POLITECNICO DI TORINO

Master’s Degree Course in Mechatronic Engineering

THESIS

CRITICAL ANALYSIS OF COLLABORATIVE ROBOT USED FOR RAPID PROTOTYPING

Advisor:

Prof. Paolo Chiabert

STUDENT:

Kuejo Michel Sardou

ID: S296224

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ABSTRACT

This thesis focuses on the topic that is frequently used nowadays, namely 3D printing. The term 3D printing encompasses several manufacturing technologies that build the parts layer-by-layer. This thesis proposes the new approach to the 3D printing process by using a robotic arm which offers 6 degrees of freedom and flexibility in production industries using additive manufacturing(AM).

The first part of this thesis introduces and compares the different types of AM technologies, then proposes the framework using 6-axis of cobot for deposing modelling (FDM) with the extrusion filament system mounted on the end effector of cobot. The whole system is first drawn in computer aided design (CAD) in order to verify all the parameters of the objects, after it is imported in RoboDK. RoboDK is the software used for programming and simulate the system, because it allows to represent the system to be used and transform the remote simulation into the reality.

The third part of this thesis proposes another framework with the heat bed fixed on the cobot and the extruder fixed on the work cell. This new framework has less payload and less vibrations than the first framework. The last part proposed the solution to print the multi planar objects by using the slicer software in ubuntu and importing the gcode in RoboDK.

The two systems proposed in this thesis offers greater flexibility(quickly change the end effector to do another task), and the changeable environment. These advantages underlines the benefits to use the cobot for 3D printing instead of cartesian 3D printer. These systems increase the capabilities of cobot and proof that it is possible to human to collaborate with cobot for the development of additive manufacturing.

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1 INTRODUCTION

The term rapid prototyping (RP) is more exploited in industries to give a detail on a process for rapidly creating a system or part representation before final release or commercialization (1). This manufacturing system offers greater flexibility in making different products with less time, low cost consuming and it’s fit as many working environments as possible.

In recent years, the field of robotics has undergone a remarkable transformation with the introduction of collaborative robots, commonly referred to as “cobots.” These innovative machines are designed to work alongside human operators, facilitating enhanced productivity, efficiency, and safety within various industries.

This thesis delves into the intersection of these two cutting-edge domains to assess the implications, challenges, and opportunities arise when cobots are integrated into the rapid prototyping process.

2 ADDITIVE MANUFACTURING

"Additive Manufacturing (AM) is a process of creating an object by building it one layer at a time." "It is the opposite of subtractive manufacturing, in which an object is created by cutting away at a solid block of material until the final product is complete (2)."

"Technically, additive manufacturing can refer to any process where a product is created by building something up, such as molding, but it typically refers to 3D printing." "Additive manufacturing was first used to develop prototypes in the 1980s, these objects were not usually functional." "This process was known as rapid prototyping because it allowed people to create a scale model of the final object quickly, without the typical setup process and costs involved." "In creating a prototype." "As additive manufacturing improved, its uses expanded to rapid tooling, which was used to create molds for final products." "By the early 2000s, additive manufacturing was being used to create functional products (2)."

"To create an object using additive manufacturing, someone must first create a design." "This is typically done using computer aided design(CAD), the software then translates the design into a layer by layer framework for the AM machine to follow." "This is sent to the 3D printer, which begins creating the object immediately (2)."

The process chain of AM could be divided into four steps: engineering design, pre-processing, additive manufacturing, and post-processing.

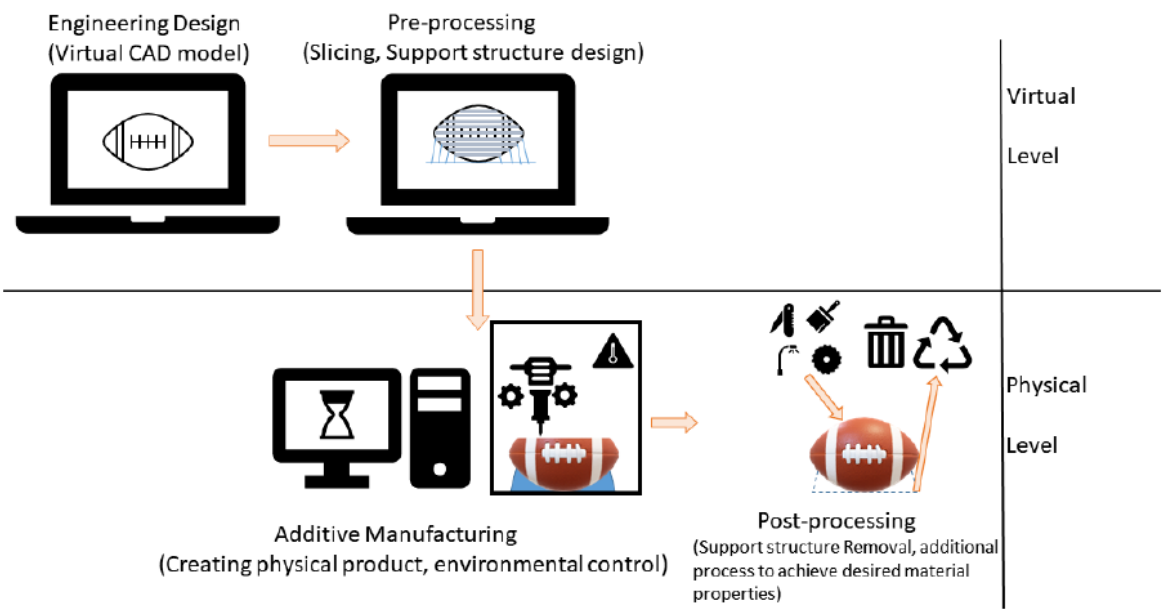


Figure 1: Process chain of AM

Step 1: Engineering design

CAD models that fully describe the external geometry are required for all AM parts. Any professional CAD solid modelling software can be used to create this, but the final must be a 3D solid or surface model.

Step 2: Pre-processing

Upon completion of the digital model, the STL (Standard Tessellation Language) file format must be used to create the stereolithography. The STL file serves as the basis for calculating the slices of the model. This file is transmitted to AM machine, which is controlled by the computer, that computer only generates the required instruction in the form of G-codes and M-codes based on the given process parameters.

Step 3: Additive manufacturing

Before the building starts, the equipment has to be set up. The settings can constitute power, speed, layer thickness, and other several parameters related to material and process constraints, etc.

Step 4: Post-processing

After the build, the part might need some post-processing before it is completely finished. Of course, depending on the material and AM process used, some parts might need machining, cleaning, polishing, removal of support structures, and heat treatments (3).

2.1 Classification of Additive Manufacturing

Everybody recognize the term 3D printing nowadays but what many people mean when talking about 3D printing is actually one of the several AM processes. Based on the methodology of formation of the product, we have seven categories of additive manufacturing: Binder jetting, Material jetting, directed energy deposition, powder bed fusion, material extrusion, sheet lamination and vat photolymaration.

2.1.1 Binder Jetting (BJT)

"The binder jetting process uses two materials; a powder based material and a binder." "The binder acts as an adhesive between powder layers." "The binder is usually in liquid form and the build material in powder form." "A print head moves horizontally along the x and y axes of the machine and deposits alternating layers of the build material and the binding material." "After each layer, the object being printed is lowered on its build platform (4)."

"Due to the method of binding, the material characteristics are not always suitable for structural parts and despite the relative speed of printing, additional post processing can add significant time to the overall process (4)."

"The technology is often referred to as 3DP technology and the different steps of production are:"

"-Powder material is spread over the build platform using a roller."

"- The print head deposits the binder adhesive on top of the powder where required."

"- The build platform is lowered by the model's layer thickness."

"- Another layer of powder is spread over the previous layer." "The object is formed where the powder is bound to the liquid."

"- Unbound powder remains in the position surrounding the object."

" - The process is repeated until the entire object has been made (4)."

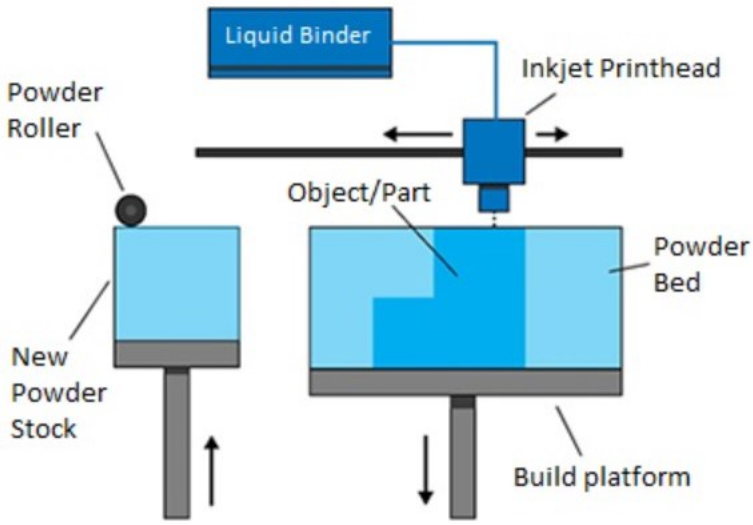


Figure 2: Binder Jetting Process

2.1.2 Directed Energy Deposition (DED)

"Directed energy deposition (DED) covers a range of technology: Laser engineered net shaping, directed light fabrication, direct metal deposition, 3D laser cladding." "It is a more complex printing process commonly used to repair or add additional material to existing components (4)."

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

Different steps:

- "A 4 or 5 axis arm with nozzle moves around a fixed object."
- "Material is deposited from the nozzle onto existing surfaces of the object."
- "Material is either provided in wire or powder form."

- “Material is melted using a laser, electron beam or plasma arc upon deposition.”
- “Further material is added layer by layer and solidifies, creating or repairing new material features on the existing object (4).”

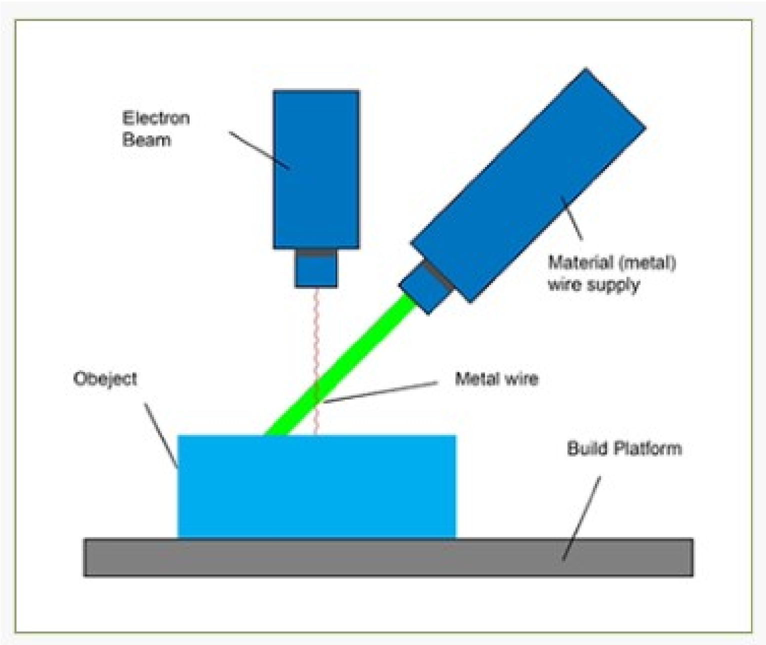


Figure 3: direct metal deposition process .

2.1.3 Material Extrusion (MEX)

“Fuse deposing modelling (FDM) is a common material extrusion process and is trademarked by the company Stratasys.” “Material is drawn through a nozzle, where it is heated and is then deposited layer by layer.” “The nozzle can move horizontally and a platform moves up and down vertically after each new layer is deposited.” “It is a commonly used technique used many inexpensive , domestic and hobby 3D printers (4).”

“The process has many factors that influence the final model quality but has great potential and viability when these factors are controlled successfully.” “Whilst FDM is similar to all other 3D printing processes, as it builds layer by layer, it varies in the fact that material is added through a nozzle under constant pressure must be kept steady and at a constant speed to enable accurate results.” “Material layers can be bonded by temperature control or through the use of chemical agents. Material is often added to the machine in spool form as shown in the diagram (4)."

Different steps:

- "The first layer is built as nozzle deposits material where required onto the cross sectional area of first object slice."
- "The following layers are added on top of previous layers."
- "Layers are fused together upon deposition as the material is in a melted state (4)."

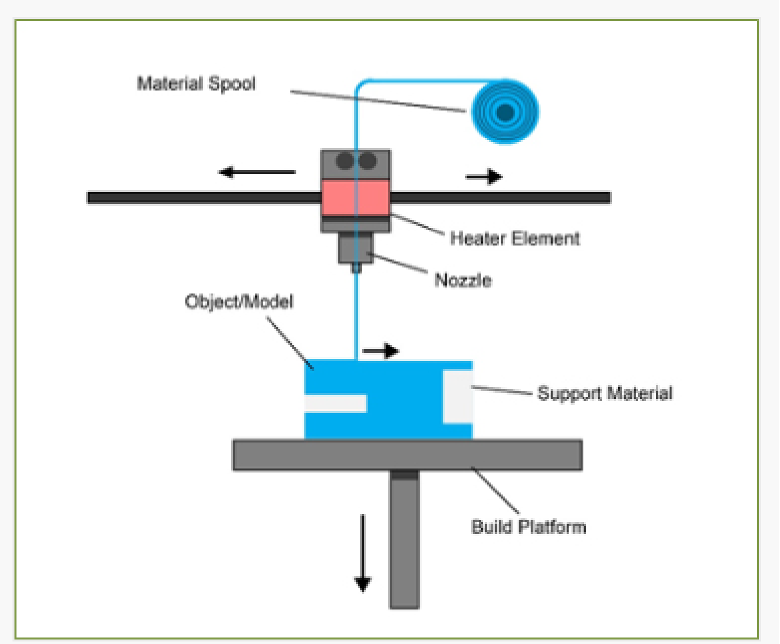


Figure 4: FDM process basis

"The Material Extrusion Process(MEX) uses polymers and plastics."

"The mean advantages of MEX : it is widespread and inexpensive process, ABS plastic can be used , which has good structural properties and is easily accessible." "The disadvantages are: the nozzle radius limits and reduces the final quality, accuracy and speed are low when compared to other processes and accuracy of the final model is limited to material nozzle thickness, constant pressure of material is required in order to increase the quality of finish (4)."

2.1.4 Material Jetting (MJT)

"Material Jetting creates objects in a similar method to a two-dimensional inkjet printer." "Material is jetted onto a build platform using either a continuous or Drop on Demand (DOD) approach (4)."
"Material is jetted onto the build surface or platform, where it solidifies and the model is built layer by layer." "Material is deposited from a nozzle which moves horizontally across the build platform." "Machines vary in complexity and in their methods of controlling the deposition of material." "The material layers are cured or hardened using ultraviolet(UV) light (4)."
"As the material must be deposited in drops, the number of materials available to use is limited." "Polymers and waxes are suitable and commonly used materials, due to their viscous nature and ability to form drops (4)."
Different steps:

- "The print head is positioned above build platform."
- "Droplets of material are deposited from the print head onto surface where required, using either thermal or piezoelectric method."
- "Droplets of material solidify and make up the first layer."
- "Further layers are built up as before on top of the previous."
- "Layers are allowed to cool and harden or are cured by UV light." "Post processing includes removal of support material (4)."

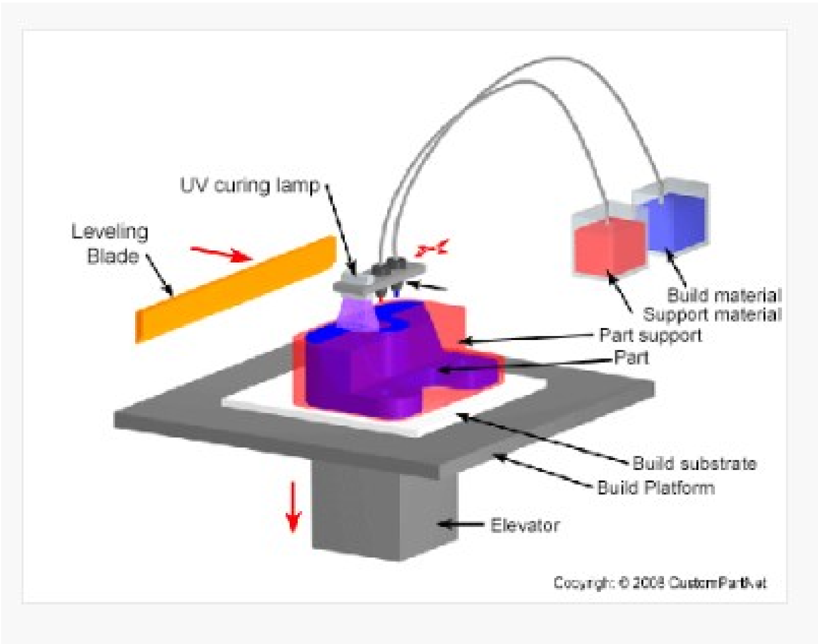


Figure 5: Representation of MJT process.

“The material jetting process uses polymers and plastics.”
“The mean advantages are : the process benefits from a high accuracy of deposition of droplets and therefore low waste, the process allows for multiple material parts and colors under one process.”
“The disadvantages : support material is often required, a high accuracy can be achieved but materials are limited and only polymers and waxes can be used (4).”

