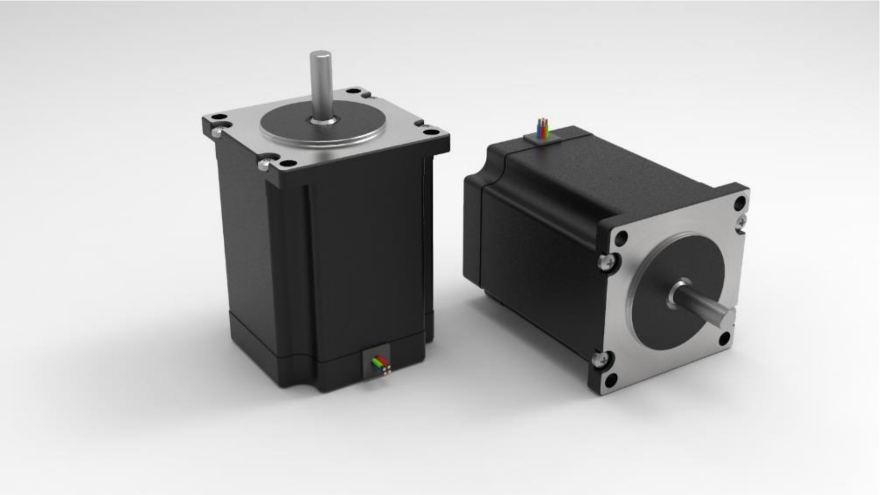


Figure 7 NEMA 23 stepper motor [51]

We selected the appropriate NEMA23HS stepper motors based on torque requirements, compatibility with stepper drivers, and the mechanical architecture of the system. The following are the specifications:

Table I NEMA 23 Stepper Motor Specifications [41]

| | |
|---|---|
| Voltage Rating | 24V |
| Current Rating | 2.8A |
| Holding Torque | 2.2Nm |
| Step Angle | 1.8° |
| Steps Per Revolution | 200 |
| No. of Phases | 4 |
| Motor Length | 3.1 in |
| No. of Leads | 4 |

### 3.2.3 NEMA17 STEPPER MOTOR

The NEMA17 stepper motor is used to control the Z-axis movement in the MIG-based metal additive manufacturing system. During the additive manufacturing process, the Z-axis is in control of the vertical placement of the MIG welding torch and the workpiece. In this area, the NEMA17 stepper motor delivers accurate and controlled motion. NEMA17 defines a standard form factor for the motor. The motor we use has four wires and a step of 1.8°. We have run the stepper at half-step settings on account of our need for precision.

Many factors influence the selection of an appropriate NEMA17 stepper motor for Z-axis movement. These considerations include the torque necessary to lift and position the MIG welding torch, compatibility with the stepper drivers and power supply, and the system's mechanical design. During the selection process, factors such as motor resolution, holding torque, and reliability are also considered.

We calculated the weight of the torch to be 6-7 Kg. We approximated the weight of the entire system to be 10 Kg. The NEMA17 stepper motor is securely mounted to the system's structure and integrated into the MIG-based metal additive manufacturing technology. The motor shaft is connected to the THK KR-20 ball screw mechanism, with a 1mm lead, which converts rotational action into linear motion for precise vertical Z-axis movement [42]. The stepper motor's wire is connected to MKS Monster8 and the power supply, ensuring proper electrical connections and signal control.

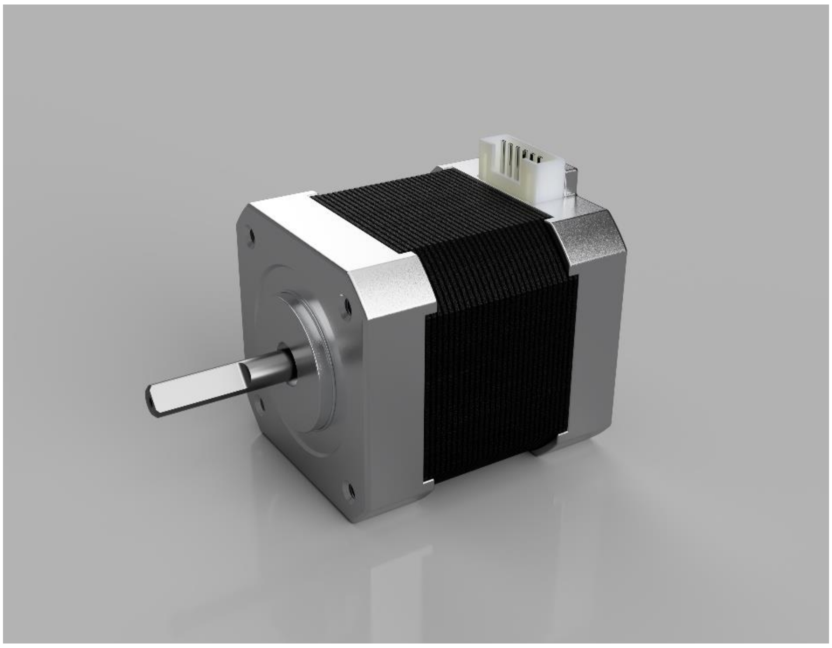


Figure 8 NEMA 17 stepper render [43]

We chose a stepper motor with 0.5 Nm torque.

### 3.2.4 DM542A STEPPER DRIVERS

The DM542A stepper driver is responsible for controlling the current and driving the NEMA23HS and NEMA17 stepper motors. They precisely drive the stepper motors by transforming the control system's digital step and direction signals into equivalent electrical impulses [44]. The ability to micro-step allows for greater control of motor movement, which results in improved positioning precision and reduced vibration.

Figure 9 DM542A render [52]

The DM542A stepper drivers include several configurable parameters, including motor current, idle current reduction, and decay mode. Following is the microstepping for each Axis.

Table 1 microstepping for each axis

| Axis | Pulses per revolution |
|---|---|
| X-Axis | 25600 |
| Y-Axis | 25600 |
| Z-Axis | 1600 |

### 3.2.5 STM32 BASED CONTROL BOARD

We have utilized a STM32F407VET6 based control board for 3D printers. It has a clock speed of 168MHz and 256K flash memory and 32K RAM. It also has native support for UART and CAN bus. The specific model we are using is marketed as MKS Monster 8. The MKS Monster 8 is a specialised controller board developed for simultaneously driving up to eight stepper motors in industrial applications. The MKS Monster 8 serves as a central control unit in the MIG-based metal additive manufacturing system, coordinating the movements of the stepper motors and other peripheral devices. The following are the functionalities of the Monster8:

#### 3.2.5.1 CAPABILITY FOR UP TO EIGHT STEPPER MOTORS:

The MKS MONSTER 8 board can drive up to eight stepper motors at the same time, allowing for multi-axis control in sophisticated motion control systems. It is very compatible with a broad range of stepper motor drivers, including the dm542a stepper motor drivers used in this project, allowing for versatile motor selection and design.

#### 3.2.5.2 CAPABILITY FOR UP TO THREE EXTRUDERS:

The MKS Monster Board is capable to use 3 extruders simultaneously, allowing the user to use 3 different filaments in the middle of a print.

#### 3.2.5.3 FLEXIBLE COMMUNICATIONS INTERFACES:

The **MKS MONSTER** 8 supports a variety of communication interfaces, including **USB, UART**, and **ETHERNET**, allowing for seamless integration with the control system and communication between the board and external devices.

#### 3.2.5.4 EXTENSIVE I/O CAPABILITIES:

The board includes a variety of input and output ports, such as limit switch inputs, emergency stop inputs, and general-purpose input/output (GPIO) ports, allowing you to connect peripheral devices and sensors with ease.

### 3.2.5.5 DEDICATED COMMUNICATION WITH EACH STEPPER DRIVERS:

This control board has dedicated communication with the stepper driver controllers. It can achieve tasks like stall detection, sensor less homing and automatic micro-stepping selection.

The MKS Monster 8 functions as a central controller, receiving commands from the control system and transmitting them to the appropriate stepper motor drivers. It ensures that several axes move in synchrony.

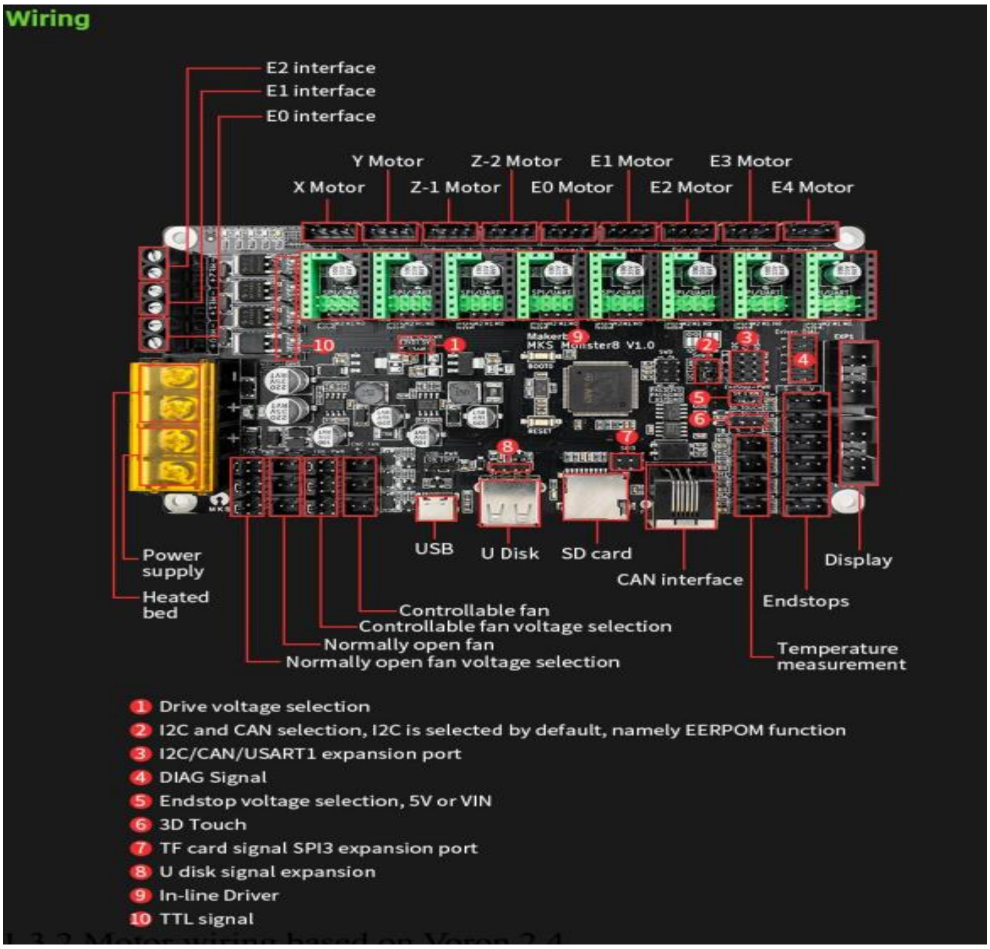


Figure 10 Wiring diagram of each port on the motherboard [45]

