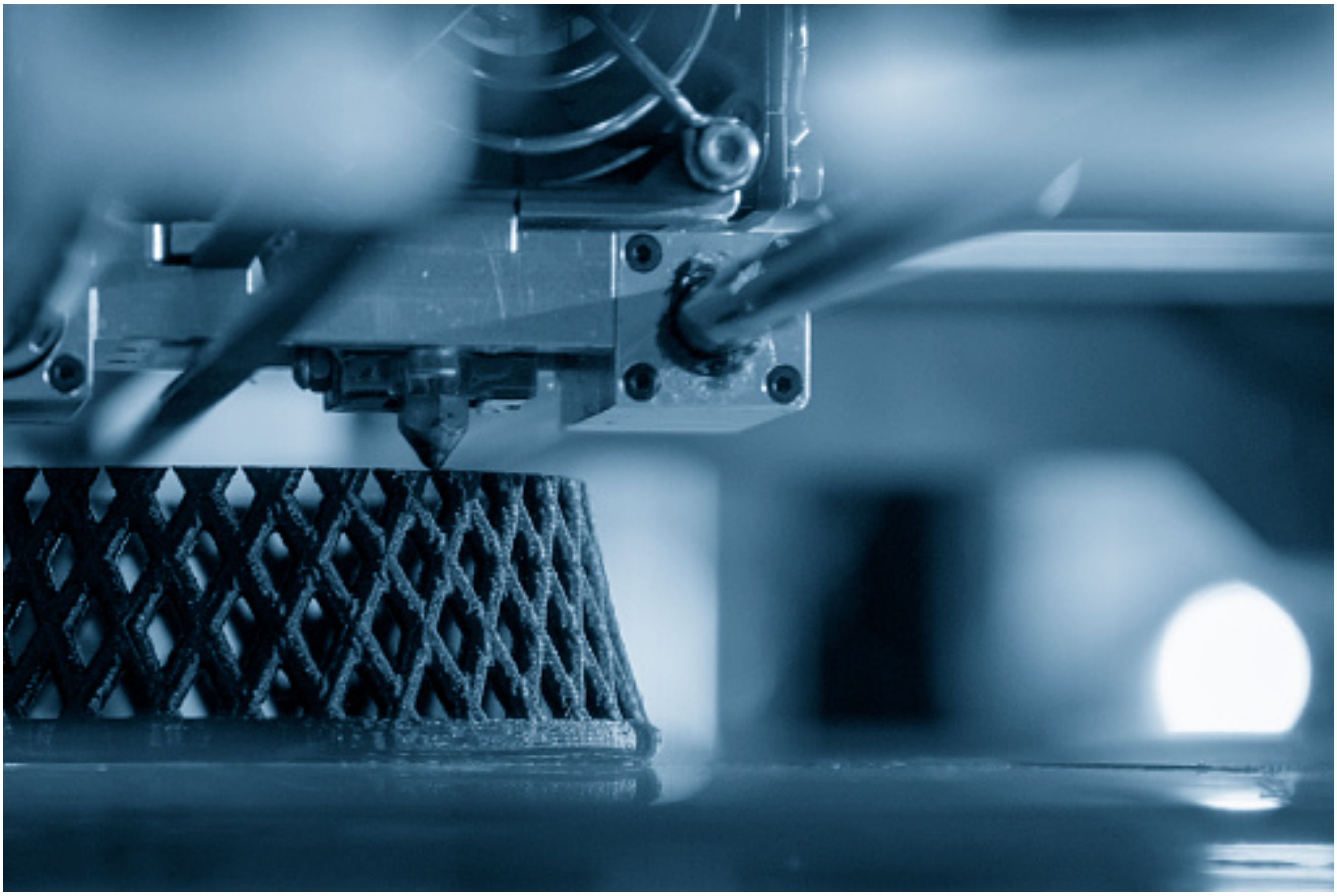
Design and manufacturing of WAAM parts to consolidate new R+D metal AM capabilities at CIM UPC's pilot plant



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Resumen

La fabricación aditiva y la robótica son dos tecnologías que han experimentado una evolución impresionante en los últimos años. Cuando se combinan, permiten resolver numerosas tareas industriales en varios campos como el aeroespacial, la automoción o cualquier sector que requiera una fabricación o modificación precisa de una pieza. Proporciona un proceso de implementación rápido, una programación robótica fácil y un uso óptimo de la cinemática del robot para un control de movimiento superior. La fabricación aditiva con arco eléctrico (WAAM) es una de las técnicas de impresión 3D que se utiliza para fabricar piezas metálicas, y está en constante evolución.

El tema de mi investigación es establecer una manera de imprimir una pieza de plástico de una forma deseada simulando la tecnología WAAM usando un robot colaborativo y realizar pruebas mecánicas en las muestras impresas para compararlas con productos fabricados de manera convencional del mismo tipo. Para ello, utilicé un cobot UR10e de Universal Robot, combinado con una herramienta de impresión de filamento de plástico de una impresora 3D Epsilon W27 de BCN3D. El uso del filamento de plástico es el punto de partida de un proyecto futuro que se centra luego en el uso del filamento metálico para imprimir piezas.

Los experimentos han llevado a una serie de intentos de impresiones, estudiando un parámetro de impresión a la vez. La primera serie no dio lugar a impresiones exitosas debido a que la distancia entre capas y entre pasadas era demasiado grande, lo que causaba discontinuidades en la trayectoria de la herramienta y un acabado superficial pobre. Para la serie siguiente, las configuraciones de impresión se optimizaron y las piezas impresas fueron mucho más precisas.

Resum

La fabricació additiva i la robòtica són dues tecnologies que han experimentat una evolució impressionant en els darrers anys. Quan es combinen, permeten resoldre nombroses tasques industrials en diversos camps com l'aeroespacial, l'automòbil o qualsevol sector que requereixi una fabricació o modificació precisa d'una peça. Proporciona un procés d'implementació ràpid, una programació robòtica fàcil i un ús òptim de la cinemàtica del robot per a un control de moviment superior. La fabricació additiva amb arc de filferro (WAAM) és una de les tècniques d'impressió 3D que s'utilitza per fabricar peces metàl·liques utilitzant un arc elèctric, y està en constant evolució.

El tema de la meva investigació és establir una manera d'imprimir una peça de plàstic d'una forma desitjada simulant la tecnologia WAAM i realitzar proves mecàniques en les mostres impreses per comparar-les amb productes fabricats de manera convencional del mateix tipus. Per fer-ho, vaig fer servir un cobot UR10e de Universal Robot, combinat amb una eina d'impressió de filament de plàstic d'una impressora 3D Epsilon W27 de BCN3D. L'ús del filament de plàstic és el punt de partida d'un projecte futur que es centra després en l'ús del filament metàl·lic per imprimir peces.

Els experiments han portat a una sèrie d'intents d'impressió, estudiant un paràmetre d'impressió a la vegada. La primera sèrie no va portar a impressió reeixides a causa de la distància entre capes i entre passes eren massa grans, portant a discontinuïtats en la trajectòria d'eina i acabat de superfície pobre. Per a la següent sèrie, les opcions d'impressió van ser optimitzades, i les peces impreses van ser molt més precises.

Abstract

Additive manufacturing and robotics are two technologies which have undergone a dazzling evolution over the last few years. When combined, they allow the resolution of numerous industrial tasks in various fields such as aerospace, automobile, or any sector that requires a precise manufacturing or modification of a workpiece. It provides a fast process implementation, an easy robotic programming, and an optimal use of the robot's kinematics for superior motion control. Wire arc additive manufacturing (WAAM) is one of the 3D printing techniques that is used to manufacture metallic parts using an electric arc, and it is in constant evolution.

The subject of my research is about setting up a way to print a plastic part of a desired shape simulating the WAAM technology with a collaborative robot and perform mechanical tests on the printed samples to compare them with conventional manufactured products of the same kind. To do so, I used a UR10e cobot from Universal Robot, combined with a plastic filament printing toolhead of an Epsilon W27 3D printer from BCN3D. The use of plastic filament is the starting point of a future project focusing then on the use of metallic filament to print parts.

The experiments have led to a series of attempts of prints, studying a parameter of impression at a time. The first series did not lead to successful prints because of the distance between layers and between passes were too big, leading to discontinuities in the toolpath and poor surface finish. For the following series, the printing settings were optimized, and the printed pieces were much more accurate.

Acknowledgments

I would like to express my appreciation for all of the support and guidance that Mrs. Pamela Lustig have provided me throughout my internship.

I would also like to thank my director Mr. Felip Fenollosa whose ambition and objectives for this project have been challenging and they have helped me to gain a deeper understanding of the field and have provided me with invaluable experience that I will carry with me throughout my career.

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Finally, I want to thank all of the employees at CIM UPC for having helped on this project at some point. The support and willingness to share the knowledge have been greatly appreciated, and I am grateful for the opportunity to have been a part of such a valuable experience.

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Introduction

Additive manufacturing and robotics are two technologies that have undergone rapid growth in recent years, with significant potential to revolutionize the way industrial tasks are performed. By combining these technologies, it is possible to achieve improved motion control, faster process implementation, and more efficient robotic programming. One of the most promising additive manufacturing techniques in terms of metallic parts is Wire Arc Additive Manufacturing (WAAM), which utilizes an electric arc with high precision and speed.

However, the cost of implementing WAAM technology remains a major concern. The aim of this project is to explore a cost-effective solution to this problem by simulating the WAAM technology using a UR10e collaborative robot from Universal Robot and a plastic filament printing toolhead from BCN3D. The goal is to print 3D plastic parts that mimic the production patterns of parts produced by WAAM and to perform mechanical tests to compare them to conventional manufactured parts.

By doing so, the project will investigate how the combination of a collaborative robot and a 3D printing toolhead can contribute to reduce production costs and increase the efficiency and accuracy of the manufacturing process. In addition, using a plastic filament will help identify and overcome the encountered problems of the setup. By starting with low-cost, easily accessible materials like plastic, the system can be optimized before moving on to more expensive and complex materials like metal in the WAAM process. The objective is, in the future, to replace the plastic filament printing toolhead with a TIG torch provided by the welding company Codesol, in order to further improve the accuracy and efficiency of production of metallic parts.

The results of this research will have the potential to pave the way for the large-scale implementation of WAAM technology, and to revolutionize the way metallic parts are produced in various industries such as aerospace, automobile, and others that require precision manufacturing or modification of workpiece.

Objective

As part of my internship, my objective is to combine a UR10e cobot with a printing toolhead in order to be able to use the robot to print 3D parts. The aim of this project is to contribute to the improvement of knowledge about additive manufacturing and robotics.

The UR10e robot is a collaborative robot that is able to work closely with humans. By combining it with a printing toolhead, I hope to be able to use the robot to print 3D parts more efficiently and accurately. This will help to reduce production costs and speed up the manufacturing process.

The further objective would be in the future to replace the printing toolhead with a TIG torch for WAAM, improving accuracy and efficiency of production of metallic parts.

By working on this project, I hope to contribute to the progress of research on on these topics and help develop new technologies and applications.

I. State of the Art

I.1. What is additive manufacturing?

I.1.1. Definition

Additive manufacturing (AM) is a generic term for engineering processes that aim at the fabrication of pieces by deposing material layer-upon-layer on a surface. These technologies appeared in the late 1980s and have known major evolutions throughout the decades. Today, they allow the production of pieces at a very low fly-to-buy ratio compared to other conventional manufacturing methods. The fly-to-buy ratio is the result of the fraction of the raw material's weight over the final part weight. It can go up to 98% of raw material removed. [1]

One of the key advantages of additive manufacturing is that it allows for the creation of complex shapes and structures that may not be possible using traditional manufacturing techniques such as casting or molding. It also allows a wide variety of composition for the pieces with the possibility to use many types of material and even blend them together, creating compounds.

Additive manufacturing is used in a variety of industries, including aerospace, automotive, medical, and architecture, and has the potential to revolutionize the way we design and manufacture products.

AM is a manufacturing technique that allows objects to be created using various materials such as plastic, metal, ceramics, composites, concrete and more. Generally, 3D printers use a single type of build material, which can be in different colors. Some printers even allow for the creation of multicolored objects by mixing multiple colors of material. The selection of materials compatible with 3D printers is constantly expanding. It is also possible to create objects made of different materials using some 3D printers. [2]

According to the ISO/ASTM 52900 standard, seven families of additive manufacturing can be discerned [3]:

1. Powder bed fusion (PBF): This family includes processes that use a laser or electron beam to melt or fuse together small particles of a metal or polymer powder, layer by layer, to create a solid object. Examples include selective laser sintering (SLS) or Multi Jet Fusion (MJF-HP) for plastic powder and Selective Laser melting (SLM) for metal powder. PBF processes are commonly used to create metal parts, and they can produce parts with high precision and good surface finish.

2. Material extrusion: This family includes processes that use a nozzle to extrude a thermoplastic or other material, layer by layer, to create a solid object. Examples include fused deposition modeling (FDM) and thermoplastic extrusion (TPE). Material extrusion processes are commonly used to create parts in thermoplastic materials, and they are often used for rapid prototyping, low-volume production, and direct digital manufacturing. It is the technology used in the present project.

3. Vat photopolymerization: This family includes processes that use a vat of liquid photopolymer resin and a light source (such as a laser or projector) to cure the resin layer by layer, creating a solid object. Examples include stereolithography (SLA) and

digital light processing (DLP). Vat photopolymerization processes are commonly used to create parts in photopolymer materials, and they can produce parts with high accuracy and good surface finish.

4. Material jetting: This family includes processes that use a print head to jet droplets of material, layer by layer, to create a solid object. Examples include PolyJet and MultiJet modeling (MJM). Material jetting processes are commonly used to create parts in photopolymer materials, and they can produce parts with high accuracy, high resolution, and good surface finish.

5. Binder jetting: This family includes processes that use a print head to jet droplets of binder material, layer by layer, onto a powder material, creating a solid object. Binder jetting processes are commonly used to create parts in metal and ceramic materials, and they can produce parts with high accuracy and good surface finish.

6. Sheet lamination: This family includes processes that use a lamination process to build objects by bonding layers of material together, such as paper or metal foil. Sheet lamination processes are commonly used to create parts in paper and metal materials.

7. Directed energy deposition (DED): This family includes processes that use a heat source, such as a laser or an electron beam, to deposit material in a specific location, layer by layer, to create a solid object. DED processes are commonly used to create metal parts, and they can produce parts with high precision and good surface finish. WAAM technology is included in this category.

I.1.2. Comparison with other techniques of manufacture and limits

AM contrasts with traditional manufacturing techniques, which typically involve subtractive processes in which material is removed or shaped to create an object.

One of the main advantages of additive manufacturing is its flexibility that can lead to significant cost savings, as it reduces the need for tooling and other specialized equipment. Additionally, additive manufacturing can be faster and more efficient than traditional manufacturing methods for small batch production, as it does not require the setup and teardown of specialized machinery.

While this technology has the potential to revolutionize traditional manufacturing techniques, it also has its limitations.

One of the main limitations is the limited range of materials that can be used. While some 3D printers can print with a wide range of materials, the majority are limited to printing with a single material at a time. This limits the potential for creating complex and multi-material objects.

Another limitation is the size of the objects that can be printed. While some 3D printers can print objects as large as a car or a house, the majority are limited to printing objects that are much smaller in size. This limits the potential for large-scale production using 3D printing.