2.1.5 Powder Bed Fusion (PBF)

“The Powder Bed Fusion process includes the following commonly used printing techniques: Direct Metal Laser Sintering (DMLS), Electron Beam Melting (EBM), Selective Heat Sintering (SHS), Selective Laser Melting (SLM) and Selective Laser Sintering (SLS) (4).”
“Powder Bed Fusion (PBF) methods use either a laser or electron beam to melt and fuse material powder together.” “Electron beam melting methods require a vacuum but can be used with metals and alloys in the creation of functional parts.” “All PBF processes involve the spreading of the powder material over previous layers.” “There are different mechanisms to enable this, including a roller or a blade.” “A hopper or a reservoir below of aside the bed provides fresh material supply.” “Direct metal laser sintering is the same as SLS, but with the use of metals and not plastics.” “The process sinters the powder, layer by layer.” “Selective heat sintering differs from other processes by way of using a heated thermal print head to fuse powder material together.” “As before, layers are added with a roller in between fusion of layers. A platform lowers the model accordingly (4).”
Different steps:
- “A layer, typically 0.1 mm thick of material is spread over the build platform.”
- “A laser fuses the first layer or first cross section of the model.”
- “A new layer of powder is spread across the previous layer using a roller.”
- “Further layers or cross section are fused and added.”
- “The process repeats until the entire model is created. Loose, unfused powder is remains in position but is removed during post processing (4).”

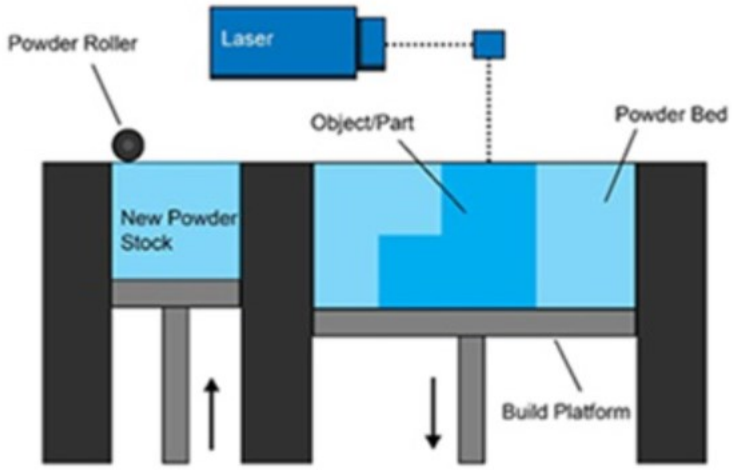


Figure 6: PBF additive manufacturing.

“PBF process uses any powder based materials, but common metals and polymers used are: nylon, titanium and aluminum.”

“Advantages: Relatively inexpensive, suitable for visual models and prototypes, powder acts as an integrated support structure, large range of material options.”

“Disadvantages: Relatively slow speed, lack of structural properties in materials, size limitations, high power usage, finish is dependent of powder grain size (4).”

2.1.6 Sheet Lamination (SHL)

"Sheet lamination processes include ultrasonic additive manufacturing (UAM) and laminated object manufacturing (LOM)." "The UAM process uses sheets or ribbons of metal, which are bound together using ultrasonic welding." "The process does require additional cnc machining and removal of the unbound metal, often during the welding process." "LOM uses a similar layer by layer approach but uses paper as material and adhesive instead of welding." "The LOM process uses a cross hatching method during the printing process to allow for easy removal post build." "Laminated objects are often used for aesthetic and visual models and are not suitable for structural use." "UAM uses metals and includes aluminum, copper, stainless steel and titanium." "The process is low temperature and allows for internal geometries to be created." "The process can bond different materials and requires relatively little energy, as the metal is not melted (4)."
Different steps:

- "The material is positioned in place on the cutting bed."
- "The material is bonded in place, over the previous layer, using the adhesive."
- "The required shape is then cut from the layer, by laser or knife."
- "The next layer is added."
- "The second and third steps can be reversed and alternatively, the material can be cut before being positioned and bonded (4)."

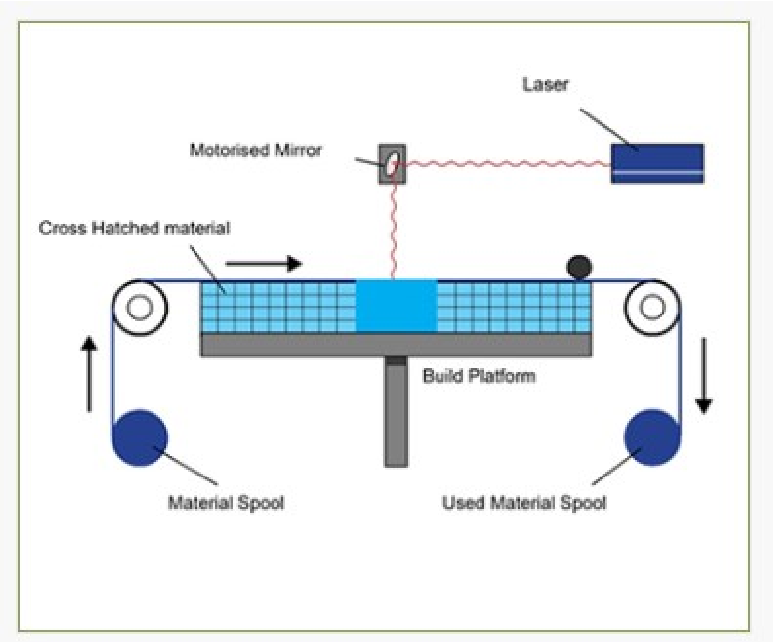


Figure 7: SHL process.

"The material used is effectively any sheet material capable of being rolled. Paper, plastic and some sheet metals." "The most commonly used material is A4 paper."
"Advantages: benefits include speed, low cost, ease of material handling, bit the strength and integrity of models is reliant on the adhesive used." "Cutting can be very fast due to the cutting route only being that of the shape outline, not the entire cross sectional area."
"Disadvantages : finishes can vary depending on paper or plastic material but may require post processing to achieve desired effect." "Limited material use." "Fusion processes require more research to further advance the process into a more mainstream positioning (4)."

2.1.7 Vat Photopolymerization (VPP)

"Vat polymerization uses a vat of liquid photopolymer resin, out of which the model is constructed layer by layer." "An ultraviolet (UV) light is used to cure or harden the resin where required, whilst a platform moves the object being made downwards after each new layer is cured."
"As the process uses liquid to form objects, there is no structural support from the material during the build phase." "Unlike powder based methods, where support is given from the unbound material." "In this case, support structures will often need to be added." "Resins are cured using a process of photo polymerization or UV light, where the light is directed across the surface of the resin with the use of motor controlled mirrors." "Where the resin comes in contact with the light, it cures or hardens."
Different steps:

- "The build platform is lowered from the top of the resin vat downwards by the layer thickness."
- "A UV light cures the resin layer by layer. The platform continues to move downwards and additional layers are built on top of the previous."
- "Some machines use a blade which moves between layers in order to provide a smooth resin base to build the next layer on."
- "After completion, the vat is drained of resin and the object removed."

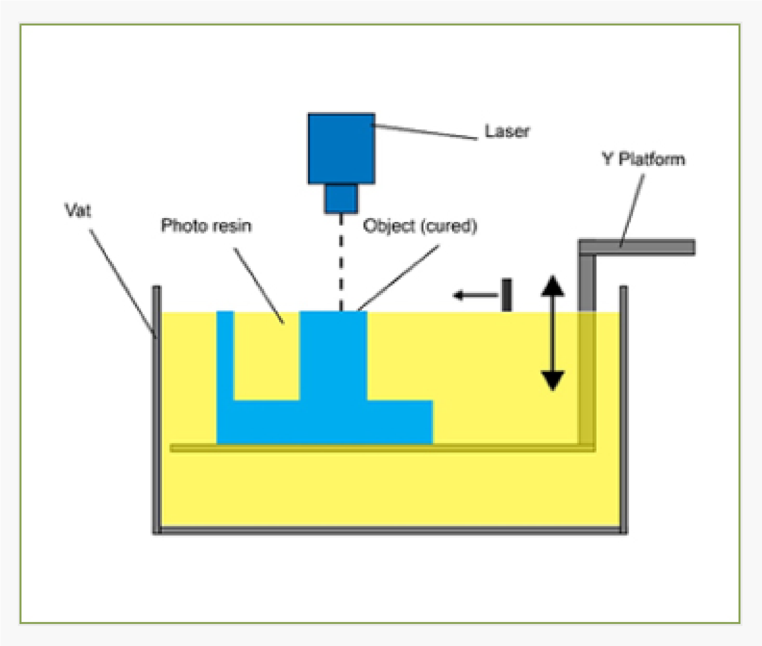


Figure 8: VPP process.

“The Vat polymerization process uses Plastics and Polymers.”
“Advantages: high level of accuracy and good finish, relatively quick process, typically large build areas and max model weight.”
“Disadvantages: relatively expensive, lengthy post processing time and removal from resin, limited material use of photo-resins, often requires support structures and post curing for parts to be strong enough for structural use.”

2.2 Applications and Challenges Additive Manufacturing

As additive manufacturing technologies have advanced, 3D printed parts have moved decidedly outside the research and development arena and onto the production line. These pivotal processes are developing and producing concepts previously unattainable in the manufacturing world.

2.2.1 Advantages and disadvantages compared to conventional manufacturing.

There are many advantages of additive manufacturing compared to subtractive manufacturing and each of these individual advantages have in common a certain degree of waste reduction and/or energy savings.

- **Advantages**

∗ **Customization:** Additive manufacturing allows for customization of products, as each object can be designed and printed to meet specific needs and requirements.

∗ **Waste reduction:** Additive manufacturing produces less waste than traditional manufacturing methods, as only the necessary amount of material is used to create the object.

∗ **Speed:** Additive manufacturing can be faster than traditional manufacturing methods, as the process is automated and requires less human intervention.

∗ **Design flexibility: "**Additive manufacturing allows for more complex designs that may not be possible with traditional manufacturing methods, as the process can create intricate and detailed shapes."

∗ **Accessibility:** Additive manufacturing can make manufacturing accessible to smaller businesses and individuals, as it requires less investment in infrastructure and can be done with relatively inexpensive equipment (5).

● **Disadvantages**

∗ **Limited materials:** Additive manufacturing can be limited by the materials that are available for printing, as not all materials are suitable for the process.

∗ **Quality control:** Additive manufacturing requires strict quality control to ensure that the printed object meets the desired specifications, which can be challenging.

∗ **Cost:** Additive manufacturing can be more expensive than traditional manufacturing methods, as the equipment and materials required can be costly.

∗ **Size limitations:** Additive manufacturing is limited by the size of the printed bed, which can restrict the size of the object that can be printed.

∗ **Environmental impact:** Additive manufacturing can have a negative environmental impact, as the materials used for printing may not be recyclable or biodegradable, and the process may require significant energy consumption (5).

2.2.2 Application of additive manufacturing

“Additive manufacturing has a wide range of applications across various industries due to its versatility and capability to create complex and customized objects.” Some of the notable applications are:

a. **Tooling**

“One of the chief applications of 3D printing in the industrial sector is tooling which involves the printing of light and durable jigs, fixtures, gauges.” “Injection molding dies can also be easily manufactured with the help of metal 3D printing.” “A lot of time and design iterations go into this die making.” “But with the ability of 3D printing to achieve complex designs, conventional patterns in mold cooling can be replaced with advanced cooling channels which reflects in the efficiency by improving the cooling mechanism of the mold (6).”

b. **End-use parts**

“Metal 3D printing along with polymer 3D printing has already proved their worth in the market.” “Many sectors like automotive and aerospace have already started using additive manufacturing in their operations because of the reduced lead time and low cost in prototyping.” “Automotive giant Porshe has started manufacturing engine piston with 3d printing (6).”

Figure 9:Pistons from 3D printer, 2020 Porshe AG.

"Swiss aerospace company RUAG has used 3D printing in optimizing its existing satellite bracket design, thereby launching 3D printing even into space (6)."

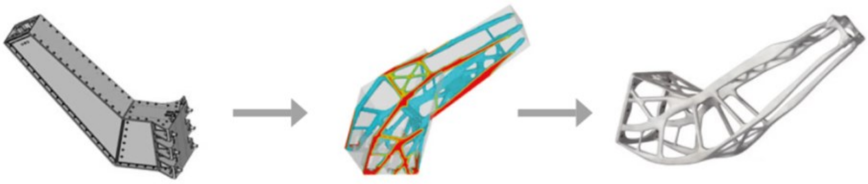


Figure 10: Antenna bracket for RUAG' sentinel satellite (6).

c. **Spare part production**

"With the help of CAD, designs for literally all parts can be stored as a digital copy in a computer hard drive thereby eliminating the need to maintain an inventory." "With the use of 3D printing, a spare part could potentially be produced on-demand." "The accessibility of the technology will encourage suppliers to open up new spaces to provide an easy supply of 3D printed components and spare parts (6)."

"Even parts that no longer exist can be remade to requirement, on reverse-engineered based on digital scans of existing parts." "Older designs may find themselves with a new lease of life and on the other side, spare parts of classic cars can be reproduced easily (6)."

2.2.3 Challenges of additive manufacturing

“Additive manufacturing has many advantages over traditional manufacturing techniques like its ability to create complex shapes, lighter weight products, and lower energy consumption.” “However, there are also several challenges associates with additive manufacturing that must be considered before implementing this technology (6).”

“One of the biggest challenges of additive manufacturing is the high cost of equipment and materials.” “In order to print a 3D object, you need a 3D printer, which can cost thousands of dollars.” “Additionally, the filaments or powders used in 3D printing can be expensive, especially if you require multiple colors or materials (6).”

“Another challenge with additive manufacturing is the time it takes to print a 3D object.” “Depending on the size and complexity of the object, it can take hours or even days to print.” “This can be impractical for mass production or when time is critical (6).”

“There are also limitations on types of materials that can be used with additive manufacturing.” “While more and more materials are being developed for use with 3D printers, there are still many items that cannot be printed using this technology.” “This includes items made from metal or glass or that have intricate details (6).”

“Despite these challenges, additive manufacturing is an exciting and rapidly evolving technology with great potential for businesses and consumers alike.” “As costs continue to fall and capabilities increase, we will see more and more amazing applications for this transformative technology (6).”

2.3 Type of AM technique chosen for this project

"A fused deposition modeling (FDM) of MEX was chosen for this project for the implementation of the AM system used for rapid prototyping." The FDM is considered the most economical and less dangerous method among all AM techniques. One FDM household 3D printer has been bought. The extruder is used to form the end effector for the first implementation of the AM system and the heated plate is used to form the end effector for the second implementation of the system.

3 HUMAN COBOT COOPERATION

The cobots are robots designed to work alongside humans in a collaborative and safe manner. The goal is to augment human capabilities and improve productivity in various industries, from manufacturing to healthcare. Human-cobot cooperation is an exciting field that has the potential to transform various industries by combining the strengths of human workers and robots. It's important to emphasize the safe and effective integration of cobots into workplaces to ensure a harmonious collaboration between human and machines (7).

"The Collaborative robots (cobots) increase the productivity but without taking the cost of losing safety and the flexibility of changes in production lines." "In this chapter, the characteristics and applications of cobot are presented."

3.1 Characteristics of Cobots

"Conceived in the late 1990s by two professors from Northwestern University, J. Edward Colgate and Michael Peshkin, cobots have become increasingly efficient and safe." "The Danish company Universal Robots introduced them to the market in the 2000s, selling the first product in 2008 and thereby paving the way for smart manufacturing."

"Collaborative cobots are innovative robots designed to facilitate cooperation and interaction between workers and machines. They can lighten the operator's workload and support them in more risky heavy tasks."

"This collaboration is made possible by some fundamental characteristics that differentiate cobots from traditional robots, such as lightweight design and innovative features including safety sensors." "On one hand, these features ease the integration of the machine into the workplace, and on the other hand, they enhance its (artificial) intelligence to improve and maximize productivity by automating almost all operations (8)."

The purpose of this section is firstly to describe the standards and specifications of UR10e and secondly present the mains differences between collaborative robots and industrial robots.

3.1.1 Standards and test specifications

To understand the slight complexity of cobot safety, it is useful to understand what features they are designed with to make them safe.

The core standard that cobots need to comply with is ISO/TS 15066. This is an international standard that specifically addresses the safety requirements of collaborative robots (9).

Examples of cobots features that make them safe are:

- **Power, force and torque limits** – A force limited robot will not apply a force that is applied by each joint, and/or the power it draws. If it does breach the limit, it will stop immediately.
- **Speed limits** – The robot will not move fast enough that a collision at full speed with a person would cause harm. This is why cobots often move slowly, even though they are capable of moving faster.
- **Safety-rated stop modes** – Cobots have several levels of stop mode depending on the type of safety event that has occurred. For example, an “emergency stop” will only happen in emergencies but a “protective stop" might be employed when a person enters the robot’s workspace.
- **Speed and separation monitoring** – Some applications, like the robotic palletizing solution, require extra safety sensors to detect when a person enters the robot’s workspace. This uses a feature called speed and separation monitoring.
- **Ergonomic design** – Collision aren’t the only potential danger with robots. Cobots are also designed to be ergonomic so that they can’t injure a person if, say, their hand was trapped between the robot’s joints (9).

3.1.2 Difference between cobot and industrial robot

"Delineating cobots and industrial robots, this analysis drives deep into their respective roles and divergent characteristics that make each a vital cog in the machinery of Industry 4.0."

"Key differences between Cobots and Robots:"

- **Safety Features**

  "Cobots are designed with safety as a top priority, as they are intended to work alongside humans in a shared workspace." "They are equipped with force and torque sensors that enable them to detect and respond to contact with humans or objects, stopping or slowing down their movement to prevent accident." "Additionally, cobots often have rounded edges and soft padding to minimize the risk of injury in case of contact (10)."

  "In contrast, industrial robots are typically separated from human workers by safety cages or barriers, as they can pose a risk due to their speed, power and size." "While robots also have safety features, such as emergency stop buttons and safety-rated monitored inputs, their primary focus is on efficiency and precision rather than direct human interaction (10)."