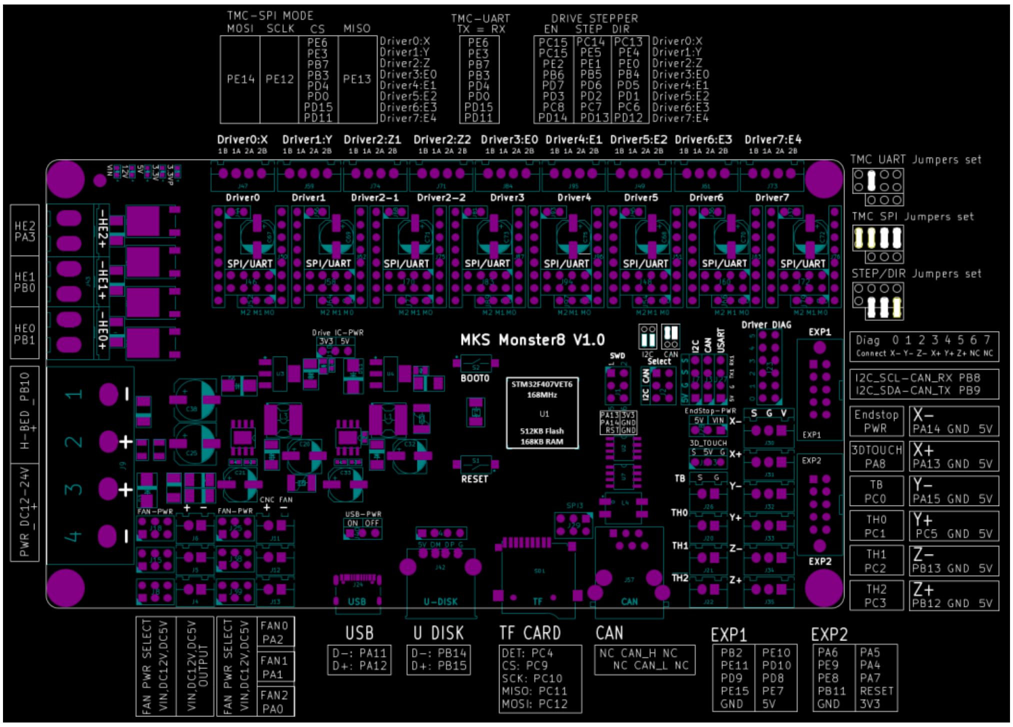


Figure 11 Wiring diagram for MKS Monster 8

Because of the MKS Monster 8's comprehensive I/O capabilities, limit switches, emergency stop switches, and other peripheral devices can be integrated, improving the system's overall safety and functionality. The simple software interface simplifies setup and configuration, providing a convenient platform for controlling and monitoring stepper motors [45].

### 3.2.6 RASPBERRY PI ZERO

The Raspberry Pi zero is a compact and affordable single board computer. This can run distributions of Linux OS and can be made to run small programs that require a complete computer to process. This device comes in a small package and allows the user to create portable systems and run desktop applications, similarly in this project it is being utilized to run Klipper firmware and Mainsail interface. The main advantages of this is that it allows the user to control a 3D printer from a network and allow the user to modify every aspect of the printer with minimum difficulty [46].

Figure 12 Raspberry pi zero [46]

## 3.3 SOFTWARES USED

### 3.3.1 SOLIDWORKS

SolidWorks software was used to produce a detailed 3D model of the MIG-based metal additive manufacturing machine. The three-axis machine, the wire feeder, the torch with two degrees of freedom, and the printer bed coupled to parallel linear slides are all included in this model. We have also included the stepper motors and THK KR20 ball screw motors. The design iteration process considered the project's specific requirements, allowing for an accurate portrayal of the system's physical components.

The MIG-based metal additive manufacturing system's design approach has been iterative, driven by changes in project requirements and practical problems encountered along the way. SolidWorks has been essential in this area, as it enables rapid 3D model revisions and upgrades. The design team was able to easily alter the system's components to solve challenges such as structural integrity, compatibility, and manufacturability by exploiting the software's parametric modelling capabilities.

### 3.3.2 ANSYS

Ansys is a powerful finite element analysis and engineering simulation software, which we used to conduct transient thermal analysis and structural load analysis. ANSYS considers mild steel material parameters such as thermal conductivity, specific heat, and thermal expansion coefficients during the simulation, which are critical for effectively modelling the system's thermal response.

We get insights into the impacts of welding heat on the 8-mm-thick mild steel plate by doing transient thermal analysis, allowing us to optimise the system design to minimise warping and ensure the dimensional accuracy of the final product. By simulating thermal behaviour, we can improve the design to minimise temperature-induced distortions and maintain the system's longevity. We can also figure out the stresses that the block endures through carrying the weight of the bed.

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### 3.3.3 ULTIMAKER CURA

Ultimaker Cura is a slicing software which we used to convert the solid model into G codes. The programme provides fine control over the depos-ition process by defining parameters such as layer height, bead width, and bead spacing. We can achieve regulated and consistent mild steel weld bead deposition. This is done on the mild steel plate by using custom slicing profiles.

### 3.3.4 KLIPPER

Klipper is an open-source firmware that runs on a single board computer such as Raspberry Pi. It offloads the computational- intensive tasks from the main motherboard (MKS Monster

8) of the 3d printer to a more powerful single board computer (Raspberry Pi Zero). The Raspberry Pi and the MKS Monster 8 board work in a master-slave configuration, with the Raspberry Pi computing everything required for the printer to function. In this configuration the controller board is just being utilized as a salve device that controls the stepper motors, observes the end stops or any other sensors connected to the printer and reports their condition/progress to the Raspberry Pi and waits on further commands. Utilizing the Klipper firmware allows the printer to keep up with any updates and utilize any advanced features like bed mesh levelling, resonance compensation and user-defined macros. The Klipper firmware communicates with the Controller board via the serial port and processes G-code and instructs the printer on how to proceed further with the printing service. Following are some of the advantages of using Klipper.

#### 3.3.4.1 COMPATIBILITY

Klipper is compatible with a wide variety of 3D printers this includes Cartesian printers, Delta printers, CoreXY printers and CoreXZ printers. It supports a large number of controllers and due to online repositories, the number of compatible controllers is increasing.

#### 3.3.4.2 IMPROVED PERFORMANCE

By utilizing Raspberry Pi or any other single Board computer Klipper can handle complex calculations, such as trajectory planning or kinematics, which results in a smoother and faster printer.

#### 3.3.4.3 FLEXIBLE CONFIGURATION

Klipper offers a highly configurable system that allows users to configure, add new devices or write user-defined macros. This makes the printer highly configurable and allows hobbyists to improve upon their printers with custom routines. In our case this has been the biggest advantage as this has allowed us to use custom routines, to make our printer support a MIG welding system instead of a regular plastic extruder system.

It is worth noting that Klipper offers many advantages for its users, and it doesn’t require a lot of technical knowledge to set up a basic printer. However, this is a perfect tool for users that want control over every single aspect and want to customize their 3D printing experience.

### 3.3.5 MAINSAIL INTERFACE

Mainsail interface provides a user-friendly web interface accessible through any browser of a device connected to the same network. It doesn’t require to install any software or device drivers to connect to the printer itself. This allows the user to monitor or command the printer remotely. Overall, the mainsail interface for Klipper enhances the user experience by providing an easier to understand and simple interface for managing and controlling the 3D printer remotely. The salient features of the Mainsail interface for Klipper are as follows:

#### 3.3.5.1 WEB-BASED CONTROL

The Mainsail interface is accessed through a web browser, and it only requires that you are connected on the same network. Hence eliminating the need for installing any software or drivers for controlling the 3D printer.

#### 3.3.5.2 REAL-TIME MONITORING

Mainsail offers its user to monitor the progress of the printer in real time. This includes temperature, progress, and print status. It also allows the user to view the part being made and at an individual layer level. This is all available to be shown at its web interface.

#### 3.3.5.3 FILE MANAGEMENT

Mainsail offers to manage files such as G-code. User can upload G-code files from their own systems which could be a mobile phone, laptop, or a PC. The G-code files are stored in Raspberry Pi’s memory card and allows the user to access them from anywhere and give print commands.

#### 3.3.5.4 CONFIGURE AND SETTING

Mainsail provides a very user-friendly way to configure and adjust parameters of the Klipper firmware. Users can modify parameters like sensors pins, rotational distance, end stop locations Stepper configurations and essentially everything about the printers.

## 3.4 CAD MODEL

The cad model was our initial deliverable. Design of the 3-axis system was the fundamental initial step which determined the planning and design of the rest of the project. We carried this out on Solidworks. A bill of materials was also compiled, which served as a roadmap for our fabrication and assembly processes. Following are some of the design considerations for this sort of 3-Axis machine.

1) The design should be able to support a heavy Mild steel Bed that would allow the heat to dissipate.

2) The actuating mechanism should be highly accurate and repeatable with a very low step resolution.

3) The design should be rigid and shouldn't allow the any sort of deflection due to momentum induced forces or vibrations.

4) The design should be V-slot compatible. This would allow the freedom to mount anything else.

The CAD model went through 3 design iterations. Following are the summary of design iterations made and changes done.

### 3.4.1 FIRST DESIGN ITERATION

The initial design approach was based on using linear rails for each axis. However, it became evident that this design was lacking structural integrity and couldn't bear the dynamic stresses and the thermal stresses of a bed required for MIG welding. The Z-axis was based on a belt driven system, which was unable the sustain the constant load of the gantry, stepper motor and would have been unable to move the heavy MIG torch to a reasonable accuracy. The joints selected for this arrangement also weren't to the mark and if fabricated it would have resulted in a very fragile construction and prone to a lot of vibrations. Its movement wouldn't have passed a mechanical repeatability test to a reasonable level.

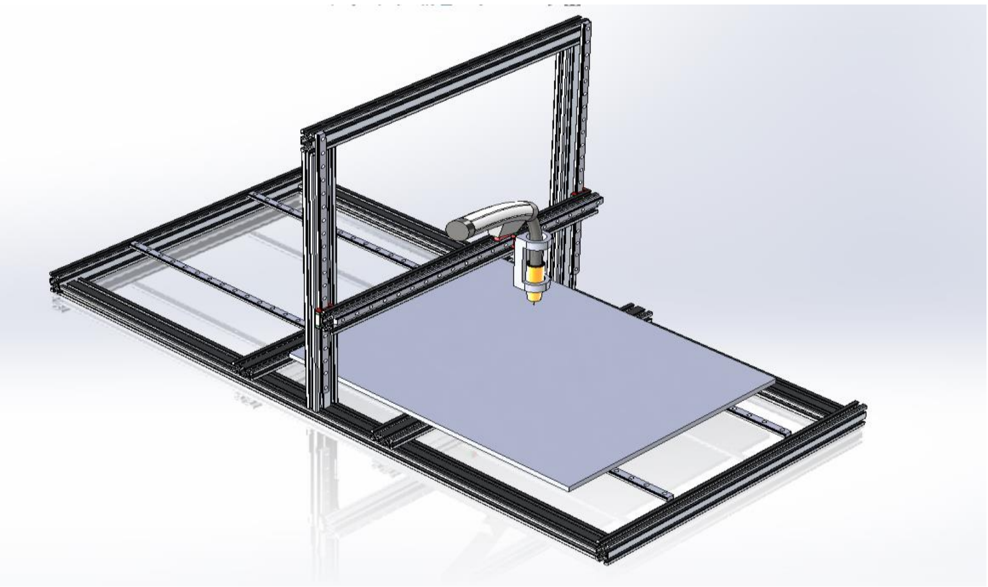


Figure 13 First iteration for the design of the system

### 3.4.2 SECOND DESIGN ITERATION

The second iteration was designed to incorporate a V-slot system. The V-slot system incorporated the linear actuation as well as load bearing on the same blocks which were supported on slotted wheels. However, it became apparent that this system of linear actuation would not meet the necessary standards of accuracy and repeatability. This design also include a Linear actuator for the Z-Axis. Unfortunately, after incorporating these change the construction was still unable to take the stresses of a heavy bed. The mounting for the bed was also unable to keep a heavy bed in the correct orientation. To mitigate these issues, mechanical design was revised.

