YRKESHÖGSKOLAN NOVIA

Upgrading the Electronics of a Robotic Arm 3D Printer

Modification of the control electronics of a 3D printer based on ABB IRB-1200 90/5

Ricard Bitriá Ribes

Degree thesis for Bachelor of Engineering

Degree Programme in Electrical Engineering and Automation

Vaasa 2021

Acknowledgements

I would like to thank Philip Hollins for his dedication and inexhaustible feedback, always aiming to give our best and improve in every project. Thank you for taking the time to read through our work countless times and teaching us all the invaluable writing skills.

Thanks to all the TB RAM team and especially Miguel Zamora and Dennis Bengs who supported me through the project and listened to my ideas. Thanks also to Rayko Toshev for the opportunity to work on this amazing project.

Thanks also to Roger Mäntylä for his incredibly useful classes, all the support and dedication. To UdL and Novia for this amazing experience and for preparing us for our professional future.

And last but not least, thanks to all my friends, family and people who shared with me this amazing experience.

BACHELOR'S THESIS

Author: Ricard Bitriá Ribes
Degree Programme: Electrical Engineering and Automation
Supervisor(s): Philip Hollins

Title: Upgrading the Electronics of a Robotic Arm 3D Printer

Date: May 14, 2021 Number of pages: 46 Appendices: 1

Abstract

The Technobothnia Robotic Additive Manufacturing project in the Technobothnia laboratory, Finland, is developing an extruder tool to enable a robotic arm to print in 3D. The control electronics of this tool have barely changed since the first prototypes and are composed of multiple parts that add to the complexity of the tool.

Therefore, this thesis aimed to redesign and optimize the electronics system with parts already available in the market. The ultimate goal was to make the current prototype closer to a production-ready product.

Firstly, the state of the extruder tool before any modifications was reviewed and the changes needed were evaluated. Other projects and research were described as well for comparison. Based on this evaluation different replacement alternatives were considered and discussed. The old driver board was replaced by a more capable and compact one. The cabling was upgraded with a single multi-wire cable and smaller connectors. Additionally, an automated bed levelling probe is implemented for easier initial calibration.

As a result, the new control electronics simplified the overall setup and made it easier to reproduce. The components used are well established in the market and have extensive support, facilitating the troubleshooting and replacement of the parts. Finally, the auto levelling system eliminated the manual calibration process, saving setup time.

Language: English
Key words: Robotics, 3D printing, Electronics, Additive Manufacturing, ABB

Table of contents

List of figures

List of tables

Glossary

3D	Three Dimensional
ABS	Acrylonitrile Butadiene Styrene
AM	Additive Manufacturing
CAD	Computer Aided Design
CNC	Computer Numeric Control
DLP	Digital Light Processing
DMD	Deformable Mirror Device
EPS	European Project Semester
FDM	Fused Deposition Modelling
LCD	Liquid crystal display
PETG	Polyethylene Terephthalate Glycol-modified
PLA	Polylactic Acid
SLS	Selective Laser Sintering
TB RAM	Technobothnia Robotic Additive Manufacturing
UV	Ultraviolet

1 Introduction

Additive manufacturing and, in particular, the Fused Deposition Modelling (FDM) technique, has seen in the last ten years an impressive development reflected in the growth of manufacturers by a factor of three (AMFG, 2019). This has been mainly driven by the proliferation of low-cost, open-source desktop machines in the consumer market (3D Insider, 2017). According to Bandyopadhyay *et al.* (2015), these machines, better known as three-dimensional (3D) printers, allow the rapid fabrication of solid objects by selectively adding material (usually some type of polymer) in the right place, gradually creating their final form. This opens a new world of possibilities in object shapes that other traditional manufacturing techniques cannot achieve (Sertoglu, 2021).

1.1 Background

There are many different technologies of 3D printers but the most common ones work by successively adding thin planar layers of material that stack to form the final shape (Gebhardt *et al.*, 2019, pp. 3–5). However, this method presents some drawbacks when dealing with overhanging areas. Moreover, as Ahlers (2018) stated, it offers a lower resolution in the direction perpendicular to the layers. This loss in resolution is reflected in the stair-stepping effect caused by the discretized layer structure which is showcased in Figure 1a. Figure 1b shows an object with an overhanging area where support material has been added to successfully print it.

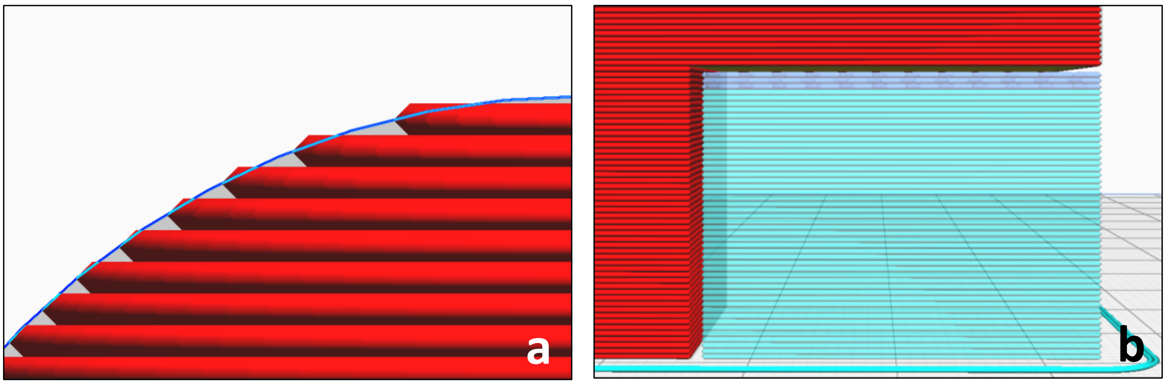


Figure 1: (a) Original model (blue) and generated layers (red) (b) Object (red) and support material (blue)

As seen in Figure 1a, as the object approaches the horizontal plane the stepping effect gets more noticeable, compromising the final object’s shape. The problem with overhanging areas, shown in Figure 1b, is that it requires support material that will be just thrown away after the print process, generating waste material.

The material is extruded from a single nozzle in a (mostly) continuous string. As a result, the printing pattern and direction also influence the part's mechanical properties. For example, tensile strength in the layer plane is greater than in the perpendicular direction (Torrado *et al.*, 2016).

To solve these problems some techniques have been proposed. Llewellyn-Jones *et al.*(2016) proposed the use of curved layers (nonplanar) on top of flat layers to smooth the surface finish and solve the stair problem. In addition, this approach reduces the weakness in the layer stacking direction as the curved surface bonds various flat layers.

Another possible solution is the use of a robotic arm as a 3D printer. Robotic arms offer more degrees of freedom than traditional 3D printers, opening new possibilities to solve these problems. Trommelen *et al.* (2017) proposed in a European Project Semester (EPS) a prototype of this kind of printer based on an ABB IRB-1200 90/5 from the Technobothnia labs in Vaasa, Finland. With the aid of the robot, the ultimate goal was to implement free-form printing capabilities.

Free-form printing is an evolution of the nonplanar layer technique that consists of adding material in any direction to create the object (Oxman *et al.*, 2013). This means that layers can be oriented in any way and modified across the model's shape seeking the best orientation to achieve certain object properties. Furthermore, layers can be completely eliminated and only use strings of material to create the structure.

The EPS team developed a first draft of a simple extruder that could be attached to the robotic arm and build simple models using PLA material. This prototype, however, was still not capable of free-form printing and used the traditional planar layer method. Since then, the project has been further developed by the Technobothnia Robotic Additive Manufacturing team (TB RAM), who designed a new extruder frame and a custom electronic control board. However, this was not enough to ensure the reliability of the machine and more changes have to be made.

This thesis has been developed together with the TB RAM group in an effort to improve the 3D printer. It focuses mainly on the electronic components and the microcontroller firmware parts of the machine. The rest of the team worked on the extruder design and robot software.

1.2 Aims and Objectives

The control electronics of the extruder tool have barely changed since the first prototypes. The current system uses various boards, cables and connectors bonded together to create a setup that could be tested but without paying much attention to optimization or ease of use.

Therefore, this project aims to redesign and simplify the electronic control system of the 3D printer using easily available and well-supported parts. The ultimate goal is to make the current prototype easy to reproduce for potential future manufacture. The main focus will be on the electronic control board, auto levelling sensor and cabling.

To achieve this, the following objectives are defined:

- Upgrade the electronic control system to a single compact board
- Implement proper wiring and connectors between the board and the tool head
- Install a new sensor probe for automated bed levelling

1.3 Document Structure

The first section (section 2) provides an overview of the theory involved in 3D printing, how it works, and the current technologies available. Section 3 contains a review of the state of the project prior to any modifications and a description of other similar projects. It also evaluates the limitations of the setup and how they can be solved. Section 4 describes the changes made to the robot and the reasoning for the decisions made. Finally, the last three sections (sections 5, 6, 7) evaluate the outcome of the project, whether the objectives have been achieved and possible future research.

2 Technological Concepts

This section describes the technological concepts that will be used through this thesis, with the main focus being additive manufacturing and the fused deposition modelling technique. The process from the design to the final 3D printed object and other fabrication techniques will also be discussed.

2.1 Additive Manufacturing Technology

According to Gebhardt (2019, p. 2), Additive Manufacturing (AM) is defined as the production technique used to create three-dimensional physical objects based on a computer 3D design. The parts are generated by adding material volumes, hence the AM name. Together with subtractive technologies, like milling or turning and formative processes, like pressing and casting, additive manufacturing is the third production technique available in current production technology.

Additive manufacturing is also known as rapid prototyping, generative manufacturing, desktop manufacturing, etc. This is because each inventor named its technology according to the particular capabilities of the developed system. Some of these names are even protected by trademarks. The number of different terms may lead to confusion for newcomers to the field. However, the term “3D printing” now includes all the others as it represents the general concept of producing a physical object and can be easily understood (Gebhardt *et al.*, 2019, p. 2).

2.2 The Printing Process

Regardless of the technology used for the actual manufacturing of the part, the steps or stages in the printing process remain the same (Chua *et al.*, 2017, chap. 2). As shown in Figure 2 it consists of four steps: Modelling, tool path generation, printing and post-processing.