- **Flexibility and Adaptability**

  "Cobots are designed to be highly flexible and adaptable, allowing them to be easily reconfigured for different tasks and applications." "They are lightweight and often have a smaller footprint, making them easy to move and integrate into various workspace." "Cobots can also be quickly reprogrammed, often using intuitive interfaces or even by physically guiding the robot through the desired motion (10)."

  "Robots, on the other hand, are generally less flexible and adaptable. They are often designed for specific tasks and require more time and expertise to reprogram or reconfigure." "Industrial robots are typically larger and heavier, making them more difficult to move and integrate into new workspaces (10)."

- **Ease of Programming and Integration**

  "Cobots are designed to be user-friendly and easy to program, even for individuals without extensive robotics experience." "Many cobots feature intuitive programming interfaces, such as graphical or touchscreen interfaces, that allow users to quickly create and modify robot programs. Some cobots can even be programmed by physically guiding the robot through the desired motion, which the robot then records and repeats (10)."

Figure 11: Utilizing simple techniques such as block programming, some cobots can be programmed or reconfigured dynamically and seamlessly within their operational environments.

"In comparison, programming and integrating industrial robots can be more complex and time-consuming." "They often require specialized programming languages and expertise, as well as additional hardware and software for integration." "This can result in a steeper learning curve and longer setup times for robots compared to cobots (10)."

- **Cost and Return on Investment**

  “Cobots are generally more affordable than industrial robots, with lower upfront costs and a faster return on investment.” “Their ease of programming and integration, as well as their flexibility and adaptability, can lead to reduced setup and training costs.” “Additionally, cobots can often be used without the need for expensive safety infrastructure, such as cages or barriers, further reducing costs (10).”

  “Robots, while often more expensive upfront, can provide a higher return on investment in certain applications, particularly those requiring high precision, speed or payload capacity.” “The higher initial cost of robots can be offset by their increased efficiency and productivity in the specific applications.” “However, the cost of safety infrastructure, programming and integration should also be considered when evaluating the return on investment for robots (10).”

- **Payload and Speed Capabilities**

  “While cobots and robots both serve roles in automating tasks, their performance characteristics can differ significantly.” “Industrial robots typically offer higher speed and payload capacities, making them suitable for heavy-duty operations that require swift movements (10).”

  “Cobots, due to their design for safe human interaction, generally operate at slower speeds and have lower payload capabilities.” “These characteristics make cobots perfect for light-weight, precise tasks that require human collaboration (10).”

❖ **Level of Human Intervention**

"The level of human intervention required by cobots and robots also sets them apart." "Cobots are designed to work with humans and as such, often require a degree of human intervention, such as programming new tasks, performing regular maintenance, or even working together on complex tasks (10)."

"On the other hand, once programmed and set up, industrial robots can perform tasks autonomously for extended periods, requiring human intervention primarily for maintenance, upgrades, or error rectifications (10)."

❖ **Environmental Requirements**

"Robots often require specific environmental conditions to function optimally, like a stable temperature, specific power requirements, or safety enclosures to prevent human harm."

"Cobots, due to their inherent safety design, can usually operate in a wider range of environments, often those that are also suitable for human workers." "This can include variable temperature conditions, closer proximity to human and without the need for substantial safety infrastructure (10)."

❖ **Degree of Specialization**

"Industrial robots are often more specialized in their functionality." "They are commonly designed and programmed to perform a specific set of tasks repeatedly with high precision and speed." "This makes them well-suited for applications that require high repeatability."

"Cobots, on the other hand, offer more general-purpose utility." "Their design facilitates easy reprogramming and reconfiguration, enabling them to handle a wider variety of tasks, albeit generally at a slower pace (10)."

❖ **Durability and Longevity**

"Due to their often heavy-duty applications, industrial robots are typically built to be robust and durable, with a longer operational life."

"Cobots, while also built to be durable, are generally not designed for the same degree of ruggedness, considering their application in less harsh, more human-friendly environments (10)."

- **Regulatory and Compliance Considerations**

  "Different safety regulations might apply to cobots and robots due to their intended use and interaction with humans." "For example, cobots, designed to interact with humans, need to comply with regulations ensuring human safety during interactions, which might not be as stringent for traditional robots operating in isolated environments (10)."

3.2 Universal-Robot UR10e and ON Robot end effectors

The objective of this section is to describe the equipment and tools used in this project. The customers receive only the Robot with its connection, communication and power supply equipment from Robot manufacturers. The customers need to purchase the end effectors from the other manufacturers or customized according to user's requirements. This section will also present details of how the manufacturers can integrate their system.

3.2.1 Features of UR10e

"Universal Robots was the first company to launch a collaborative robot that could safely operate alongside employees, eliminating the need for safety cages or fencing (11)." "Universal robots was founded in Odense, Denmark in 2005 by Esben Østergaard, Kasper Støy, and Kristian Kassow." "During joint research at the Syddansk Universitet Odense, the founders came to the conclusion that the robotics market was dominated by heavy, expensive, and unwieldy robots." "That led them to develop the idea to make robot technology accessible to small and medium-sized businesses (11)."

"In 2012 the second cobot, UR10, was launched and in 2018, UR10e was released." The Universal Robot e-Series doesn't look much different on the outside from the older models. But it's what's inside the UR10e that counts, the company says that it offers more precision and sensitivity, enabling a wider range of applications, faster set up times and new safety features (12).

"The UR10e is an extraordinarily versatile collaborative industrial robot, delivering both high payload (12.5 kg) lift and long reach (1300 mm) which makes it well suited for a wide range of applications in machine tending, palletizing and packaging." "The UR10e is also offered as an OEM robot system and with a 3-position enabling teach pendant (13)."

Robot Type	UR10e
Weight	33.5 kg
Reach	1300mm
Maximum Payload	12.5 kg
Speed	Base and Shoulder joints: Max 120 °/s. All other joints: Max 180 °/s Tool: Approx. 1 m/s
System Update Frequency	500 Hz
Force Torque Sensor Accuracy	5.5 N
Pose Repeatability	± 0.05 mm

Table 1:specifications of UR10e (12).

By default, the UR10e is delivered with a regular teach pendant. The teach pendant contains Universal Robots PolyScope software to control the cobot and ensure optimal safety when working closely to the robot (14).

Built for any environment, the standard control box of the UR10e only weighs 12 kg and offers a holder to attach the teach pendant for optimal storage. The controller serves as the centralized hub for power, safety features and communication, providing a compact and efficient solution for managing the operation of the UR10e system (14).

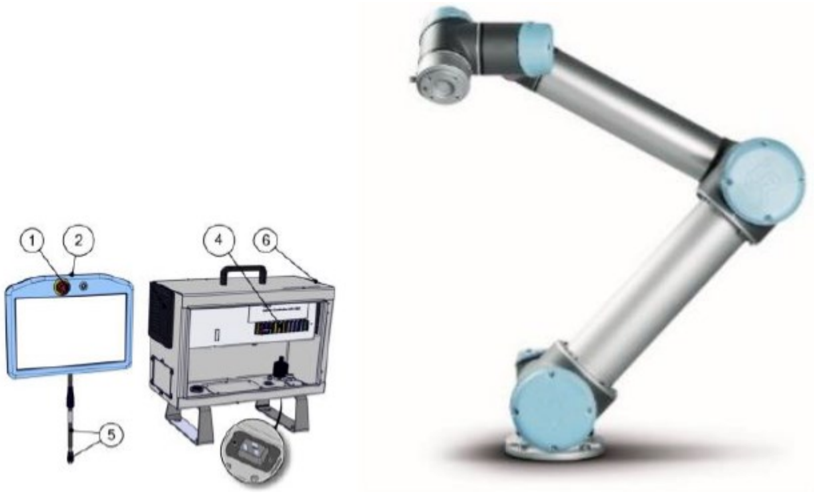


Figure 12: UR teach pendant, control box and UR10e robot arm.

3.2.2 Reason to use a cobot in the AM system

As manufacturing methods and advanced technology evolve, more robots are expected to be used for 3D printer, as most commercial 3D printers (plastic, metal, and other) are very expensive and are relegated to one specific job with a specific print area size. Robots add flexibility for part size options and allow for upgrading print heads as needed. A seventh axis can even be added for an extremely large part, especially helpful with creating a large range of parts, such as remote service facilities and prototyping (15).

"The use of AM when used with robots is an expedient, cost-effective option for various applications." "Fused Deposition Modeling (FDM) method is selected due to its direct compatibility with the range of materials used and its adaptability to our specific robotic arm, allowing for precise control over the material deposition." "This method aligns with the current trends in the field which favor materials that facilitate optimal performance, especially for parts with complex surfaces." "The extrusion challenges posed by these materials are effectively addressed by FDM, considering the geometry and dimensional characteristics of the part, thus avoiding the need for post-processing interventions (16)."

4 COBOT ADDITIVE MANUFACTURING SYSTEM DESIGN

This section show the different steps for build the work cell of cobot by going from design of pieces in SolidWorks to assembly in RoboDK passing through control software and electronic connections.

4.1 Hardware design

To evaluate the possibility of the multiplanar object production with the continuous movement of the hot bed attached to the robot, an UR10e cobot is firstly integrated with an extrusion system on the end-effector typically in MEX type 3D printer and after the heated plate will place of the end-effector.

4.1.1 End effector design

The extrusion system is composed of two sheets metal brackets and a set of Bowden extruder components which include a stepper motor NEMA 17, cold side of extruder, nozzle hot end. They are coming from a Creality Ender-3 3D printer. Since the aim is to quickly change the tool on the end-effector of robot to allow it to do different tasks, to enable quick changes the system is fixed to an OnRobot finger gripper using screws, .

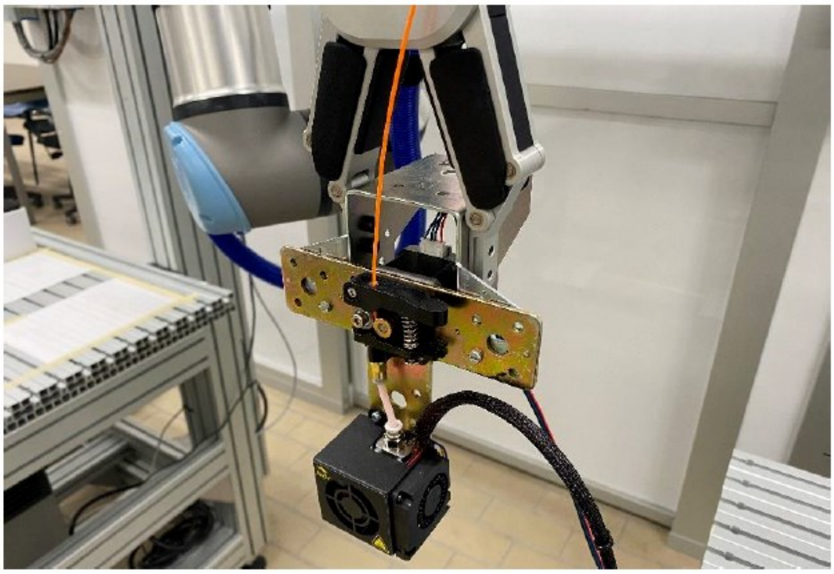


Figure 13: Extrusion system.

4.1.2 Printing Platform Design

The heated bed is a printing platform coming from the Ender-3 3D printer. The heated bed is placed on 2 pieces of 20 x 20 aluminum profile to keep the plane level, these aluminum profiles are in the same way as they are held on the traditional 3D printer, “with all 4 levelling knobs in the bottom” which help to adjust the height of heated bed.

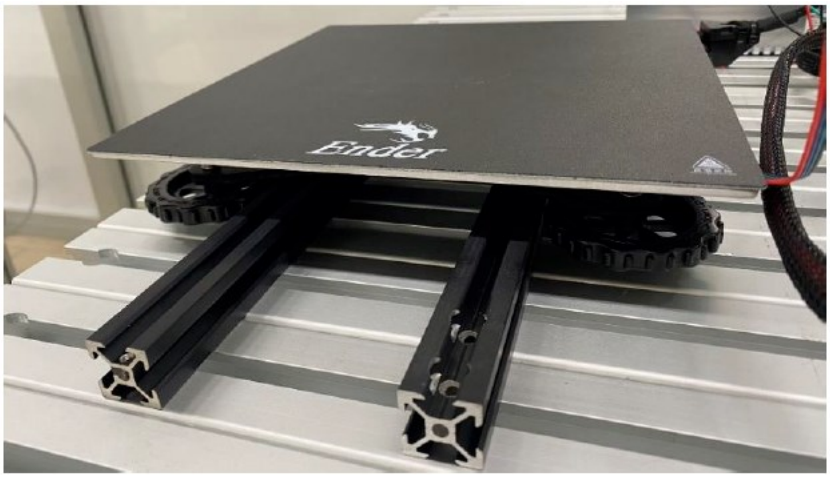


Figure 14: Heated bed coming from Ender-3 of 3D printer

4.1.3 Other devices

“To complete the list of needed devices for this project, to build the entire FDM system we have to use a control box from UR10e to generate a signal, an Arduino Uno and an A4988 stepper motor driver for controlling the stepper motor, a screen with a knob and the mother board from Ender-3 to control the temperature, and a 24V power supply.” “The connections between all devices will be explained in more detail in the following sections.”

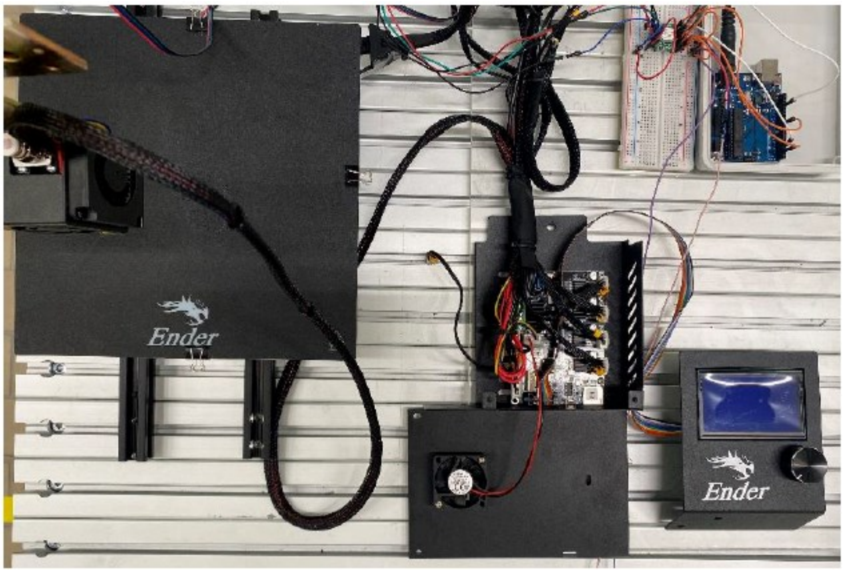


Figure 15: Other devices (Temperature and extrusion control).

4.2 Program design

“The G-code generated by slicing software is usually relayed by the traditional 3D printers to control the coordinates of the extruder and the amount of material to be extruded.” “A software is needed to translate the G-code generated by the slicing software into commands that the robot can execute (STL code) in order to use a cobot for additive manufacturing task.” Therefore, for this project, RoboDK is chosen to translate a G-code into STL code and to make also offline programming .

4.2.1 Work cell design for RoboDK

"RoboDK is a powerful and cost-effective simulator and offline programming tool for collaborative and industrial robots. With this software, you can simulate any robotic application using many different robot brands and over 600 different robots." "You can perform reach study, collision checking, cycle time estimation and much more." "In addition, RoboDK allows you to program robots outside the production environment, eliminating production downtime caused by shop floor programming." "You can also generate complex CAD to Path programs with no prior coding experience."

a. **Work cell digital model replication.**
   It's important and required to reproduce as precisely as possible the work cell environment in RoboDK to make an accurate program. RoboDK provides a library which enables the simulation of UR10e to precisely reproduce the movements of the cobot to be used, reducing some defaults of printing and identifying potential collisions risks during the printing process.

Figure 16: UR10e work cell.

"All the pieces to use to replicate a work cell in RoboDK are firstly projected in SolidWorks according to the parameters measured." "Then it is imported into RoboDK as the base where UR10e is fixed."

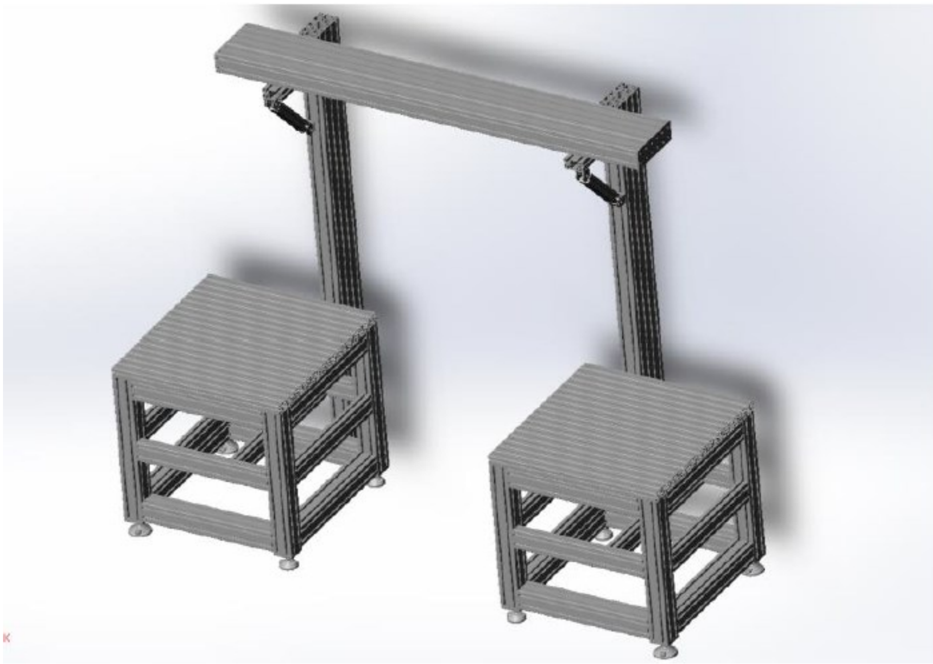


Figure 17: Work cell structure CAD model in SolidWorks.