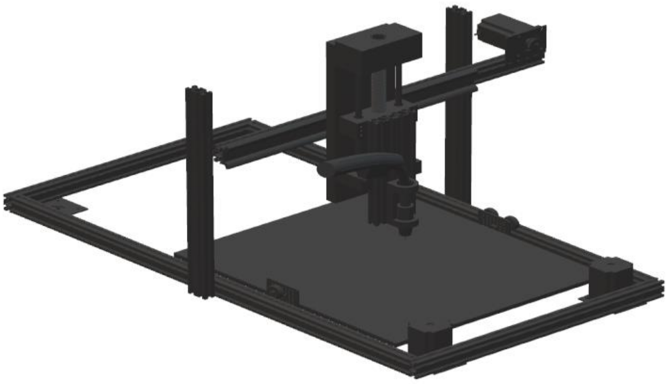


Figure 14 Second iteration of the design

### 3.4.3 THIRD DESIGN ITERATION (FINAL)

This final design iteration is based on linear rails for X and Y-axis and their actuation is controlled by a belt driven system while the Z-axis is actuated by a lead screw, while having incorporated linear rails in the assembly itself. This design was found to have the required rigidity and hence was repeatable and possess very high accuracy. Blind Joints were utilized in majority of the places to reduce the number of corner brackets which always results in a non-rigid joint. To make these joint the extrusions were threaded and drilled in the corresponding. To accommodate the weight of the bed 15mm linear rails were used. This design iteration also included the first iteration of the wire feeding system. Some of the parts were design to be fabricated in sheet metal as currently the laser cutting sheet metal is the fastest and the most dimensionally accurate prototyping method accessible. The project's sturdy structure, developed using 2040 aluminium extrusions, was a critical factor in minimizing operational vibrations. By offering a high degree of stability, it ensured accurate weld bead placement, and the thoughtful placement of components complemented the overall function and aesthetics of the machine.

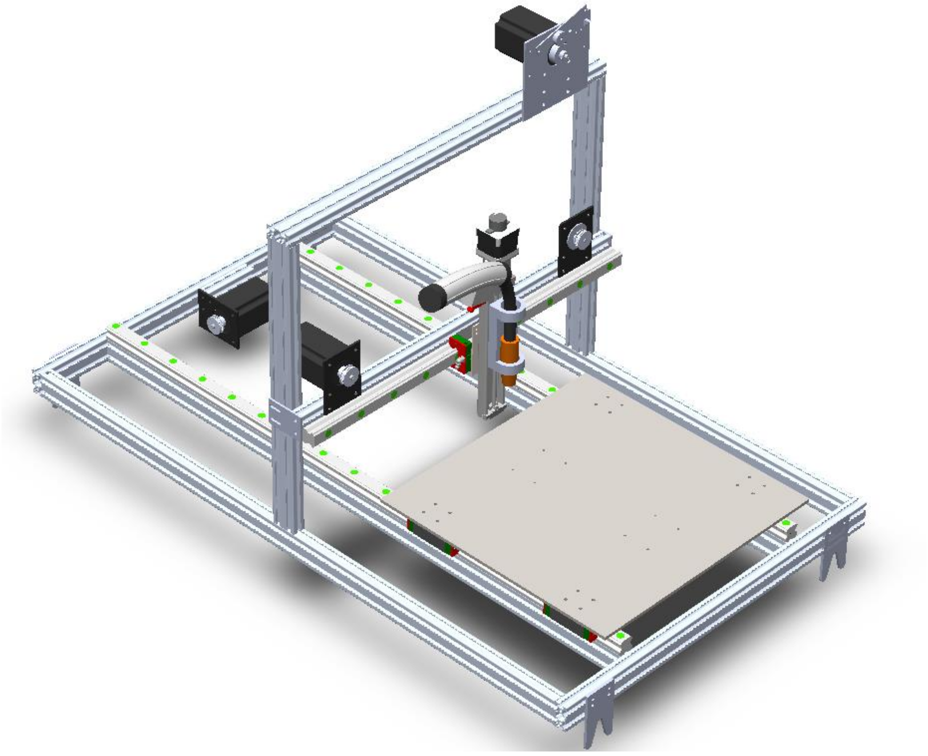


Figure 15 final CAD model of the printer

## 3.5 FABRICATION

The fabrication of each part of this project was done by hand by the group. It is divided into the following parts.

### 3.5.1 BASE

The base of the complete project is made from 2040 aluminium extrusion. These provide a stable structure while allowing the ability to mount anything at a variable distance with and permanent alterations such as bolt holes. Furthermore, blind joints were utilizing to make the structure. These joints are one of the strongest joints in the whole construction and this also keep the extrusions perpendicular to each other.

Figure 16 Fixing the frames together.

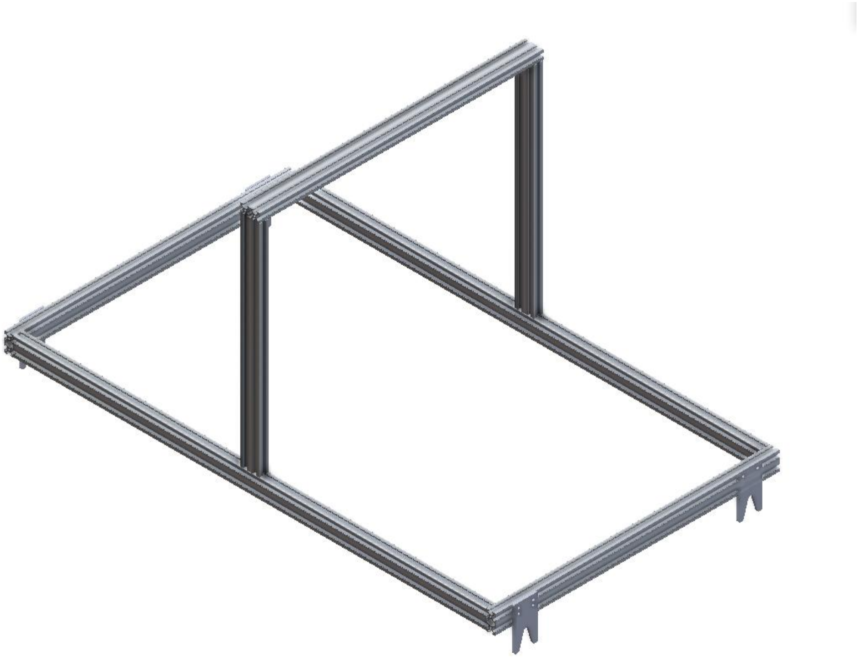


Figure 17 Structure of outer frame.

### 3.5.2 X-AXIS ASSEMBLY

The X-Axis assembly is made on a 2040 extrusion. It consists of a MGN12 Linear rail, Carriage of the linear rail, NEMA 23 motor with a 24T pulley, Idler pulley, Axis assembly connecting plate and, Z-Axis mounting plate.

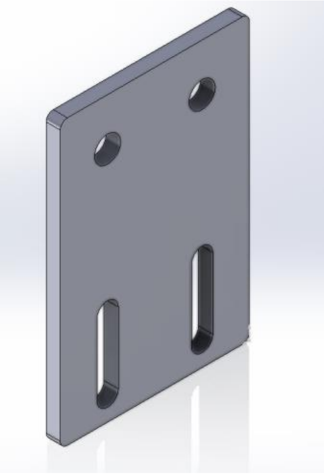


Figure 18 Mounting plate 1

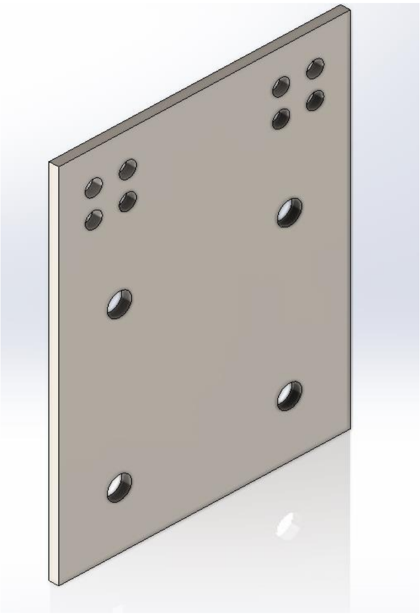


Figure 19 Mounting plate 2

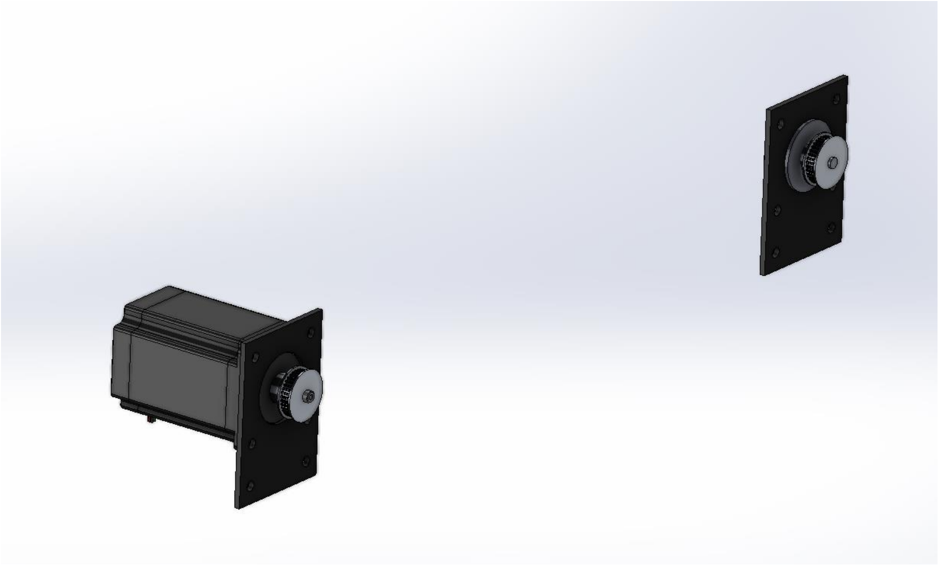


Figure 20 Mounting plates connected to the stepper motors and the pulleys.

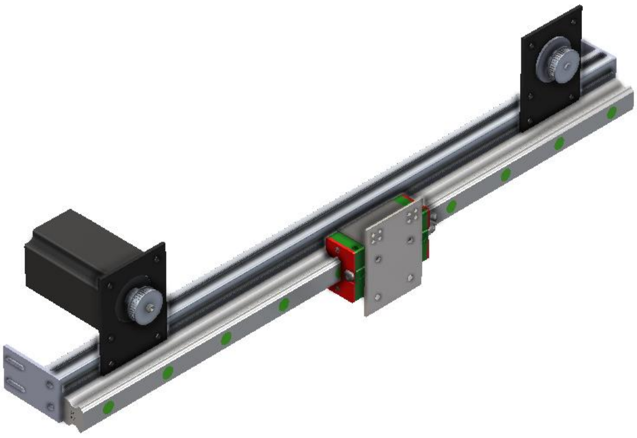


Figure 21 Finalised assembly of the y axis

The carriage is actuated by a belt mechanism attached. This allows the complete Z-Axis assembly to move from one end to the other while carrying a lot of loads and maintaining accuracy.

### 3.5.3 Y-AXIS

Y-Axis consists of Linear Rails attached to aluminium extrusions. It is also actuated by a belt mechanism using NEMA 23 motor with 24T pulley.

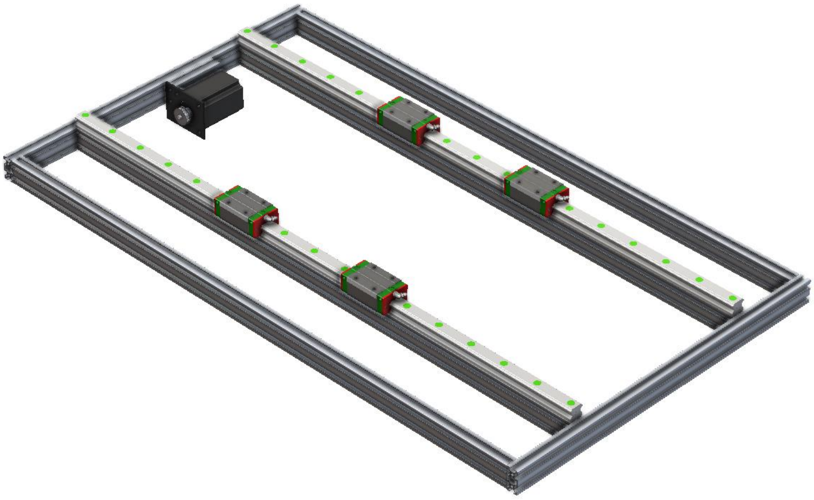


Figure 22 Finalised assembly of the x axis

### 3.5.1 Z-AXIS

The Z-Axis assembly is made from a linear actuator. Its part number is THK_KR20 this has an included Lead screw of 1mm pitch and has linear slides embedded. This actuator assembly is also coupled with a NEMA 17 motor that allows the actuation of assembly in a controlled and calculated manner.