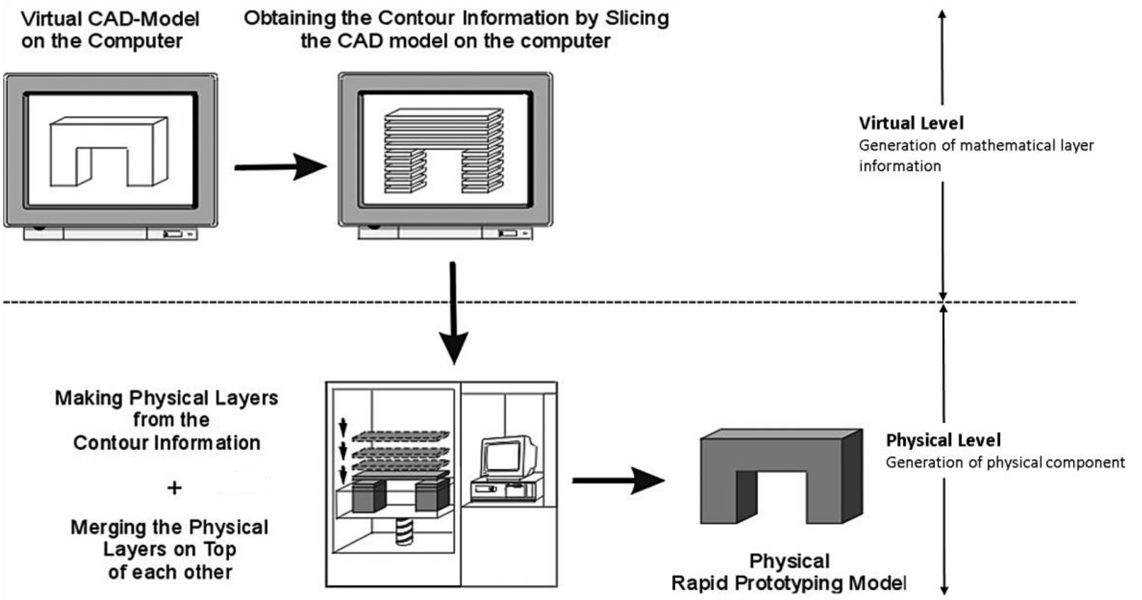


Figure 2: Additive manufacturing process (Gebhardt *et al.*, 2019, fig. 1.2)

In the image above, it can be seen that the first two steps consist of the model design and its preparation to be fabricated. In this stage, the object only exists as a mathematical representation inside the computer. Once the printing process begins in the third step, the physical object is created. Finally, after some post-processing, the final model is obtained. In the following sections, the whole process will be discussed in greater detail.

2.2.1 Modelling

First of all, the object must be designed and converted into a digital file format. The most common design method in engineering is the use of CAD (Computer Aided Design) software as they produce a precise 3D representation of the model. Other methods involve 3D scanners to generate a digital copy of a real object (Formlabs, 2021a).

When the design is finished, the model is commonly saved as a stereolithography file formal (.STL extension), although there are others formats available (Chua *et al.*, 2017, p. 6). The STL format describes object surfaces using a triangular mesh as the one shown in Figure 3.

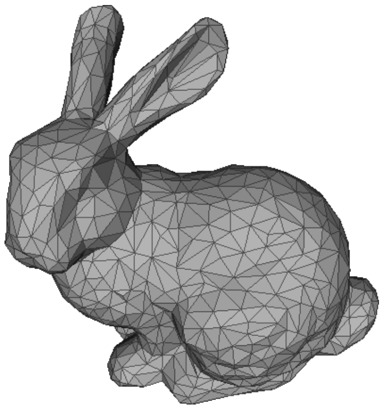


Figure 3: Example of mesh (Polytechnique, 2021)

It first defines the position in space of several vertices using a cartesian coordinate system (XYZ axis). The vertices are then connected to each other through lines or edges. When three vertices are connected in a loop, they form a face (Library of Congress, 2019). The combination of many vertex and faces creates a representation of a 3D object.

2.2.2 Tool Path Generation

Once the 3D model has been generated it has to be translated into a specific format that the 3D printer is able to execute. As Sanladerer (2020) said, most machines have little knowledge of the actual object they are creating and only execute a series of simple instructions. This process is often also called slicing, as it involves (in most machines, but not all) splitting the model in a discrete number of flat layers (Chua *et al.*, 2017, p. 31). In configurations where a mobile head is used, these layers are then filled using a pattern depending on the desired properties (Jin *et al.*, 2014). Figure 4a and Figure 4b show an example of this processes.

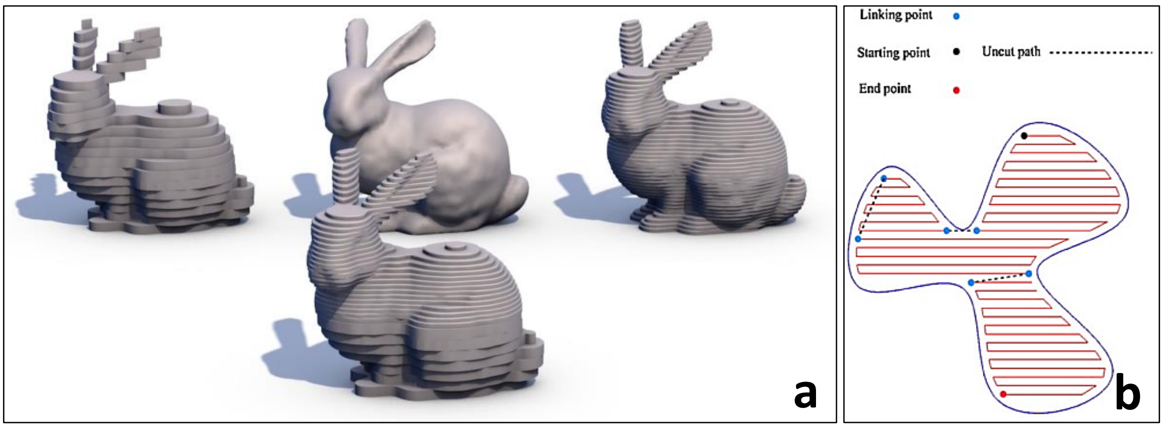


Figure 4: (a) Example of model slicing and different layer thickness. Adapted from (Stevenson, 2016) (b) Layer toolpath example. Adapted from (Jin *et al.*, 2014)

The process of generating the toolpath is done by the slicer, a software that converts the object model (STL file) into the format needed for each machine (Cuellar, 2019). Modern slicing software allows great customization and tweaking of the process to closely match the user's needs.

In common filament 3D printers, the generated toolpath is finally stored in a G-Code file. This is a common format used for CNC tools that contain simple standardized action commands. These tell the printer where to move the extruder, the movement velocity, the extruded amount, heater temperatures, etc (Kramer *et al.*, 2000; Reprap, 2021). Other printer types use specialized file formats.

2.2.3 Printing

In this stage, the file obtained from the slicer is sent to the machine and the fabrication of the part begins. This process is highly dependent on the technology used to create the part and is further explained in the Manufacturing Technologies section. However, as explained by Gebhardt (2019, pp. 3–5), almost all current technologies are layer-based. Therefore, the print process generally consists of successively depositing multiple thin layers of material on top of each other until the complete object is created. Consequently, the differences between technologies lay in how to build that layer and the method to bond them.

2.2.4 Post-Processing

Once the print process has finished, additional processing may be required to obtain the final piece. Again, it depends on the actual printing method but, generally, it involves removing support material, cleaning the part and some machining (Monroe Engineering, 2020; Formlabs, 2021a).

2.3 Manufacturing Technologies

As explained earlier, most of the additive manufacturing processes are based on creating layers and attaching one to another. In this section, different technologies for the fabrication of these layers will be described. Fused Deposition Modelling, in particular, will be more extensively discussed as it is the technology used in this thesis project.

2.3.1 Fused Deposition Modelling

Fused Deposition Modelling (FDM), although being a tradename, registered by Stratasys, has become a generic term for industrial machines using this technique. As the name suggests, it uses an extruder system to lay down melted material (generally a polymer) in a specific pattern according to the object design. The material is rapidly solidified once it has been deposited and keeps its position. The accumulation of thin layers of this material slowly creates the shape of the final object (Walker *et al.*, 2017; Khan *et al.*, 2019). When referring to low-cost consumer machines, this method is also known as Fused Filament Fabrication (FFF). It is the most popular 3D printing technology among the general public thanks to the great impact it had in the hobbyist community and has been extensively developed (Forge Labs, 2020). The whole process is exemplified in Figure 5:

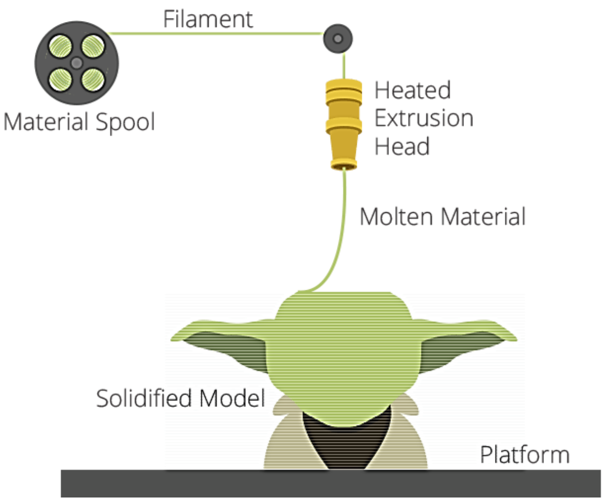


Figure 5: FDM process (Sertoglu, 2021)

The material is generally provided as a spool of filament. This filament is guided into a mobile head which contains a heating element that melts the material. The material is then pushed through a thin nozzle (usually less than a millimetre in diameter) and deposited on top of the previous layers or the print platform. The heat of the extruded filament partially melts the previous material and bonds the strings together (Sertoglu, 2021). This method cannot print overhanging areas without supporting material below. For this reason, support structures are created at the same time as the object to overcome this issue. Those must be removed during the post-processing step after the print process, either manually or with some kind of dissolvent like water, limonene or even caustic soda (Airwolf 3D, 2019; Gebhardt *et al.*, 2019, p. 51).

2.3.1.1 Characteristic Parts

One of the most vital and characteristic parts is the extruder head, which contains the heating element and the nozzle. It is responsible for delivering the correct amount of material in the right place while moving as fast as possible to keep the print time low (BCN3D Technologies, 2020). There are two types of configurations. If the print head contains the material feeding system it is called a Direct extrusion system and otherwise Bowden system. Those are represented in Figure 6.