Indeed, traditional manufacturing techniques are generally more efficient for large-scale production and for producing products with a high degree of uniformity. They also tend to be more cost-effective for producing simple or commodity products, as the equipment and processes are often optimized for high volume production. In addition, some materials may not be suitable for additive manufacturing, and the quality of 3D printed objects can be affected by the resolution of the printer and the properties of the material being used [3] [4].

I.1.3. FDM extruder

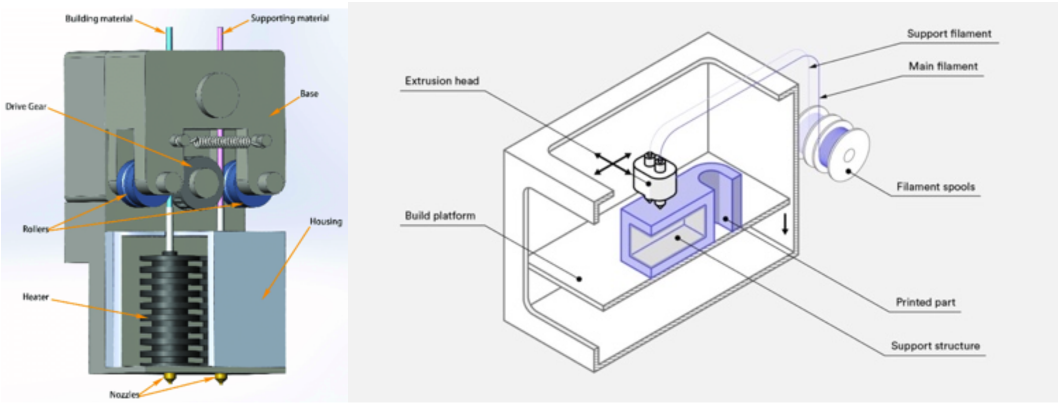


Figure 1 and 2: 3D Layout of an FDM extruder (1) [5] and scheme of an FDM 3D printer (2) [6]

Fused deposition modeling (FDM) is the most common process in 3D printing. It works by feeding a filament of plastic into a heated block in order to melt and deposit it to create a desired part (Figure 1 and 2).

The process is described as follows: the filament of plastic is pushed into the block by rollers, and it is heated up to its melting temperature. Then the melted plastic comes out of a nozzle and is deposited on a heated bed layer by layer with the desired pattern. In some printers, a support material is added to print the parts that are dedicated to be removed from the main structure. This support material comes from another filament and is fed through another nozzle.

The extrusion head is controlled by a 3-axis system that allows it to move across the X, Y and Z directions. To execute all the commands such as moving the extruder, heating the nozzle, heating the bed, etc. the printer system reads a file called a G-Code [7] [8].

I.1.4. Pellet extruder

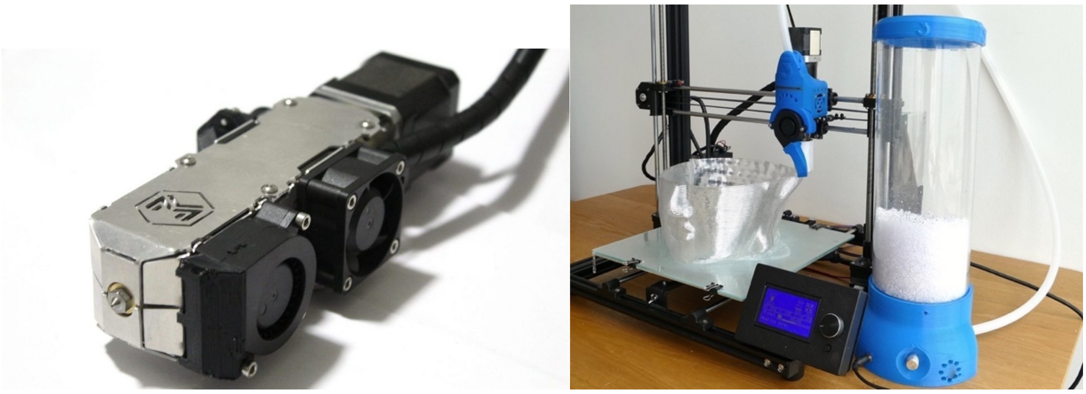


Figure 3 and 4: Mahor XYZ pellet extruder (3) [9] and Pellet printer (4) [10]

A pellet extruder is an alternative to an FDM extruder for additive manufacturing. It is composed of a melting and a pushing mechanism to allow the printing process.

The pellets are fed into the extruder by an inlet, and they are pushed through it where they are heated to their melting temperature. The method to push the material out of the nozzle uses a screw that applies a certain pressure on it (Figure 2 and 4).

The extruder is fixed and controlled in the same way as the FDM extruder. [11]

I.1.5. What are the differences between a pellet extruder and an FDM extruder?

Pellet extruders are commonly used in industrial settings for large-scale production of plastic parts and have high production rates and cost-effective. They can handle larger volumes of material and have more robust and durable components. However, pellet extruders are typically limited to the use of a specific type of plastic, and are more complex, requiring more maintenance and calibration, and specialized knowledge to operate.

FDM extruders, on the other hand, are commonly used in desktop 3D printing and are more versatile, they can use a wide range of thermoplastic filaments, including ABS, PLA, TPU, PETG, and more, so they can produce parts in a variety of colors and with different properties. FDM extruders are relatively low cost, easy to use, and more suitable for small-scale production and prototyping as they can produce parts with high precision and fine details [12].

For these reasons and considering the availability of materials at CIM, a FDM extruder has been chosen to use a filament printing toolhead for the rest of the project.

I.1.6. 3D printing process

The process of printing in additive manufacturing is divided in four major steps which are listed below:

- Step 1: CAD part
- Step 2: Segmenting
- Step 3: Slicing
- Step 4: Printing

Each of these steps are detailed on this section.

Step 1: CAD part

The beginning of the manufacturing process of a piece is the creation of its numerical 3D model. To do so, a computer-aided design (CAD) software is required. It allows the user to create, modify, analyze, and optimize a design. It exists many of them, for example: Solidworks, marketed by Dassault Systèmes, and widely used in mechanical engineering.

SolidWorks is a 3D computer-aided design (CAD) software that is used to create, analyze, and document mechanical designs.

SolidWorks includes a range of tools and features that enable users to create 3D models of parts, assemblies, and assemblies using a variety of geometric shapes and features. Users can also apply engineering principles and physical properties to their designs, such as materials, loads, and constraints, in order to simulate and analyze their behavior.

It also includes a range of tools for creating technical drawings and documentation, such as engineering drawings, exploded views, and bill of materials. This enables users to communicate their designs clearly and effectively to others, such as colleagues, manufacturers, and customers [13].

The 3D design is eventually drawn from a 2D sketch to which several operations have been applied, leading to the desired geometry.

Step 2: Segmenting

Once the numerical 3D model of the piece is created, it is exported and must be converted into a stereolithographic (STL) file. An STL file describes the raw surfaces of a model with triangles using a 3D cartesian coordinate system. The data in it only contains the geometry of the model, without any specifications on the texture, color, or material.

Step 3: Slicing

The second step of the 3D printing is slicing. A slicing software for 3D printers, or slicer, is the software which is the intermediary between the 3D model and the 3D printer. It doesn't allow the user to design its workpiece, it is simply uploaded into the software, and it must be designed downstream or downloaded from a 3D models database. The slicing operation transforms the 3D model into a number of 2D layers with their own thickness. Each layer is composed of toolpath passes which are a deposition of material with a single start and stop.

The toolpath passes are composed of straight-line section such as raster, zigzag, contours, space-filling curves, and hybrid toolpath planning approaches. These elements and their advantages and disadvantages are listed on the figure 5 below.

References	Tool-path strategy	Advantages	Disadvantages
[14]	Raster	+ a	− b, − c, − d
[15, 16]	Zigzag	+ a	− b, − c, − d
[17–19]	Contour	+ b	− a, − c
[20, 21]	Spiral	+ c	− a
[22, 23]	Fractal space curves	+ c	− a, − d
[22, 24, 25]	Continuous	+ c	− a, − d
[11, 26]	Hybrid	+ a, + b	− c, − d
Major performance indicators of tool-path generation methods			
a	Easy implementation and simple algorithms		
b	Good geometrical accuracy		
c	Less tool-path passes		
d	Less tool-path elements		

Figure 5: Summary of AM toolpath generation main methods [14]

Step 4: Printing

Finally, the software converts the sliced workpiece from an STL file into a G-Code file readable by the 3D printer.

The G-Code is the numerical language that the 3D printer reads to execute commands necessary to the printing. It is composed of letters and numbers which correspond to a certain element or function of the devices that can be found in the 3D printer. The figure 6 shows an example of a G-Code used in 3D printing.

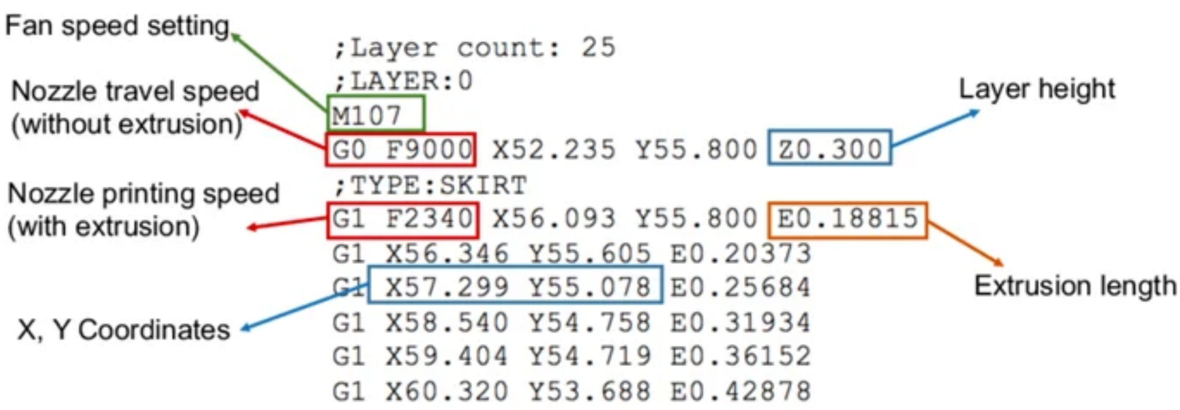


Figure 6: Examples of commands for 3D printing [15]

The letters x, y, and z correspond to the three axes of the cartesian coordinate system of the 3D printer. For example, in the blue frame corresponding to X, Y Coordinates in figure 6, the toolhead moves to 57.299 mm in the right direction and to 55.078 mm backwards. A positive value after a Z would move it upwards.

A G-Code is mainly composed of two types of commands: G and M commands, the most common of which are listed below.

- G commands:
  - G0: It is the most basic one, it asks the printer to move towards a certain coordinate position without extruding material and as fast as possible.
  - G1: It asks the printer to do a linear movement towards a certain coordinated position.
  - G20: It defines the length unit to inches.
  - G21: It defines the length unit to millimeters.
  - G28: It homes the axes of the printer.
- M commands:
  - M0: Program stop
  - M18 - Stop all motors
  - M104 - Start extruder heating
  - M109 - Wait for extruder to reach a certain temperature
  - M140 - Start bed heating
  - M190 - Wait for heating plate to reach a certain temperature
  - M106 - Set fan speed
- Other commands:

When preceded by G0, the F letter corresponds to the speed (in mm/min) at which the toolhead moves. In the first red frame of figure 6, it moves at 9000 mm/min.

When preceded by G1, the F letter corresponds to the speed (in mm/min) at which the material is extruded. In the second red frame of figure 6, it is extruded at 2340 mm/min.

The E letter corresponds to the length (in mm) of material extruded. In the orange frame of figure 6, 0.18815 mm of material is extruded.

The ";" symbol allows the user to add comments which won't be read by the printer. [16]

I.2. Robotics and collaborative robots

I.2.1. Definition

Robotics is a field of engineering that focuses on the design, construction, operation, and use of robots. Robots are automated machines that can perform tasks without the need for human intervention. They are used in a variety of industries, including manufacturing, healthcare, agriculture, and military, to perform a wide range of tasks such as welding, painting, assembly, inspection, and packaging.

Robots can be classified into different types based on their size, shape, and movement capabilities. Some common types of robots include industrial robots, service robots, and mobile robots. Industrial robots are typically large, stationary machines that are used in manufacturing environments to perform tasks such as welding, painting, and assembly. Service robots are smaller and more mobile, and they are used in a variety of settings, including hospitals, schools, and homes, to perform tasks such as cleaning, delivery, and assistance. Mobile robots are self-propelled robots that can move around and perform tasks in a variety of environments.

Robotics technology is constantly evolving, and new advancements in areas such as artificial intelligence, machine learning, and sensor technology are enabling robots to become more intelligent, adaptable, and autonomous. This has the potential to revolutionize many industries and change the way of working and living [17] [18].

Collaborative robots, also known as cobots, are designed to work alongside humans in a shared workspace. They are typically smaller and safer than conventional industrial robots and can be easily integrated into existing production lines. Collaborative robots are typically easier to program and require less safety equipment, while conventional robots often require specialized training and safety precautions.

I.2.2. 6-axis robots

6-axis robots are industrial robots that are capable of moving in six degrees of freedom, allowing them to move very flexibly and precisely in space. They are commonly used for manipulation and assembly tasks in an industrial environment, but they can also be used in other applications such as welding, drilling, and milling. 6-axis robots are typically controlled by a computer and programmed to perform specific tasks by following a series of predetermined movements. They are often used in conjunction with other automated production equipment to improve the efficiency and accuracy of industrial production [19].

6-axis robots and additive manufacturing can work together in a number of ways to enhance the production process such as post-processing, assembly, quality control and material handling. Using a 6-axis robot for additive manufacturing can have a significant impact on the results of the production process such as increased precision, greater flexibility, enhanced automation, improved safety, and the ability to print complex geometries.

I.2.3. UR10e

Figure 7: Universal Robots UR10e [20]

The UR10e cobot is a collaborative robot from the Danish brand Universal Robots (Figure 7). Cobots are designed to work in collaboration with humans, offering assistance with tasks or performing specific tasks. The UR10e cobot is a 6-axis articulated arm robot that is capable of moving flexibly and precisely in the workspace. It is typically used in handling and assembly applications but can also be used in other areas such as packaging, palletizing, and product testing. The UR10e cobot is easy to program and use thanks to its intuitive interface and ability to work safely with humans through its built-in safety features that prevent collisions and injuries. It can be integrated into a wide range of production environments and is particularly suitable for small and medium-sized businesses [21].

I.3. The WAAM process

I.3.1. Definition

Wire Arc Additive Manufacturing (WAAM) is an additive manufacturing process especially used to print or repair metal products (figure 8). It is a combination of Gas Metal Arc Welding (GMAW) and additive manufacturing. The printing process is carried out by a robot composed of a welding torch that melts a wire feedstock using an electric arc and deposing metal layers following a certain toolpath, and thus, creating a desired 3D Workpiece. WAAM has the advantage of a high deposition rate, low costs, and safe operations.