The UR10e and the tools attached on the end effector of the cobot are imported in the simulation software, which name in our work cell is " 3D printing workstation", from the online library. However, some pieces of end effectors are not standard and require personal 3D models to be imported into the station as it is shown in the figure below. The next step is to adjust the geometry of the part imported with respect to the tool flange and define the tool center point (TCP) when all necessary components are imported.

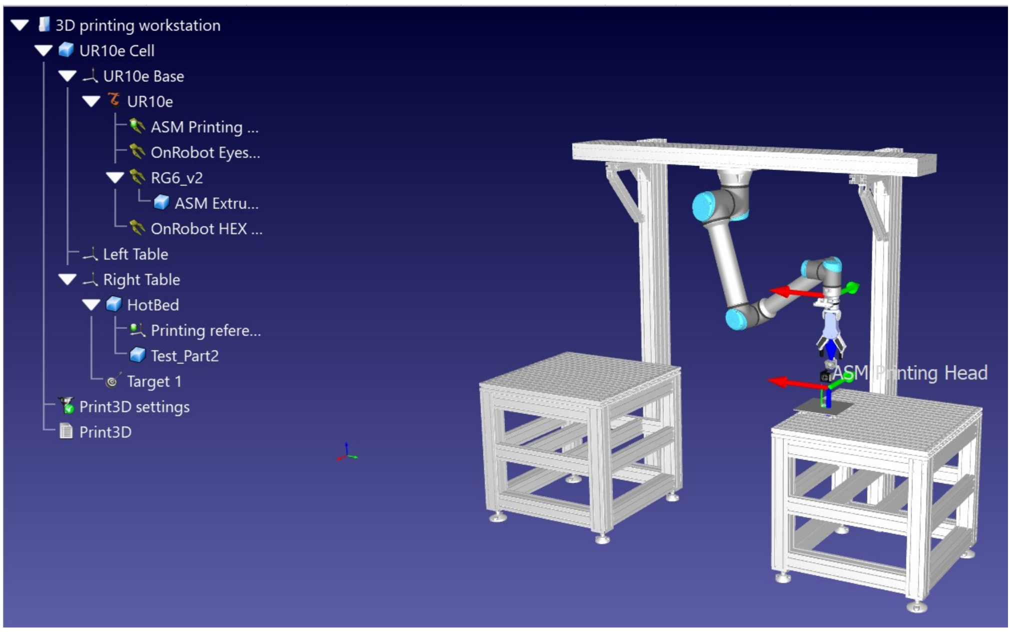


Figure 18: work cell digital model in RoboDK.

“The robot tool or Tool Center Point (TCP) is the point used to move the robot to a cartesian position(such as a cartesian target given XYZWPR values).” “The TCP is defined as a transformation from the robot flange. Defining the TCP properly is important in any robot application, whether it involves Offline Programming or not.”
“In this project, the TCP teaching function supported by UR teach pendant was used to compute the TCP.” “To compute a TCP of a cobot, a fixed position represented by the tip of a pen is chosen, move the hot end nozzle from 4 different angles and save the corresponding positions of the end effector.” “The TCP position of the end effector with respect to the robot base will be computed automatically.”

Figure 19: Set up TCP by reaching a fixed position in different angles.

Guiding the hot-end nozzle to 4 different angles using the teach pendant and saving each position will lead to compute automatically the end effector position with respect to robot tool flange.

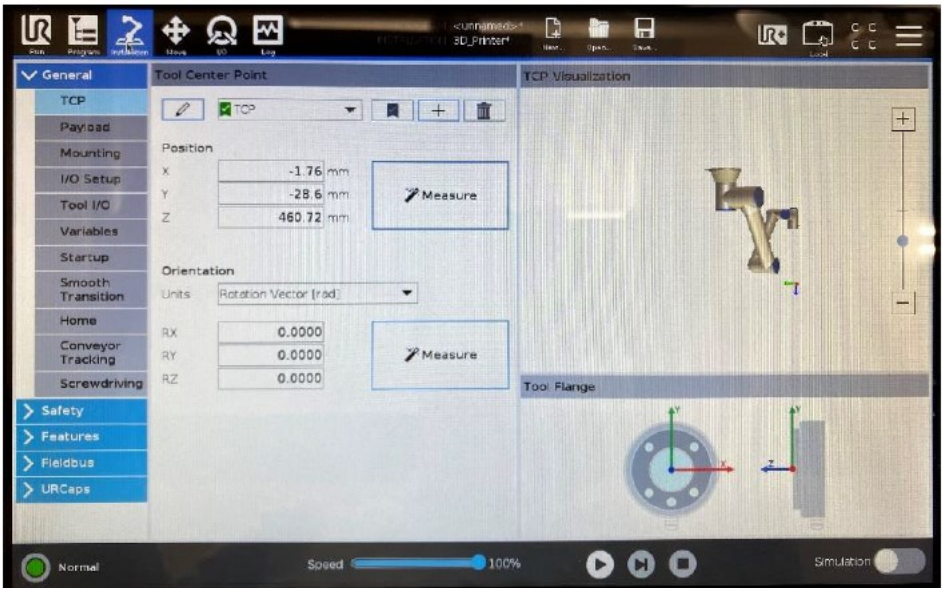


Figure 20: TCP position with respect to robot flange.

This TCP has to be set in RoboDK in order to adjust the TCP that the robot compute automatically when we import all the elements in RoboDK for design cell.

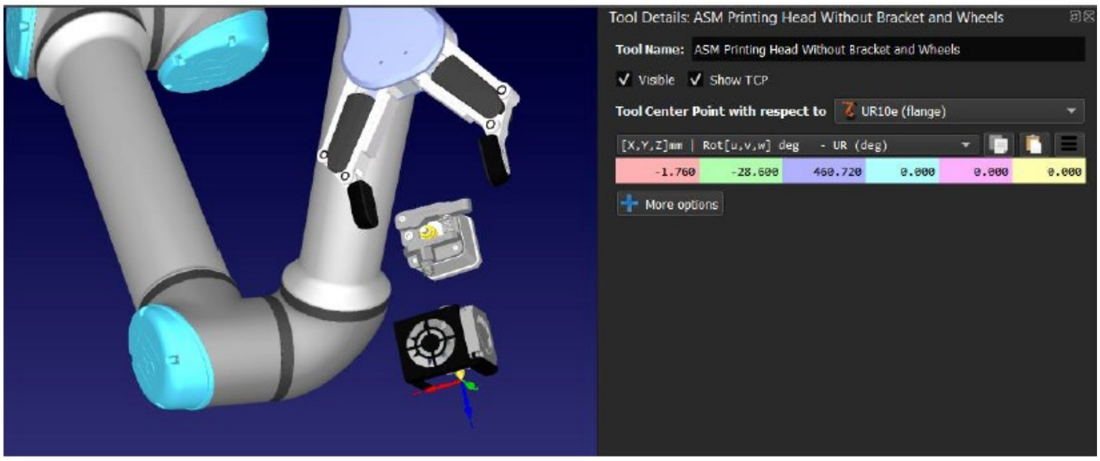


Figure 21: TCP configuration in RoboDK.

“It is important to keep the four knobs at the bottom of the heated bed in the air so that there is space for fine tuning, this is why the heated bed is elevated from the table by two aluminum profiles.”

“The distance between the face of hot bed and the top of table has to be measured in order to get the best layers deposing during the production and set this Z coordinate value of the heated bed position with respect to the table in RoboDK.” Despite the fine measurement, it is possible to have an inaccurate distance between the heated bed and robot base. This is why before running the program on the robot, A bed leveling process should be performed. In the next chapter, the calibration method will be introduced.

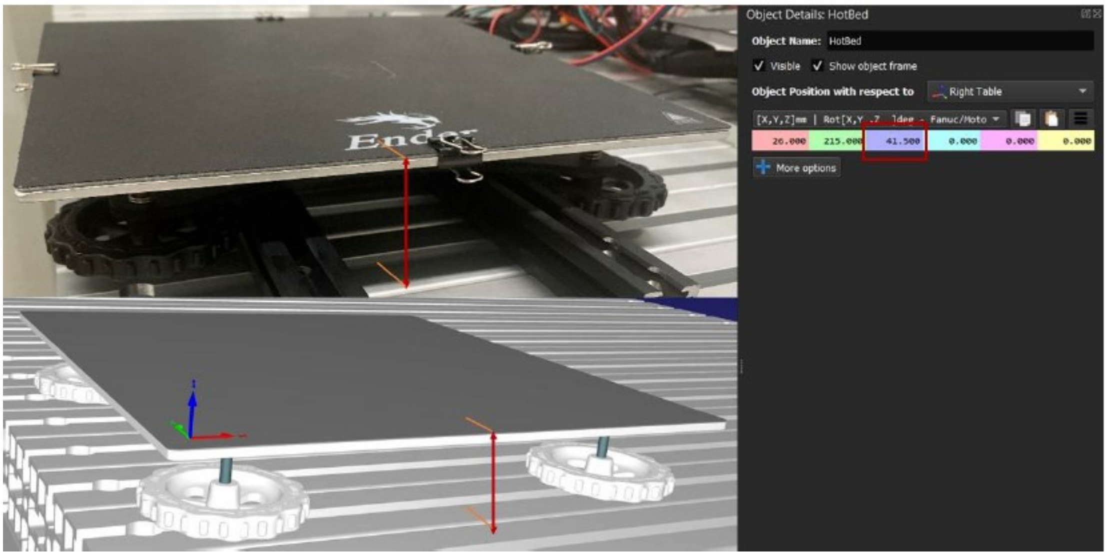


Figure 22: Heated bed Z configuration according to measurement.

4.2.2 Extrusion control

The UR control box generates the analogue signal to switch on and off the stepper motor. An Arduino microcontroller receives the analogue signal coming from control box, interprets it and send a digital signal to the A4988 driver which controls the stepper motor. The NEMA 17 stepper motor is in charge of pushing the filament from the extruder cold end to the nozzle hot end.

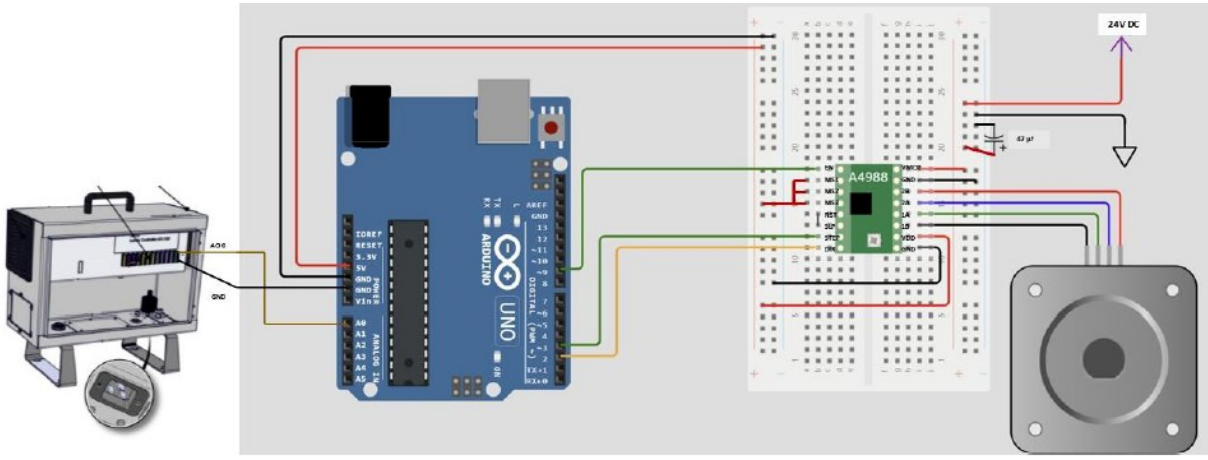


Figure 23: Electronic connections to control extrusion.

According to the dimension of each layer of material extruded and the flow rate of the filament, The speed of the stepper motor is set constant.
Annex 1 and 2 presented the Arduino code which interpret the signal coming from the control box and send the digital signal to turn On and Off the stepper motor.
The 24V DC power supply taken from the Ender-3 printer, supply the temperature of extruder hot end and that of the heated bed.

4.2.3 Temperature control

"The temperature of the extruder hot end and the heated bed is controlled by the mother board of the Ender-3." "They are set manually from the firmware running in the mother board of the Ender-3."

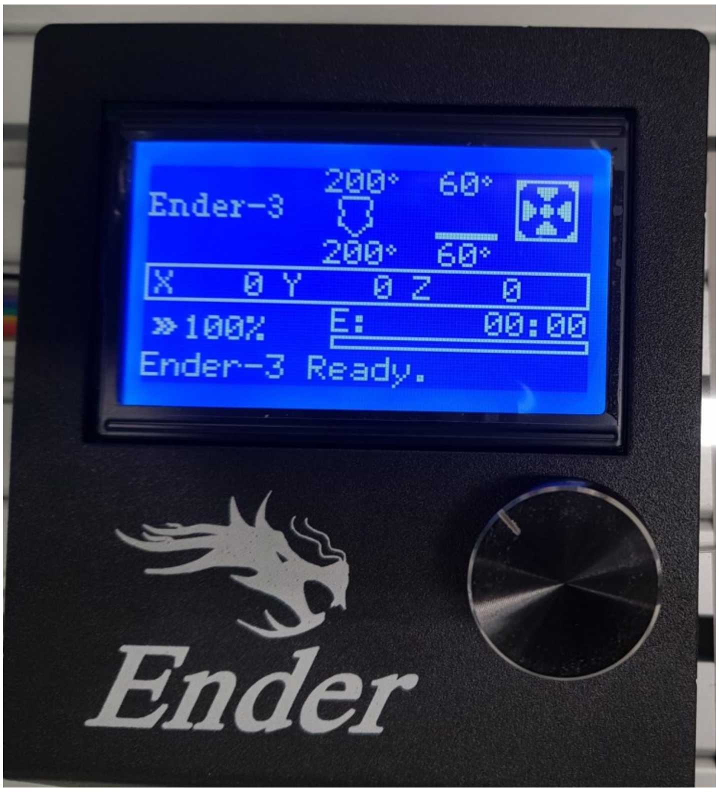


Figure 24: Temperature control and monitoring.

4.2.4 G-code conversion

"The few lines of G-code show below are just to explain the interpretation of extruded value and how the G-code is converted to the program readable by robot(post processor)."
"It is the G-code that tells the printer where to move the printhead, how fast to move it and when to extrude the filament." "The structure of G-code is relatively straightforward." "Each line begins with a letter, which represents a specific command, followed by a number, which specifies the value or parameter for that command."

So G1 is used for printing moves followed by coordinates that specify the destination of the move. The E values the amount of material needed to be extruded before the extruder should be in movement.

G1 X71.820 Y68.481 E2.14192
G1 X74.000 Y68.375 E2.17858
G1 X121.000 Y68.375 E3.72564

When the extruder moves from one position to another one, the length of material deposed is represented by the difference between the values of E of two successive commands.

The Extruder command and the value as its parameter represent in RoboDK program the E value translated, as shown in Figure below. These 'Extruder()' commands will be skipped when the program is running in RoboDK.

The simulation running in RoboDK can also run directly on the robot but it will transmit only robot's movement but it cannot drive the extrude. To drive the extruder connected to steeper motor using the command we need another element called Post Processor. The post processor of RoboDK has the role to convert the value of extruder into signal output.

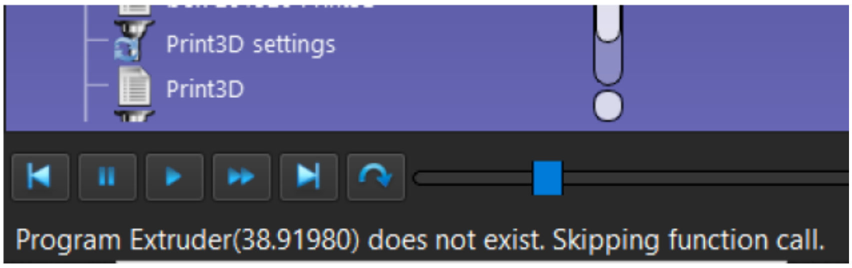


Figure 25: Extruder() command skipped in simulation.

"Post processors are a key step in Offline Programming because they can generate robot programs for a specific robot controller." "Robot programming must follow vendor-specific programming rules, these rules are implemented in the post processor." "A robot post processor defines how robot programs must be generated for a specific robot controller (17)."

"The conversion from the RoboDK simulation to a specific robot program is done by a Post Processor." "Each robot is linked to a post processor which will define a specific robot programming style." "The post

processor is used when the program is generated offline.” “RoboDK includes many post processors to support over 50 different robot manufacturers and controller.” “Alternatively, it is possible to create customized post processor or modify an existing post processor (17).”
For this project, the post processor used is Universal Robots 3D Printing because we are working with Universal Robot and the modified part of this Post processor simplifies the process by skipping the time value and ask the Cobot controller to send 5V analogue signal to Arduino board when the material need to be dispensed.