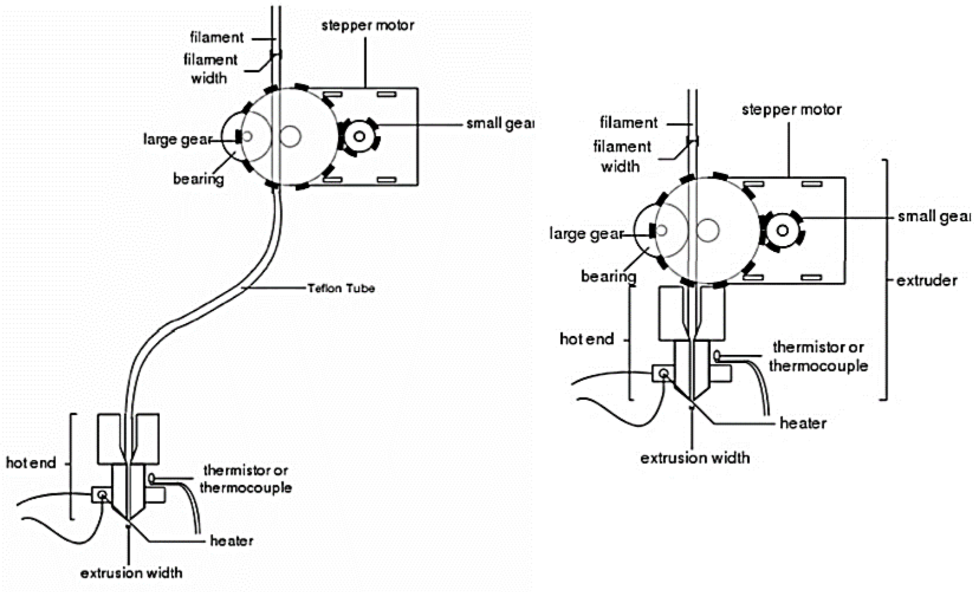


Figure 6: Bowden extrusion system (left) and direct extrusion system (right) (Shaqour, 2016)

Direct drives offer more accurate control over the material flow rate but increase the mass of the tool head and require either slower print speeds or a more robust gantry system. The Bowden system provides the opposite, low moving mass but less accurate material control (Hullette, 2018).

The tool head is mounted in a gantry system that moves the extruder over the printing area in the three-dimensional space. There are multiple configurations of gantry systems but the most common is a simple cartesian type with 3 axes arranged in the spatial dimensions X, Y and Z (O'Connell, 2020).

All the system is generally driven by stepper motors. This kind of motors do not rotate continuously when connected to a power source but they rather lock in a specific position (Monolithicpower, 2021). By modifying the voltage levels in the input connections, the locking position can be controlled. This provides accurate position control but requires special electronic drivers to achieve this positioning.

Finally, the print platform is where the material will be added and will hold the part during the whole process. For this reason, the first layer must be properly bonded to the platform or the object may move during the printing and ruin the process. Some printers also have the ability to heat the print platform (Pick3dprinter, 2019). This allows the model to adhere better and to reduce deformations caused by material contraction while cooling (pick3dprinter.com, 2019).

2.3.1.2 Common Materials

There is a wide range of materials designed for the FDM and FFF processes although all of them are based on polymers. According to Simplify3D (2019a), the go-to material for most users is PLA (Polylactic Acid). It is the easiest material to print, offers good mechanical properties, is affordable and widely available. The major drawback is that it becomes brittle with moisture and rapidly loses its strength with high temperatures.

ABS (Acrylonitrile Butadiene Styrene) is another material mainly used for durable final parts. It was one of the first to be introduced for FDM. It has good impact and wear resistance, can withstand high temperatures and is perfect for outdoor applications (Yadav *et al.*, 2019). However, because of its high expansion coefficient with temperature, the part may suffer from deformation if not printed in a heated chamber.

Other used materials are PETG (Polyethylene Terephthalate Glycol-Modified) and Nylon. PETG is easy to print and water-resistant. Nylon is one of the best materials when wear resistance is needed.

Finally, plastics filled with some reinforcement material, like carbon fibre or metal, are also used in some demanding applications. However, those are generally complicated to print and increase nozzle wear (Simplify3D, 2019b).

2.3.2 Resin Polymerization

According to Gebhardt (2019, p. 36), the polymerization technique generally consists of the selective polymerization and solidification of a liquid resin using short-wavelength (ultraviolet, UV) light. The multiple available systems differ in the way the UV radiation is generated.

2.3.2.1 Digital Light processing

Digital Light Processing (DLP) uses a powerful UV source that is guided through a liquid crystal display (LCD) or a deformable mirror device (DMD). The light is then projected at the bottom of a resin tank as shown in Figure 7.

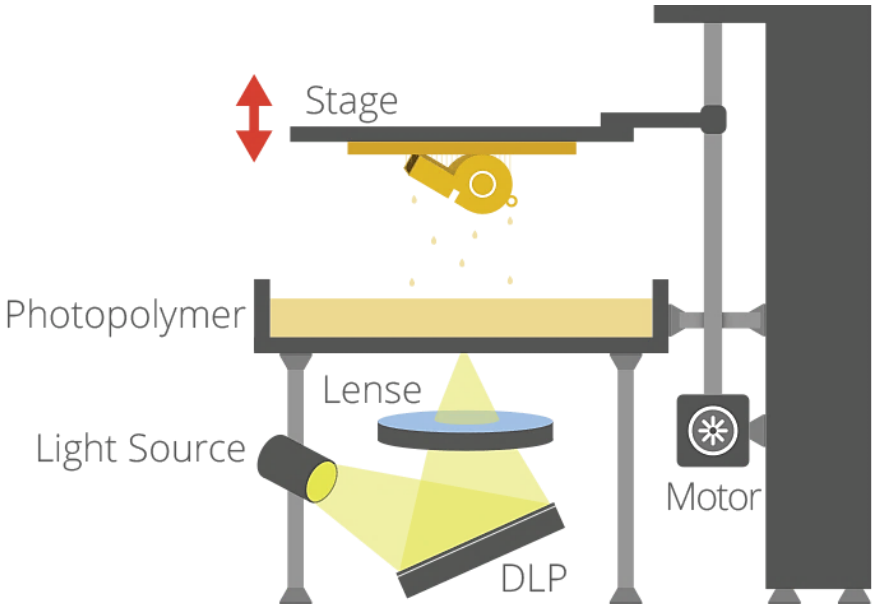


Figure 7: DLP setup scheme (Sertoglu, 2021)

The platform can move in the vertical axis and is moved into the photopolymer bath until only a thin gap remains (fraction of millimetre). Then, the light coming from the bottom of the tank solidifies the resin trapped in this gap. The job of the LCD or DMD is to expose only certain parts of the print surface (Chua *et al.*, 2017, pp. 71–73). When the layer is cured, the platform is elevated to allow more resin to flow under the recently created layer and the process is repeated (Formlabs, 2021b).

One of the advantages of this technique is that the entire surface is created at once in a single pass, resulting in much greater print speed.

2.3.2.2 Stereolithography

Stereolithography was the first commercialized AM process, developed by 3D Systems in 1986 (Gebhardt *et al.*, 2019, p. 37; 3D Printing, 2021). This process is very similar to DLP but instead uses a laser beam to solidify the resin. A scanner system is used to guide the laser across the print surface. The final result is slightly smoother and can achieve greater resolution than DLP machines as it does not rely on the LCD pixel size.

2.3.2.3 Polymer Jetting

This method uses a print head to apply a liquid monomer on the printing surface in a similar way as regular printers. The head is provided with thousands of small injectors which deliver a precise amount of material in the right place. The head also carries a UV light source that solidifies the liquid and bonds it to the previous layers (Chua *et al.*, 2017, pp. 55–56).

2.3.3 Sintering

Sintering consists of selectively melting material powders and then re-solidifying to form an entire object. This method allows printing metal as well as polymers.

2.3.3.1 Selective Laser Sintering

In selective laser sintering, a laser beam and a scanner system are used to melt the surface of material powder evenly distributed. The layout of the system is shown in Figure 8.

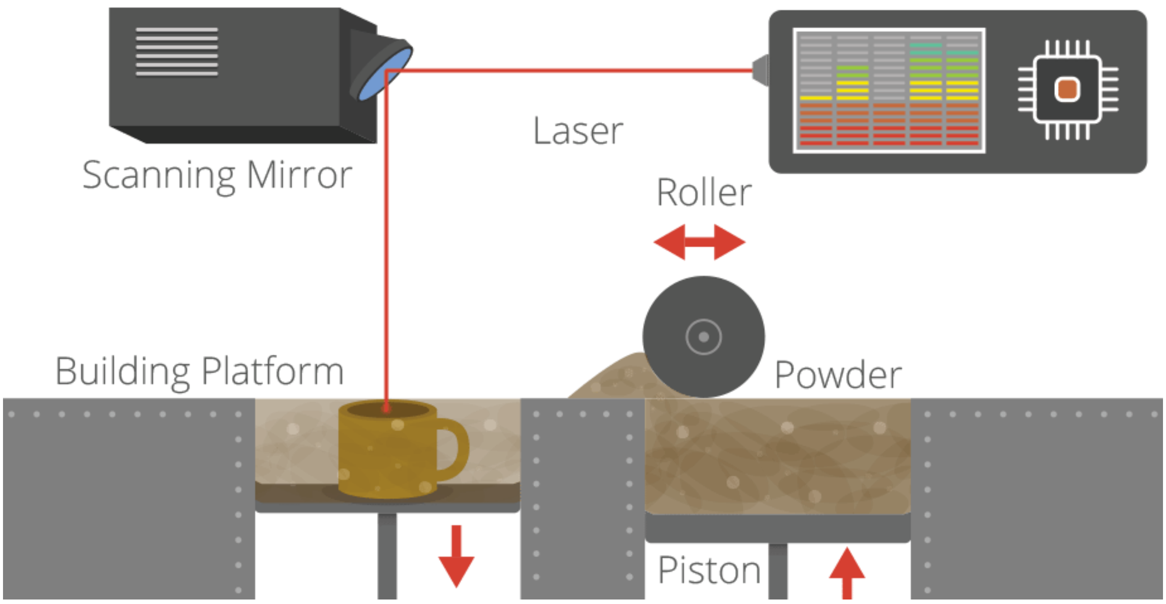


Figure 8: Selective Laser Sintering (Sertoglu, 2021)

A layer of powder is spread inside a well using a roller that ensures an even and flat surface. Then, a laser scanning system melts the surface of the powder according to a slice of the model and creates one layer. When the laser finishes, the build platform is lowered and more powder is spread repeating the process (Yan *et al.*, 2021).