Figure *23* The THK KR-20 motor used for actuating in the z axis.

### 3.5.2 BED

The bed of the printer is made from Mild Steel and has a thickness of 5mm. It is laser cut to add bolt holes for attaching the belt and connecting with the carriages.

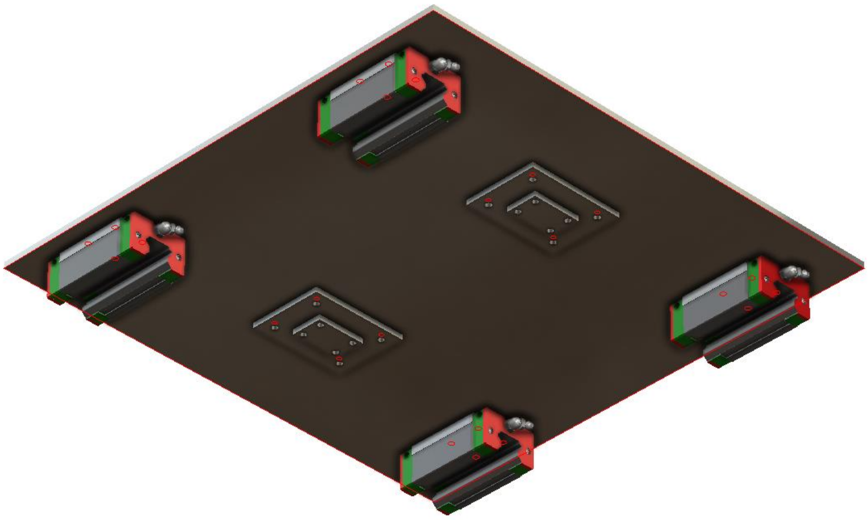


Figure *24* Assembly of the welding bed

## 3.6 WIRE FEEDER

The design of a wire feeder required us to ensure that it fits with the specific wire that we would be working with. For aluminium with thickness of 3.5mm, this corresponds to a recommended wire diameter of 0.9mm according to practices.

## 3.7 RASPBERRY PI CONFIGURATION

Raspberry PI Zero was used in this project. Considering raspberry pi zero has limited computational resources so to limit its processes a lighter distribution of Linux was used. Raspbian Lite was installed as an alternative lighter operating system. After the installation of the OS the Klipper firmware was installed from the guide found on the Klipper official documentation [53]. Installation files can be found on the official Klipper repositories on GitHub [55]. After this installation we need to install Moon Raker [54]. It is a Python 3 based webserver. This allows the communication between the Klipper firmware and Mainsail web interface and creates an access through an IP address. After the installation is completed, Mainsail needs to be installed on the Raspberry Pi. This is web interface that allows the user to control the 3D printer through a browser and send commands or G-code files for the printer to print.

## 3.8 KLIPPER CONFIGURATION

The Klipper firmware once installed allows the user to configure the printer as they seem fit. This is an advantage over a GRBL based systems. The Mainsail interface used in parallel to control this 3D printer allows the user to change the parameters of the printer over the network. After the parameters are changed the Raspberry automatically flashes the STM32 board and restarts the printer. Klipper is also under constant development hence there are always updates present and constantly new features are being introduced. To complete this printer following is code for the configuration file.

```
[include mainsail.cfg]
[virtual_sdcard]
path: /home/pi/printer_data/gcodes
on_error_gcode: CANCEL_PRINT

[mcu]
serial:                                    /dev/serial/by-id/usb-
Klipper_stm32f407xx_490031000950474835363920-if00
```

```
[safe_z_home]
home_xy_position: 20,20
speed: 100.0
z_hop: -10
z_hop_speed: 15.0


[probe]
pin: !PB13
x_offset: 36
y_offset: -24
z_offset: 0
samples:3
samples_result: median
sample_retract_dist:3
samples_tolerance:0.1
samples_tolerance_retries:3

[stepper_x]
step_pin: PC14
dir_pin: !PC13
enable_pin: !PC15
microsteps: 128
rotation_distance: 120
endstop_pin: !PA14  # PA13 for X-max; endstop have'!' is NO
position_endstop: -2
position_max: 350
position_min: -3
```

```
homing_speed: 100

[stepper_y]
step_pin: PE5
dir_pin: PE4
enable_pin: !PC15
microsteps: 128
rotation_distance: 120
endstop_pin: !PA15  # PC5 for Y-max; endstop have'!' is NO
position_endstop: 0
position_min: -1
position_max: 350
homing_speed: 50

[stepper_z]
step_pin: PE1
dir_pin: PE0
enable_pin: !PE2
microsteps: 8
rotation_distance: 2
endstop_pin:  probe:z_virtual_endstop   #  PB12  for  Z-max;  endstop
have'!' is NO
#position_endstop: -2
position_min: -5
position_max: 50
homing_speed: 15

[gcode_arcs]
resolution: 1.0

#fan for printed model FAN0
```

```
[fan]
pin: PA2

[printer]
kinematics: cartesian
max_velocity: 1000
max_accel: 500
max_z_velocity: 15
max_z_accel: 500

[bed_mesh]
speed: 200
horizontal_move_z: 5
mesh_min: 35, 6
mesh_max: 300, 300
probe_count: 5, 5
mesh_pps: 2, 2
fade_start: 1
fade_end: 10
fade_target: 0
algorithm: bicubic
bicubic_tension: 0.2
```

As seen in the code above it is written in simple language, selecting the parameters required and setting up the pin configurations of the controller to be used as suited to the custom arrangement of parts and devices being used on the 3D printer. Following are some of the advanced features that have been setup on the printer.

### 3.8.1 BED MESH

The 3D printers after a being used again and again are prone to warping. This is caused by being constantly under changing temperatures and is also known as thermal deformation. This feature allows the user to check where there are low or high spots on the bed by lowering the probe of the printer is lowered at specified number of points and then a few more points are interpolated. In this case interpolation is being done by bicubic method. After the pints have been generated the heightmap of the complete bed is generated. This heightmap is then overlayed the G-code and then the Z-axis automatically compensates for the difference in height of the bed. Following is the code that enables this feature.

```
[bed_mesh]

speed: 200

horizontal_move_z: 5

mesh_min: 35, 6

mesh_max: 300, 300

probe_count: 5, 5

mesh_pps: 2, 2

fade_start: 1

fade_end: 10

fade_target: 0

algorithm: bicubic

bicubic_tension: 0.2
```

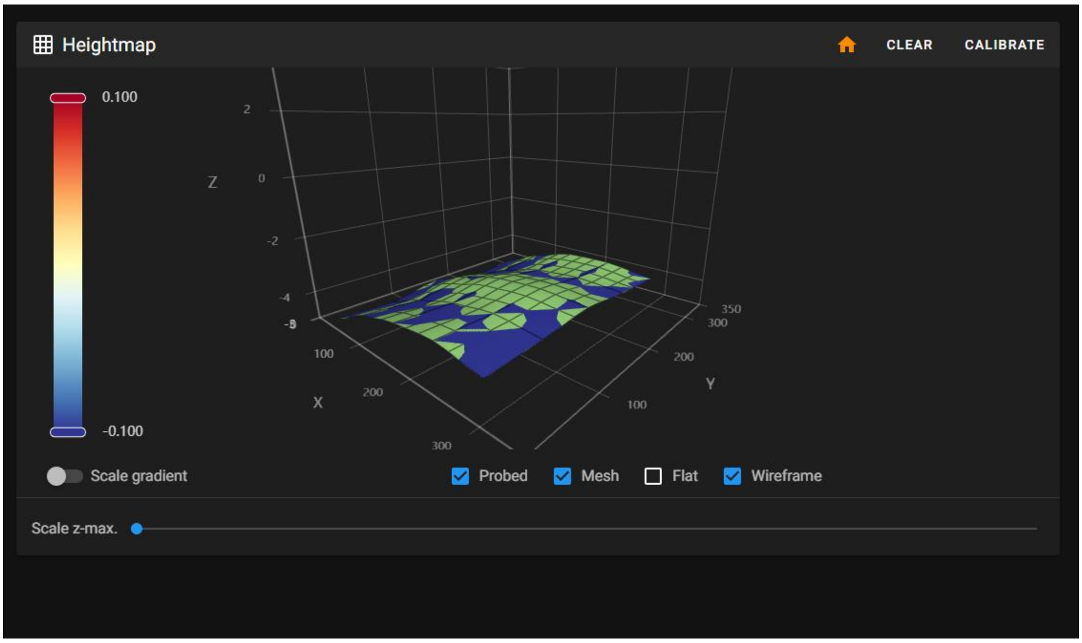


Figure 25 Generation of height maps

SAFE Z HOME

This feature allows the printer to home its z axis while being in a safe area. As it was required in this project. The printer has a smaller bed compared to the rest of the assembly hence it has the capability to move the bed completely out of the way and collide with the extrusion. So it was necessary that when the Z-axis is homing it is placed in a safe range not at the corner of the printer. Following is piece of code that enables this feature.

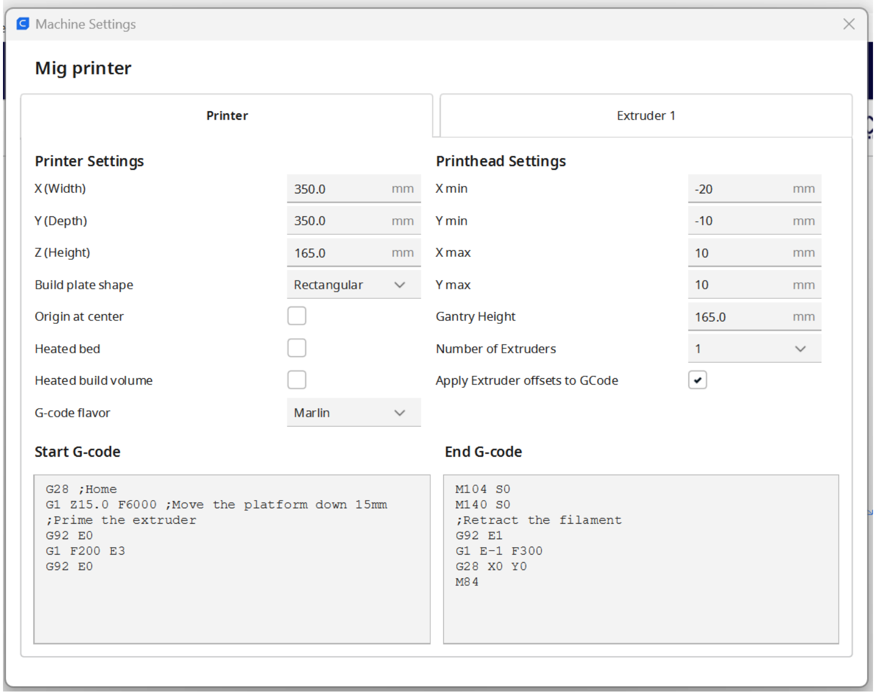
```
[safe_z_home]

home_xy_position: 20,20

speed: 100.0

z_hop: -10

z_hop_speed: 15.0
```

## 3.9 ULTIMAKER CURA

We have used the following steps for generating G codes using Cura:

### 3.9.1 SETTING UP THE CUSTOM PRINTER PROFILE

In Ultimaker Cura, a custom printer profile was created to match the specifications of the 3-axis machine. The build volume was set to 40cm x 40cm x 1cm, and the nozzle size was set to match the diameter of the mild steel wire being used. The bed dimensions were set to 350 to account for the unavailability of the edges. We will be using a wire diameter of 0.8mm and have measure the nozzle size of 1.2mm (the spring conduit diameter). The nozzle offset is set to 42mm.