The WAAM process is a part the AM family of DED and is similar to other additive manufacturing processes of the kind, such as Laser Metal Deposition (LMD) and Direct Metal Deposition (DMD), in that it involves building up layers of material to create an object. However, the WAAM process has some unique characteristics that make it well-suited for certain applications. For example, the process can be used to create large-scale objects with high accuracy and good surface finish, and it can be used with a wide range of materials, including metals, alloys, and composite materials. Additionally, the WAAM process uses filaments as raw material, is relatively fast and has a high material utilization rate, making it an attractive option for certain manufacturing applications [22].

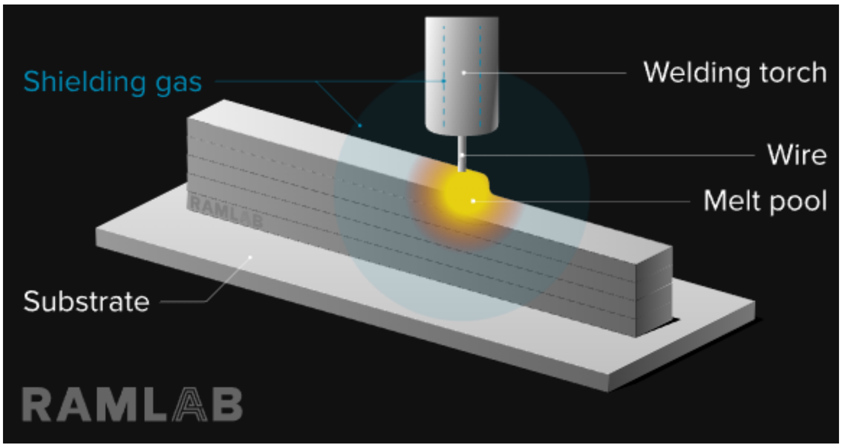


Figure 8: Scheme of the WAAM process [23]

I.3.2. 3D printing process

The printing process in WAAM involves several steps [24]:

- First, a computer-aided design (CAD) file of the part to be printed is prepared. This file contains detailed instructions on the shape and size of the part, as well as any internal features or surface details that need to be included.

- The CAD file is then sliced into a series of thin layers, typically ranging from 0.1 to 0.5 millimeters in thickness. A toolpath is generated and then are converted into machine code that the WAAM machine can understand and execute.

- The WAAM machine is set up with the appropriate wire feed, power supply, and control system to begin the printing process. The wire feed is typically made of a metal alloy such as steel, aluminum, or copper, and is fed into the machine through a spool or reel.

- The machine starts by melting the wire feed with an electric arc and depositing the molten material onto the build platform. The arc is guided by a robot arm or other motion control system, which moves the wire feed in a predetermined pattern to create the desired shape of the part.

- As the material is deposited, it cools and solidifies, forming a layer of the part. The build platform is typically cooled to help the material solidify more quickly and evenly.

- The process is repeated, building up additional layers of material until the final part is complete. The thickness of each layer and the number of layers required will depend on the size and complexity of the part being printed.

- Once the printing process is complete, the completed part is removed from the build platform and undergoes post-processing, such as heat treatment and finishing, to achieve the desired properties and appearance. This may include sanding, grinding, polishing, or other mechanical or chemical treatments to remove excess material or smooth out any roughness on the surface.

I.3.3. Differences between WAAM and FDM toolpath

Because of the characteristics of the arc welding deposition process, the WAAM toolpath has some requirements that are summarized as follows [25] [26] [27] [28] [29]:

- The geometrical accuracy must be carried out using contour patterns to print the outlines of the 2D geometries, this is because the resolution of arc welding is relatively low.

- The number of toolpath passes must be minimized. Indeed, the more passes there are, the more it will be probable that errors accumulate and make the piece unusable. It is preferable to use a continuous pass.

- The number of toolpath elements must be minimized. Indeed, for each toolpath elements the wire feed rate is readjusted. The less it is done, the more accuracy there is.

- The path planning algorithms must be simple to implement. To do so, domain decomposition is used to divide the layer geometries into a set of simpler shapes better suited for path generation.

- It also needs to consider the welding parameters, such as the wire feed rate and angle, the arc current, voltage and angle, and the travel speed, in order to control the heat input, the penetration, the bead shape, and the quality of the weld.

Some of the factors to consider when selecting a toolpath for FDM 3D printing include:

- Layer height: The thickness of each layer of material can affect the overall quality of the printed part. Using a thinner layer height can result in a higher quality part with a smoother surface finish, but it will also take longer to print.

- Infill density: The infill density refers to the amount of material used to fill the interior of the part. A higher infill density can result in a stronger part, but it will also take longer to print and may require more material.

- Support structures: In some cases, it may be necessary to include support structures to help hold up overhanging or complex features of the part during the printing process. The type and placement of the support structures can affect the quality and ease of removal of the support material.

- Printing speed: The printing speed can impact the quality of the printed part, as well as the time it takes to complete the print. Slower printing speeds can result in a higher quality part but will take longer to print.

In summary, selecting a toolpath for WAAM and FDM is different because each technology uses different methods to build parts and has unique requirements for achieving the desired quality and accuracy.

For the WAAM simulation purpose of the project, the parameters related to the geometry of the piece such as the infill pattern and the contour passes are considered to suit for WAAM at the expense of the welding parameters.

However, because the actual printing technology used is FDM, the parameters having an impact on the extrusion and the quality of the piece such as the infill density, the layer height and the printing speed will be considered to suit the best for FDM.

II. Materials and methods

In this section, the different specific materials and processes that were used in the project are described. This section is divided into two main parts: the "3D printing hardware process" and the "3D printing software process."

The "3D printing hardware process" part describes the physical components and equipment that were used in the 3D printing process and how they work together.

The "3D printing software process" part describes the software and technology that were used to control the 3D printing process and the robot motion.

Both parts are related as they collaborate to achieve the final 3D printed piece. The software process is responsible for assuring the function of extrusion and creating a specific toolpath for a CAD piece, while the hardware process uses the information provided to physically create the object.

II.1. 3D Printing hardware process

II.1.1. Tool: Motor + extruder

The tool that would be used as a printing toolhead is composed of a motor and an extruder working together. These components are presented below.

- Motor:

The motor used for this purpose was an extruder motor used on BCN3D 3D printers. It is a type of electric motor that is used in a 3D printer to drive the movement of the extruder. The extruder motor is typically a small, high-torque motor that is able to rotate at a high speed in order to push the printing material through the nozzle of the extruder. It is typically controlled by the 3D printer's control board, which sends signals to the motor to adjust its speed and direction as needed. Its function is shown on figure 9.

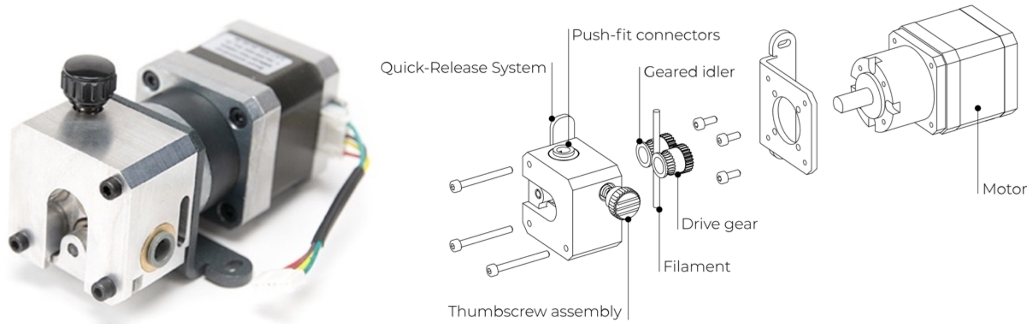


Figure 9: Sigma motor (a) [30] and its isometric CAD view (b) [31]

- Extruder:

The extruder is the device used in a 3D printer to melt and deposit the printing material (typically plastic) onto the build platform in order to create the desired 3D object. The extruder consists of a heating element called hotend, a nozzle and two fans to regulate the global temperature inside the extruder. The hotend melts the plastic, which is then forced through the nozzle by the extruder motor. The nozzle is typically very small, with a diameter of just a few millimeters, and is able to deposit the melted plastic with a high level of precision. The extruder is an essential component of a 3D printer and is responsible for creating the individual layers of the 3D object as it is being printed.

The one used in the tooling system was a 0,4 mm nozzle extruder for BCN3D printers.

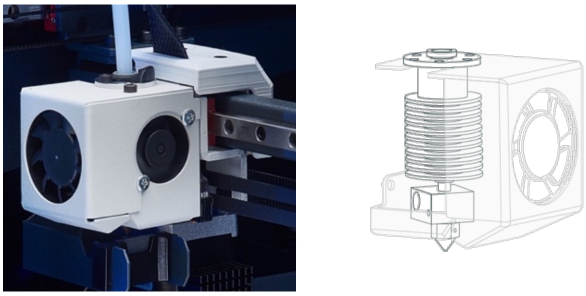


Figure 10: Extruder (a) and its isometric CAD view (b) [32]

The motor and the extruder work together to extrude filament onto the build platform.

As the extruder motor rotates, it drives a mechanism (such as a gear or a screw) that pushes the filament through the heating element, which melts it. The melted plastic is then forced through the nozzle (Figure 10).

II.1.2. Filament spool and polymer

A filament spool is a type of spool or reel that is used to hold and dispense filament for 3D printing (figure 11). The filament spool is designed to hold a long, continuous strand of filament that can be fed into the 3D printer as needed. The one used during the experiments was a 2,85 mm diameter PLA.

Figure 11: White PLA filament spool [33]

PLA (polylactic acid) is a type of biodegradable plastic that is commonly used in 3D printing. It is made from renewable resources such as cornstarch, sugarcane, or potato starch, and is known for being strong, lightweight, and easy to work with [34].

There are several reasons why PLA is popular in 3D printing:

- It is easy to print: PLA has a low melting point, which makes it easy to extrude through a 3D printer's hot end. It is also less prone to warping or curling than other types of filament.
- It is environmentally friendly: Because it is made from renewable resources and is biodegradable, PLA has a lower environmental impact than other types of plastic.
- It has good mechanical properties: PLA has good tensile strength and stiffness, which makes it suitable for a wide range of applications.
- It has a wide range of colors and finishes: PLA is available in a wide range of colors and finishes, including translucent, metallic, and wood-like. This makes it easy to achieve a variety of looks and effects.

Overall, PLA is a popular choice for 3D printing because it is easy to work with and has a low environmental impact. It is often used for prototyping and other applications where strength and accuracy are not critical. This made it a logical option for the purpose of the project [35].

II.1.3. Electronical control: Duet 2 ethernet

In this project, the electronical control of the extrusion was assured by a main board called a Duet 2.

A Duet 2 board is a type of control board that is used in 3D printers, CNC machines, and other types of robotics and automation systems. It is designed to control the movement and operation of the motors, sensors, and other components of the system.

The Duet 2 board is equipped with a powerful processor and a range of connectivity options, including Ethernet, WiFi, and USB. It is able to receive commands and input from a host computer or other controller, and to send signals to the motors, sensors, and other components of the system in order to execute the desired tasks.

The Duet 2 board is highly configurable and can be programmed using a range of software tools, such as G-code, the Duet Web Control interface, or the Duet API. It is able to support a wide range of motors, sensors, and other components, and is capable of performing a variety of tasks, such as 3D printing, CNC milling, laser cutting, and more.

Overall, the Duet 2 board is a versatile and powerful control solution for a wide range of robotics and automation applications. It is able to control the movement and operation of the system with high precision and accuracy and is highly configurable and flexible in terms of its capabilities and functionality [36].

A picture and scheme of the Duet 2 ethernet is shown of figure 12a and b.

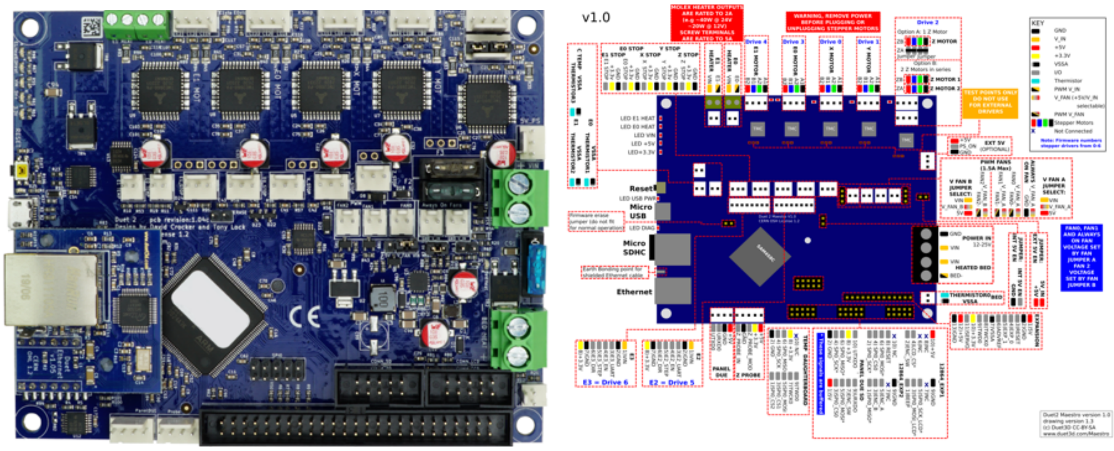


Figure 12: Picture of a Duet 2 ethernet (a)[37] and its connections (b)[38]

II.1.4. Power supply

To power with electricity the duet board, a Mean Well power supply of 24V is used (Figure 13).

Figure 13: Mean Well 24V power supply [39]

II.2. 3D printing software process

II.2.1. YAT

The Duet 2 board was connected to the computer using an ethernet cable and was recognized by using an emulator provided by the software YAT.

YAT (Yet Another Terminal) is an open-source terminal emulator software that is designed to provide an interface for accessing and interacting with serial devices, such as microcontrollers, 3D printers, and other types of embedded systems.

On YAT, an IP address is set and then written on the html search bar of an internet browser, leading to the interface of the board controller called Duet Web Control [40].

II.2.2. Duet web control

Duet Web Control (DWC) is a web-based interface for the Duet 2 control board. DWC allows users to connect to and control their Duet-powered devices over a network using a web browser, without the need for additional software or drivers.

DWC provides a range of tools and features for controlling and configuring the Duet control board and connected devices, including the ability to:

- Send and receive G-code commands to control the movement and operation of the device
- Monitor and adjust the status and settings of the device, such as temperature, fan speeds, and axis movements
- View and control the device remotely from any location with an internet connection
- Customize and configure the device using a range of advanced settings and options

An example of the interface is shown on the figure 14.