2.3.3.2 Electron Beam Melting

This process uses nearly the same principle as the SLS but an electron beam is used instead to melt the material. The Electron Beam Melting process requires vacuum to operate and the chamber has to be totally sealed. Additionally, the powder bed is heated to a higher temperature than the laser-based systems. As a result, it has faster build rates and achieves very good material properties due to the reduced material stress (Jan Galba *et al.*, 2015, p. 106).

3 Literature Review

This section is a review of the current state of the project (prior to this thesis) and an evaluation of its limitations. It will describe the reason for the problems that are later addressed in the Methodology section. Additionally, other similar systems are reviewed focusing on its control system.

3.1 Technobothnia Robotic Additive Manufacturing

Since the first design made for the EPS, the project has evolved into a more advanced setup that differs significantly from the original. The tool head has been completely redesigned, the electronic boards upgraded and the software improved.

The whole project consists mainly of three components: the robotic arm, the extruder tool head and the extruder control board.

3.1.1 Robotic Arm ABB IRB-1200 90/5

The robotic arm used for the 3D printer is an IRB-1200 90/5 from the ABB manufacturer. It is a general-purpose robotic arm with a reach of 900 mm and a maximum payload of 5 Kg. The robot offers 6 rotational axes which makes it extremely versatile to reach the print volume from different directions (ABB, 2021). The robot structure can be seen in Figure 9.

Figure 9: IRB-1200 90/5 (ABB, 2021)

The robot carries the extruder tool at its end and provides compressed air for cooling the printed part. The control board and the power brick are mounted on the back of the robot to reduce space usage in the head. The power for the control board, heaters and fans is supplied through an external 12V power brick because they cannot be directly connected to the robot. The robot itself is controlled through the IRC5 controller and is programmed using RobotStudio IDE and the programming language RAPID Code.

3.1.2 Extruder

The extruder is the part that allows the robotic arm to be an actual 3D printer and where most of the work has been focused. This can be clearly seen in Figure 10 where the original design and the current one are compared.

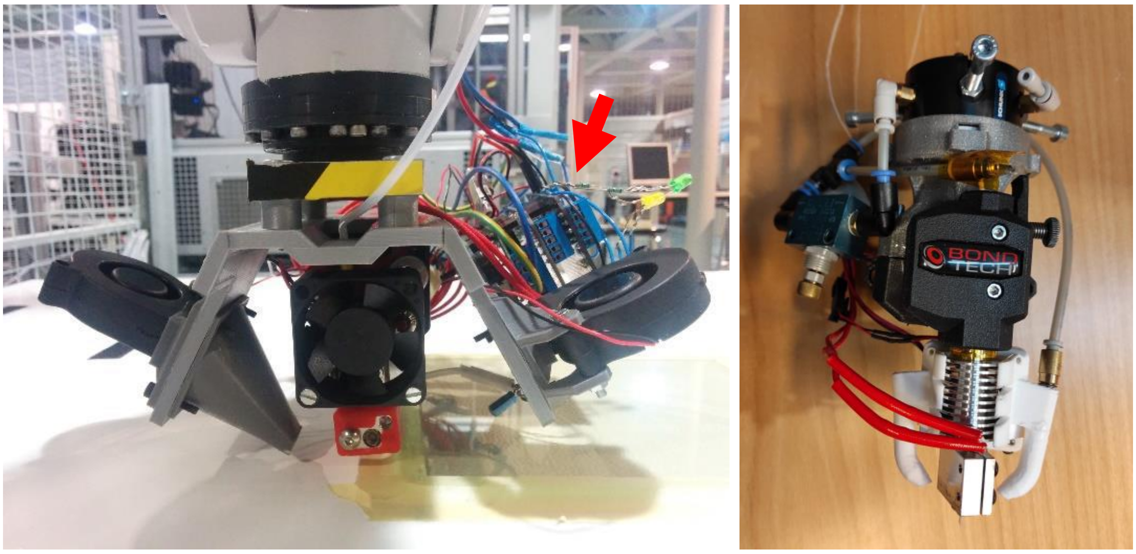


Figure 10: Original Extruder (left) and current Extruder (right) (TB RAM project)

The design has been greatly improved by eliminating unnecessary parts and rearranging some components. The control board, for example, was first mounted together with the extruder in the robot end (indicated by an arrow in the image) but later moved to the back of the arm. The new design also uses an E3D Volcano heater and a Bond Tech extruder to push the filament into the heater which allows for faster print times. Additionally, the cooling fans were replaced by compressed air tubes, reducing the tool head total size.

3.1.3 Control Electronics

The control electronics before the changes made in this project were comprised of an Arduino UNO board, an RS232 communications board and a custom PCB that provided the remaining components.

- **Arduino UNO**

The Arduino UNO is a very popular microcontroller board used across many projects and extensively documented. According to Arduino (2018), the board is based around the ATmega328P which is an 8-bit AVR microcontroller designed by Atmel. The board offers a total of 20 GPIO (General Purpose Input/Output) pins, 6 of which can be used as analogic inputs. The pins are distributed in two rows as shown in Figure 11.

Figure 11: Arduino board (Arduino, 2021c)

The board is responsible for controlling the stepper driver, the extruder heater and reading the heater thermistor. It also communicates with the robot controller to provide status information and receive commands.

- **Communications board**

The ATmega328P integrates support for serial USART communication but does not provide the voltage levels used in the RS232 standard (TIA, 1997) required for the robot. That is why an adaptor board is attached containing the MAX3232 line driver chip. The board used can be seen in Figure 12.

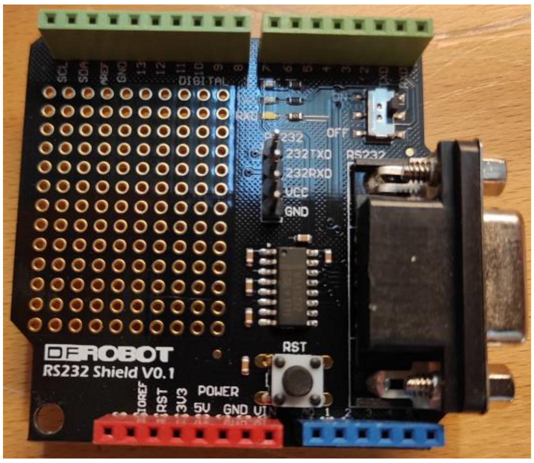


Figure 12: Communications board (TB RAM project)

The board uses the same layout as the Arduino UNO and can be easily plugged on its top without losing access to the unused pins. Additionally, a standard COM connector is provided which is used to connect to the robot controller.

- **Custom PCB**

The Arduino board itself only provides 5V logic signals and is not capable of delivering high power. However, some peripherals such as stepper motor, heater or fans require high voltages and currents to operate. This is why the team developed a PCB with the necessary components to drive these loads. Figure 13 shows the final design.

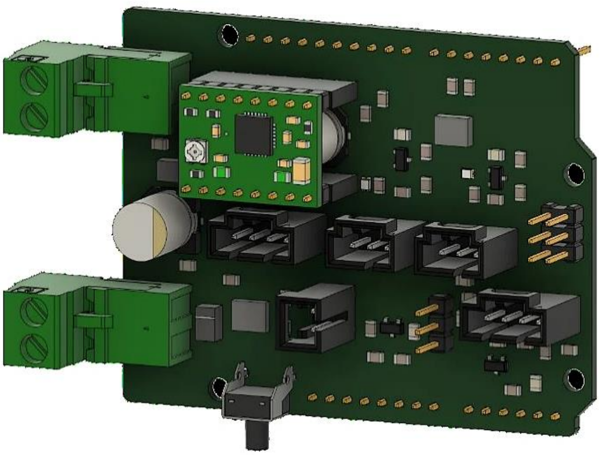


Figure 13: Controller PCB design (TB RAM project)

As can be seen in the image above, the board contains all the needed electronic components and the connectors for the extruder elements. Additionally, the board supports one stepper driver (light green square in the middle) which facilitates the control of the stepper motor to the microcontroller.

3.2 System Evaluation

The parts discussed so far have their limitations when trying to achieve reliable prints and to commercialize the setup. In line with this thesis objectives, the electronic system limitations will be discussed, but there are also issues in the mechanical part of the extruder.

3.2.1 Control Board

The problem with the control board is that it requires a lot of external components. As seen before 3 different boards are required and one of them is a custom design. This custom board is suited for all the system needs but does not allow for any further change and cannot be bought anywhere. If the 3D printer was to be purchased by a company, it would be required to manufacture its own board. Hence the need for a readily available board stated in the objectives of this thesis. Additionally, having many boards increases complexity and failure points, which is not desired.

3.2.2 Wiring and Connectors

In the current setup, each component has its own connector and cable. The cables are then grouped inside a flexible tube which guides them from the control board to the extruder. This solution is a bit bulky and not flexible enough to allow the tool head to move freely. Moreover, the main connector on the extruder side takes a lot of space.

3.2.3 Automated Bed Levelling

As previously discussed, the printed object must adhere to the print surface during the whole process to avoid any movements. For this reason, the first layer is the most important of them all. However, a good first layer can only be achieved if the distance from the nozzle tip to the print platform is exactly what it should be. This often requires manual calibration of the extruder position to align it with the platform. With the aid of a sensor, however, this process could be done automatically. The robot takes samples of the print platform before the print and makes the necessary adjustments to compensate for any height variations. This is why an auto bed levelling probe will be introduced.

3.3 Other Projects

There are other companies and research groups that have been working on the same idea of using a robotic arm for 3D printing. Some of these even have final products on the market producing on-demand models. A few of these projects are described below.

3.3.1 MX3D

MX3D is a company based in The Netherlands that develops and integrates large scale industrial metal 3D printers using robotic arms. According to MX3D (2021), they have combined an ABB robot with a wire arc welding machine to achieve metal additive manufacturing capabilities. The result is their M1 Metal AM System shown in Figure 14.

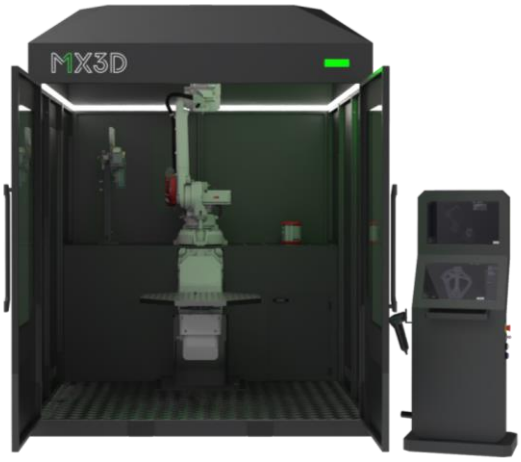


Figure 14: M1 System (MX3D, 2021)

The technology used in this machine is called Wire Arc Additive Manufacturing (WAAM) and uses the same principles as wire arc welding. A high voltage is applied between the tool head and the object. When the two parts are close enough an electric current flows and partially melts the piece and a wire coming from the tool head. With the aid of the electric current, the metal from the wire is attached to the object adding a layer to it. The tool head gradually feeds more wire to keep the process going (Twi-global, 2021).