Mig printer

**Printer Settings**

| | |
|---|---|
| X (Width) | 350.0 mm |
| Y (Depth) | 350.0 mm |
| Z (Height) | 165.0 mm |
| Build plate shape | Rectangular |
| Origin at center | ☐ |
| Heated bed | ☐ |
| Heated build volume | ☐ |
| G-code flavor | Marlin |

**Printhead Settings**

| | |
|---|---|
| X min | -20 mm |
| Y min | -10 mm |
| X max | 10 mm |
| Y max | 10 mm |
| Gantry Height | 165.0 mm |
| Number of Extruders | 1 |
| Apply Extruder offsets to GCode | ☑ |

**Start G-code**

```
G28 ;Home
G1 Z15.0 F6000 ;Move the platform down 15mm
;Prime the extruder
G92 E0
G1 F200 E3
G92 E0
```

**End G-code**

```
M104 S0
M140 S0
;Retract the filament
G92 E1
G1 E-1 F300
G28 X0 Y0
M84
```

Figure 26 Setting up the printer.

### 3.9.2 IMPORTING THE 3D MODEL

A 3d model of the desired structure, a square with 5cm sides and 1cm height, was created using a cad software and saved in the stl file format. This file was then imported into Ultimaker Cura.

### 3.9.3 DEFINE CUSTOM MATERIALS

Using properties of mild steel, a custom material was created for simulating the welding through wire.

### 3.9.4 CONFIGURING PRINT SETTINGS

The print settings were adjusted to suit the gasless mig-based metal additive manufacturing process. The following parameters were assumed:

- layer height: 0.2mm
- infill density: 100%
- print speed: 5cm/min
- travel speed: 100mm/s
- retraction distance: 5mm
- retraction speed: 25mm/s
- initial layer height: 0.3mm
- initial layer print speed: 5cm/min

### 3.9.5 GENERATING G-CODE

After configuring the print settings, Ultimaker Cura was used to slice the 3d model and generate the g-codes. The g-code file was then saved and transferred to the 3-axis machine through Klipper.

## 3.10 FINITE ELEMENT ANALYSIS

We have focused on analysing the thermal performance of our gasless mig-based metal additive manufacturing system. The system comprises a 5mm thick mild steel bed mounted on a 2mm thick mild steel sheet. The thermal analysis is performed using Ansys software to ensure that the bed can handle the heat generated by the welding process. We have outlined the steps used for the analysis, including the assumptions made, the transient thermal analysis process, and the optimization of the design.

### 3.10.1 ASSUMPTIONS

For the analysis, the following assumptions are made to simplify the problem and reduce computational complexity:

- A single layer of weld deposit is considered representing a simplified scenario.

- The heat-affected zone is assumed to be negligible, allowing for a more straightforward analysis.
- Welding parameters of 200A and 20V are used as input for the calculation of heat input from the torch, representing typical values for this type of welding process.
- The bed is assumed to be homogenous, without variations that may affect heat transfer, simplifying the heat transfer calculations.
- The weld torch is assumed to be constantly operating for 30 seconds, providing a fixed time frame for the analysis.

### 3.10.2 TRANSIENT THERMAL ANALYSIS

Transient thermal analysis is chosen for this study as it considers the dynamic behaviours of temperature changes over time. This is crucial for understanding the heat dissipation capabilities and potential deformations that may occur during the welding process. The following steps outline the transient thermal analysis process using Ansys software:

#### 3.10.2.1 PRE-PROCESSING

Import the cad model into Ansys workbench and create a new "transient thermal" analysis system. Connect the "geometry" cell of the analysis system to the imported cad model and open Ansys mechanical.

#### 3.10.2.2 MATERIAL PROPERTIES

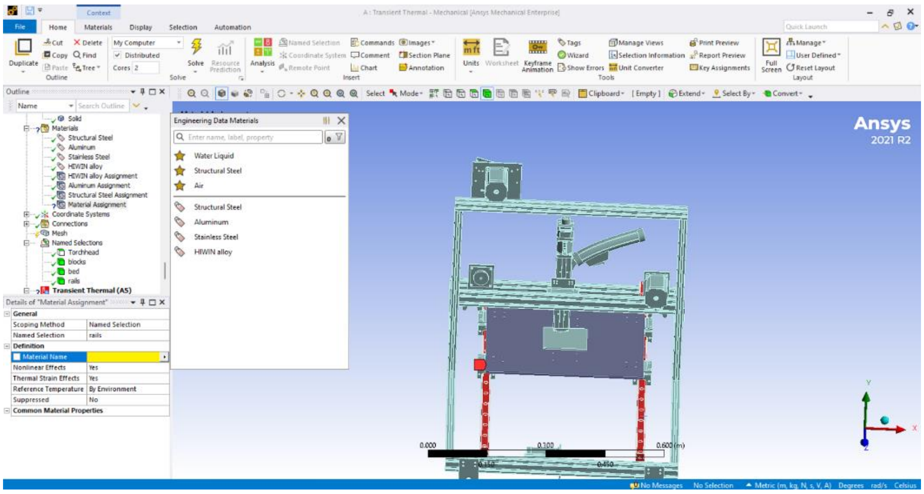
In Ansys mechanical, add the materials "mild steel" and "aluminium alloy" from the material library to the "engineering data" tab. Ensure that the thermal conductivity, specific heat capacity, and density values are correct for both materials. The following are the material properties for the propriety alloy used in HIWIN blocks:

Table 2 Material properties of HIWIN alloy

| | |
|---|---|
| Density | 2700 kg |
| Elastic Modulus | 200 GPa |
| Poisson’s ratio | 0.3 |
| Thermal Conductivity | 400 W/mK |
| Specific Heat Capacity | 900 J/KgK |
| Coefficient if thermal expansion | 20/K-1 |

### 3.10.2.3 ASSIGN MATERIALS TO THE MODEL

Assign the "mild steel" material to the bed and plate components, and the "aluminium alloy" material to the v-slot extrusions in the "model" tab in Ansys mechanical.



Details of "Material Assignment"

| | |
|---|---|
| **General** | |
| Scoping Method | Named Selection |
| Named Selection | rails |
| **Definition** | |
| Material Name | |
| Nonlinear Effects | Yes |
| Thermal Strain Effects | Yes |
| Reference Temperature | By Environment |
| Suppressed | No |
| **Common Material Properties** | |

Figure 27 A picture of assigning materials to a geometry

### 3.10.2.4 MESHING

Adjust the mesh settings to achieve an appropriate level of detail for the model. A finer mesh will provide more accurate results but will require more computational resources.

### 3.10.2.5 BOUNDARY CONDITIONS

Calculate the heat input from the mig torch. Calculate the heat input to the flux. Apply a "heat flux" boundary condition to the welding area on the mild steel plate. Insert a "convection" boundary condition and apply it to all external surfaces of the model, using typical values for air convection and ambient temperature. Calculate the radiation coefficient of mild steel using typical values from the range of mild steel.

#### 3.10.2.6 ANALYSIS SETTINGS

Set the "end time" to 30 seconds and choose an appropriate time step size for the analysis. A smaller time step will provide more accurate results but will require more computational resources.

#### 3.10.2.7 SOLVE THE MODEL

Insert a "temperature" result and click on "solve" to run the transient thermal analysis.

#### 3.10.2.8 ANALYSE RESULTS

Review the temperature distribution in the model over time, identify any areas with excessive temperatures or potential thermal issues, and assess the impact of the temperature distribution on the weld bead quality and system performance.

#### 3.10.2.9 OPTIMIZE THE DESIGN

If the analysis results indicate a need for design changes, modify the bed's dimensions or add features such as hole cut-outs in the cad software. Re-import the updated cad model into Ansys workbench and repeat the analysis process to verify the effectiveness of the design changes.

### 3.10.3 DESIGN OPTIMIZATION

Based on the analysis results, the design of the bed may need to be optimized to minimize cost and weight while maintaining the required performance. This may involve modifying the bed's dimensions or adding features such as hole cut-outs. However, care must be taken to ensure that the structural integrity of the bed is not compromised. The optimization process should be iterative, with multiple design variations analysed to find the best balance between performance, cost, and weight.

### 3.10.4 MODEL SIMPLIFICATION

Due to limited computational power, the analysis model is simplified to include only the bed, the welding torch, the linear rails, and the basic structure. This reduces complexity while still providing valuable results of the thermal performance of the system. While this simplification may not capture all the practical complexities of the real system, it serves as a starting point for understanding the thermal behaviour and identifying potential issues.

## 3.11 3-AXIS MACHINE

The three axes system was fabricated using a timing belt on the y axis. The y axis is connected to the linear actuator. using a driver wheel and an idler wheel. This arrangement is connected through a belt. The linear actuator is used to drive the MIG torch and has a pitch of 1mm. It is then connected to a stepper motor with micro step settings to further increase the precision of the system.

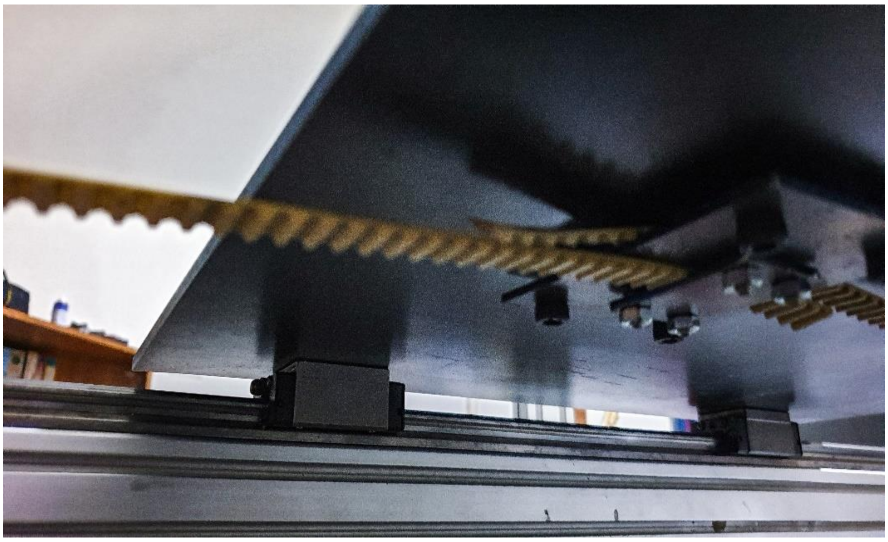


Figure 28 Linear guides for levelling and timing-belt system for bed

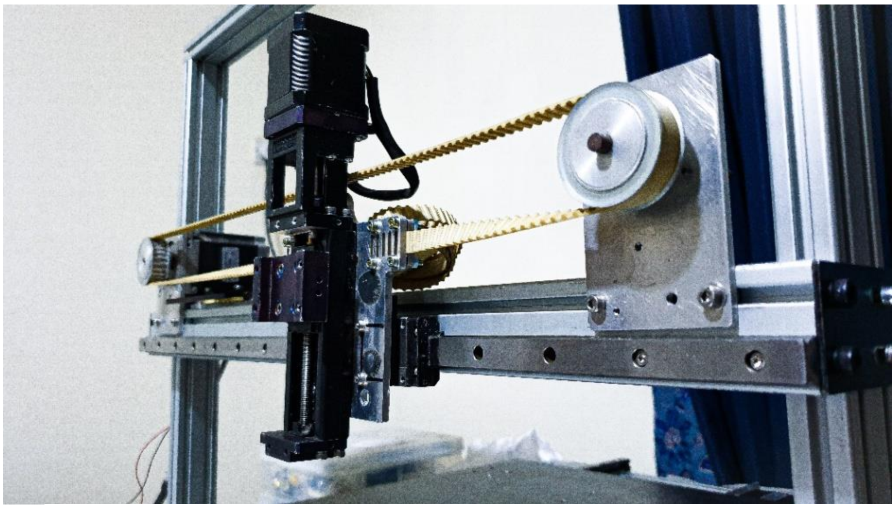


Figure 29 Z-axis assembly

The bed was also connected through a timing belt system using NEMA23 motors, through a similar setup to the above mentioned one.