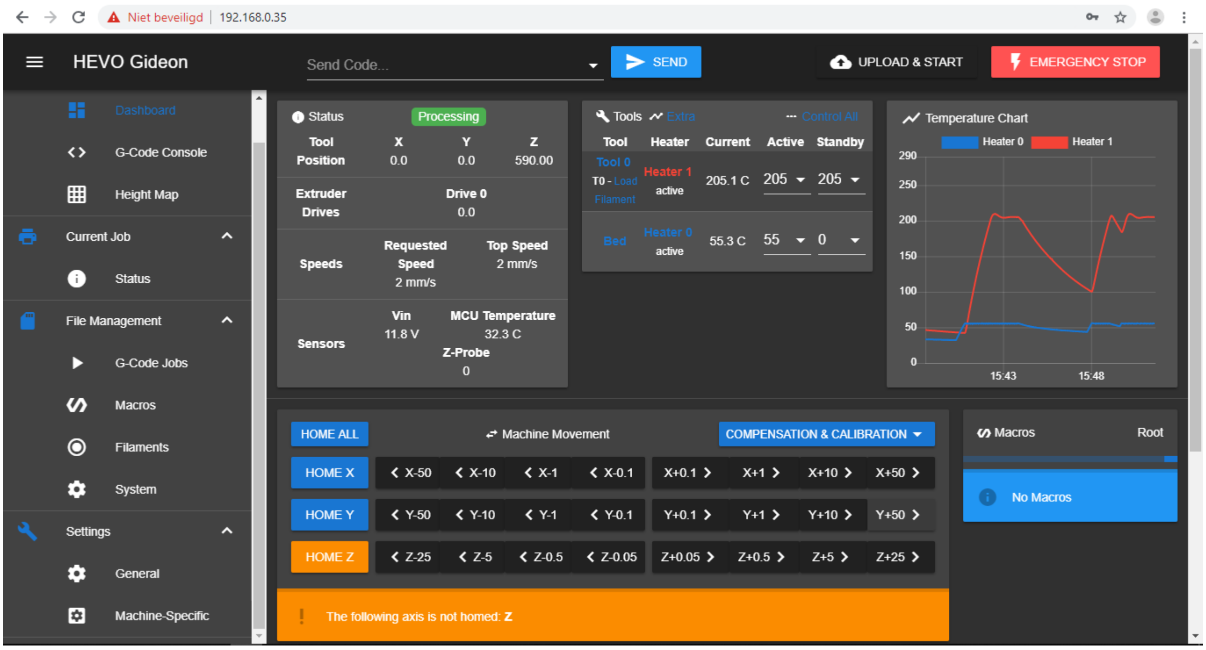


Figure 14: Duet Web Control (DWC) interface [41]

II.2.3. Mastercam and Robotmaster

The robot motion was carried out by a program generated on an off-line robot programming software called Mastercam.

Mastercam is a computer-aided manufacturing (CAM) software platform that is used to create toolpaths for machining parts on a variety of computer numerical control (CNC) machines. It is commonly used in the manufacturing and engineering industries to produce precise, high-quality parts.

It includes a wide range of features and tools for creating toolpaths for different types of machining operations, including milling, turning, and 3D sculpting. It also includes tools for creating and editing geometry, simulating machining processes, and generating toolpaths for multi-axis machines.

Robotmaster is an offline robot programming and robot simulation plugin inside Mastercam that allows users to create and simulate robot programs for manufacturing applications. It provides a range of tools for creating and optimizing robot paths, as well as for defining robot workcells and programming robot controllers. With Robotmaster, users can easily create complex robot programs for a variety of manufacturing tasks, such as welding, assembly, and material handling.

Even though there are many others software for toolpath editing in additive manufacturing, choosing these tools to carry out this part of the project seemed appropriate as they suit perfectly for a WAAM purpose. Furthermore, the distribution of Mastercam and Robotmaster is assured by Tecnocim, a company with whom CIM has close relationships and from where experts could bring the proper help in case of requirement [42] [43].

III. Upstream tasks

In this section, the different tasks that have been carried out prepare the 3D printing tests are described.

First of all, the understanding of the principle of a standard 3D printing process with an FDM printer should be done before moving on to integrating it to the robot printer.

The various tools used and created for the project are presented in the "Setting up the tools" part.

The "Converting the robot into a 3D printer" part explains how the different software are used to pass from a CAD part to a readable code by the robot.

Finally, the "3D Printing" part focuses on the configuration of the Duet Web Control to execute the printing.

III.1. Understanding and use of a 3D printing slicing software

In order to get acquainted with 3D printing, it was first necessary to start by printing pieces of various geometries with an FDM printer. To do so, the printer used was an Ender-3 Pro marketed by Creality and the slicer used was Cura Ultimaker.

Cura is aslicing software that converts 3D models into instructions that a 3D printer can understand and use to build a physical object. Ultimaker Cura is the slicing software developed by Ultimaker, a company that manufactures 3D printers. It is designed to work specifically with Ultimaker 3D printers but can also be used with other 3D printers as well.

Cura allows users to customize and optimize the printing process by setting parameters such as the print speed, infill density, and support structures. It also includes a range of features and tools to help users prepare their models for printing, including the ability to repair and fix errors, add or remove material, and add custom supports to prevent the piece from bending or the impression from failing [44].

The print settings were tuned so that they best matched the part to be printed. Because those printings were only for training purposes, only the infill, material and speed parameters were considered. The infill density was fixed at 20 % so the printing time does not take too long, and the infill pattern selected was cubic (Figure 15). The cubic pattern makes a good infill because the orientation of the cubes allow an equal and good overall strength in all directions. The material used was a generic PLA that was heated up to 200°C through a 0.4 mm nozzle and deposited on a heated bed at 60°C. The print speed was fixed at 60 mm/s.

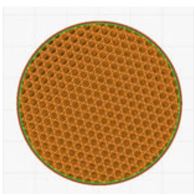


Figure 15: Cubic pattern in 3D printing [45]

Once the settings are entered, the software slices the workpiece and creates the g-code for the impression.

An example of a piece printed in 3D with the Ender-3 Pro and with black PLA is shown on figure 16, the thin filaments observables are the remains of the removes support.

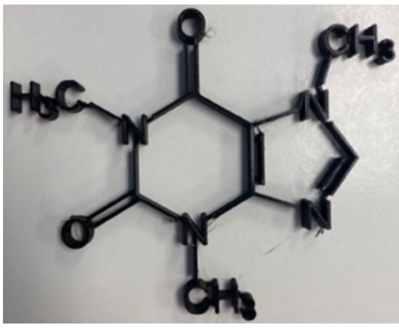


Figure 16: 3D printed piece of a caffein molecule

III.2. Setting up the tools

III.2.1. Tool flange

In order to transform the robot into a 3D printer, an adapted tooling is necessary.

The tooling that would be fixed on the robot should be designed so it could hold the elements in such an orientation that they allow the filament to pass from the motor gears end to the extruder hotend entry. It should also be fixed properly to the robot, so it doesn't move while the arms are moving, preventing then printing defaults.

It has been designed with the software SolidWorks considering the tool flange dimensions shown on figure 17b:

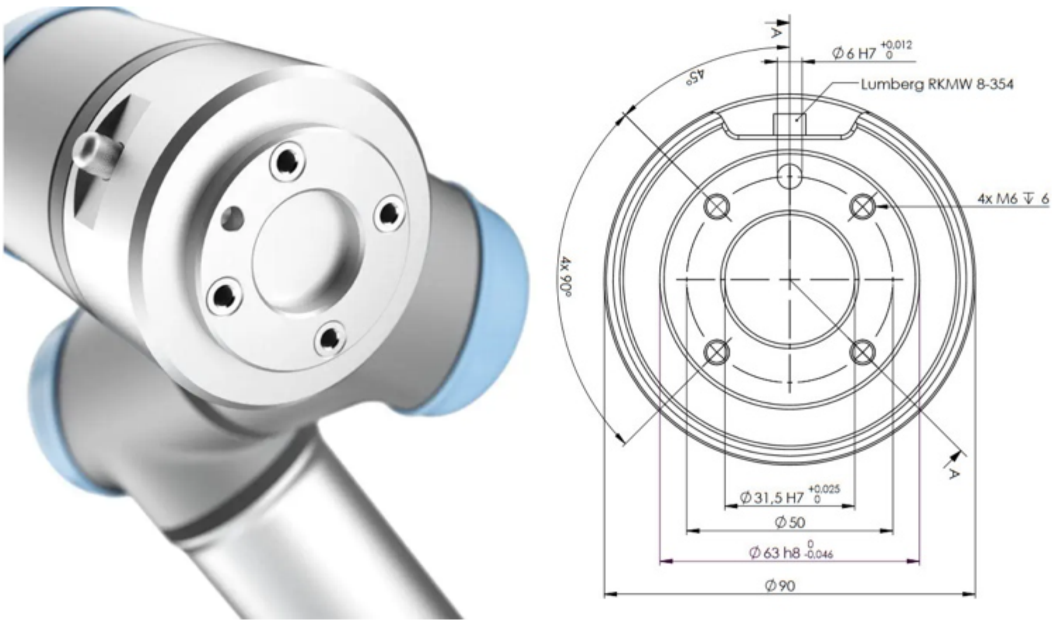


Figure 17: UR10e tool flange (a)[46] and its dimensions (b) [47]

Two holes of 7 mm of diameter are added on the surface that touches the robot tool flange so they allow a screw to be put. Five other holes are added on the surface that touches the motor and the extruder for the same purpose. All of the other elongated holes are meant to let wires pass through them if required.

The final dimensions and shape of the tooling are presented on figure 18.

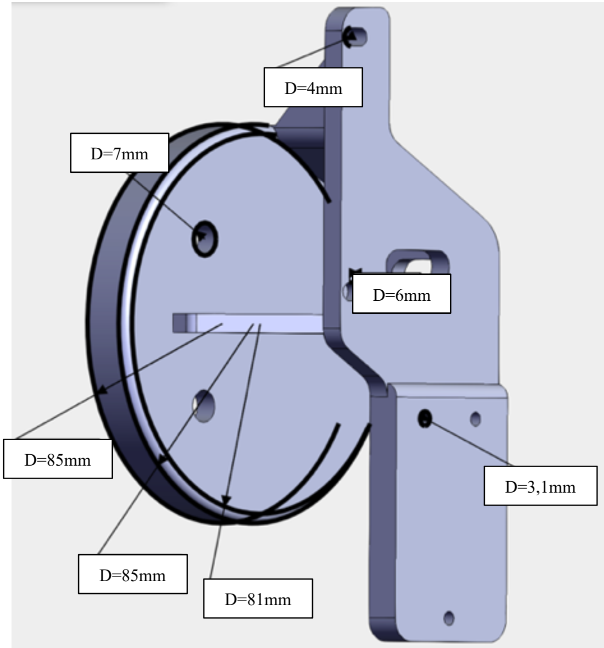
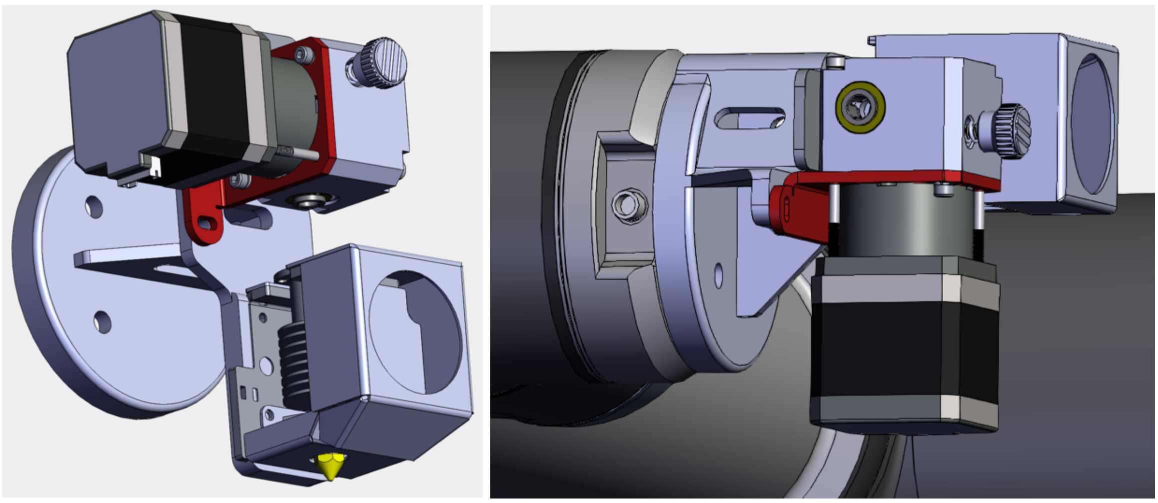


Figure 18: 3D model of the tooling and its dimensions

All of the elements were first assembled together using the SolidWorks assembly tool to check if the motor gear end and the hottend entry axis were aligned and if the part could be fixed to the robot (Figures 19a and b).



Figures 19: 3D model of the assembled tool (a) mounted on the robot (b)

All of the part working well together, the tooling was printed, assembled with the motor and the extruder and fixed on the robot. All fixations were assured by screws and nuts (Figures 20a, b and c).

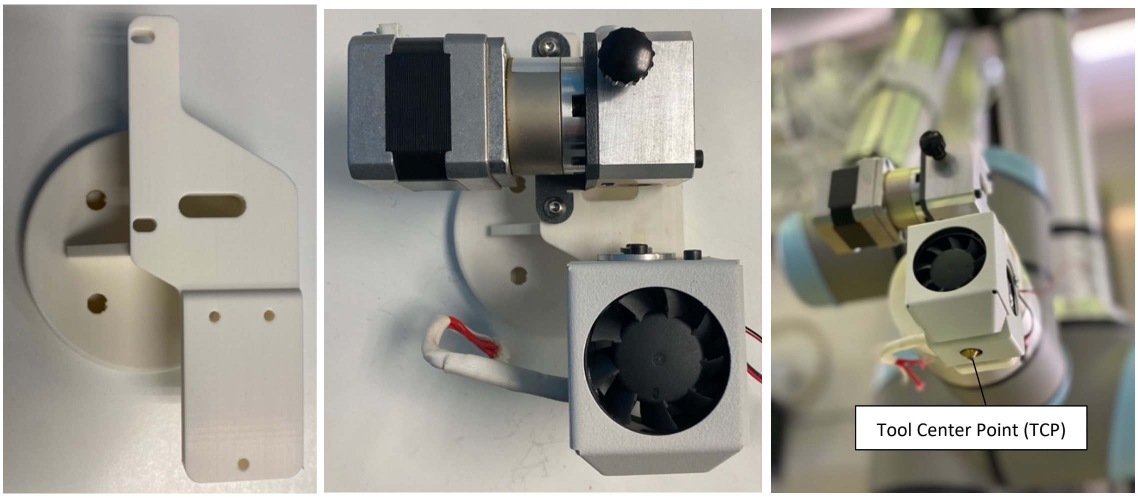


Figure 20: Printed tooling (a) assembled with the motor and extruder (b) mounted on the robot (c)

The last step to calibrate the robot was to teach it a new Tool Center Point (TCP) telling it where the printing part of the extruder where (Figure 20c).

Indeed, when changing tools on a UR10e robotic arm, it is necessary to set a new TCP in Polyscope. The TCP is the point on the tool that is used as a reference point for the arm to know where the tool is located in relation to the workpiece.

Setting a new TCP in Polyscope involves measuring the location of the TCP on the new tool and inputting the coordinates into the software. This can be done using a touch probe or other measuring device, or by entering the coordinates manually.

In this project, the TCP has been determined using Polyscope. To do this, the robot was moved to a desired position using the virtual joystick. Then, this action was repeated four different times from various angles of the tool and positions of the robot arms, so the TCP was determined as precisely as possible.

Once the new TCP was set in Polyscope, the arms were able to properly control the new tool and produce accurate results. [48]

III.2.2. Filament spool holder

A filament spool holder is a device that is used to hold a spool of filament in place while it is being fed into the 3D printer. Filament spool holders are typically used in conjunction with 3D printers that use the Fused Deposition Modeling (FDM) technology.