For the machine control, this company uses a controller developed on their own which is also shown in Figure 14 (on the right). Additionally, they provide their own software for robotic WAAM technology, Metal XL.

3.3.2 Branch Technology

Branch Technology partnered with KUKA to develop a 3D printing process using a 7-axis robot. This company is focused on architectural and structural design with a new approach to AM technology. Their method allows carbon fibre reinforced ABS to solidify in open space creating almost any possible shape without using the traditional layer method (Branch Technology, 2020; KUKA, 2020). Using this technique, they manufacture custom-designed structures like the one shown in Figure 15.

Figure 15: Branch Technology structure demonstration (Branch Technology, 2020)

These structures can then be filled with some type of material to further enhance the properties of the object depending on the customer needs. The result is a lightweight and strong structure with complete freedom in design shape.

There is not much information about the equipment used by this company but, from the pictures and videos on its web page, it can be seen that they use KUKA robots with some kind of custom tool.

3.3.3 Research Projects

There are also some published papers about the implementation of 3D printers using robotic arms. Oxman *et al.* (2013), for example, developed a tool for free form printing with similar capabilities as Branch Technology. It uses a KUKA KR5 Sixx R850 robotic arm that carries an extruder system developed by them. The extruder consists of an auger bit that pushes plastic pellets into a heated section where the plastic is melted. The melted plastic is finally pushed through the nozzle and deposited in the model. The goal was to create a system that could fabricate self-sustaining structures. For the control electronics, they used a Gecko G201X Digital stepper driver, to control the extruder motors, and an Arduino to take care of the heaters.

Another project is the one developed by Dine *et al.* (2018), where they created an extruder tool for the Stäubli RX90L robot. This project is conceptually very similar to the TB RAM project but the implementation is significantly different. They developed an extruder tool as shown in Figure 16.

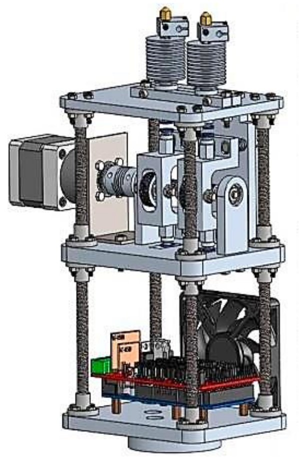


Figure 16: Extruder mechanism (Dine *et al.*, 2018)

The extruder is formed by three tiers or stages. The first tier contains the electronics and control system, the middle stage holds the material feeding system and the last tier contains the heaters and nozzles. As it can be seen this system has two extruders and therefore can work with two different materials. The whole setup is attached at the end effector of the robot.

For the control of the extruder tool, they used an Arduino Mega with a RAMPS 1.4 shield which took care of the heaters and the stepper motor of the feeding system. The synchronization with the robot was done by sending a logic signal to the robot controller when the extruder was ready. However, there was no further exchange of information between the two controllers.

4 Methodology

This chapter describes the procedure followed to upgrade the various components in the 3D printer. The selection criteria and search process will be discussed as well as the modifications needed to accommodate the new parts.

4.1 Main Control Board

The control board is the brain of the extruder tool. It manages the heaters, the stepper motor and the sensors. In the next sections, the selection of the new board is described as well as its implementation.

4.1.1 Board Selection

Before starting to search for new components it is important to obtain a list of the needed specifications that the parts have to accomplish to be suitable for the printer. These parameters are defined under the Product Requirements Definition (PRD) document. According to Daniels (2020), the elaboration of this document is the most important phase of product development. It serves as the basis for all subsequent phases and, therefore, is a vital step to avoid having to later redevelop or modify the product. The following specifications have been discussed and approved with the other team members and are meant to provide support for current features and future expansion. The requirements for the electronic control board are listed below in Table 1:

Table 1: Product Design Specification

Need	Metric	Importance (1-5)	Units	Marginal	Ideal	Comments
1	Stepper drivers	5	pcs	>1	>1	Can be either integrated or external
2	Output current	5	A	>3	5	Needed for the extruder
3	Servo motor outputs	5	pcs	>2	4	
4	Input voltage	5	V	12-24	12-48	
5	UART Interface	4	pcs	1	>1	
6	Supported by Arduino IDE	3	-	-	-	
7	Good documentation and user community support	3	-	-	-	

The first and most important requirement is to allow the control of at least one stepper motor, which will be used in the extruder to push filament into the heater block. Therefore, the board should include one or more stepper drivers or provide sockets to connect external ones. However, it is preferable to use external drivers as they can be easily replaced in case of damage or driver upgrade.

The second requirement is to have a controlled power output capable of delivering at least 3A of power. It will be used to control the heater cartridge in the heater block of the extruder and melt the filament. Since the printer is most likely to be using large nozzle sizes and high flow rates, the more power capacity the better.

To control the new auto-levelling probe, which will be discussed later in chapter 4.3, two servomotor connections are needed. One will control the servo motor that moves the probe mounting arm and the other will manage the probe itself.

The communication with the robot computer is done through a UART interface, therefore having at least one is a must. There are other communication protocols like I2C and SPI which are not required but can be used for future upgrades.

The supply voltage that will be used is 12V but the requirements were set to support 24V as well so that the system can be easily upgraded if more power is needed.

Finally, good documentation and support from the end-user community is not absolutely necessary but is a good point to consider, as it facilitates access to the needed information and assistance in case of problems. Some examples of this support are the RepRap Forum and the Thingiverse Groups.

Additionally, being able to program the board through the Arduino IDE is highly desired to be able to easily port the previous firmware to the new microcontroller.

With these requirements, different products were searched online through manufacturers like Makerbase, Ultimachine, Fysetc and Panucatt. The boards were then compared and evaluated according to their specifications. Some of the candidates considered are shown in Table 2 and discussed below. For more details and links see Appendix I.

Table 2: Available options comparison (See Appendix I)

Board	Motor drivers	Input voltage	Servos	UART	Power output	Arduino IDE	Price
Archim 2	5 integrated	12-24V	0*	Yes	5A	Yes	140€
Fysetc S6	6 externals	12-28V	1*	Yes	5A	Yes	35€
SKR MINI E3	4 integrated	12-24V	1*	Yes	5A	Yes	32€
MKS GEN1.4	5 externals	12-24V	4	Yes	5A	Yes	25€
Fysetc F6	6 externals	12-24V	4	Yes	5A	Yes	23€

* More servo outputs can be created using other expansion pins

First of all, notice that some of the boards presented in Table 2 apparently do not have the required servo outputs. This is because the board itself does not provide a specific connection for servos but these can still be connected to some of the expansion pins available.

The first board in the table, Archim2, is a high-end control board created by UltiMachine, a leading 3D Printer component manufacturer that produces high-quality equipment. The controller is well supported and documented, has a large community behind it and has a robust design with high-quality components. However, quality comes at a cost, making this board very expensive (UltiMachine, 2018).

The Fysetc S6 board offers an incredible set of features at a good price and seems to have a good design. It has a powerful 32-bit microcontroller, has many controlled power outputs and a rich set of peripherals. The major downside is that the process for uploading new firmware is a bit complicated and the board is not very well known, having little support from the community (Fysetc, 2019).

SKR mini E3 is also a good option with a 32-bit microcontroller and a nice design. It has been developed by BigTreeTech, a well-known cheap manufacturer with many products in the DIY (Do it yourself) 3D printing sector. This board does not have dedicated servo connectors and therefore will increase the complexity of the wiring process (Bigtree-tech, 2021).

The Fysetc F6 is the best board discussed so far in terms of features, price and quality. It is very similar to the Fysetc S6 in look and features but a bit cheaper. In fact, in Appendix I can be seen that they look almost identical. It uses the ATmega2560 chip, has 4 servo connections and supports many external stepper drivers (Fysetc, 2014). However, as with the other Fysetc board, the manufacturer is not very well known and support is scarce.

Finally, the MKS Gen1.4 is a board made by Makerbase that has been in the market for a long time (Reprap, 2018). It features the popular ATmega2560 8-bit microcontroller which is the same used in the Arduino Mega board (Arduino, 2021b). The board satisfies all requirements, can be easily obtained and has large support from the community. As a result, this was the selected board for the new 3D printer.

4.1.2 Board Implementation

Once the board was selected, all the old connections and the code had to be adapted to work with it.

Connecting all the parts into the board was very straightforward since it has dedicated connectors for each component as can be seen in Figure 17.

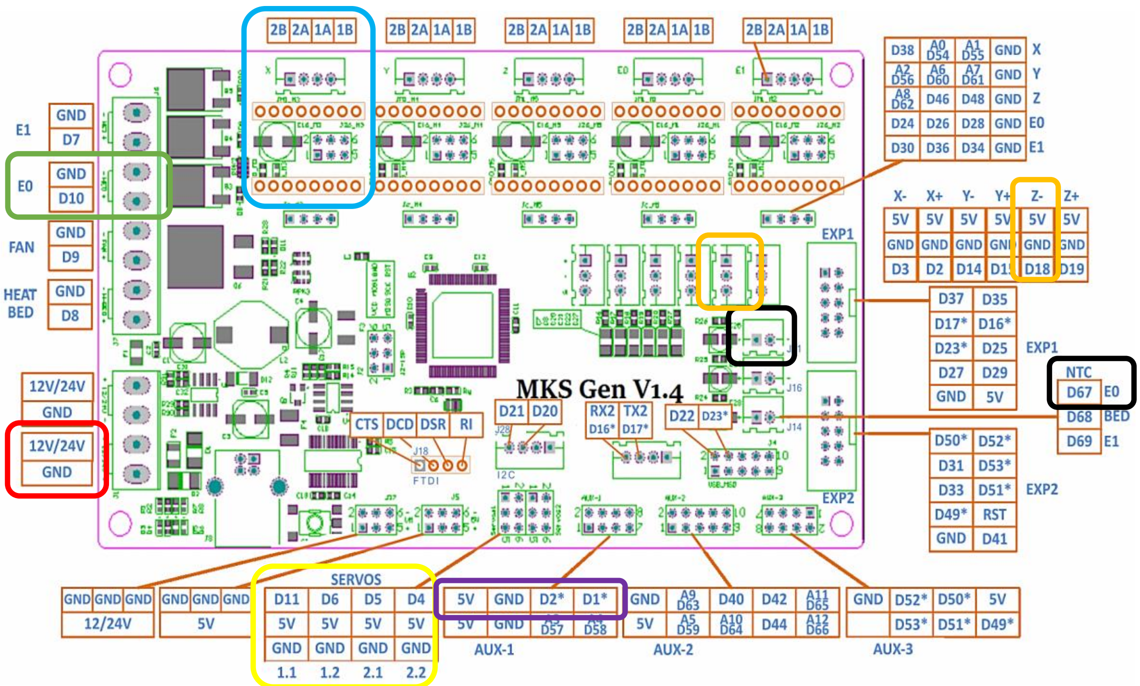


Figure 17: Board pinout with additional coloured box annotation. Adapted from Ralph (2017)

Based on the schematic above, the different components were connected. First of all, the power supply was connected to the 12V/24V and GND pins (red box). The other input connection was left unconnected because the terminals were missing in the board used.