Figure 30 Timing-belt assembly

## 3.12 CONTROL BOX

We have placed all the electrical components within a control box for easier management and to increase the resilience of the system. The control box also serves as a safety feature for the operator.

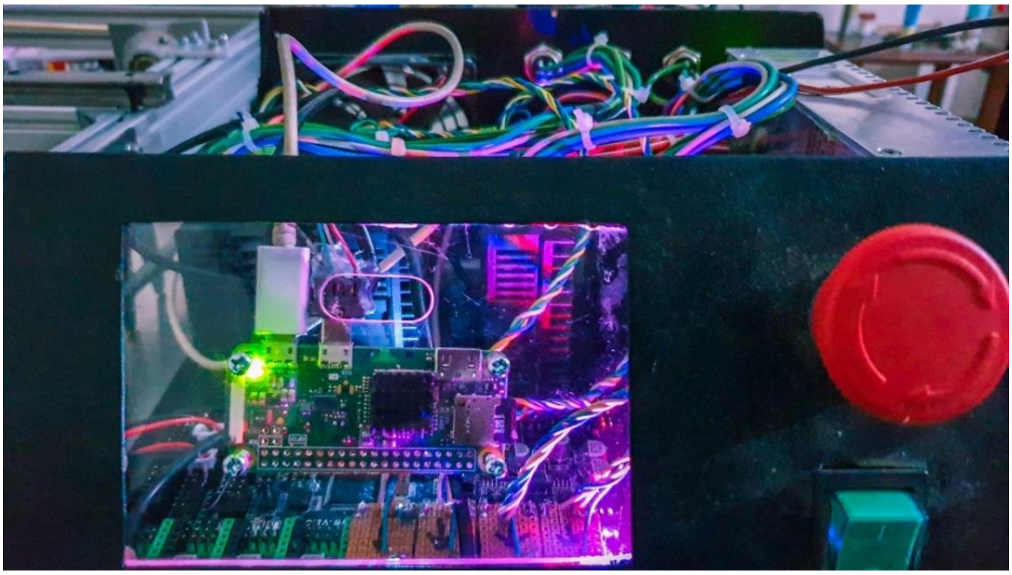


Figure 31 Control box containing all the electronics.

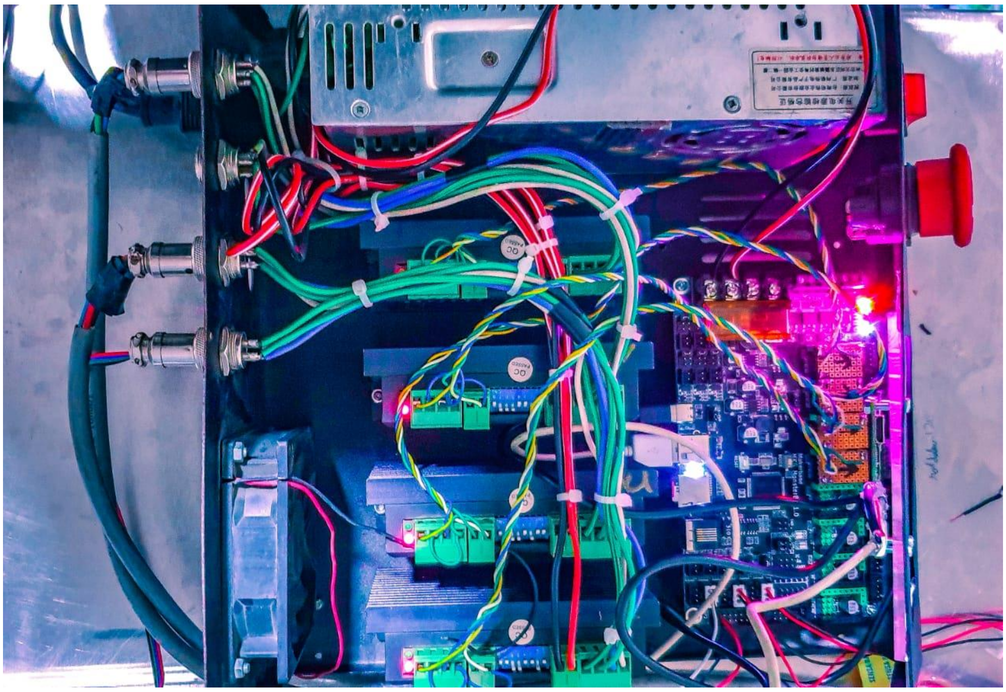


Figure 32 Electronics component assembly within the control box

# CHAPTER 4- RESULTS

## 4.1 BED DESIGN

The design of the bed required thermal analysis to be carried out, as it would be subject to heat, as well as structural analysis to be carried out as we needed to figure out what dimension of the bed the current slides would hold.

The following is the structural analysis of the bed. The bed is of 40 by 40 cm and has a thickness of 5 mm. We have placed a 2mm thickness of mild steel plate on top of the bed for analysis, upon which the welding would be carried out. We have visualised the deformations, as well as the stresses induced in the HIWIN HG series. We had initially theoretically calculated a maximum temperature of 165**°C** at the centre of the plate induced due to welding and have re-evaluated the results through FEA. The later analysis used an extension of Ansys that simulated moving heat fluxes that simulated the path of the weld torch at 200A and 20V conditions.

### 4.1.1 DESIGN OF MODELS USED:

Initial analyses were conducted on a very simplified design based on a bed and two blocks. At this stage, we were still fabricating the system and needed rough estimated for the design process of the system. The following models were used:

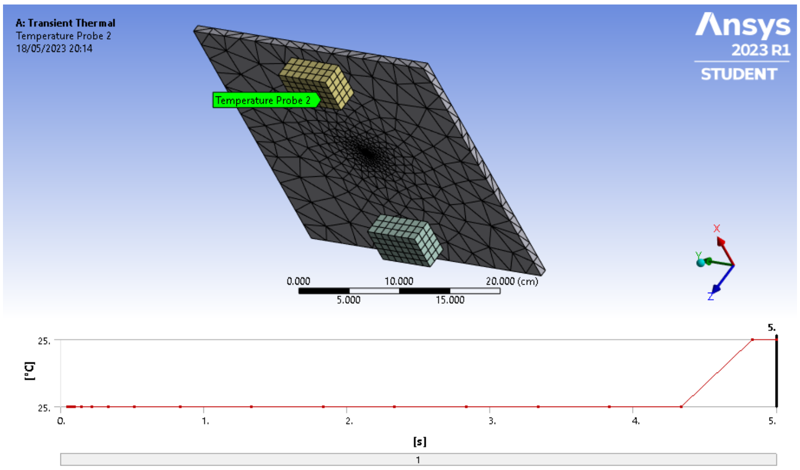
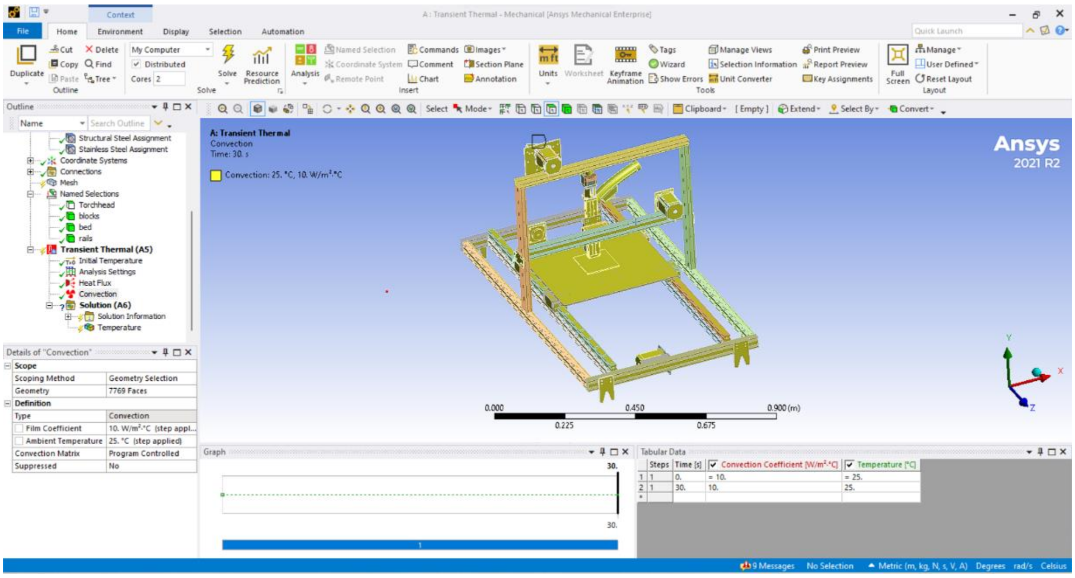


Figure 33 Temperature variation for linear guides

This model helped us in the fabrication process. Initially. The complete CAD model was then used for testing the limits of the system.



Details of "Convection"

| | |
|---|---|
| **Scope** | |
| Scoping Method | Geometry Selection |
| Geometry | 7769 Faces |
| **Definition** | |
| Type | Convection |
| ☐ Film Coefficient | 10. W/m²·°C (step appl... |
| ☐ Ambient Temperature | 25. °C (step applied) |
| Convection Matrix | Program Controlled |
| Suppressed | No |

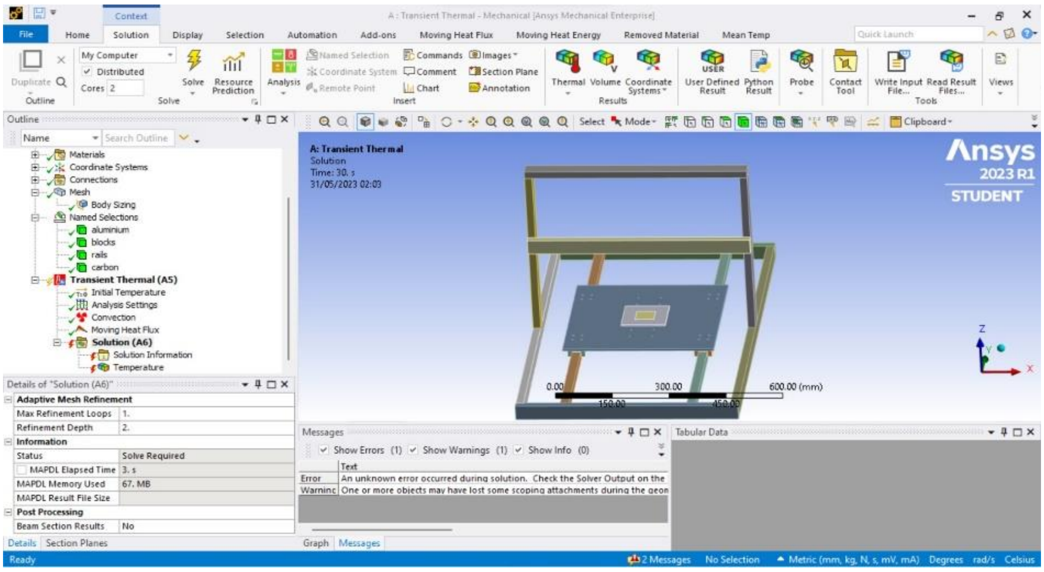
Tabular Data

| | Steps | Time [s] | ☑ Convection Coefficient [W/m²·°C] | ☑ Temperature [°C] |
|---|---|---|---|---|
| 1 | 1 | 0. | = 10. | = 25. |
| 2 | 1 | 30. | 10. | 25. |
| * | | | | |

Figure 35 Failed model for analysis.

This model proved too impractical for testing as the computational requirements were high. This resulted in failed analyses and costed a lot of time.

We simplified the model to the following one that we are still using currently.