Filament spool holders are typically mounted on the side or back of the 3D printer, or on a separate stand nearby.

The one used with the robot should be designed so it can be fixed on its closest arm to the tooling. It has also been done with Solidworks [49] considering the robot arm diameter and the filament spool diameter and dimensions, that were measured backwards (Figure 21).

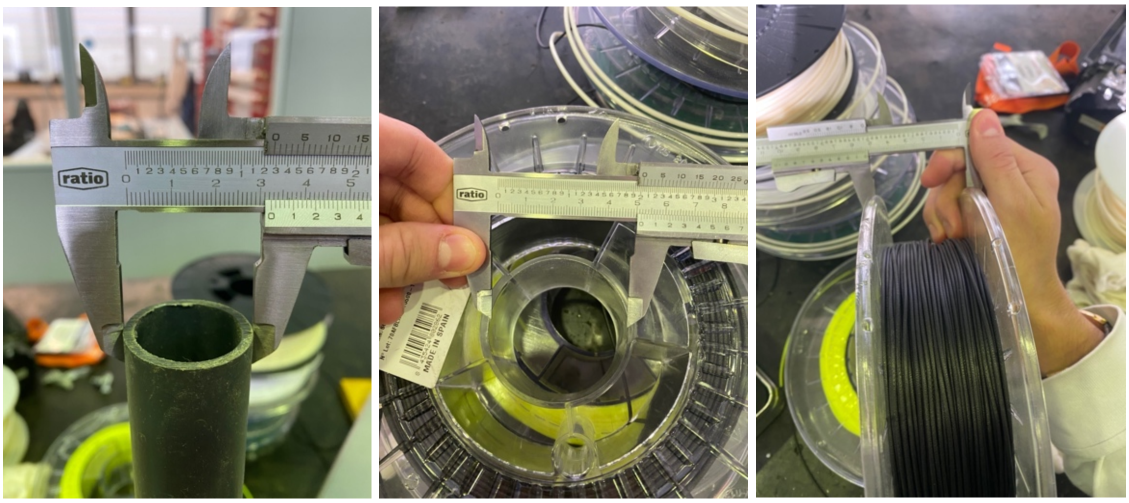


Figure 21: Filament spool dimensions

It ended up as the three following pieces (Figure 22) that were to be mounted together using screws and nuts.

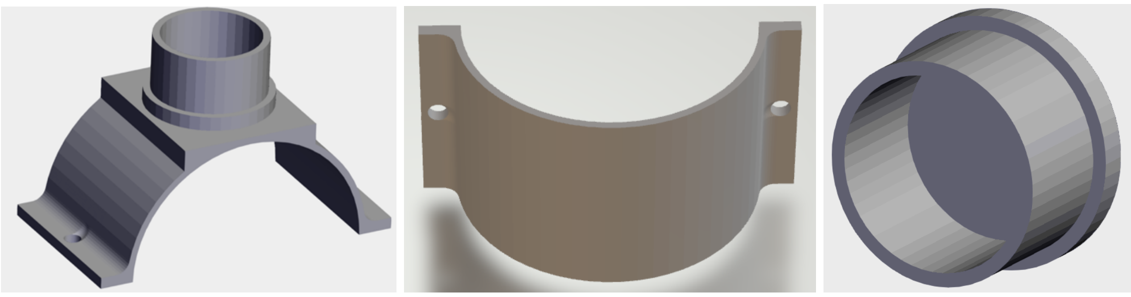


Figure 22: 3D models of the three different parts of the filament spool holder

Then, they were mounted on the robot using adhesive material to prevent the whole part from sliding on the arm. A piece of a plastic tube has been cut to be placed on the cylinder's hole (Figure 23a).

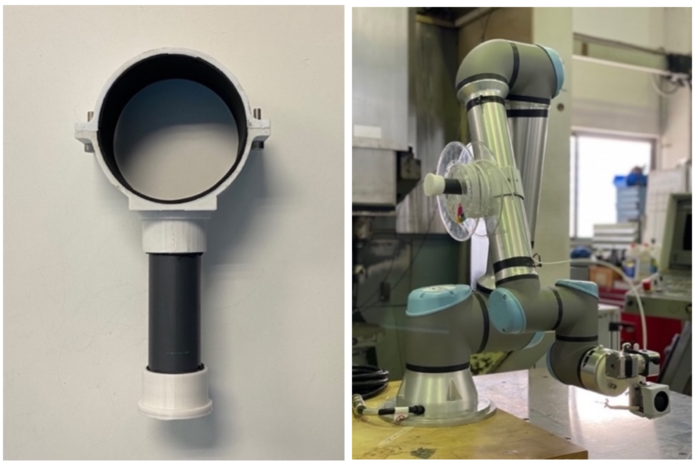


Figure 23: Printed filament spool holder (a) and its fixation on the robot (b)

III.2.3. Connecting the Duet 2 ethernet

The power supply of 24V is wired to the board "power in" entry and the other components were linked using cut wires and then welded to the board, the connections are presented in figure 24 and in figures 25a and b [50].

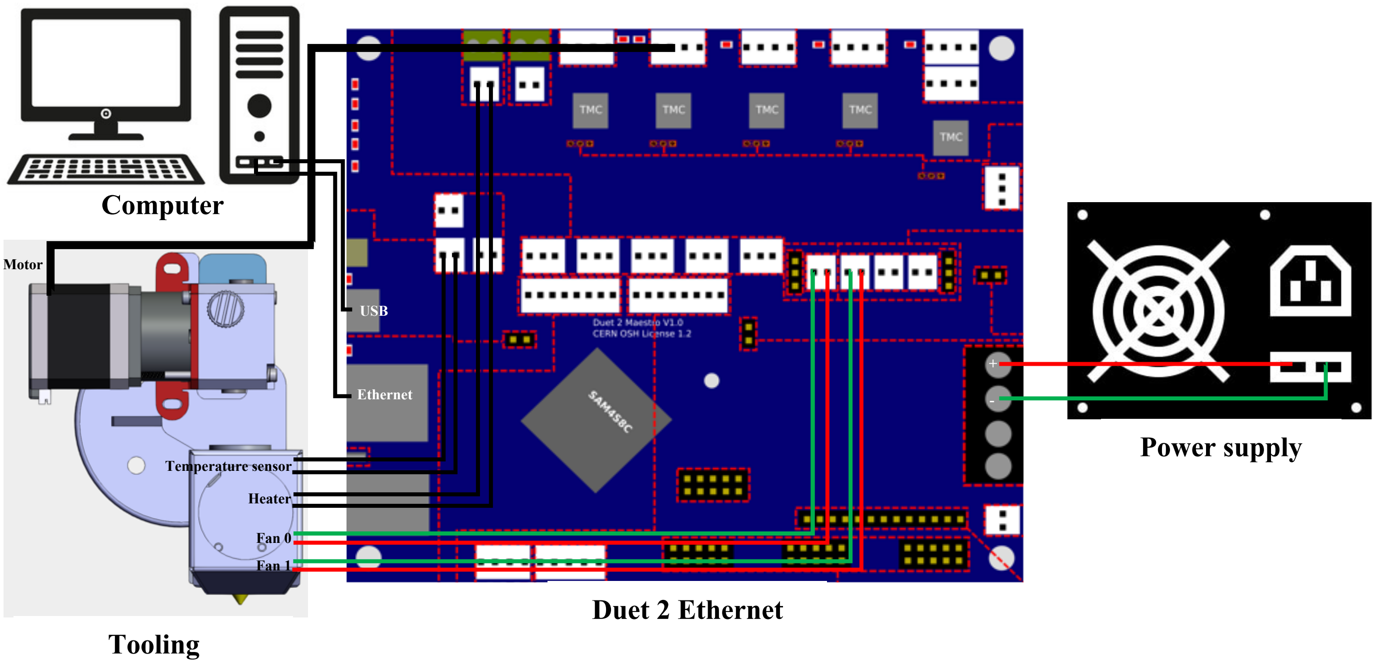


Figure 24: Scheme of the connections between the Duet board and the other components

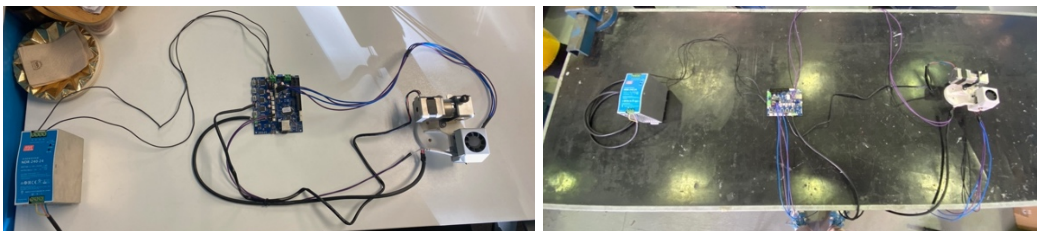


Figure 25: Connections between the Duet board and the other components

Finally, the wires were stripped to the robot to prevent them from tangling when the robot is in motion (Figure 26).

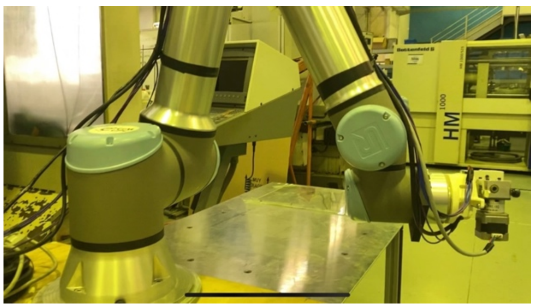


Figure 26: Final setup

III.3. Converting the cobot into a 3D printer

III.3.1. Understanding the UR10e

Before any programming or software work, it was important to understand how the robot moves manually. The UR cobots are controlled by their graphical user interface (GUI) called PolyScope.

PolyScope is a software platform developed by Universal Robots for programming and operating collaborative robots. It is the user interface of the robot, located on the teach pendant panel, and allows users to access a wide range of features and functions.

With PolyScope, users can control the robot's movements, write programs, monitor the robot's performance, and troubleshoot any issues. It includes a visual programming interface that allows users to drag and drop blocks of code to create robot programs, as well as tools for simulating and testing robot programs and for monitoring and troubleshooting cobots during operation. PolyScope also has a built-in safety toolbox to help users create safe and secure automation solutions.

The FreeDrive feature lets users physically move the robot to the perfect position with an effortless press of a button.

It is this last function that was used to get familiar with the cobot and that helped understanding its behavior of motion [51] [52].

III.3.2. Creating a program

Making the robot follow the desired toolpath properly is a fundamental task of the project. Indeed, selecting a proper toolpath in 3D printing is important because it can significantly impact the quality and accuracy of the final printed part. The way in which the nozzle moves, and the orientation of the layers can have a significant effect on the strength, surface finish, and overall accuracy of the printed part [53].

The toolpath creation on Mastercam consists of three major steps which are described below:

- Step 1: Selecting a machine

Machine selection is an important step in Mastercam because it determines the specific capabilities and limitations of the machine that will be used to manufacture the part.

By selecting the appropriate machine definition in Mastercam, it ensures that the generated toolpaths are optimized for the specific capabilities of the machine. For example, selecting a machine definition for a 3-axis milling machine will ensure that the toolpaths are generated with the appropriate axis limitations and tool motions. Similarly, selecting a machine definition for a 3D printer, will ensure that the toolpaths are optimized for the specific material and process parameters of the printer.

In addition to defining the specific capabilities and limitations of the machine, selecting the appropriate machine definition in Mastercam also allows to use the appropriate tools and strategies for the particular manufacturing process. This can help ensure that the toolpaths are efficient and accurate, and that the final manufactured part meets the desired quality and tolerances.

The delivered version of Mastercam was installed with a preset of machines including the UR10e. It is chosen so it selects the Universal Robots post processor for the code generation in Robotmaster.

- Step 2: Creating a 3D model

While it is possible to import or create and manipulate 3D models in Mastercam, it is not a dedicated 3D modeling software and is not intended for creating 3D models from scratch. To manipulate a 3D model in Mastercam, it will generally need to use a separate 3D modeling software and then import the completed model into Mastercam for further processing.

However, because the first printing trials were meant to test the process, very simple shapes were designed, therefore the CAD section inside Mastercam was enough for this purpose.

An example of the creation of the 3D model of a cone is shown in figure 27.

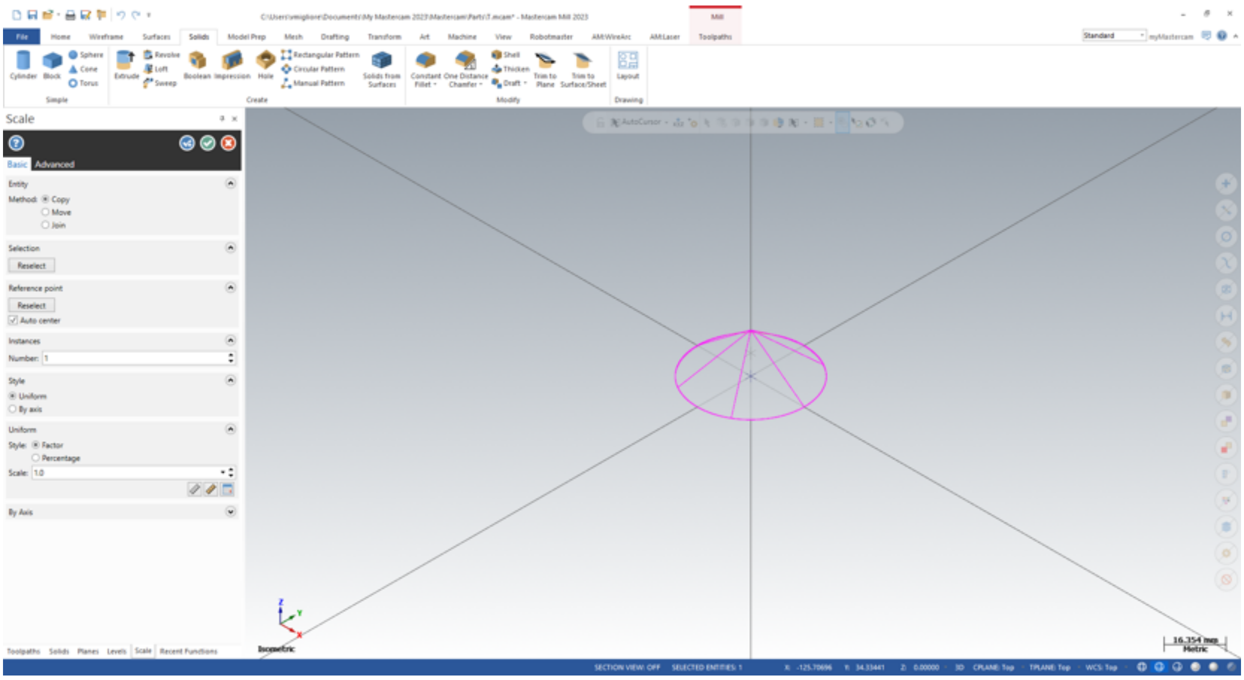


Figure 27: 3D model of a cone on Mastercam

In this section, the dimensions and every aspect of the part can be set.

- Step 3: Setting up toolpath parameters

Setting up the toolpath parameters in Mastercam is important when using the software for additive manufacturing because it determines the specific material, process, and machine parameters that will be used to produce the 3D printed part (Figure 28).