The board has four high power outputs connected directly to the main supply. Those are labelled as Heat Bed, Fan, E0 and E1. The extruder heater was attached to the E0 output (green box) and the others were left for future expansion. The thermistor sensor was connected in the designated slot, labelled as J21 (black box). The servo motor and the probe were mounted in slots 1.1 and 1.2 respectively of the servos socket (yellow box).

One of the changes made, compared to the previous board, is the addition of two status LEDs like the one shown in Figure 18.

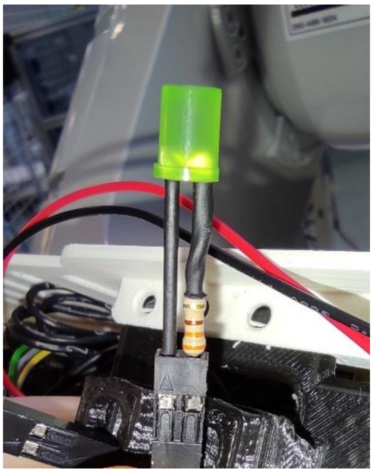


Figure 18: Green status LED connection

Those LEDs were connected in the remaining servo slots (2.1 and 2.2) and provide visual information on the state of the program (i.e., ready, error, …). The selected LEDs work at 3.3V while the board provides 5V. To overcome this problem a 330Ω series resistor was added as can be seen in Figure 18.

Serial communication was used to transmit data between the board and the robot. As with the old board, the MKS Gen 1.4 cannot generate the voltages required for the RS232 standard and a small adaptor had to be included in the case.

The stepper motor is connected to the driver through pins 2A, 2B, 1A and 1B (blue box). Finally, the sensor signal from the probe is routed into the Z- end stop connector (orange box).

The connectors described above are routed through the board into the microcontroller's input/output (I/O) pins. In order to get everything working, these pins must be correctly defined in the controller's code. Table 3 shows the mapping for all the components to the corresponding pin.

Table 3: Board connections

Component		Signal	Pin	Old pin	Notes
Hotend		V+	D10 (E0+)	D3	Polarity N/A
		V-	GND (E0-)	GND	
Thermistor		T	D67 (A13)	A0	Polarity N/A
		GND	GND	GND	
BL Touch	Servo	S	D6	-	
		5V	5V	-	
		GND	GND	-	
	Prove	Z-	D18 (S)	-	
		GND	GND (-)	-	
LEDs	Green	S	D5	-	
		GND	GND	-	
	Red	S	D4	-	
		GND	GND	-	
Mount servo		S	D11	-	
		5V	5V	-	
		GND	GND	-	
Stepper		1B	1B	1B	Some motors may have different pin arrangements. Switching the two middle cables usually solves the problems.
		1A	1A	1A	
		2A	2A	2A	
		2B	2B	2B	

In the table can be seen that many of the pins did not have a previous version in the old controller. That is because features like the BL Touch probe, the LEDs and the servomotor were not yet implemented.

The old and new microcontrollers are both from the ATmega family and share similar features. Additionally, both are well supported through the Arduino IDE. This made the code very cross-compatible on its own and only minor modifications were needed. These include changing the timer used to generate the control signal for the stepper driver and adding the probe control functions. The full code, however, cannot be shown in this report as it is part of the TB RAM project.

4.2 Wiring and Connectors

In a similar way as with the board, the requirements for the new wiring system were defined before starting the search. These are summarized below:

Table 4: Product Requirements Definition

Need	Metric	Importance (1-5)	Units	Marginal	Ideal	Comments
1	Nº of conductors	5	pcs	12	14	Not solid core wires
2	Supported current flow	5	A	>3	>5	Related to the board output capabilities
3	Support continued flexion	4	-	-	-	
4	Compact and lightweight	3	-	-	-	

The most important parameter is the number of needed conductors in the cable so that all components receive the needed power and signals. A list of all the components and their needed connections is shown in Table 5.

Table 5: Components' connections

<table>
<tr><th colspan="2">Component</th><th>Signals</th><th>12V</th><th>5V</th><th>Ground</th><th></th></tr>
<tr><td colspan="2">Stepper Motor</td><td>4</td><td></td><td></td><td></td><td></td></tr>
<tr><td colspan="2">Heater</td><td></td><td>1</td><td></td><td>1</td><td></td></tr>
<tr><td colspan="2">Thermistor</td><td>1</td><td></td><td></td><td>1</td><td></td></tr>
<tr><td colspan="2">Arm Servo</td><td>1</td><td></td><td>1</td><td>1</td><td></td></tr>
<tr><td rowspan="2">BL Touch</td><td>Control</td><td>1</td><td></td><td>1</td><td>1</td><td></td></tr>
<tr><td>Sensor</td><td>1</td><td></td><td></td><td>1</td><td></td></tr>
<tr><td colspan="2">Total</td><td>8</td><td>1</td><td>2</td><td>5</td><td>16</td></tr>
</table>

As it can be seen a total of sixteen wires would be required if all components were to be connected individually. However, the 5V supply and ground connections can be shared between the servo and the BL Touch control reducing the total to fourteen wires (highlighted in the table). The ground cable in the thermistor and the BL Touch sensor could also have been connected together but it was not done. That would reduce the number of cables to twelve but leaves no room for further modifications. Additionally, power and data ground signals would be mixed and it is a good practice to keep separated wires for power supply and data transfer to avoid interferences (Academy of EMC, 2021). Moreover, the heater ground cannot be shared because it carries high power levels that may interfere with or damage sensible components.

One of the requisites for the board was to provide at least 3A of current output. To handle this current, the wires and connectors must also be able to withstand 3A.

Because of the dynamic nature of the robot, the wires connecting the tool head to the control board will be under continuous flexing. This may cause material stresses and eventually damage to the conductors, reducing their ability to carry current. That is why wires capable of working under dynamic conditions have to be searched. For the same reason, the cable should be as lightweight and compact as possible, to allow the robot to freely move.

The components were finally selected from an electronic hardware store in Vaasa, Starelect Oy. The selected cable is the FLEX-14x0.5 from the Helukabel manufacturer which has 14 conductors of $0.5mm^2$ each. The connectors used are of the Micro-Fit type, manufactured by Molex and with fourteen pins.

Once the components were selected a layout for the connector and cable was created which can be seen in Table 6 and Figure 19.

Table 6: Connector layout

Pin	Signal		Pin
1	A1	A2	2
3	B1	B2	4
5	5V	GND	6
7	S	S	8
9	T	Z-	10
11	GND	GND	12
13	V+	V-	14

Figure 19: Cable layout

The colour codes used above correspond to the colours used in Table 3. There are no particular reasons for this concrete arrangement other than organization and convenience. The four first signals (pins 1 to 4) are used for the stepper motor, followed by power and ground for the BL Touch and the servo (pins 5 and 6). Next to them, there are the control signals for the servo and BL Touch (pins 7 and 8 respectively). Signal and ground for the thermistor and the BL Touch sensor are arranged in pins 9, 11 and 10, 12 respectively. Finally, power for the heater is supplied through pins 13 and 14.

4.3 Automated Bed Levelling

The automated bed levelling process consists of taking height samples in multiple points across the print platform to compensate for small deviations in the surface. This process also gives the machine the true home position (position 0) in the Z-axis and allows the first layer to better adhere to the platform.

4.3.1 Probe Description

To implement the automated bed levelling system to the robot the BL Touch sensor was used. This sensor was chosen by the TB RAM team because it offers reliable measurements regardless of the heated bed material. It comes in a compact and lightweight package that can be easily mounted in the robot tool head. Figure 20 shows the BL Touch sensor (green box) mounted on its arm and the servomotor (red box) that moves the assembly.

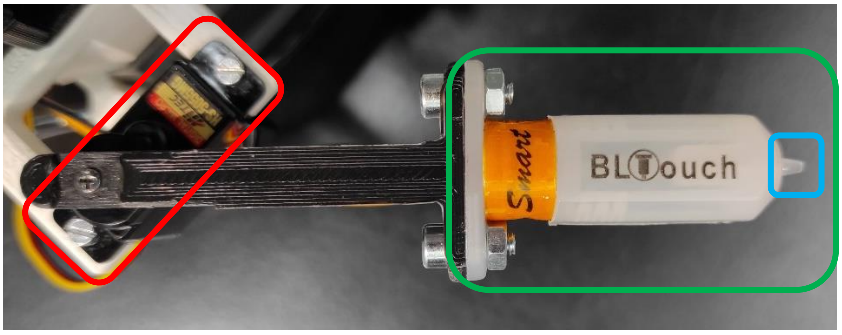


Figure 20: BL Touch sensor mounted in its arm

The sensor consists of a push pin that can be moved up and down (blue box in Figure 20). This pin is controlled by a solenoid inside the sensor casing which moves the pin up when the sensor is not being used and down during the measurement. The sensor works by determining whether the pin is fully extended or not.

Because during the print process the extruder area should be as clear as possible, the team came up with the idea of mounting the sensor in a mobile arm. With this mechanism, a servomotor would move the BL Touch sensor to the back of the extruder and avoid collisions with the printed object.

4.3.2 Probe Control

According to the manufacturer (Antclabs, 2014), the BL Touch sensor is controlled by the microcontroller as a servo motor using a Pulse Width Modulated (PWM) signal. The general principle for this kind of control is shown in Figure 21.