Details of "Solution (A6)"

| | |
|---|---|
| **Adaptive Mesh Refinement** | |
| Max Refinement Loops | 1. |
| Refinement Depth | 2. |
| **Information** | |
| Status | Solve Required |
| ☐ MAPDL Elapsed Time | 3. s |
| MAPDL Memory Used | 67. MB |
| MAPDL Result File Size | |
| **Post Processing** | |
| Beam Section Results | No |

Messages

✓ Show Errors (1) ✓ Show Warnings (1) ✓ Show Info (0)

| | Text |
|---|---|
| Error | An unknown error occurred during solution. Check the Solver Output on the |
| Warninc | One or more objects may have lost some scoping attachments during the geon |

Figure 36 Final model used for analysis.

### 4.1.2 SELECTED PARAMETERS

Square path of 5cm by 5cm

Weld pool diameter of 1.9 mm

Value for heat flux:

$$P = V * I * \eta$$

$$= 20 * 200 * 0.8$$

$$= 320\ W$$

0.8 is the average efficiency of a MIG welding system.

Value for convection coefficient: 10 W/m$^2$K

Value of emissivity: 0.6

Segments= 200

Steps for cooling phase = 20

Weld speed = 7 cm/min

### 4.1.3 STATIC STRUCTURAL ANALYSIS:

We analysed the warping in the bed using the above parameters to understand the bending in the bed that could occur. We could see through the analysis that the stresses in the structure are at a minimum, while the deformations at the bed are not of a concern, with the maximum deformation of 0.05cm at the edges. This although would have a possible impact over the long run and the bed would need to be replaced eventually.

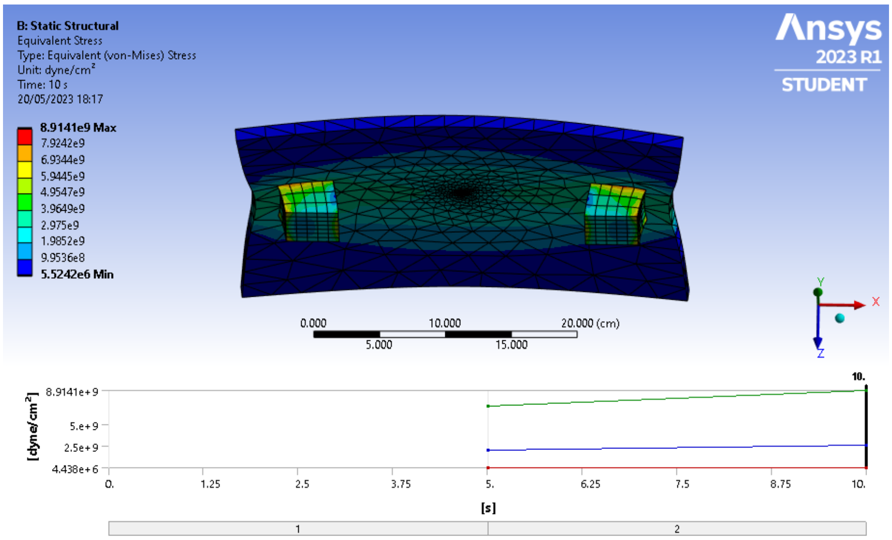


Figure 37 Stresses in the blocks.

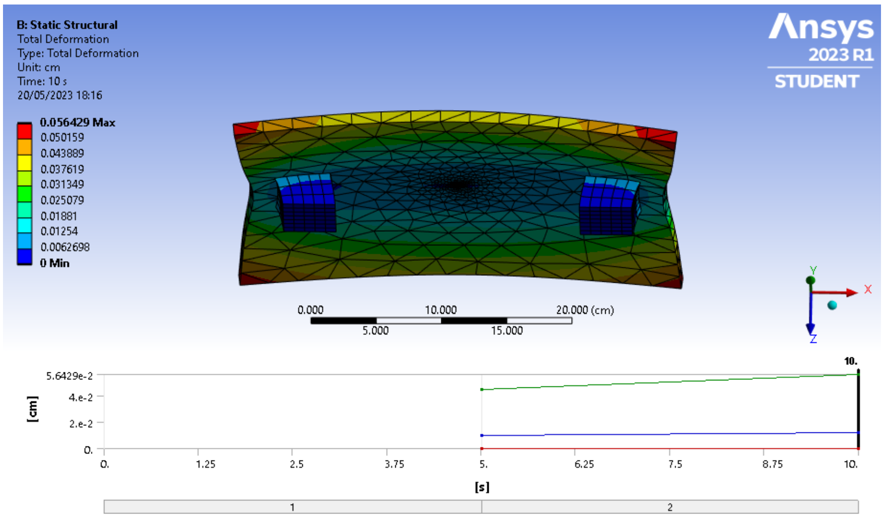


Figure 38 Deformations due to the weight.

### 4.1.4 TRANSIENT THERMAL ANALYSIS:

The transient thermal analysis allowed us to monitor how the temperature changes in the system for the first layer. Due to the short operating time, we have not seen any significant heat output onto the structure, with the maximum temperature reaching 298.79 Celsius at the plate.

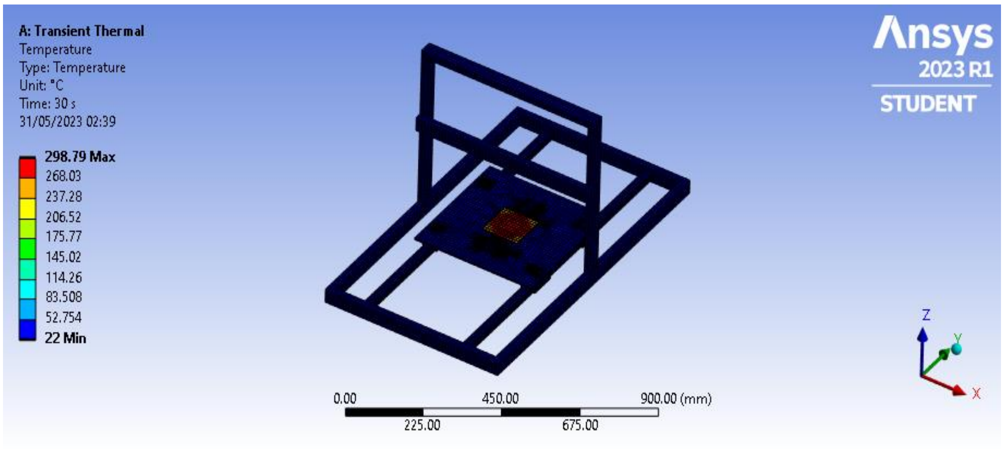


Figure 39 Temperature output of the welding path

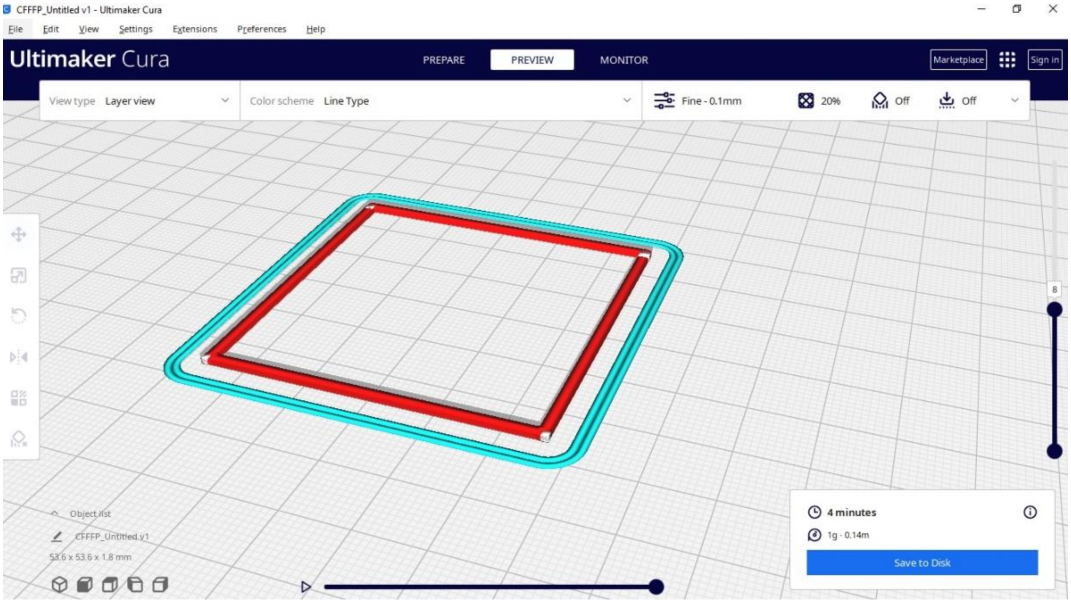
## 4.2 G-CODE GENERATION

The g-code results were extensive, and the beginning snippet is attached below:

```
M104 S245

M105

M109 S245

M82 ;absolute extrusion mode

G28 ;Home

G1 Z15.0 F6000 ;Move the platform down 15mm

;Prime the extruder

G92 E0

G1 F200 E3
```

```
G92 E0

G92 E0

G92 E0

G1 F1500 E-8

;LAYER_COUNT:16

;LAYER:0

M107

G0 F3600 X169.825 Y169.805 Z0.3

G0 X168.4 Y173.809

;TYPE:SKIRT

G1 F1500 E0

G1 F1800 X168.409 Y173.144 E0.03753

G1 X168.458 Y172.527 E0.07246

G1 X168.585 Y171.92 E0.10745

G1 X168.79 Y171.336 E0.14238

G1 X169.068 Y170.782 E0.17736

G1 X169.415 Y170.269 E0.21231

G1 X169.825 Y169.805 E0.24725

G1 X170.291 Y169.398 E0.28217

G1 X170.806 Y169.054 E0.31712

G1 X171.361 Y168.779 E0.35207

G1 X171.947 Y168.578 E0.38703

G1 X172.554 Y168.454 E0.42199
```

```
G1 X173.207 Y168.4 E0.45897

G1 X226.162 Y168.4 E3.44731

G1 X226.86 Y168.41 E3.4867

G1 X227.477 Y168.459 E3.52163

G1 X228.083 Y168.587 E3.55658

G1 X228.668 Y168.792 E3.59156

G1 X229.221 Y169.071 E3.62651

G1 X229.734 Y169.418 E3.66146

G1 X230.198 Y169.828 E3.69641

G1 X230.605 Y170.295 E3.73136

G1 X230.948 Y170.81 E3.76628

G1 X231.223 Y171.366 E3.80129

G1 X231.423 Y171.952 E3.83623

G1 X231.547 Y172.559 E3.87119

G1 X231.6 Y173.21 E3.9080

…
```



CFFFP_Untitled v1 - Ultimaker Cura

View type Layer view

Color scheme Line Type

Fine - 0.1mm

20%

Off

Off

CFFFP_Untitled v1

53.6 x 53.6 x 1.8 mm

4 minutes

1g · 0.14m

*Figure 40 Results of slicing through Cura*

Additionally, an estimated print time was generated, along with an estimate of the material used. The actual parameters would be higher due to the practicalities of MIG welding.

## 4.3 3-AXIS MACHINE

We have configured the DM542A stepper motors using the specific configuration on the DIP switches for 16 microsteps per full step.

The accuracy of the system is shown to be withing 0.5 mm, not accounting for the error due to method used to measure the accuracy.

### 4.3.1 STEP RESOLUTION

Our NEMA17 stepper motor has a 1.8° step angle and 1/128 step mode.

The motor takes 128 e-steps in between each step of the motor and hence it increases the resolution of the motor by a factor of 128

The calculations are as follows:

$$Step\ Resolution = (360°)\ /\ (Step\ Angle \times\ Micro\ stepping\ Setting)$$

$$Step\ Angle\ =\ 1.8°$$

$$Micro\ stepping\ Setting\ =\ 128$$

$$Step\ Resolution\ =\ (360°)\ /\ (1.8° \times\ 128)$$

$$Step\ Resolution\ =\ 1.56°\ per\ step$$

### 4.3.2 ROTATIONAL DISTANCE

The rotational distance of a stepper motor is a parameter used in Klipper firmware. This is a easier to calculate and hence becomes easier to set up Klipper firmware.