In order to generate a toolpath specifically for additive manufacturing, a tool called Aplus is used. Aplus is a plugin for Mastercam that provides additional tools and features for programming and machining parts using additive manufacturing methods. The plugin is developed by Aplus Computer Systems, Inc., a company that specializes in software solutions for the manufacturing industry [54].

The version of Aplus included in Mastercam allowed a toolpath generation for WAAM and Laser additive manufacturing. Because the objective of the project was to simulate a WAAM process, the WAAM toolpath generator was used.

Furthermore, as the moving part and printing part were totally separated in that project, the only relevant parameters to tune were the following ones:

- The moving speed of the robot (in mm/min)
- The toolpath pattern
- The distance between each layer (in mm)
- The overlap between two layers (in mm)
- The distance between two passes (nozzle diameter, in mm)

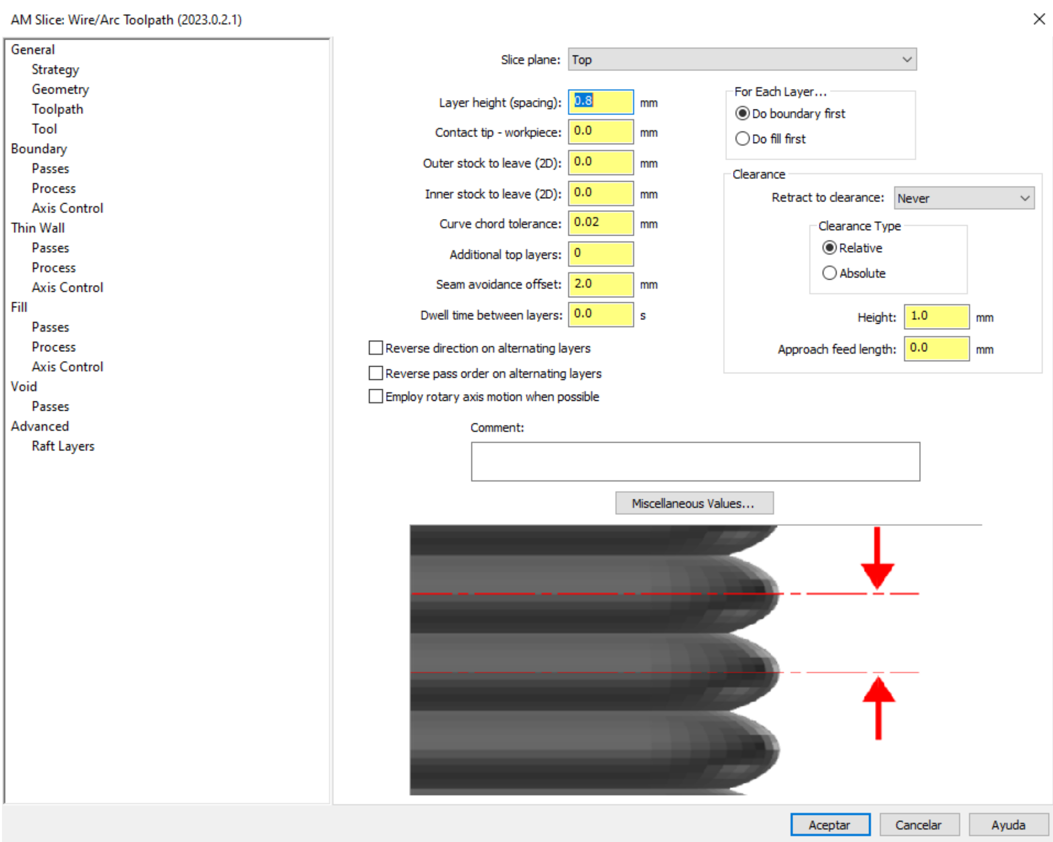


Figure 28: Examples of toolpath parameters

The script code generation on Robotmaster consists of three major steps which are described below:

- Step 1: Global settings

In Robotmaster, the global settings refer to a set of configuration options that apply to the entire project or program. These settings can be accessed and modified through the "Global Settings" dialog box in Robotmaster.

Some of the options that may be included in the global settings in Robotmaster include:

- Robot type: This setting determines the specific type and model of the robot that will be used to execute the program.

The robot selected was the UR10e, previously added manually on the software.

- Work coordinate system: This setting determines the origin and orientation of the robot's coordinate system, which is used to specify the position and orientation of the robot and its tools.

These values also set the position of approach and retract of the robot, they correspond to the position of its 6 axes, they are shown on figure 29.

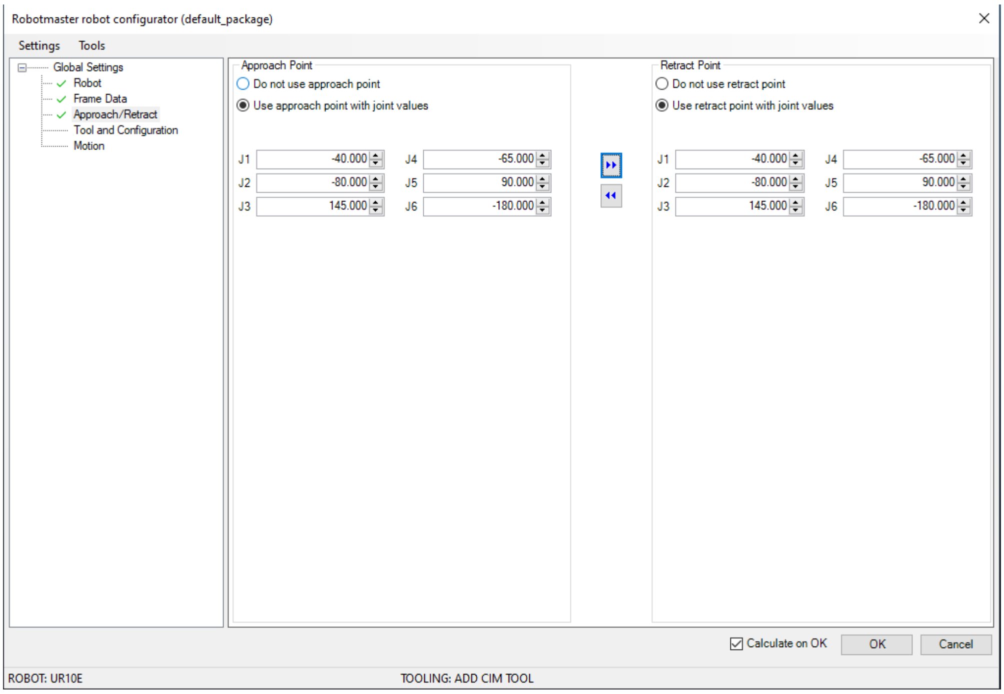


Figure 29: Work coordinate system values on Robotmaster

- Zone data: This setting determines the size and shape of the robot's work envelope, as well as any physical constraints or limitations that may affect the robot's motion.

- Safety settings: This setting determines the safety parameters and behavior of the robot, such as the minimum and maximum speeds, acceleration, and deceleration values.

- Tool and frame definitions: This setting determines the specific tools and frames that will be used by the robot during the program, as well as their dimensions and orientation.

The tool selected was the tooling (Figure 22) designed and printed upstream, assembled to the motor and extruder on SolidWorks and implanted on the software manually.

The frame defines the location where the printing starts relatively to the base of the robot, and was determined backwards (Figure 30)

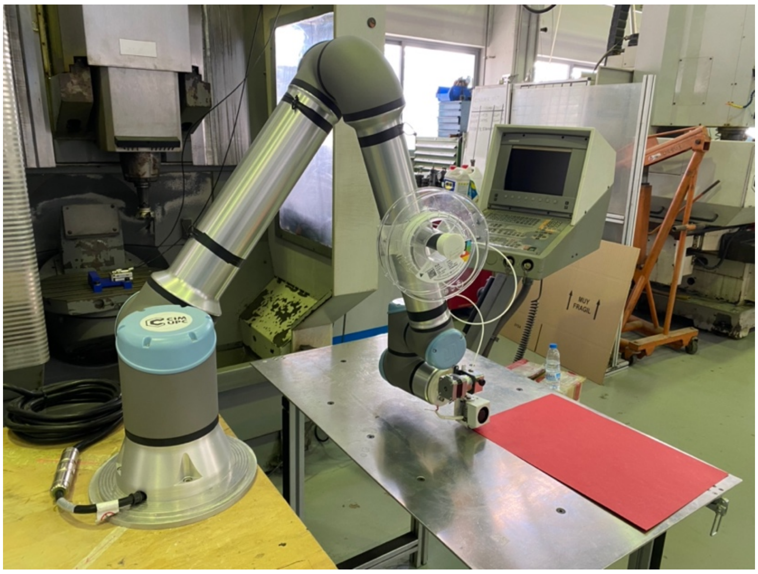


Figure 30: Frame coordinates determination

The coordinates chosen for the frame were determined considering the robot work environment, they are shown on figure 31.

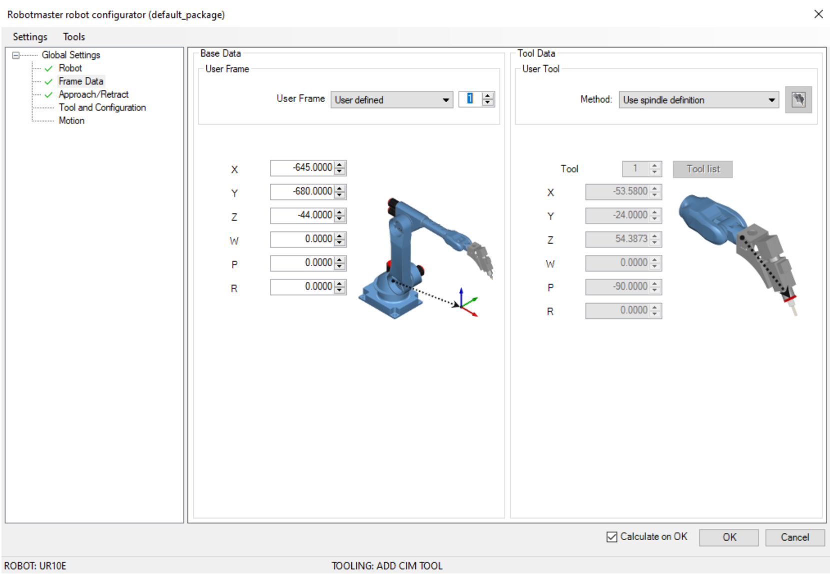


Figure 31: Frame coordinate values on Robotmaster

- Motion settings: This setting determines the specific motion parameters that will be used by the robot during the program, such as the interpolation method, velocity mode, and feed rate.

The configuration of the approach of the robot towards the frame is an important step because if it not well done, there is a probability of collision during the printing. The settings were also chosen considering the robot working environment, as shown in figure 32.

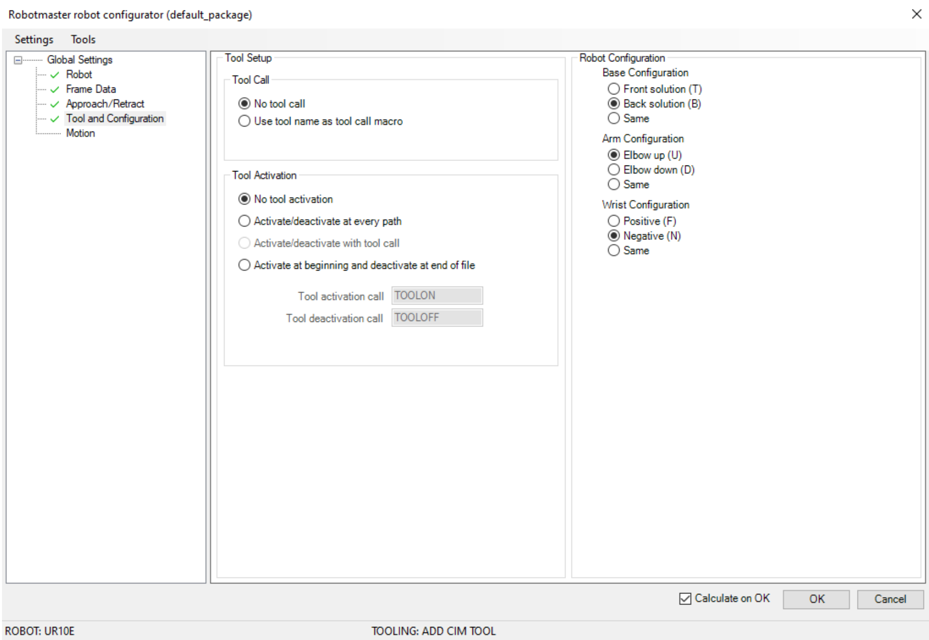
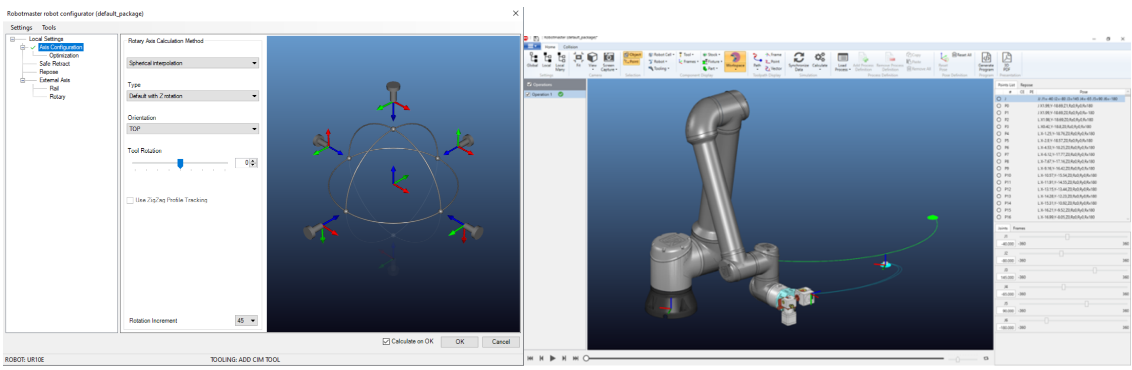


Figure 32: Robot configuration on Robotmaster

- Step 2: Local settings

In Robotmaster, the local settings refer to a set of configuration options that apply to a specific motion or operation within a program. These settings can be accessed and modified through the "Local Settings" dialog box in Robotmaster.



Figures 33 and 34: Local settings (33) and toolpath simulation (34) on Robotmaster

This operation will allow to calculate the simulation of the robot executing the pre-generated toolpath on Mastercam (Figures 33 and 34).

- Step 3: Code generation

In Robotmaster, code generation refers to the process of creating a script or program that can be used to control a robot and execute a specific task or series of tasks.

It is done by selecting the code generation option from the "File" menu in Robotmaster, choosing the specific programming language and format that needs to be used for the code.

Then, the code is generated (Figure 35) and can be found in the output location specified backwards and with its given file name.