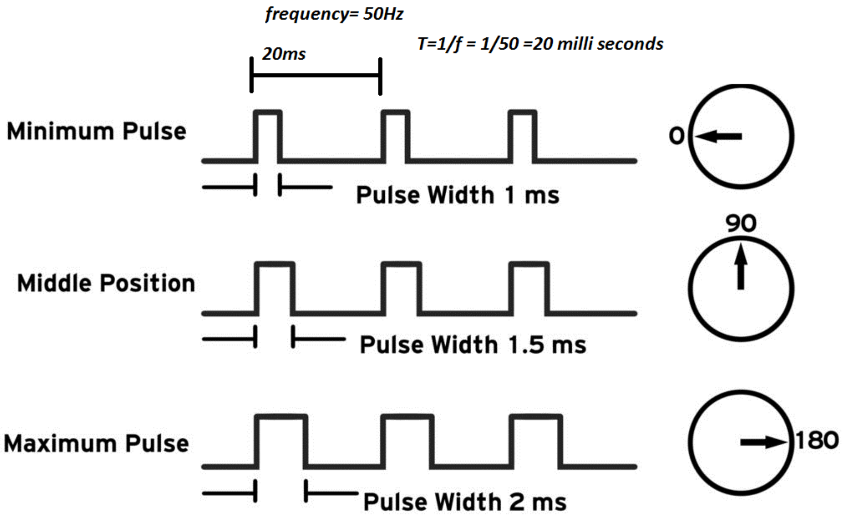


Figure 21: Servomotor control signal (EG Projects, 2020)

The controller sends a square signal with a fixed frequency defined by the manufacturer, as an example, in Figure 21 the frequency is 50 Hz. The duration of the pulse is then modified between a minimum and a maximum width representing the minimum and maximum angle of the motor shaft. The values in between can be calculated using simple linear interpolation. In the case of the BL Touch sensor, there is no shaft to control, but each pulse duration corresponds to a specific instruction, as shown in Table 7.

Table 7: BL Touch Instructions. Adapted from Antclabs (2014)

BL Touch Instruction	Pulse Width (±20 µs)
Push-pin Down (deploy)	647µs
Alarm Release & Touch SW Mode	1162 µs
Push-pin Up	1473 µs
Self-test	1782 µs
EEPROM Conversion Request	1884 µs
EEPROM 5V Logic Zmin	1988 µs
EEPROM Logic voltage Free Zmin	2091 µs
Alarm Release & Push-pin Up	2194 µs

Each instruction has its own pulse width which can differ in ±20 µs from the reference value and still be correctly interpreted. Most of the commands are self-explanatory and will not be further discussed, however, the Touch SW Mode and the EEPROM instructions should be mentioned.

Most of the instructions try to maintain the pin position by either pushing it up or down. For example, Push-pin down will try to keep the pin extended even if some external force does not allow it. Touch Switch (SW) Mode is a mode for probing that lets the pin move freely and is kept down only by gravity. If this mode wasn't used during probing, the pin would be forced into the surface, causing damage to the component or triggering the sensor alarm.

The EEPROM commands set the signal mode to be used as the output signal. The sensor can work in open-drain or 5V modes. In open-drain mode, the signal is connected to ground when the sensor is triggered. Otherwise, the sensor sends a 5V signal. In this project, the open-drain mode is used.

To generate the control signals, the PWM functionality of the microcontroller was used. The ATmega2560 offers four 8-bit PWM channels and twelve 16-bit channels (Atmel *et al.*, 2015, p. 1). Each channel is bound to a specific pin from the microcontroller. Looking at the pin arrangement described in Table 3 and the Arduino Pin Mapping (2021a) it can be determined that the needed channels for the probe and the servo are OC4A and OC1A respectively (corresponding to pins 6 and 11). These PWM channels are controlled by hardware Timer 4 and Timer 1, which are 16-bit timers and thus are capable of counting up to 65535. The timers will be running in Fast PWM non-inverting Output Compare mode, whose operation is shown in Figure 22.

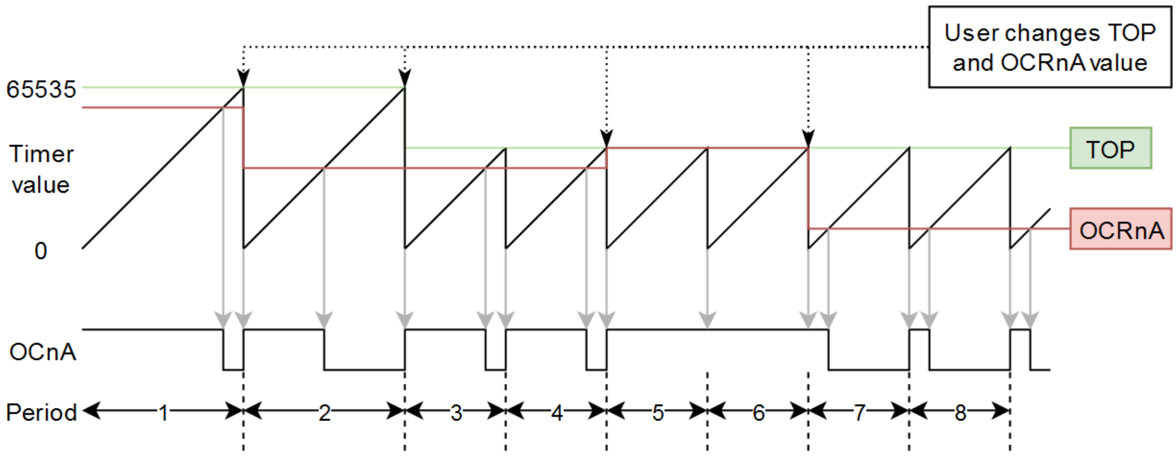


Figure 22: Fast PWM mode. Adapted from Atmel (2015, fig. 17–7)

In this mode, the timer starts counting from 0 up to the value set as TOP at a speed related to the controller's clock. The ATmega2560's clock is running at 16MHz and it can be divided by 1, 8, 64, 256 and 1024 using the built-in prescaler. This means that for every 1, 8, 64… clock cycles the timer will add 1 to its value.

As shown in Figure 22, the OCnA output (OC1A and OC4A) will be set (high level) when the timer resets to 0 and will be cleared (low level) when the timer reaches a certain value defined in the OCRnA register. Additionally, the frequency of the signal can be adjusted by setting the TOP value, which is the maximum value that the timer will reach before resetting to zero. By adjusting these parameters any custom square wave can be generated.

Based on Hitec's Servo Manual (2002) the signal for the servo must have a frequency of at least 50Hz (period of 20ms). The frequency for the BL Touch sensor is not stated in the official documentation, but 50Hz was proven to work fine. As a result, there are multiple ways of generating a 20ms period using (1):

$$TOP \cdot \frac{1}{\frac{16MHz}{prescaler}} = 20ms \tag{1}$$

Those are:

- Set the prescaler to 8 and count up to 40000
- Set the prescaler to 64 and count up to 5000
- Set the prescaler to 256 and count up to 1250
- Set the prescaler to 1024 and count up to 312(.5)

The first option was selected because it has a wider range of available values and will allow more resolution in the pulse duration. The resulting setup code for timers 1 and 4 is shown in Code Example 1.

Code Example 1: Timer 1 and 4 setups

```
pinMode(PROBE_ZMIN_PIN, INPUT_PULLUP);
pinMode(PROBE_MOUNT_PIN, OUTPUT);
pinMode(PROBE_SERVO_PIN, OUTPUT);

// Mode 14: Fast PWM    Count from 0 to ICR1    Activate OC1A (PWM in pin 11)
// Mode 14: Fast PWM    Count from 0 to ICR4    Activate OC4A (PWM in pin 6)
TCCR1A = _BV(WGM11) | _BV(COM1A1);  // TCCR1A = 0b10000010
TCCR4A = _BV(WGM41) | _BV(COM4A1);  // TCCR4A = 0b10000010

// Set prescaler to 8 (16M/8 = 2M)
TCCR1B = _BV(CS11) | _BV(WGM12) | _BV(WGM13); // TCCR1B = 0b00011010
TCCR4B = _BV(CS41) | _BV(WGM42) | _BV(WGM43); // TCCR4B = 0b00011010

// Count from 0 to 40000 (20ms period, 50 Hz)
ICR1 = usToTicks(PROBE_PWM_REFRESH_INTERVAL);
ICR4 = usToTicks(PROBE_PWM_REFRESH_INTERVAL);
```

Finally, the values in the OCRxA can be calculated using (2).

$$OCRxA = \frac{pulse\_width \cdot 16 \times 10^6}{8} \quad (2)$$

In the case of the servo, it uses a pulse width between 0.75ms and 2.25ms that corresponds to a range of 0 to 178 degrees of rotation. Therefore, the minimum and maximum values of the OCR1A register are 1500 and 4500. Linear interpolation can be used to get any other rotation angle as shown in Code Example 2.

Code Example 2: Set pulse duration

```
OCR1A = map(angle, 0, 180, PULSE_DURATION_MIN, PULSE_DURATION_MAX)*16000000/8;
```

To summarize, timers 1 and 4 are set to Fast PWM mode with a maximum count value of 40000 and a prescaler of 8. To adjust the pulse width, the values in OCR1A and OCR4A are set according to (2).

4.3.3 Probing Procedure

The process for calibrating the printing surface works like this:

First of all, with the extruder nozzle pointing down, the probe is deployed by moving the mount arm down and extending the BL Touch pin. Then the sensor is set to probing state and the robot starts moving the extruder down into the print platform. When the push-pin touches the surface, the sensor sends a signal to the controller board and the robot stops.

The main problem here is that there is no way of knowing the exact position where the sensor triggered. The cause is that the communication between the probe and the robot controller has a significant delay. The reason is that it has to go through the extruder controller board and then through the serial communication to the robot computer. By the time the robot receives the trigger signal, the tool might have been moved. A simple solution would be to move the extruder in small steps and wait for the sensor reading. However, to achieve a precise measurement the steps would need to be very small, and the process would take too much time. To overcome this problem, the team came up with the idea of using binary search to accurately determine the height. This idea is demonstrated in Figure 23.