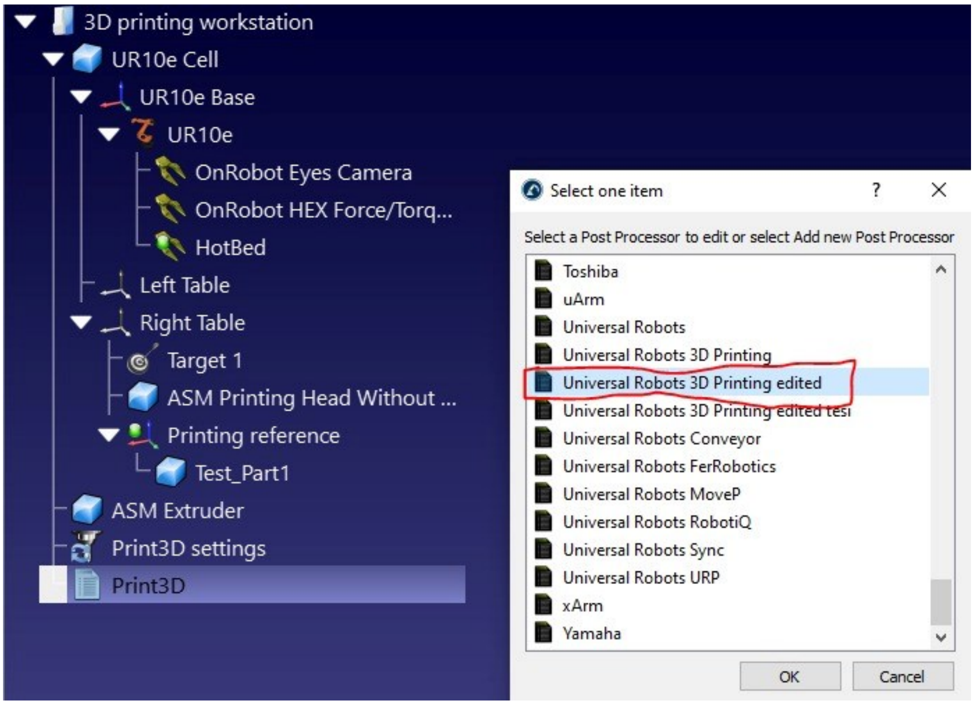


Figure 26: Post processor choose.

In the slic3r present in RoboDK, it is important to set all the speeds 10 mm/s in order to allow the extruder hot end to have the constant movement during the process. This will increase the quality of production and facilitate the control of stepper motor.
The start and stop function for the stepper motor is triggered by the python code of post processor. A 5V analogue signal is sent from the I/O port 0 of the control box of cobot to Arduino board when the material needs to be extruded. The signal stops when no material needed to be extruded.

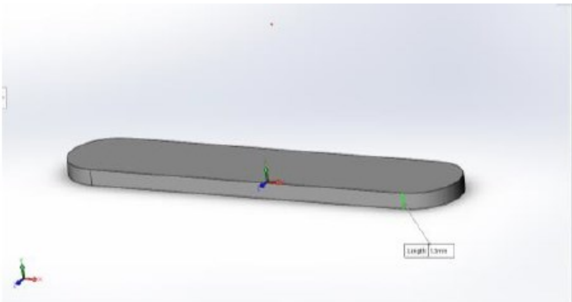
“So, the analogue signal will be received by Arduino micro-controller at port A0 when the printing program is running in the cobot, this Arduino will drive the stepper motor running in a constant speed, while stopping extrusion if no material needs to be extruded.”

5 TEST THE SYSTEM

A calibration has to be performed before using the system to produce the 3D model with more complicated shape. The calibration operation consist of print the several sample objects in order to allow the filament extrusion to become steady and to get satisfaction by the layer-to layer adhesion.

5.1 Design and import the 3D model to print

The first thing to do is to design the model in SolidWorks and import it in the RoboDK. The system could be unstable at the first time and its performances may be unknown. This is why it is important to make the calibration process by producing at the first time a model with less material.



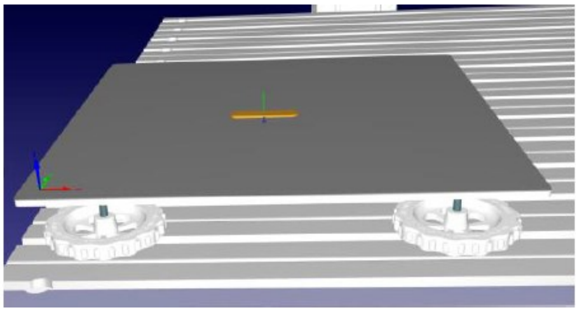


Figure 27: At the left: the model in SolidWorks, at the right: the model imported in RoboDK.

Before slicing the object in layers using slic3r, the model has to be imported and placed on the printing reference frame located on the heated bed.

"After this operation, we have to inter in Utilities to choose 3D print project to generate the tool path." "To avoid the collision between printed head and the other element in the work cell, we have to change the tool orientation and the starting point of the cobot." "We have also to eliminate redundant paths and reduce the possibility of collision between the printing head and the object being printed."

"In this project, to avoid the excessive pulling forces on the cables around the cobot, the tool orientation is rotated to 180 degrees around the flange Z-axis.” “In addition, the posture of the cobot at the starting point is adjusted according to the reality.” “The adjusted parameters have been marked in the red boxes in Figure below.”

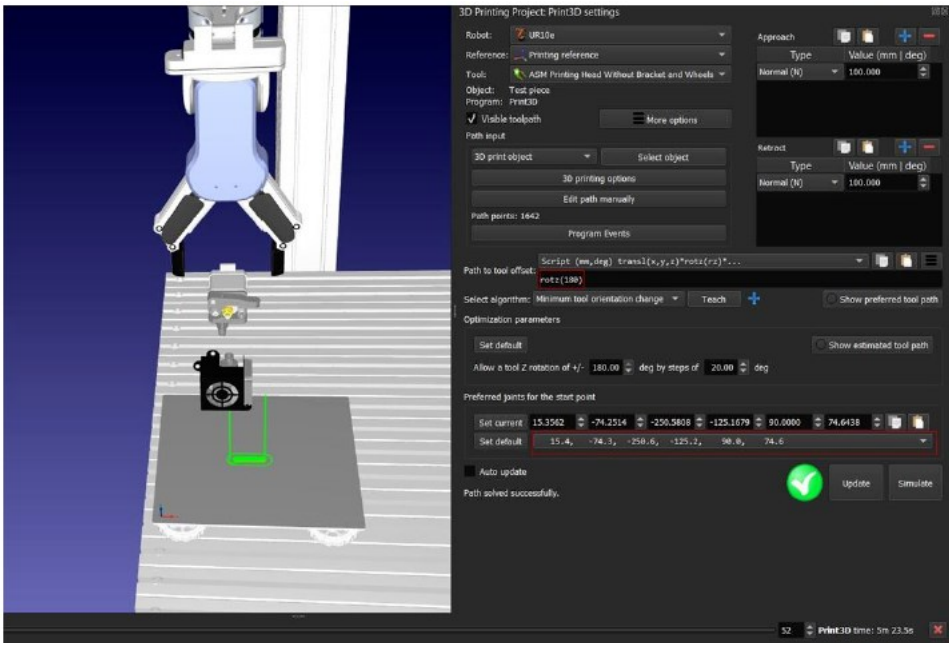


Figure 28: RoboDK printing configuration.

“The following step is to setting the parameters in the slicing software.” Slic3r is the default slicing in RoboDK software, which is used in this project.

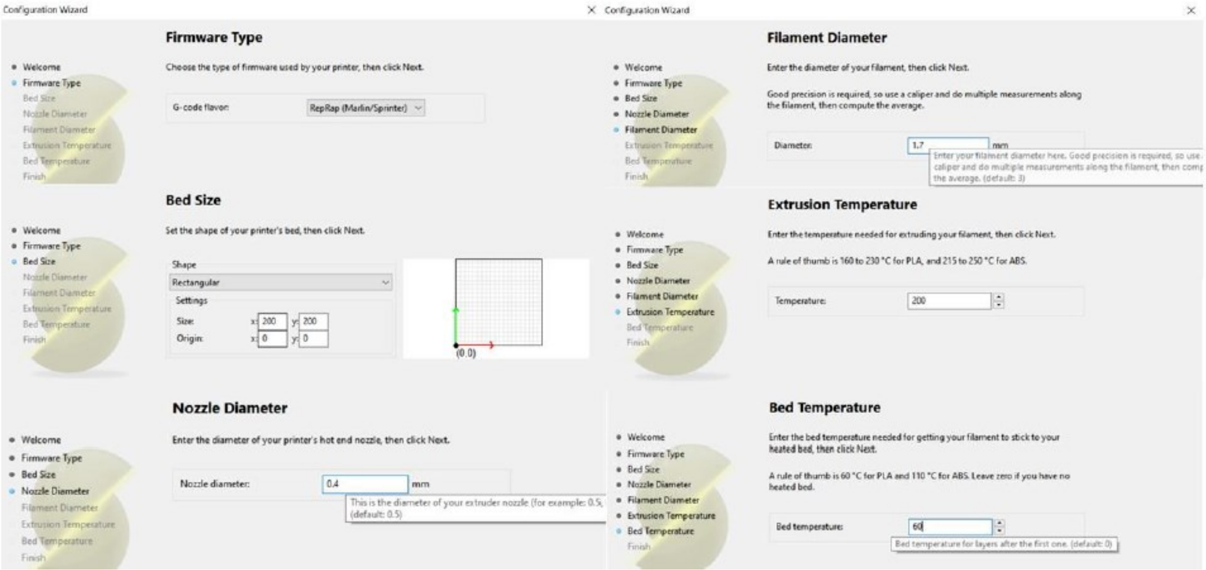


Figure 29: Slic3r configuration

The last Figure show us the configuration parameters in Slic3r, we can notice that the most important parameters are the nozzle diameter, the bed size and the filament diameter. We could be left blank or set as default the firmware type and the bed temperature. “If the temperature control needs to be integrated with the main system, the setup of firmware type and the bed temperature are useful.” Which is not the case in this project.

5.2 Robot program generation

It is important to make the simulation in RoboDK before transferring the program to the cobot. This process allow us to check the potential collision during the printing process.

A universal robot 3D printing post process has to be selected in order to generate a printing program written in UR Script.

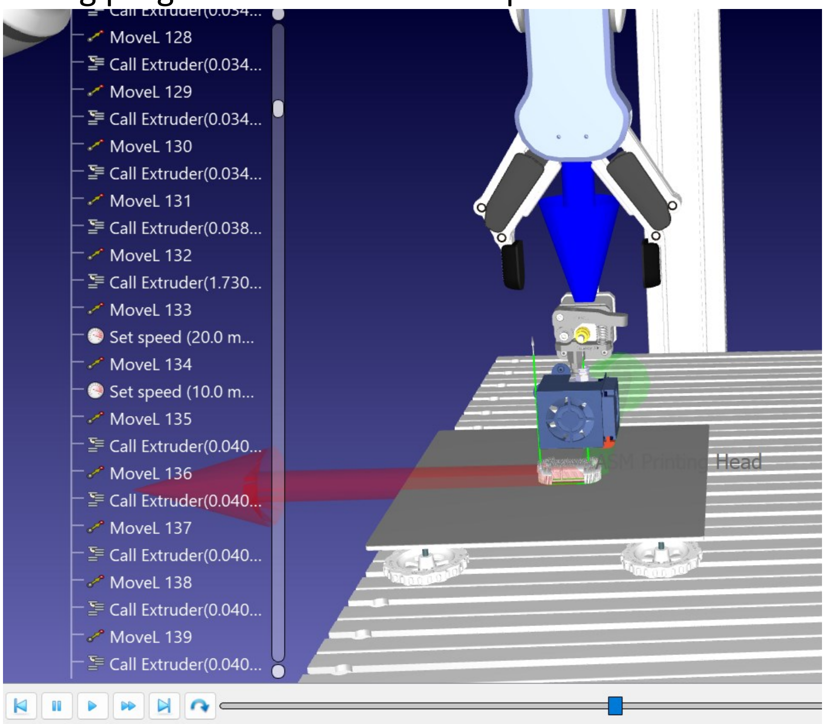


Figure 30: Simulation running in RoboDK for collision detection.

“The figure above shows the starting part of the printing program. Firstly, the moving speed is defined, followed by the blend radius and the TCP.” “What follows behind are the commands for moving the coordinates, with defined acceleration, speed and whether to activate the analog output during the movement.” “As can be seen from the program, the analog output commands are telling the analog I/O 0 port in UR control box to output 5V or 0V.”

```
# Main program:
# Program generated by RoboDK v5.5.0 for UR10e on 09/02/2024 10:45:45
# Using nominal kinematics.
blend_radius_m = 0.001
speed_ms     = 0.083
speed_ms     = 0.100
# set_reference(p[-0.605289, -0.488399, 1.123500, 0.000000, -3.141593, 0.000000])
set_tcp(p[-0.000670, -0.031970, 0.420880, 0.000000, 0.000000, 0.000000])
# Show ASM Printing Head Without Bracket and Wheels
movej([0.251203, -1.310550, -4.436993, -2.106438, 1.570796, 1.319593],accel_radss,speed_rads,0,0)
movel(p[-0.702052, -0.391755, 1.118500, 0.000000, 0.000000, 0.000000],accel_mss,speed_ms,0,0)
speed_ms     = 0.020
set_standard_analog_out(0, 0)
movel(p[-0.702052, -0.391755, 1.123200, 0.000000, 0.000000, 0.000000],accel_mss,speed_ms,0,blend_radius_m)
speed_ms     = 0.040
set_standard_analog_out(0, 5)
movel(p[-0.702052, -0.391755, 1.123200, 0.000000, 0.000000, 0.000000],accel_mss,speed_ms,0,0.000)
speed_ms     = 0.020
speed_ms     = 0.040
set_standard_analog_out(0, 0)
movel(p[-0.702052, -0.391755, 1.123200, 0.000000, 0.000000, 0.000000],accel_mss,speed_ms,0,0.000)
speed_ms     = 0.010
set_standard_analog_out(0, 0)
movel(p[-0.702599, -0.392259, 1.123200, 0.000000, 0.000000, 0.000000],accel_mss,speed_ms,0,0.000)
set_standard_analog_out(0, 5)
movel(p[-0.703450, -0.392922, 1.123200, 0.000000, 0.000000, 0.000000],accel_mss,speed_ms,0,0.000)
set_standard_analog_out(0, 0)
movel(p[-0.704073, -0.393328, 1.123200, 0.000000, 0.000000, 0.000000],accel_mss,speed_ms,0,0.000)
set_standard_analog_out(0, 5)
movel(p[-0.705022, -0.393842, 1.123200, 0.000000, 0.000000, 0.000000],accel_mss,speed_ms,0,0.000)
set_standard_analog_out(0, 0)
movel(p[-0.705617, -0.394103, 1.123200, 0.000000, 0.000000, 0.000000],accel_mss,speed_ms,0,0.000)
set_standard_analog_out(0, 5)
movel(p[-0.706723, -0.394491, 1.123200, 0.000000, 0.000000, 0.000000],accel_mss,speed_ms,0,0.000)
set_standard_analog_out(0, 0)
movel(p[-0.707444, -0.394673, 1.123200, 0.000000, 0.000000, 0.000000],accel_mss,speed_ms,0,0.000)
set_standard_analog_out(0, 5)
movel(p[-0.708509, -0.394851, 1.123200, 0.000000, 0.000000, 0.000000],accel_mss,speed_ms,0,0.000)
set_standard_analog_out(0, 0)
movel(p[-0.709249, -0.394912, 1.123200, 0.000000, 0.000000, 0.000000],accel_mss,speed_ms,0,0.000)
set_standard_analog_out(0, 0)
movel(p[-0.709789, -0.394935, 1.123200, 0.000000, 0.000000, 0.000000],accel_mss,speed_ms,0,0.000)
set_standard_analog_out(0, 5)
movel(p[-0.735789, -0.394935, 1.123200, 0.000000, 0.000000, 0.000000],accel_mss,speed_ms,0,blend_radius_m)
set_standard_analog_out(0, 0)
movel(p[-0.736329, -0.394912, 1.123200, 0.000000, 0.000000, 0.000000],accel_mss,speed_ms,0,0.000)
set_standard_analog_out(0, 5)
```

Figure 31: UR Script of printing program.

“The printing program is loaded from USB drive by using the socket on the UR10e teach pendant as can be seen in Figure above.”

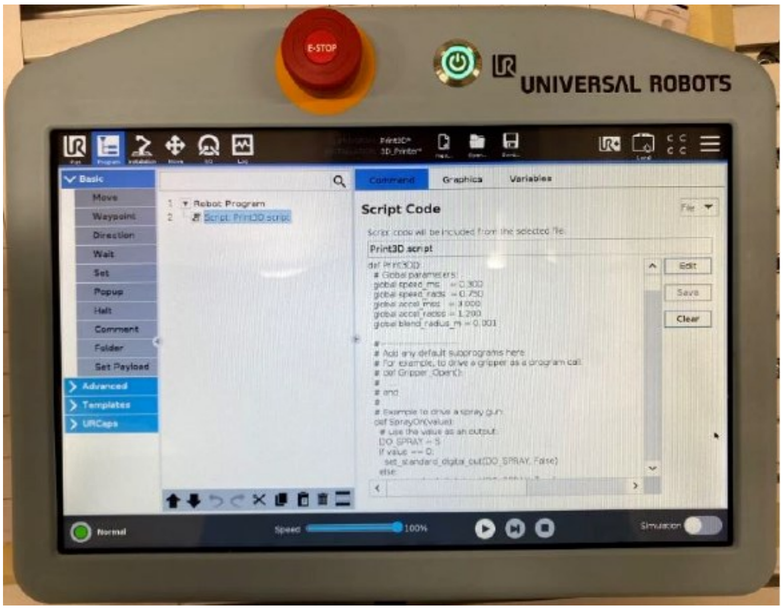


Figure 32: Tech pendant of cobot, loading the program from USB drive to cobot.