For a belt-driven system,

$$Rotational\ Distance = (belt\ pitch) \times (\ \#\ of\ \ teeth\ on\ a\ pulley)$$

In our case

$$Rotational\ Distance = (5mm) \times (24)$$

$$Rotational\ Distance = 120mm\ per\ revoltuion$$

### 4.3.3 TORQUE REQUIREMENT

To calculate the torque required to lift a 10 kg load on the ball screw, we must consider the mechanical advantage supplied by the ball screw as well as the gravitational force acting on the load.

The torque can be calculated using the following formula:

$$\tau = F \times r$$

Where:

- Force is the gravitational force acting on the load, which can be calculated as the mass of the load multiplied by the acceleration due to gravity (9.8 $m/s^2$).
- Radius is the effective radius of the ball screw, which can be calculated as half the diameter.

Given that the load is 10 kg, we can calculate the force as:

$$F =\ m\ \times a$$

$$F\ = 10kg \times 9.8ms^{-2}$$

$$F\ = 98N$$

We have determined the radius of the ball screw to be 0.03m from the datasheet. Now, we can calculate the torque required:

$$Torque = Force \times Radius$$

$$Torque = 98N \times 0.003m$$

$$Torque = 0.294Nm$$

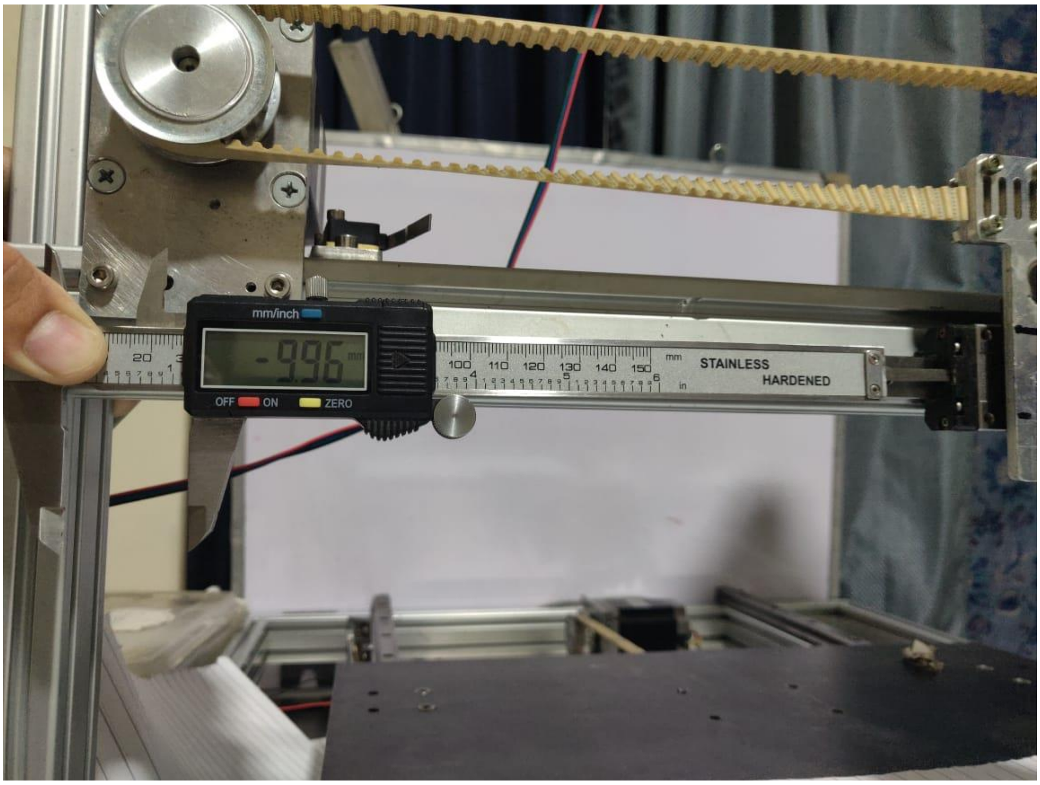
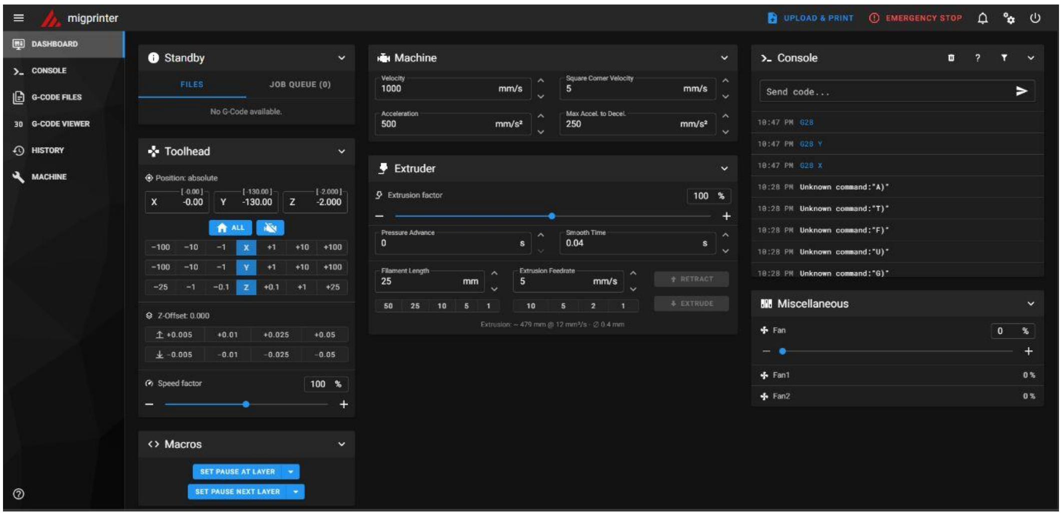


Figure 41 Measuring the accuracy of the y-axis using a vernier calliper.

Mainsail has been configured to the 3 axes and is used to adjust the parameters according to the requirements.



No G-Code available.

Position: absolute

X -0.00
Y -130.00
Z -2.000

Z-Offset: 0.000

Speed factor 100 %

Velocity 1000 mm/s

Square Corner Velocity 5 mm/s

Acceleration 500 mm/s²

Max Accel. to Decel. 250 mm/s²

Extrusion factor 100 %

Pressure Advance 0 s

Smooth Time 0.04 s

Filament Length 25 mm

Extrusion Feedrate 5 mm/s

Extrusion: ~ 479 mm @ 12 mm³/s - ∅ 0.4 mm

```
Send code...
10:47 PM G28
10:47 PM G28 Y
10:47 PM G28 X
10:28 PM Unknown command:"A)"
10:28 PM Unknown command:"T)"
10:28 PM Unknown command:"F)"
10:28 PM Unknown command:"U)"
10:28 PM Unknown command:"G)"
```

Fan 0 %

Fan1 0 %

Fan2 0 %

Figure 42 Setting parameters for writing "MIG PRINTER"

The following shows the output when the 3 axes machine is connected to a marker:

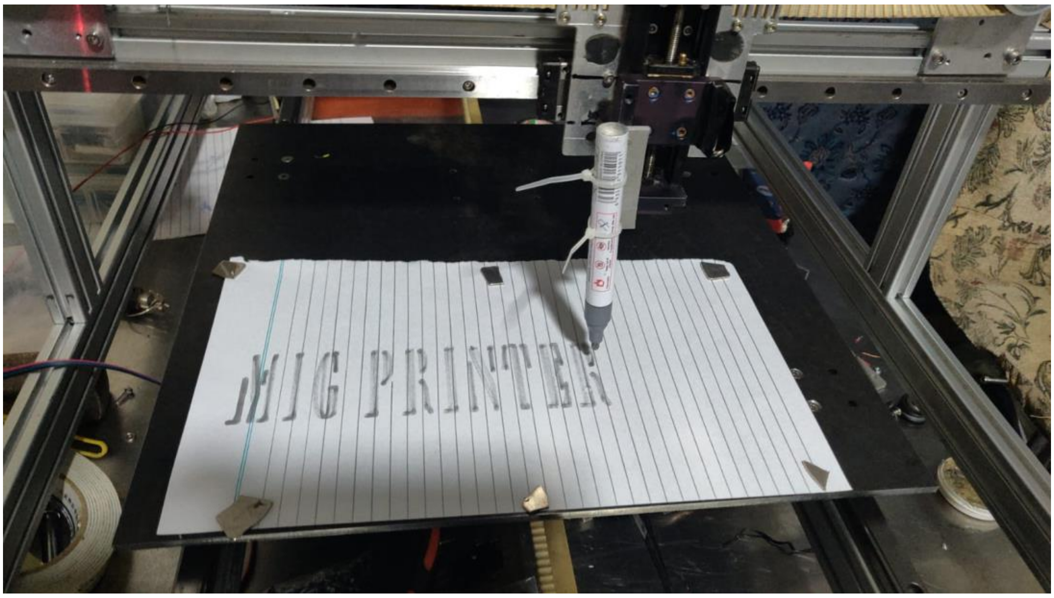


Figure 43 Using a marker to write "MIG PRINTER"

# CHAPTER 5- CONCLUSIONS AND FUTURE WORK

In our Final Year Project, we successfully established a solid foundation for constructing intricate geometries using MIG-based additive manufacturing. The system is specifically tailored for mild steel filament. Our initial deliverable involved designing a 3-axis machine through CAD modelling and planning component requirements by generating a Bill of Materials. We then proceeded to fabricate the design using aluminium 2040 extrusions, which entailed revisiting the design phase and iteratively refining the existing design. The third step involved setting up the 3-axis machine with precision that met the project's requirements, using stepper motors and limit switches. Our ultimate goal was to integrate the wire feeder and MIG torch onto the 3-axis machine, enabling metal weld bead deposition onto a metal plate.

Overcoming the project's limitations and challenges was a significant accomplishment. These included finding cost-effective alternatives to expensive equipment and procedures, as well as addressing MIG welding requirements. We designed and implemented custom engineering solutions, such as creating a custom wire feeder to facilitate torch integration. Additionally, we tackled the precision control of the z-axis and designed a bed system for placing the metal plate, minimizing heat-induced warping and protecting critical components. This experience not only expanded our technical knowledge but also sharpened our practical workshop skills, as we were personally involved in the entire process.

There are several opportunities for enhancing our current design that we could not implement due to time and budget constraints or because we developed a better understanding of the process at a later stage. The timing belt system could be replaced with ball screws or lead screws to increase the system's precision. Belt sway could cause a few degrees of translation offset in high-precision applications, potentially posing a problem when tackling more complex geometries. Moreover, the system could be made more reliable and straightforward by incorporating two degrees of freedom on the bed and one degree of freedom on the torch. This simplifies the design and control of the system, with the torch only moving in one axis during deposition. This setup also reduces vibrations and deflections in the torch during the deposition process, as it can be made rigid in one axis. Lastly, it can help increase the system's build volume.

The project could further enhance the system's precision by upgrading current build components to industrial standards. An industrial torch and wire feed system could replace the existing self-designed wire feeder and torch arrangement. Further attempts at constructing various geometries using the MIG system could be made.

Heat management of the MIG welder requires additional work. The bed's design could be improved to handle the heat generated during the process, and cooling elements could be integrated.

From a broader perspective, this project's potential applications extend well beyond our current scope. An advanced working system could prove valuable in fields such as construction, automotive, and manufacturing industries. Furthermore, it is a step towards research and development in additive manufacturing, which is a critical upcoming innovative field.

In conclusion, our project's journey has shown that MIG welding-based additive manufacturing systems can provide a feasible solution for metal deposition. The challenges we overcame not only enhanced our technical capabilities but also deepened our understanding of the complex processes contained within the project.

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