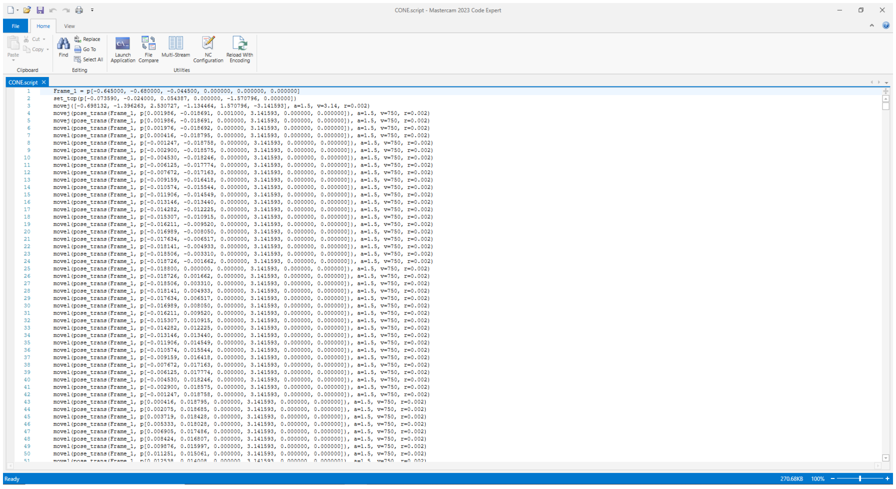


Figure 35: Generated code by Robotmaster

The generated code was a URscript code.

URscript is a proprietary script language developed by Universal Robots for programming and controlling their cobots.

URscript includes functions and commands for controlling the movements and actions of cobots. It also includes tools for integrating cobots with other equipment and systems, as well as for handling data and communication between the cobot and other devices [55].

III.3.3. Uploading a script file in the robot

Once the script code was generated, it was transferred to Polyscope using a USB key inserted into the teach pendant panel.

The process of executing the program is described as follow:

1. In polyscope, go to "Programm" -> Advanced -> Script (Figure 36a)
2. Click on Line, select Archive and click on Edit. (Figure 36b)
3. Click on Open -> USB and select the script file. (Figure 36c)
4. Click on Open -> USB and select the script file. (Figure 36d)
5. Click on Exit, on the play buton and select Reproduce from the selection.

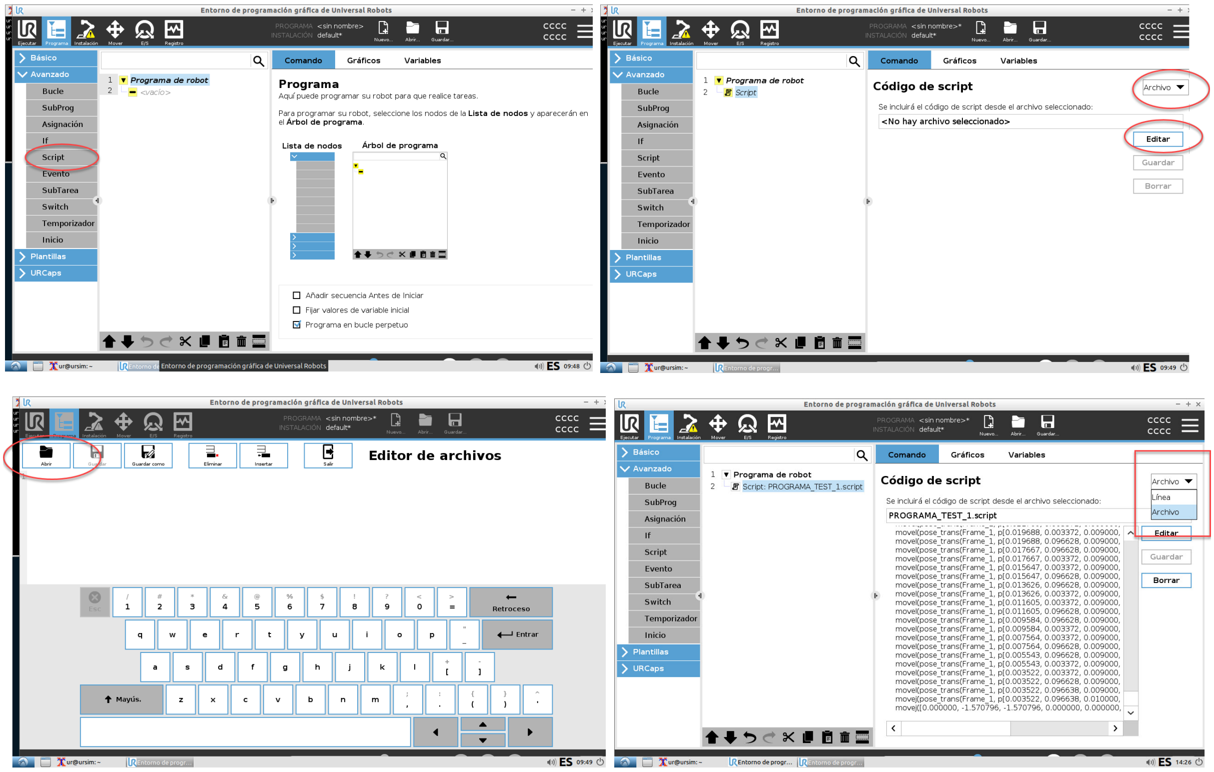


Figure 36: Execution of a program in Polyscope

At this moment, the robot will start executing the program and moving the TCP of the tool where the designed piece must be printed of the selected frame, which was a glass with the following dimensions: 29,5 x 42 cm, placed on a table nearby the robot.

III.4. 3D Printing a part

The initial idea of the project was to find a way to calibrate the robot motion and the extrusion control automatically. However, this proved to be a complicated task.

Indeed, the extrusion process and the robot motion are both critical aspects of 3D printing.

In a regular FDM printer, the extrusion process is controlled by the use of a stepper motor that is connected to the extruder and that is controlled by the printer's firmware. The firmware controls the movement of the stepper motor and the temperature of the extruder to ensure that the correct amount of filament is extruded. This is done by sending a specific number of pulses to the stepper motor, which determines the distance the filament is pushed through the extruder. The firmware also monitors the temperature of the extruder and adjusts it as necessary to ensure that the filament is at the correct temperature for extrusion. Additionally, the printer's firmware also controls the movement of the print head. This includes the movement of the print head in the x, y and z axis as well as the speed of movement.

All of these commands are sent in the same G-code directly uploaded to the printer's firmware and a specific amount of material corresponding to the toolpath passes is extruded at the appropriate velocity.

However, in this case it needs to be done while the robot motion must also be accurate to ensure that the print is of high quality. To do so, the code to upload on the robot should include an extrusion parameter, which was not possible using Mastercam as it was programmed for WAAM and not for FDM. A possible software to use could be RobotDK, which is another solution for robot programming and simulation and that allows the generation of a G-code to put in the Duet 2 and a script code to put on the robot. This software was not chosen as Mastercam was already used during the whole project.

Furthermore, the extruder should be connected directly to a robot output that would be called in the code every time an extrusion or retraction of filament is needed. Unfortunalety, this was impossible to manage within the timeframe of the internship due to the programming knowledge requirement that was lacking.

For the previous reasons, the robot motion and the extrusion control have been controlled separately. The extrusion process is described below:

For the first printing, on the DWC, a code is entered to calibrate the temperature sensor of the extruder [56].

In 3D printing, the extruder is responsible for melting and depositing the filament material. The temperature of the extruder is a critical factor in the success of the print, as it affects the flow and viscosity of the molten material, as well as its ability to bond with the previous layer.

If the temperature sensor is not calibrated accurately, the extruder may not reach the correct temperature, which can lead to problems such as under- or over-extrusion, poor layer adhesion, and warping. Calibrating the temperature sensor ensures that it is reading the temperature accurately, which helps to ensure consistent and reliable prints.

The following command is sent to the duet controller: `M303 H1 S210`

- M303 is the command to run the heater and H1 corresponds to the heater number one. In that case the extruder was composed of only one heater.

- S210 means that the heater must reach a temperature of 210°C before starting the extrusion.

Once this step is finished, the program gives a code line to enter on the g.config file present on the parameters section of DWC. The g.config file is a configuration file that specifies how the Duet 3D printer controller should behave. It contains a range of settings and options that control various aspects of the printer, including the communication protocols, the movement and positioning of the printer axes, and the behavior of the printer firmware. The file is written in the G-code programming language.

An example of code line to enter is the following one:

```
M307 H1 R2.186 K0.17:0.11 D5.67 S1.00 V24.0
```

- The H1 parameter specifies the heater.

- The R parameter is the heating rate in degC/sec at full power when the heater is close to room temperature.

- The K parameter is the heater model, the software includes non-Newtonian cooling to predict the variation of cooling rate with temperature and the maximum temperature that would be reached at continuous full power.

- The D parameter is the dead time, it is the delay between a change in PWM and an appreciable effect on the rate of temperature change.

- The S parameter is used to limit the PWM, for example S0.8 will limit the PWM to 80%.

- The V parameter is the VIN supply voltage at which the R parameter was calibrated.

Once the calibration done, a G-code for continuous extrusion must be entered in the DWC, an example of such a G-code is shown on figure 37.

```
; set up printer and filament parameters
M106 P0 S0 ; turn off fan
M109 S190 ; set nozzle temperature to 190C
M104 S190 ; set extruder temperature to 190C
G21 ; set units to millimeters
G90 ; set absolute positioning

; prime the extruder
G92 E0 ; reset extruder position
M83 ; set extruder to absolute mode
G1 F1500 E5 ; extrude 5mm of filament to prime the extruder
G92 E0 ; reset extruder position

; start continuous extrusion
G1 F60 E5000 ; extrude filament continuously at 60mm/s until 5000mm is
reached

; cool down temperatures
M104 S0 ; turn off extruder temperature
M109 S0 ; turn off nozzle temperature
```

Figure 37: Example of a code for continuous extrusion

This G-code script includes several lines of code to set up the printer and filament parameters, as well as to prime the extruder, start the continuous extrusion, and cool down the temperatures.

The first two lines (M106 P0 S0 and M109 S190) turn off the fan and set the nozzle temperature to 190°C, respectively. The third line (M104 S190) sets the extruder temperature to 190°C. The fourth line (G21) sets the units to millimeters, while the fifth line (G90) sets absolute positioning.

The next four lines (G92 E0, M83, G1 F1500 E5, and G92 E0) prime the extruder by resetting the extruder position, setting the extruder to absolute mode, extruding 5mm of filament, and resetting the extruder position again.

The seventh line (G1 F60 E5000) starts the continuous extrusion by extruding the filament at a speed of 60 mm/s until a total length of 5000 mm is reached.

Finally, the last two lines (M104 S0 and M109 S0) cool down the temperatures by turning off the extruder temperature and nozzle temperature, respectively.

At the end of the printing, the piece is removed from the glass and the robot program is stopped.

Some pictures of the robot printing are presented in figures 38, 39 and 40 below.

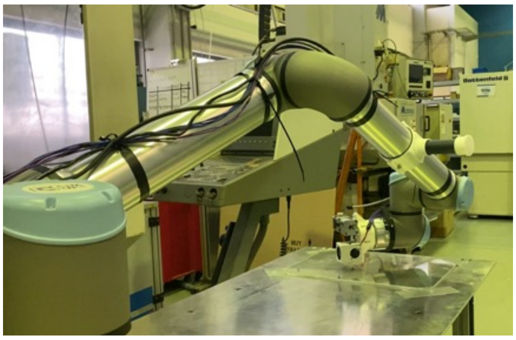


Figure 38: UR10e approaching its TCP on the frame

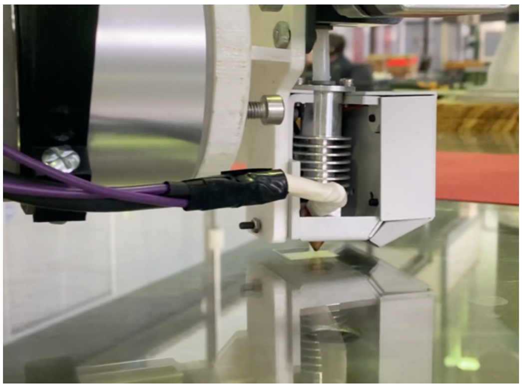


Figure 39: UR10e printing the first layer of the infill of a cube

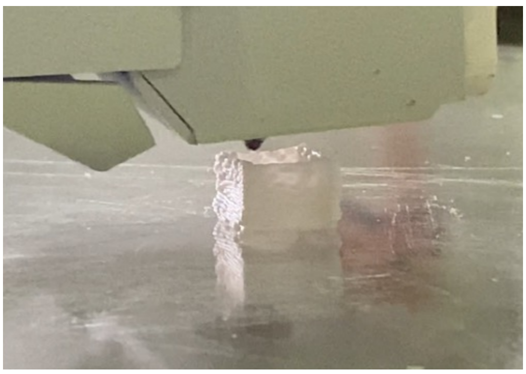


Figure 40: UR10e printing a cube with only boundary toolpath

IV. Results and discussion

IV.1. First set of trials

In these first set of trials, the printing speed was set at 15 mm/s.The extrusion temperature at 205°C which is suited for PLA.

The first trial of printing was a simple piece for which the 3D model has been designed on Robotmaster.

Because of its simple geometric shape with straight edges and flat faces, choosing a cube as a first trial makes it easy to measure and evaluate the quality of the print. Indeed, it is a simple and straightforward way to test the printer and robot's calibration and ensure that they are able to produce accurate and precise prints.

However, the attempt turned out to be a failure and was stopped prematurely. (Figure 41)

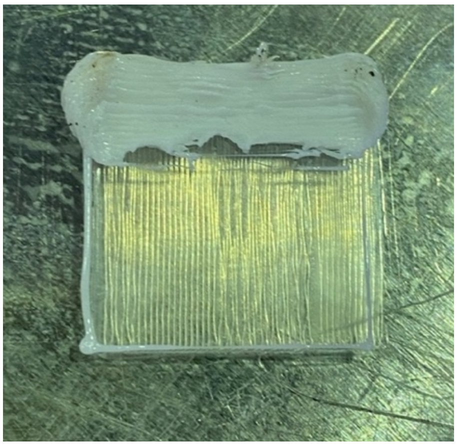


Figure 41: First trial to print

Even though the first layer's boundary and infill were observable, the second layer was not printed correctly, and the PLA stacked and was not deposited properly. It can be explained by the distance between the tool's TCP and the bed which was not high enough. As the nozzle was in contact with the bed it blocked the extrusion and was not high enough when transitioning to the second layer.

The corrected frame coordinates were entered in Robotmaster for the following print attempts.

The following series of prints had the purpose to try different geometries, sizes, and toolpaths on basic shapes. It was also meant to test different toolpath parameters to observe their effects on the printed pieces.

The figure 42 shows the prints of cubes with (cube number 7) and without infill (cubes number 1, 2, 3, 4 and 6).

Figure 42: First series of trials

The prints number 1 and 2 on figure 42 were not successful because the distance between consecutive layers was too high (1 mm), thus, they could not stick together.

This parameter was corrected to 0,5 mm and the rest of the prints were done that way. The prints number 3, 4, 5 and 6 were done with various robot motion speed rate, respectively 50%, 45%, 40 % and 35 %. It can be observed that the quality of printing increases while the speed decreases.

The print number 7 was not successful because the robot motion speed was constant and too high for the infill.

The figure 43 shows the attempts of prints of cubes with higher dimensions (number 1 and 2) and a cone (number 3).