5.3 Stepper motor speed

Choosing the right speed for your print can be quite a challenge because it depends on a lot of parameters that I will present in this section.

In this project, the PLA material is used to print and its maximum allowed printing speed is 60 mm/s. for maximum accuracy and reduced the vibration of cobot, the speed is set to 10 mm/s.

To insert the parameters that influence the speed of motor, open the Slic3r from RoboDK by clicking on utilities and after on 3D printing projects. “The layer height, filament diameter, nozzle diameter and speeds for print moves shall be inserted into the Slic3r correctly in the configuration as shown in Figure below.”

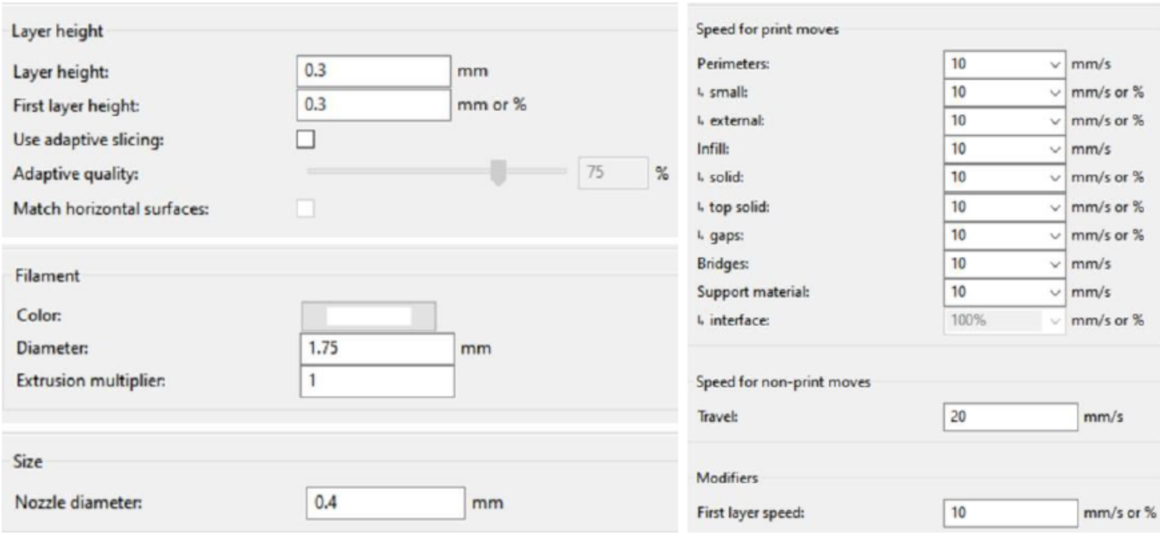
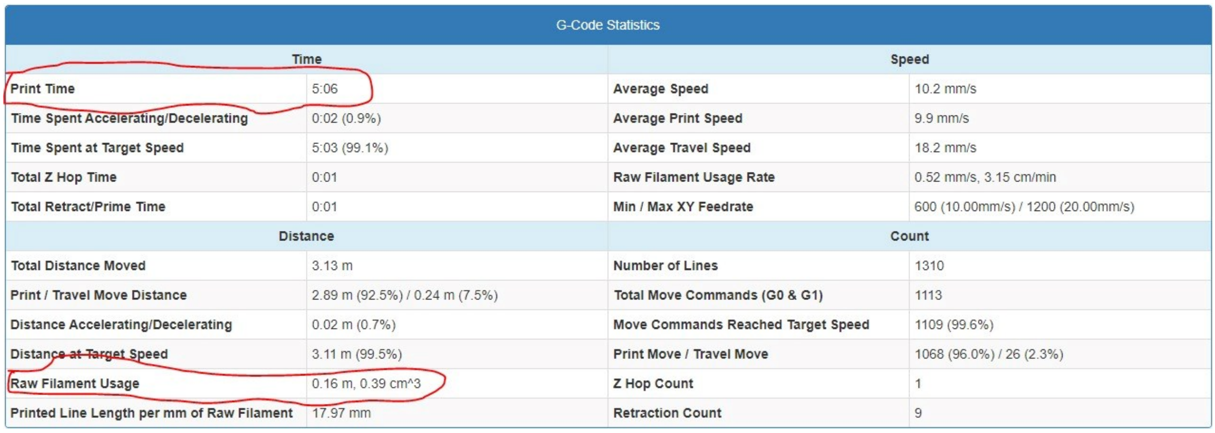


Figure 33: important setup in slic3r.

Another important step is to export the G-code from Slic3r, drag the G-code file to another app to check the time, material consumption and another information about the model to produce. In this thesis, an open-source app called gCode Analyzer is used. This allows to get some information on the material to be printed: print time, length of raw material used. These informations are important to compute stepper motor speed.



G-Code Statistics			
Time		Speed	
Print Time	5:06	Average Speed	10.2 mm/s
Time Spent Accelerating/Decelerating	0:02 (0.9%)	Average Print Speed	9.9 mm/s
Time Spent at Target Speed	5:03 (99.1%)	Average Travel Speed	18.2 mm/s
Total Z Hop Time	0:01	Raw Filament Usage Rate	0.52 mm/s, 3.15 cm/min
Total Retract/Prime Time	0:01	Min / Max XY Feedrate	600 (10.00mm/s) / 1200 (20.00mm/s)
Distance		Count	
Total Distance Moved	3.13 m	Number of Lines	1310
Print / Travel Move Distance	2.89 m (92.5%) / 0.24 m (7.5%)	Total Move Commands (G0 & G1)	1113
Distance Accelerating/Decelerating	0.02 m (0.7%)	Move Commands Reached Target Speed	1109 (99.6%)
Distance at Target Speed	3.11 m (99.5%)	Print Move / Travel Move	1068 (96.0%) / 26 (2.3%)
Raw Filament Usage	0.16 m, 0.39 cm^3	Z Hop Count	1
Printed Line Length per mm of Raw Filament	17.97 mm	Retraction Count	9

Figure 34: Information obtained from gcode viewer.

The software above give use to data useful to compute the linear speed at the gear of the extruder. This speed (v) is the velocity at which the filament is fed into the extruder and finally the rotational angular speed of the stepper motor has to be computed using these equations below.

This angular speed is set in Arduino code.

$$v = \frac{L}{T} = \frac{160}{306} = 0.52\ mm/s$$

$$v = \omega \cdot \pi \cdot \frac{r}{180}$$

$$\omega = \frac{180 \cdot v}{\pi \cdot r} = \frac{0.52 \cdot 180}{\pi \cdot 5.5} = 5.45\ {}^{\circ}/s$$

ω= rotational speed in degree / second

r= radius of the gear(in mm) which fed the filament in extruder

To convert the rotational speed from °/s to step/s, which is the unit of speed recognize by Arduino program, an additional calculation should be done. During the full-step mode of the stepper motor, it runs at 1.8 °/step and the same stepper motor in term in another unit of speed is running in 16^{th}-step mode. The following calculations are required in order to keep its running speed at 5.45 °/s .

$$\frac{1 \cdot 16}{1.8} = \frac{x}{5.45}$$

$$x = 48\ step/s$$

So, 48 step/s is the rotational speed of stepper motor to be inserted in Arduino code.

5.4 Bed Levelling

“ Make sure your 3D printer has a level build platform or bed is a critical factor for ensuring accurate prints.” “Typically, users have to manually adjust screws to level the bed, which can be time consuming and tedious.” “Additionally, this process often has to be repeated after several prints due to the possibility of the bed going out of alignment after several hours of use.” “An unlevel bed can cause unexpected first layer issues resulting in poor adhesion of the printed part.” “In some cases, it can even lead to a clogged extruder or scratch marks on the build surface if the nozzle is far too close to the bed (18).”

This operation for this project begins by aligning the heated bed with the coordinate system of the cobot. First, we have to assembled on the cobot tool flange all the components of the end effector. “Then, align the Z-axis of the tool flange with the Z-axis of the cobot base using the automatic align function on the teach pendant.”

The next step is to run the program transferred to the teach pendant at a low speed. “Before starting the program, place the piece of paper on the heated bed, run the program and when the end effector or the nozzle tip reach its last position vertically and want to start to make the movement to print, verify that the paper can be pulled out with some resistance but without hindering the process.” If it is not the case, stop the robot and use the knobs to adjust the height of the heated bed. Repeat this process until the cobot complete the movement to print the first layer of model to be printed.

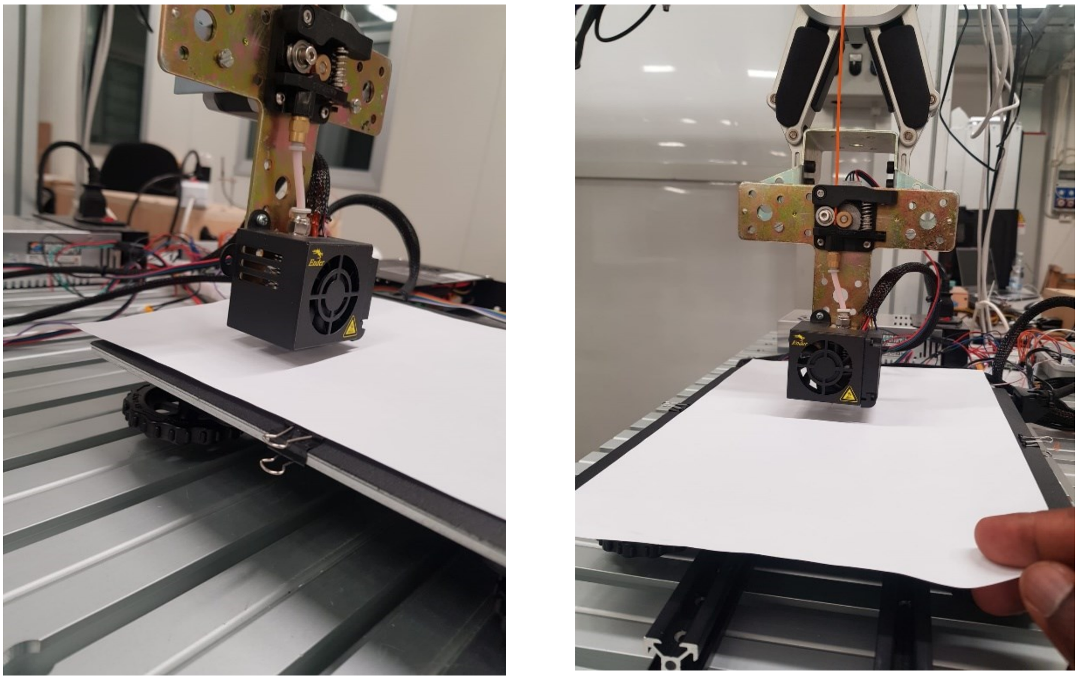


Figure 35: Bed leveling

5.5 Program Running

To run the program, the following steps might be done. Firstly, transfer the program from RoboDK to USB drive, connect the USB drive on teach pendant of cobot, load the program in cobot and add another command at the end setting the analog signal to o volt to stop the extrusion signal.

Make the first run without extrusion to check the bed leveling, load the Arduino program in Arduino board, verify the wire connections (from Arduino board to stepper motor driver and from driver to stepper motor). Throughput the ender-3 screen, set the temperature of extruder to 200°c and the temperature of hot bed to 60°c. one these temperatures are reached launch the program.

5.6 Test Result

The following characteristics have to be evaluated to verify if the system is working well.

Layer adhesion: Each layer should well bond to the layer below, so that the model printed has the structure strong having the layers aligned one on the other. If the layers don't bond together, decrease the speed scale on teach pendant or increase the layer thickness.

Surface quality: The surface should be flat without messy infill. The quality of surface indicate the different default of the system. We can have over extrusion (the print looks droopy and stringy) in this case we have to reduce the speed scale on teach pendant. We can have incomplete and messy infill in this case we have to increase the layer high or infill density.

Layer shifting: the layer shifting is caused by the position the nozzle which is too close to the hot bed so that the extruder is pressing the object and heat bed. In this case we have to repeat the process of levelling the heated bed and run the program again.

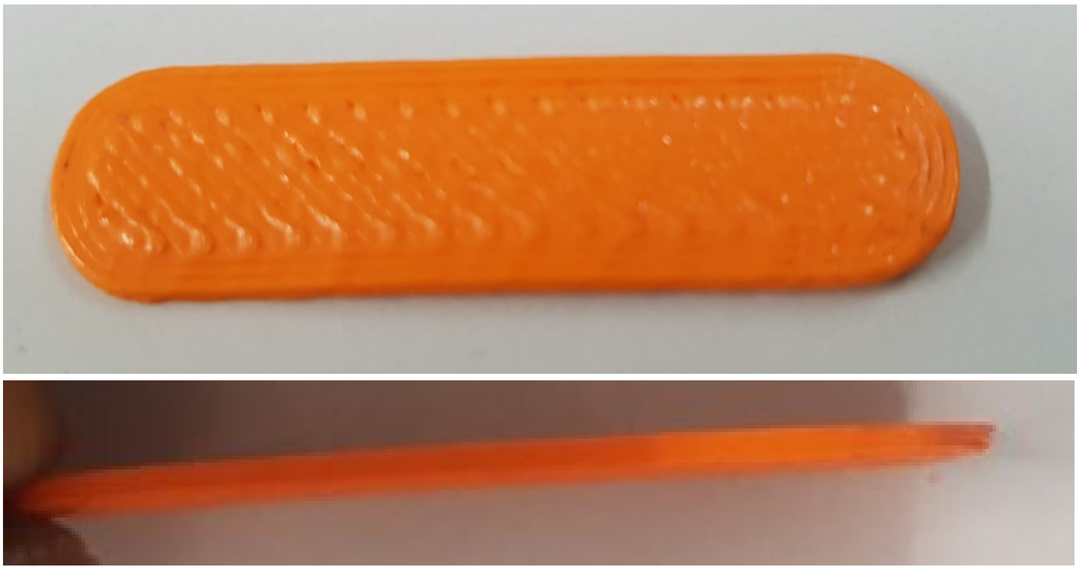


Figure 36: Final result

6 HEAT BED ON ROBOT AND EXTRUDER FIXED ON WORK CELL

In the last work cell, the extruder was fixed on the gripper of the robot and the heat bed on right table, now we will experiment another work cell which consist of fixing the heat bed on robot and the extruder fixed on the work cell. The same robot is used (UR10e), the same extruder (creality ender-3) and the advantages and disadvantages will be evaluated.

6.1 Design of the station

As it is mentioned before, the new work cell will be explored and to build this new work cell, the gripper is removed on UR10e. The heat bed is directly fixed on the end effector of cobot as shown in Figure below.

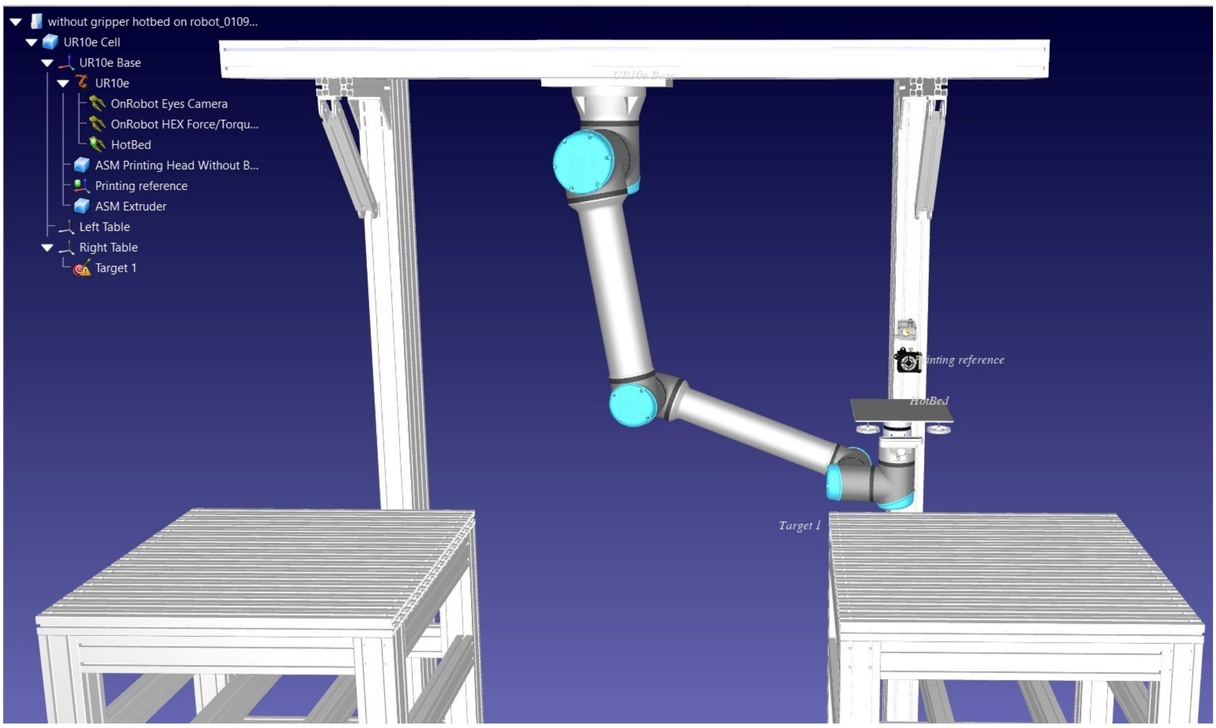


Figure 37: Work cell in RoboDK.

In this figure we can see the new position of reference printing, extruder and heat bed as described before.

Figure 38: UR10e new work cell.

The electronic connections have not been changed: The cobot send the digital output to Arduino by means of sensor connecting the control box of cobot to Arduino, Arduino send the analog output to stepper motor driver and this one drive the stepper motor to control the extrusion. The power supplier connected to the heat bed and extruder to provide the required temperature.

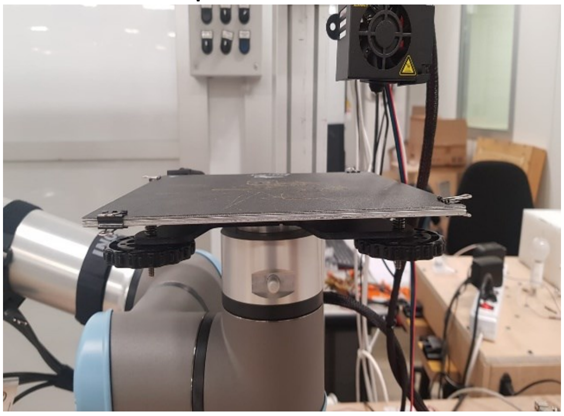
6.2 Important changes

The positions of some elements in this new work cell are different from the last work cell, in this section these differences will be discussed giving their new roles.

6.2.1 Position of heat bed and TCP

The gripper has been removed from the UR10e because the heat bed should be perpendicular to the end effector to allow the robot to align well the heat bed with the extruder to good provide the tool path.

Figure 39: Heat bed in roboDK



Heat bed in physical work cell

The Tool Center Point (TCP) is now on the heat bed instead on ASM Printing head in the last work cell because the heat bed is fixed on cobot and the cobot will move this heat bed accordingly to the tool path generated. It is also important to remind that the cobot will move downward on Z axis instead of top ward like in last work cell.

The new TCP is calculated according to the method described in section 4.2.1 and inserted in RoboDK as is shown in Figure below.

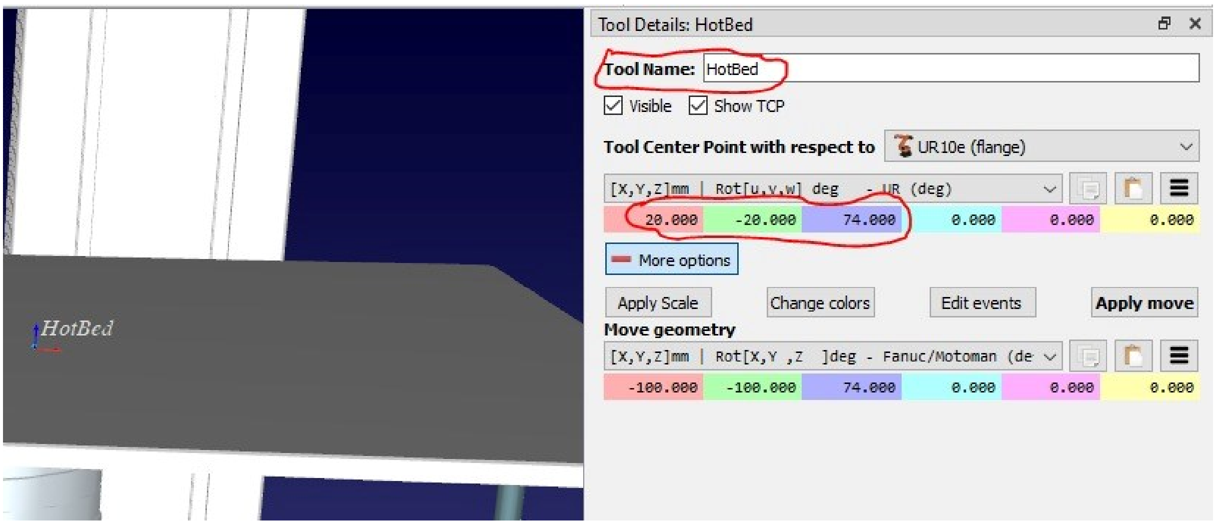


Figure 40: TCP coordinates.

6.2.2 Position of printing reference

The printing reference is a virtual representation of the 3D printer's print bed or build platform. This frame is essential for aligning the robot's toolhead with the print bed and ensuring that the printed object is accurately placed and oriented on the bed.

In this work cell, the extruder is fixed and the cobot have to move the heat bed according to the toolpath generated in RoboDK. So, the printing reference is placed on the nozzle(tip part) of extruder with the Z axes oriented downward as shown in Figure 41.

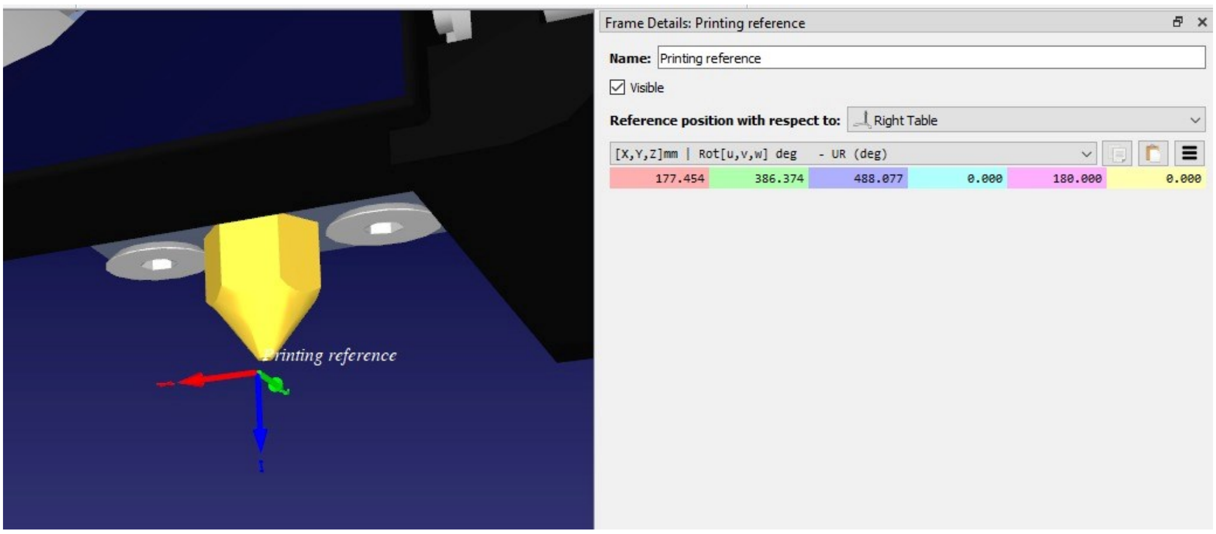


Figure 41: position of Printing Reference.

The Z axe should be oriented downward because the cobot is moving downward when printing and the object should be placed on printing reference flipping the orientation in order to allow the cobot to start printing from the bottom of the object (more details will be given after).

6.2.3 Arduino code

Arduino uno is used to control the extrusion by means of stepper motor and it receives the analog signal from the control box of UR10e. It proceeds the analog signal received by fixing a threshold value to well control the extruder.
For the last work cell, we seen that the threshold value was 950, after many tests of Arduino code with this value it doesn't work properly because we observed some missing deposed material when needed, this caused some layers missing and lead to the bad quality of final result.
By observing the analog signal plots (Figure 42), the threshold have to be changed. When the values are less or equal to 1023 the extruder is open and when they are less or equal to 0 the extruder close (Anex 9.2).

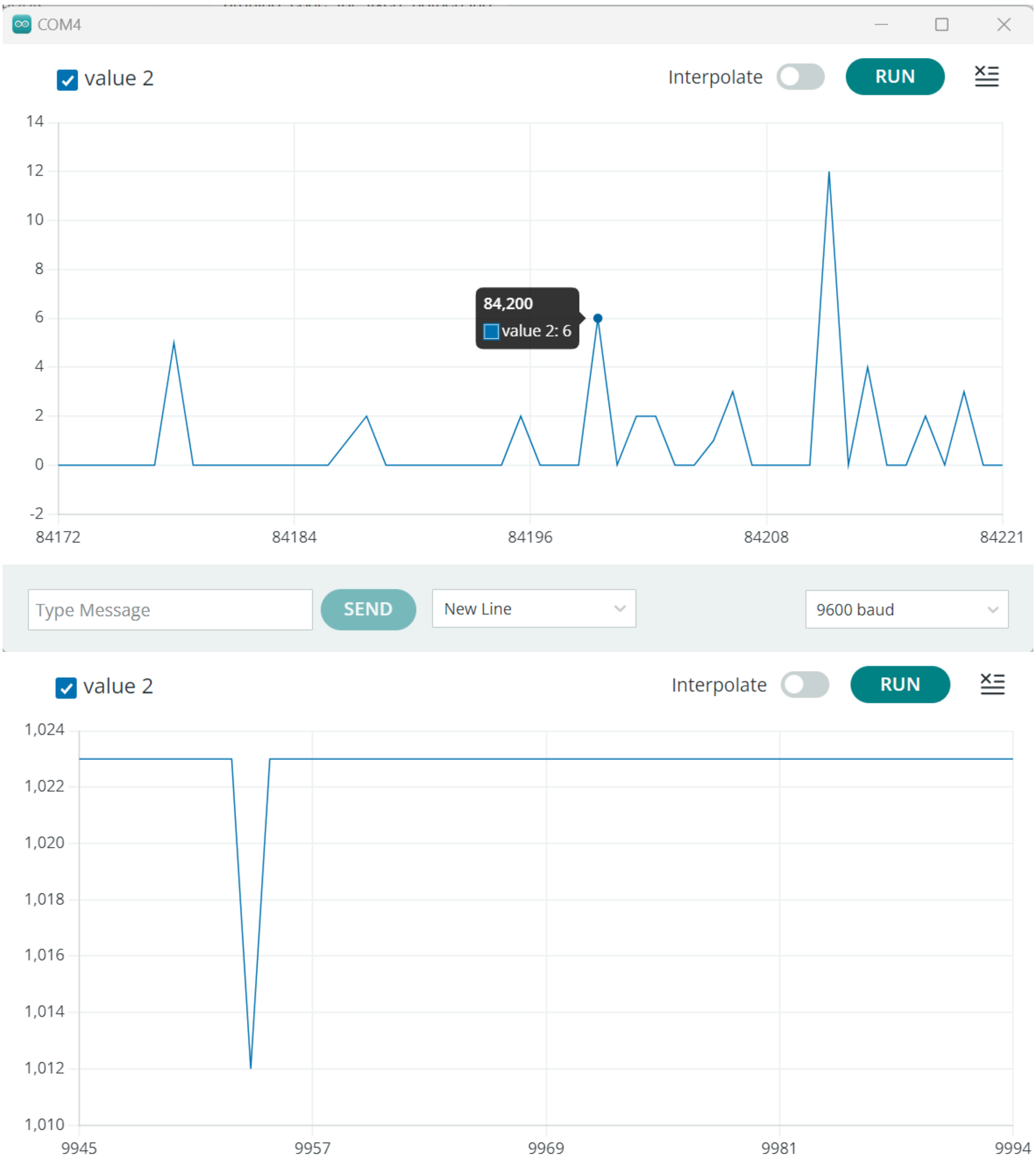


Figure 42: Analog signal values in Arduino.

6.3 Test the new system

The different steps to print an object are the same: design the object in SolidWorks or other drawing software, save it in stl or step file, import the object in RoboDK, provide the toolpath by slicing the object in layer by layer using slic3r, export the gcode to compute rotational speed of stepper motor in step/sec, simulate the program in RoboDK to check the feasibility and collision, export the robot program.

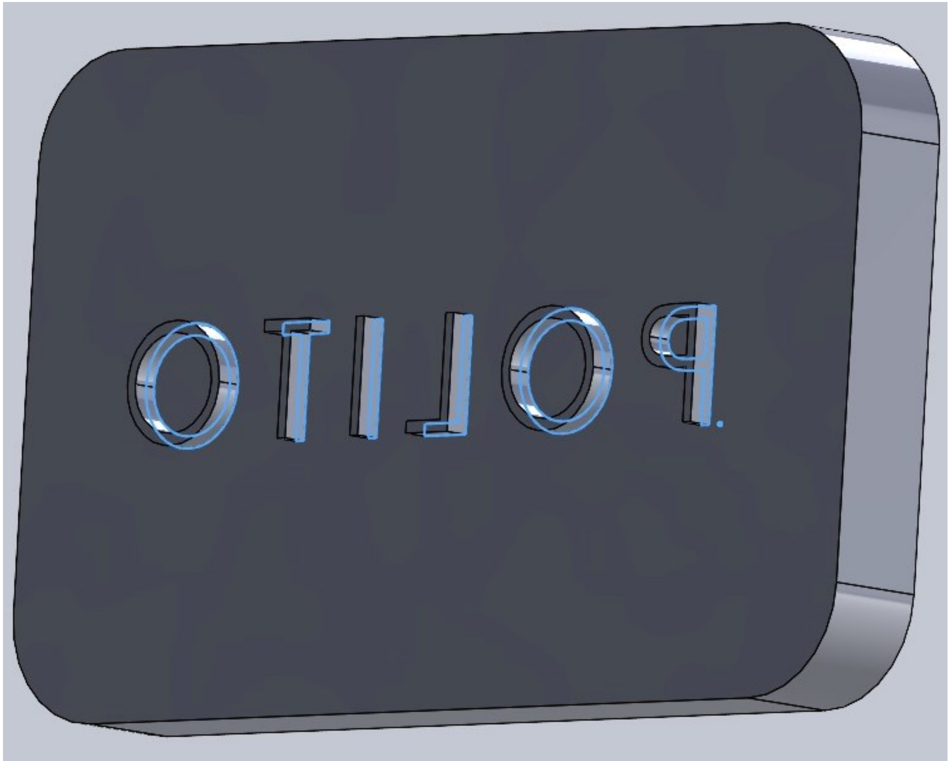


Figure 43: model to print in SolidWorks.

Because the Robot end effector is located at the bottom of the printing reference, the model and everything on it should be flipped in order to have a good result.

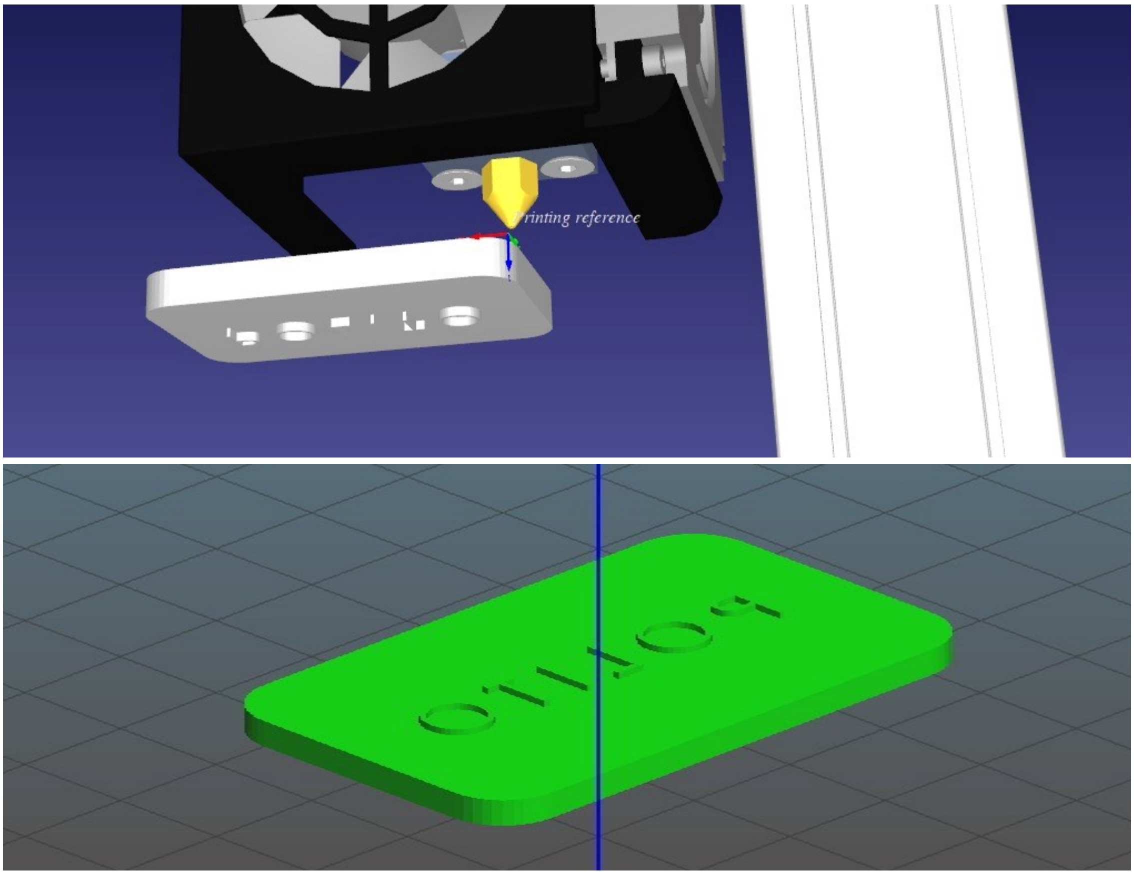


Figure 44: Model in RoboDK(top) and in slic3r(bottom).

All the settings in slicer3r are the same as in the last work cell. After having slicing the model in layer by layer and providing the toolpath, the gcode has to be exported to compute the rotational speed of the stepper motor using the gcode viewer. For this model the total print time is 2682sec, the total raw material to be used is 650mm and the rotational speed is 22.45 steps/sec.

Before exporting the robot program, the simulation should be done to verify the collision and the joints position of the robot. After that, load the program in robot using teach pendant, check the bed levelling, load the Arduino code, heat the extruder and heat bed to 200°c and 60°c respectively, launch the printing program.