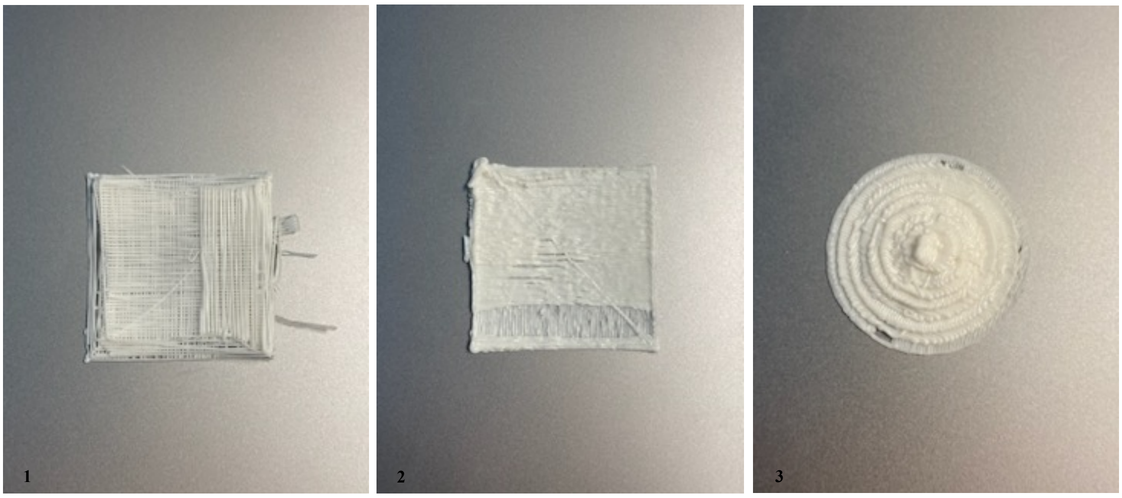


Figure 43: Second series of trials

The prints number 1 and 2 were not successful because the distance between the two passes was too high (1 mm) and because the motion speed was too high.

The print number 3 was done completely but the infill pattern chosen was not suitable for a cone. A spiral pattern would have been adapted but the size of the code did not allow its execution in the robot.

IV.2. Second set of trials

The aim of the second set of trials of printing was to study the influence of the main printing parameters on the results. To do so, the same 3D model was printed in three series while varying one parameter each time.

The results are presented in tables 1, 2 and 3. The parameter changed is in bold.

In this series of tests, the distance between two layers of the piece was studied to identify which value to keep for the following tests.

						
Distance between layers (mm)	**0,5**	**0,6**	**0,7**	**0,8**	**0,9**	**1**
Overlap (%)	50	50	50	50	50	50
Distance between passes (mm)	0,4	0,4	0,4	0,4	0,4	0,4
Temperature (°C)	205	205	205	205	205	205
Printing speed (mm/s)	15	15	15	15	15	15
Motion speed (%)	35	35	35	35	35	35

Table 1: Third series of trials

The most successful print was the one with a distance of 0,5 mm between two layers. Indeed, the closest the layers are, the more they stick to each other. This improves the global shape and quality of the printed piece and results in a smoother surface finish, reducing the visibility of layer lines.

Because the distance between layers was reduced, the overlap had to change. The overlap refers to the amount by which one layer of a printed object overlaps with the previous layer. It is used to control the strength and quality of the final printed object. A larger overlap will result in a rougher surface finish while a smaller overlap will result in a smoother surface finish. For this reason, it has been set at 0% for the rest of the experiments.

These parameters were kept for the following tests and the distance between two passes was studied in the following series according to the conditions defined in Table 2.

					
Distance bewteen layers (mm)	0,5	0,5	0,5	0,5	0,5
Overlap (%)	0	0	0	0	0
Distance between passes (mm)	**0,4**	**0,5**	**0,6**	**0,7**	**0,8**
Temperature (°C)	205	205	205	205	205
Printing speed (mm/s)	15	15	15	15	15
Motion speed (%)	35	35	35	35	35

Table 2: Fourth series of trials

It is observable that when increasing the distance between passes, the quality of printing decreases. Indeed, increasing the line spacing will result in a coarser surface finish, as the lines will be farther apart, leaving more visible gaps between them. This can also result in weaker and less durable prints, as the infill will be less dense and therefore less supportive. Thus, the best result was the one with a distance of 0,4 mm between two passes, corresponding to the nozzle diameter.

This parameter was kept for the following tests where the robot motion speed was studied in the series defined in Table 3.

						
Distance bewteen layers (mm)	0,5	0,5	0,5	0,5	0,5	0,5
Overlap (%)	0	0	0	0	0	0
Distance between passes (mm)	0,4	0,4	0,4	0,4	0,4	0,4
Temperature (°C)	205	205	205	205	205	205
Printing speed (mm/s)	15	15	15	15	15	15
Motion speed (%)	**20**	**30**	**35**	**40**	**45**	**50**

Table 3: Fifth series of trials

It can be observed that increasing the robot motion speed resulted in a slight better quality of printing. However, it is not relevant here because the result might not have been the same for another printing speed.

Overall, in every attempt some discontinuities in the toolpath passes were observed. This can be explained by the vibrations of the robot while printing due to its incertitude of motion of 0,05 mm [57].

IV.3. Third set of trials

Because none of the prints were fully satisfactory in terms of quality, the printing speed and motion speed should be optimized. To do so, the important parameter to identify was the microstepping and the steps per millimeter of the stepper motor.

Microstepping is a method of controlling stepper motors that involves dividing each full step of the motor into smaller microsteps. This allows for finer control over the motor's position and can result in smoother movement and less audible noise during impression.

In the config.g file of the DWC, the "steps per millimeter" is a setting that controls the number of steps the stepper motors need to take in order to move the printer's extruder by 1 mm. This setting is used to calibrate the printer's motion and ensure accurate and precise movement.

These settings have been calculated to correspond the best for the extruder motor and have led to an optimal extrusion speed of 0,1 mm/s.

Having the extrusion speed and knowing the filament and nozzle dimensions, it is possible to calculate the appropriate motion speed:

Filament diameter: d_f = 2,85 mm => filament's section surface:

$$S_s = \pi.(\frac{d_f}{2})^2 = 6{,}38\,mm^2$$

Nozzle diameter: d_n = 0,4 mm => deposit surface:

$$S_d = layer\ height.d_n = 0{,}1.0{,}4 = 0{,}04\,mm^2$$

The ratio between these two surfaces is calculated:

$$r = \frac{S_f}{S_d} = 159{,}5$$

The following formula allows to pass from the extrusion speed to the motion speed Vr:

$Vr = Ve.r = 15{,}95\,mm/s$ with Ve: Extrusion speed (Ve = 0,1 mm/s).

A motion speed of 15,95 mm/s or 957 mm/min is determined.

These parameters were kept for the following tests, the results are shown on figures 44, 45 and 46 below.

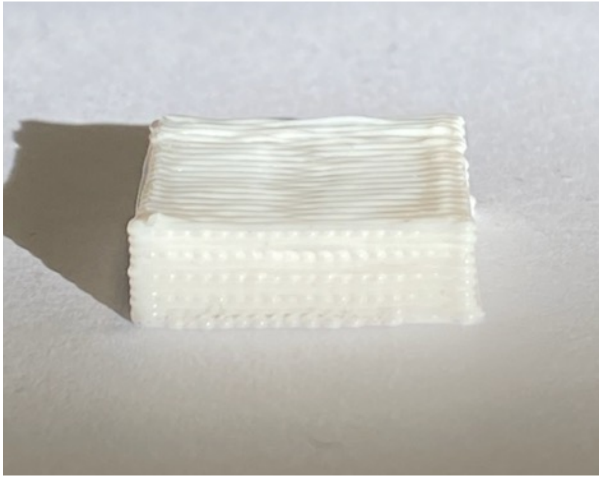


Figure 44: Printed square-based piece with optimal speed parameters

Decreasing the printing speed and motion speed parameters have increased the quality of 3D prints.

Indeed, the printing speed being slower, the extruder had more time to deposit the material in a controlled and precise manner. This prevented over-extrusion or under-extrusion in certain areas such as the corners and resulted in a smoother surface finish and more accurate details.

Decreasing the motion speed allowed the robot arms enough time to properly reposition themselves between move, preventing the print to be misaligned or have distorted shapes and resulted on less visible discontinuities.

The piece quality being optimized, different geometries have been printed.

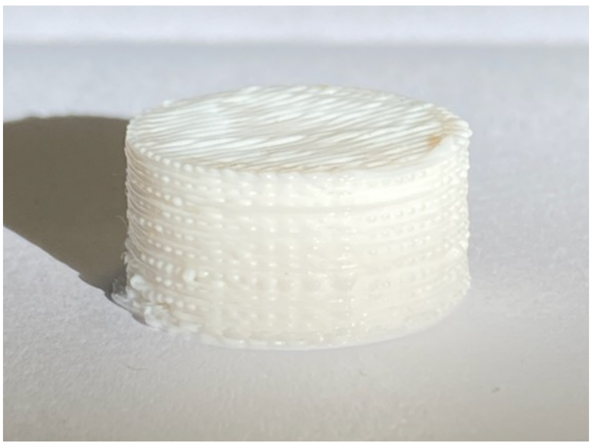


Figure 45: Printed cylinder with optimal speed parameters

The printed cylinder on figure 45 was the most successful print.

Indeed, cylinders have a simple, smooth, and symmetrical shape, which is less complex to print than a cube with its multiple faces and edges. This makes it less prone to errors.

Secondly, the issue of overhang is less of a problem when printing a cylinder. Cylinders have less overhang than cubes, making it easier for the robot to support the material while it is being printed. Overhangs can cause drooping or warping, which can result in poor surface finish and accuracy.

Finally, the problem of layers is less of an issue when printing a cylinder. Cylinders have a consistent layer thickness around their entire circumference, making it easier for the robot to lay down material evenly. A cube has corners and edges, which can be more difficult to print, as the material has to change direction abruptly which could cause unwanted warping.

To test the performances of the robot printer, a more complicated shape, which is a 90° spiral cube, has been printed.

Figure 46: Printed 90° spiral cube with optimal speed parameters

The printed 90° spiral cube on figure 46 resulted in an unsuccessful piece.

Indeed, the spiral shape created a significant overhang as the robot had to print over the edge of the spiral without any support. This caused drooping or warping of the material, resulting in poor surface finish and accuracy.

Secondly, the layers of the spiral cube had to change direction abruptly as the robot moved from one level of the spiral to the next. This caused unwanted warping of the material, making it difficult to maintain a consistent layer thickness.

To prevent these phenomena to happen, the spiral shape would have required a support structure to be printed along with the part.

IV.4. Potential optimal values for WAAM

The best values for the tool path parameters for WAAM depend on the specific application, the material being used and the equipment being used. It is important to note that there is no one set of values that will be optimal for all situations. However, here are some general guidelines for the values of the toolpath parameters for WAAM [58]:

- Travel speed: Between 200-500 mm/min
- Wire feed rate: Between 2-5 m/min
- Arc current: Between 100-200 Amps
- Layer height: Between 0.1-0.2 mm
- Arc angle: Between 15-30 degrees
- Wire angle: Between 20-30 degrees

It is important to note that these values are general guidelines, and the best values for a specific application, material, and equipment will depend on many factors such as the size and complexity of the part, the properties of the material, and the capabilities of the equipment. It may be necessary to experiment with different values and adjust them as needed to achieve the best results.

V. Conclusion

Completing this project has required the assembly, association, and setup of various components in order to coordinate the UR10e motions and the extrusion of material in a desired way and shape. Using the robot printer and analyzing the printed pieces has allowed to analyze the results and draw observations about them.

The first set of trials of prints had as a purpose to try different geometries designed in 3D in order to observe the printing and robot's behavior while depositing material with the same toolpath settings. It allowed to select the best result and test other toolpath parameters in the following sets of trials. From these tests, the following parameters could be determined: a distance between layers of 0,5 mm was kept to increase the quality of the surface finish, involving a reduction of the overlap to 0%, and a distance of 0,4 mm between passes was kept to make the piece more durable and denser. The motion speed and extrusion speed was then calculated to be more suitable, leading to a motion speed of 957 mm/min and an extrusion speed of 0,1 mm/s. The last set of trials resulted in satisfying pieces with the condition of a 3D model of simple geometry as a support is not printed alongside the piece.

The objective of combining a UR10e cobot with a printing toolhead has been achieved in terms of setup. About printing parts more efficiently and accurately, the variable quality of the pieces can explain some limitations of the robot printer.

The first limitation of the robot printer over a regular 3D printer is the absence of generation of support for the printed parts. The use of Mastercam to generate the printing toolpath did not allow to include a support in it. It resulted in the incapacity to print shapes with complicated geometries such as ones with holes in the surfaces that do not touch the glass or for which the layers do not overlap with each other. However, a support structure is generally not necessary in WAAM as an infused powder solidifies the structure during printing.

Furthermore, due to the dimension of a nozzle diameter for an FDM printing toolhead, which generally equals to 0,4 mm, the precision obtained with a regular 3D printer cannot be reached with the robot printer and its imprecision of motion of 0,05 mm. However, as this project aimed to be a simulation of wire-arc additive manufacturing, this constraint does not apply. WAAM process uses a wire as the feedstock material, and deposition diameter used is typically in the range of 1 to 3 mm, reducing the incertitude of motion and increasing the accuracy of reproduction of the toolpath.

It would have been ideal to conduct a characterization of the printed pieces to fully evaluate the capabilities of the cobot in 3D printing. However, due to the time constraints, this was not possible.

An ideal scenario would have been to coordinate accurately the robot motion and the extrusion. To do so, the generation of two different codes could be a possible solution. One with the G-Code format to implement in the Duet board and that would control the fans and the heating parameter, and one in the script format to implement in Polyscope that would control the robot motions and the extrusion and retraction of the filament. A method is currently being studied to realize such an improvement of the robot printer, using the CAM software RobotDK with the addition of a slicer plugin called "Sli6er" and a Universal Robots post-processor. The main issue is now to find a way to connect the extruder to the robot when the code generated calls for an output to activate the tool. Using such a software would also allow a variation in velocity on the toolpath, preventing over-extrusion at the corners of a cube, for example.

This internship has been the launching point of an ambitious project that aims, in the future, to replace the printing toolhead by a TIG (Tungsten Inert Gas) torch for WAAM provided by the factory Codesol. This will need the recalibrating of the robot's TCP and the generation of an adapted code. Also, the robot should be capable of moving in 6 degrees of freedom to allow movement in all three linear dimensions and all three rotational dimensions, allowing the tool to deposit material in such an orientation that assures the proper arc and wire angles. This project has made the approach to toolpath generation understandable and guided in order to facilitate the continuity of the project.

Overall, carrying out this project has brought me new scientific knowledge about additive manufacturing and robotics and has been a challenging task and an enriching experience. I was able to learn about the capabilities of the UR10e, and how it can be used with a printing toolhead to create 3D models. I also gained an appreciation for the complexity of robotic systems and CAD/CAM software and the importance of understanding their capabilities and limitations. The project provided me with an opportunity to apply my knowledge and skills to develop a solution that meets the needs of an industrial setting, and it was rewarding to see my work applied. Additionally, I was able to collaborate with other students and employees, which was a very valuable experience. Overall, these six months of internship had helped me improving working independently and there will be very valuable in my future career.

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