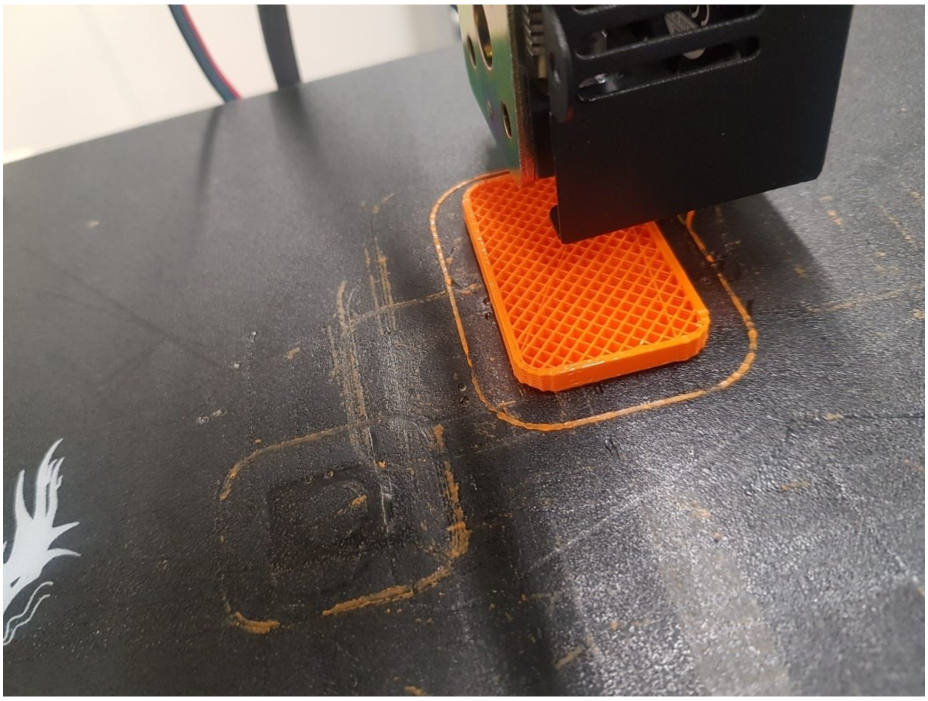


Figure 45: printing in process.

Figure 46: Final result.

Observing the final result, there is not over or under extrusion, the layers are bond well one on the other, there is not messing layer so the system is working well.

7 MULTI PLANAR 3D PRINTING

This part is dedicated to propose a solution of how to print an object not having the layers lying or able to be confined within a single plane. Some time, the prototype can be a non-planar object and our system build has to be able to print these kinds of objects.

7.1 Definition of concept

Non-planar printing involves printing using all 6-axes of the cobot at the same time. In the two last systems, the printing is done in the plane parallel to the heat bed using X Y axes and Z axe allow to move upward(in the first system) or downward(in the second system) to change the plane and continue the printing. The problem with this method is that the curves transform into more or less visible stairs depending on the thickness of the layers as shown in Figure below.

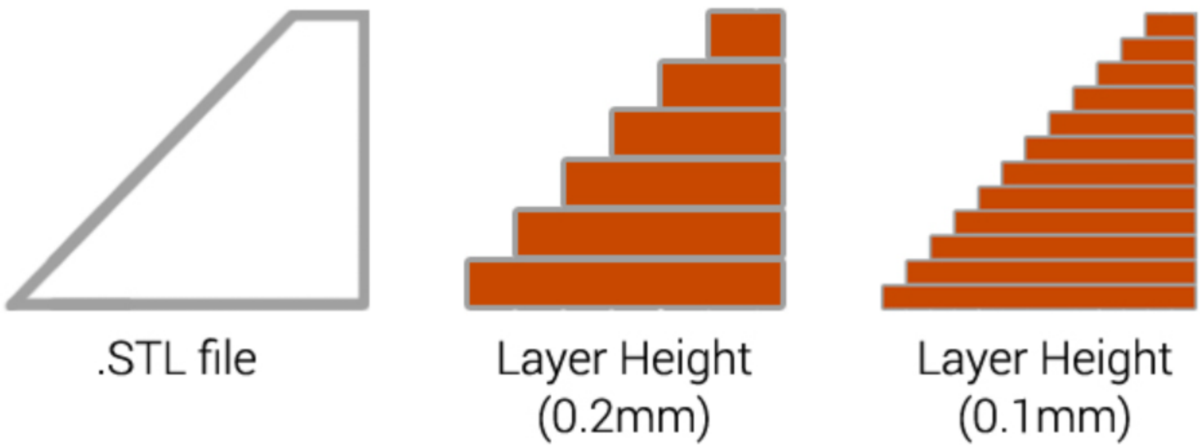


Figure 47: staircase effect why printing an object with the curves in plane parallel to heat bed.

To circumvent this problem, the multi planar 3D printing can be used. Which allows to make 3 dimensions layers, allows us to follow the curves and thus not have these staircase effects.

This new type of printing has the great advantage of the simple fact that the surface of the part is no longer made of several deposited segments, so the quality of the surface and the rigidity of the part will be better. Being curved surfaces, the rate of occurrence of the phenomenon of debonding compared to the heated plate but also between the layers decreases considerably almost to non-existent. All this type of printing increases the mechanical resistance of a 3D printed landmark.

7.2 Printing configuration and Result Evaluation

The process to implement this new type of printing start by installing the slic3r in UBUNTU by following the steeps listed in reference 25. (19)
In this case the slic3r is used in computer Linux or windows by installing virtual machine and after ubuntu because the slic3r in this case offers a new subsection in the print settings section called "Nonplanar layers" as shown in the picture below.

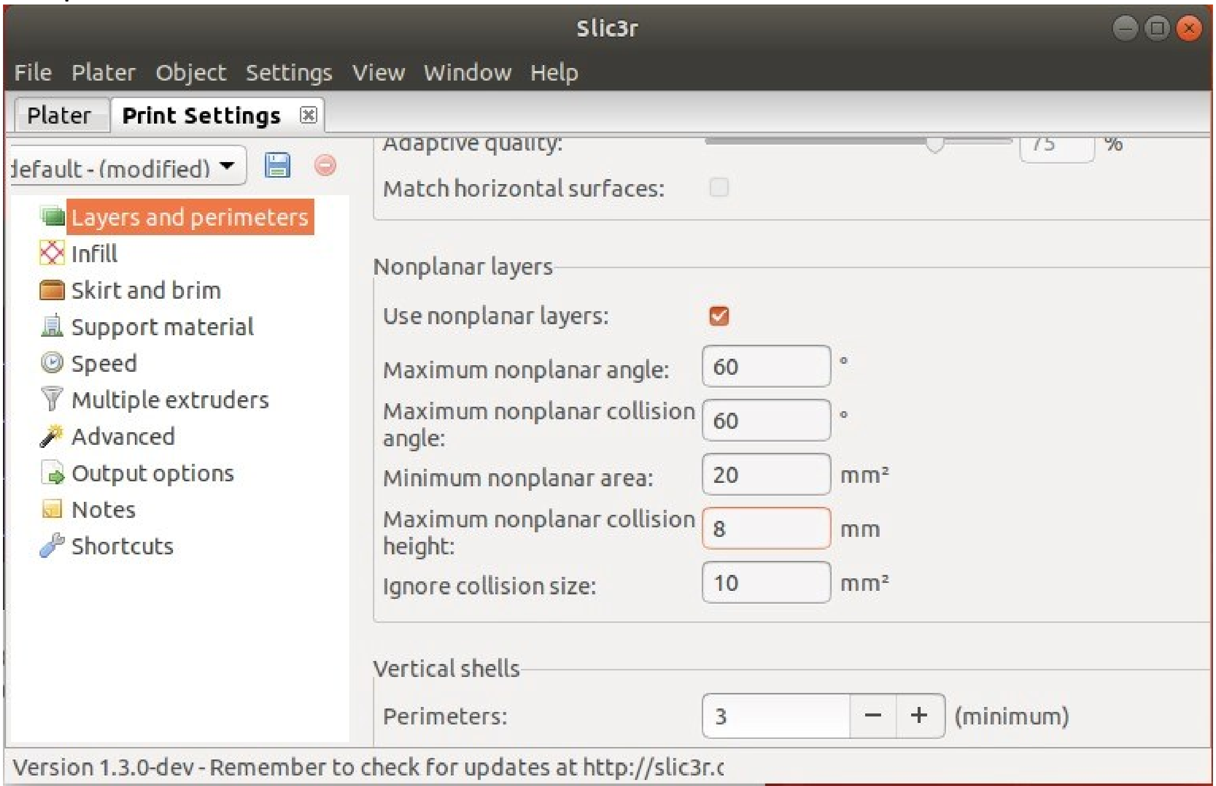


Figure 48: Nonplanar layers section in slic3r used in UBUNTU.

It is important to remember that for this kind of printing it is an advantage to have the sharpest nozzle as possible. The first parameter is the angle of the nozzle, the nozzle used in this project has the angle equal to 60°, the collision angle is the same as nozzle angle , the default value of minimum nonplanar area is 20 $\boldsymbol{mm^2}$, the maximum distance between the tip of the nozzle and the first obstacle(in this project) is 8 mm, the default parameter of collision size is 10 $\boldsymbol{mm^2}$. The others settings in the slic3r are the same as in the last system.

The first steep of the process is to draw the object in SolidWorks or other and save it uniquely in .stl file, import the object in slic3r in ubuntu, provide the gcode, import the gcode in RoboDK where there is the work cell to be use, and finally provide the cobot program.

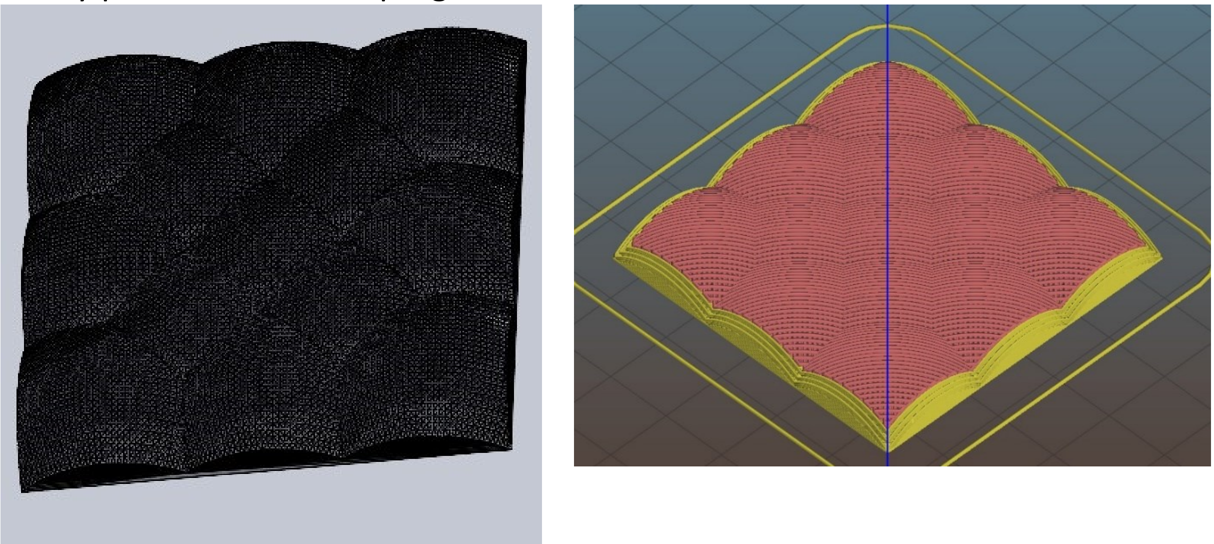


Figure 49: The nonplanar object in SolidWorks and in Slic3r.

As it is mentioned before, after slicing the object layer-by-layer his gcode has to be saved with the extension .gcode or .nc in the share file and imported in RoboDk just by drag and drop the file in RoboDK interface. One in RoboDK, make a simulation to check the potential collision and provide the cobot program.

Figure 50: Nonplanar object.

Inspecting the final result, it is clearly possible to see that there are not the staircase effects when the printing system changes the plane, it is also possible to notice this phenomenon of cobot to move up and down continuously in X and Y axes according to the shape of the object in order to deposit the material to form curves and layers not belonging to the same plane.

8 CONCLUSION AND FUTURE WORK

This section summarizes the result obtained in this experimental thesis, the performance of the cobot assisted AM system for the rapid prototyping. Furthermore, the future work upon this research is proposed.

8.1 Conclusion

Prototyping tends to become an increasingly competitive and demanding process with a very high requirement in terms of dimensional accuracy and the quality of the resulting surface, taking into account a reduction in production times and costs. The influencing factors that must be taken into account determine the establishment of optimal working conditions.

The surface quality of part is the result of complex phenomena involving the entire 3d printing process, taking into account:

- **Material to be printed (shape):** In this thesis, the objects with complicated shape(nonplanar object) have been printed to demonstrate that the system is working well, and some of objects have been slicing using the multiplanar 3D printing to avoid the staircase effects.
- **Deposit speed: "**The speed for production using this AM system is limited to 10 mm/s to keep moving stability and reduce the vibrations of cobot when it changes the direction, causing the shift of extrusion path and the defect on the object." The vibrations in the second system studied in this thesis is less than the first system with the same cobot speed due to the inferior value of payload in second system with respect to that of the first system.
- **The deposition route of the extruded material:** The path generation done in RoboDK or Ubuntu+slic3r has been done accurately to avoid the collision and misalignment of layers which can impact the final result. In this thesis, cobot has been allowed to exploit simultaneously 3 axes of movement to obtained a stronger structure.
- **The melting temperature of the material:** The temperatures used are 200° and 60° for the extruder and heat bed respectively. Using these temperatures in this project, the good adhesion was obtained and the layers bonding one on the other which lead to the good final result.

8.2 Future works

The cobot used in AM system has more potential to be discovered which can lead to produce an object with very complicated shape. The last part of this project proposed a solution to use simultaneously 3 axes of cobot while it is known that the cobot has 6 or 7 (the 7^{th} corresponding to extruder) axis of freedom, if a program is able to use simultaneously these 6 or 7 axes for printing, this program can allow to print an object having a particular shape avoiding the collisions and increasing the rigidity of the object.
Another interesting field is to design a multi-extruder system for AM system. Using a system with two or more extruders will lead to produce the same object two times at the same time or produce an object with two or more colors if the colors of the filament are not the same.

ACKNOWLEDGEMENT

I thank my academic tutor Prof Paolo Chiabert for proposing to me this interesting thesis and her ideas along the elaboration of the thesis. I would also like to thank Dr.Khurshid Aliev and Eng. Mansur Asranov for helping me to build the physical work cell at laboratory.

9 ANNEXES

9.1 Arduino code for the first work cell

```
#include <AccelStepper.h>
AccelStepper Extruder(1, 3, 2); // Configuring motor: A stepper motor
//controlled by a dedicated driver board, pin3 = step, pin2 = direction.
// Define digital communication pin names.
int AnInPin = A0; // pinA0: receives digital signals from external.
int DigOutPin = 9; // pin9: Sends digital signal to Enable pin on the driver.
int val = 0; // variable to store the read value.

void setup() {
  Serial.begin(9600); // Initialize serial communication at 9600 bits per second
  pinMode(AnInPin, INPUT); // Set DigInPin as Input
  pinMode(DigOutPin, OUTPUT); // Set DigOutPin as Output
  Extruder.setMaxSpeed(20000); // Set the maximum speed in steps per second.
  Extruder.setSpeed(48); // Set the initial speed in steps per second.
}
void loop() {
 val = analogRead(AnInPin); // store the value read by AnInPin

 if(val >= 950) {
    digitalWrite(DigOutPin,LOW);// If high: extruder runs in the speed set
      //before. Set Enable pin on A4988 driver to low to activate the extruder.
    Extruder.setSpeed(48); // Set the initial speed in steps per second.
    Serial.println(val);
    Serial.print("\t");
    Extruder.runSpeed();
  }

 if(val <= 950) {
   Extruder.stop(); // If low: stops the Extruder and sends high signal to
     //Enable pin on A4988 driver to disable the extruder control.
   digitalWrite(DigOutPin,HIGH);
  }
}
```

9.2 Arduino code for the second work cell

```
#include <AccelStepper.h>

AccelStepper Extruder(1, 3, 2); // Configuring motor: A stepper motor
//controlled by a dedicated driver board, pin3 = step, pin2 = direction.
// Define digital communication pin names.
int AnInPin = A0; // pinA0: receives digital signals from external.
int DigOutPin = 9; // pin9: Sends digital signal to Enable pin on the driver.
int val = 0; // variable to store the read value.

void setup() {
  Serial.begin(9600); // Initialize serial communication at 9600 bits per second
  pinMode(AnInPin, INPUT); // Set DigInPin as Input
  pinMode(DigOutPin, OUTPUT); // Set DigOutPin as Output
  Extruder.setMaxSpeed(20000); // Set the maximum speed in steps per second.
  Extruder.setSpeed(60); // Set the initial speed in steps per second.
}

void loop() {
 val = analogRead(AnInPin); // store the value read by AnInPin

 if(val <= 1023) {
    digitalWrite(DigOutPin,LOW);// If high: extruder runs in the speed set
      //before. Set Enable pin on A4988 driver to low to activate the extruder.
    Extruder.setSpeed(60); // Set the initial speed in steps per second.


    //float mSpeed = Extruder.setSpeed(50);
    Serial.println(val);
    //Serial.print("  ");
    //Serial.printn(mSpeed);//to display the actual speed in the serial monitor
    //Serial.print("  ");
    //Serial.println(Extruder.currentPosition());//to display the actual position
    //in order the verify that the stepper motor don't turn in other direction during the process
    Serial.print("\t");

    Extruder.runSpeed();
  }

 if(val <=0) {
   Extruder.stop(); // If low: stops the Extruder and sends high signal to
     //Enable pin on A4988 driver to disable the extruder control.
   digitalWrite(DigOutPin,HIGH);
  }
}
```

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