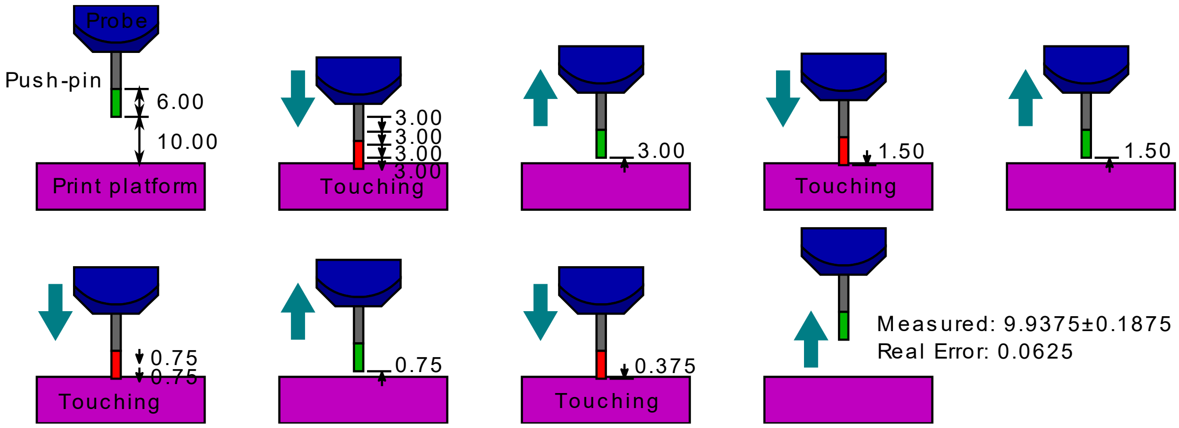


Figure 23: Step-wise bed levelling using binary search (dimensions in millimetres)

The probe starts at a height that is known to be close to the platform, but the exact distance is unknown. Then, the probe starts moving in steps of 3mm. The probe's push pin can retract up to 6mm before damaging the component and 3mm is a good point in between. When the sensor triggers, the tool is raised back to the previous step and repeats the process again with half the step size. This is repeated until a low enough error is achieved.

5 Results

After mounting and testing all the parts separately, they were assembled with the new extruder design in the robotic arm. This chapter contains an explanation of the final setup.

The control board was enclosed in a 3D printed box designed by the team. The box allows the board to be mounted on the back of the robot so that it is close to the extruder tool but does not interfere with the movement. The control board setup is shown in Figure 24.

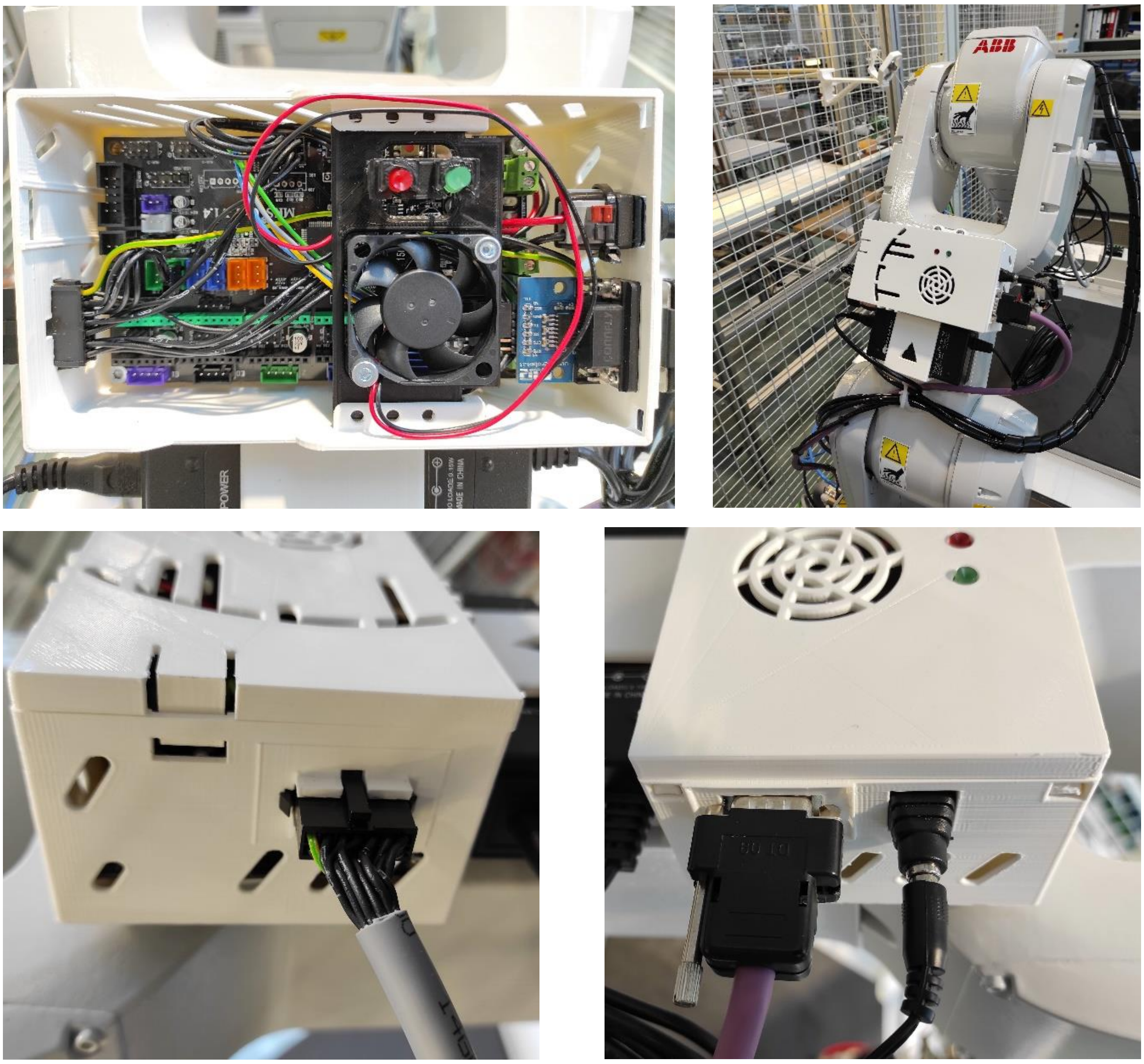


Figure 24: Assembled control board

The enclosure also holds the connectors for the control cables of the extruder, communication port and power supply. The power brick is fixed next to the electronics box by another 3D printed support. Because of the heat generated by the stepper driver and the power management electronics, an always-on fan was included to provide cooling.

In the extruder tool, the design was adapted to hold the new connector on one side. The first idea was to attach all the components directly to the 14-pin connector but that was found to be impractical. The final solution was to split the big main connector into smaller individual ones for each component as seen in Figure 25.

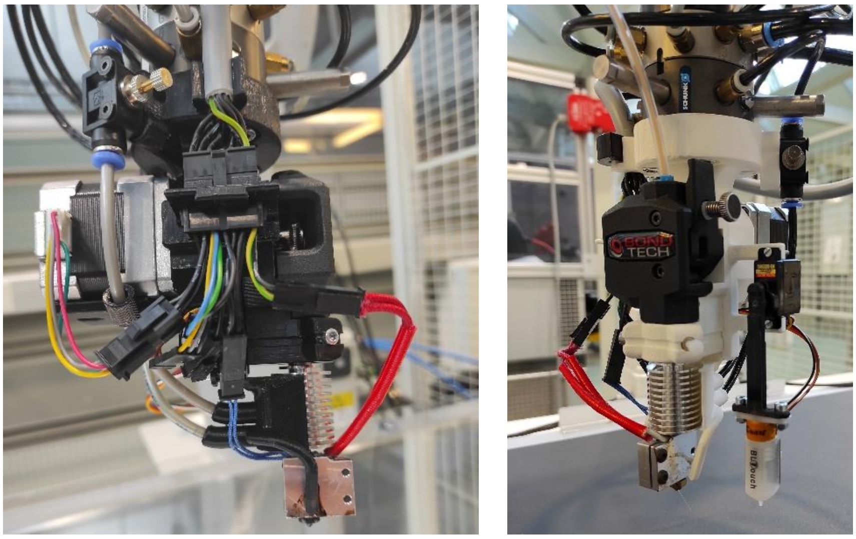


Figure 25: Final extruder setup. Connectors and cables (left) and auto levelling probe (right)

With the individual connectors, it is easier to replace components in case of damage or if an upgrade is needed. On the opposite side of the extruder, there is the sensor probe and the mounting arm. Those can also be seen in Figure 25. The servo motor is mounted in an attachment added to the extruder design. The probe is supported by the servo so that it can move freely.

Finally, the wires going from the control board to the extruder can be seen in Figure 26.

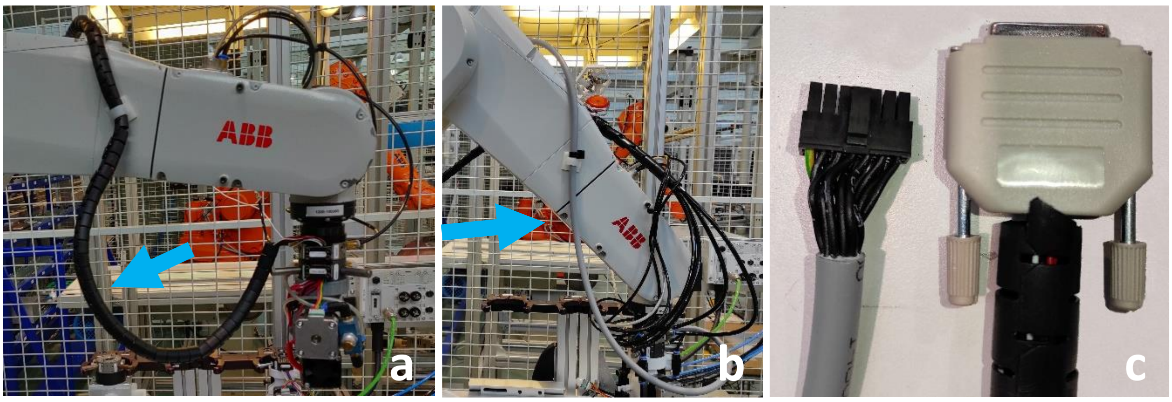


Figure 26: (a) Old system cables (b) New system cables (c) New connector (left) and old one (right) comparison

All the old cables and the tubing have been replaced by a single wire shown in Figure 26a. The connectors also have been changed for a much smaller one as seen in Figure 26c.

To test the whole setup some objects were printed as the process involves checking all components. The board should be capable of managing the whole printing without failing, the probe has to sense the platform correctly during calibration and the wires shouldn't get too hot. As it can be seen in Figure 27 the print was successful.

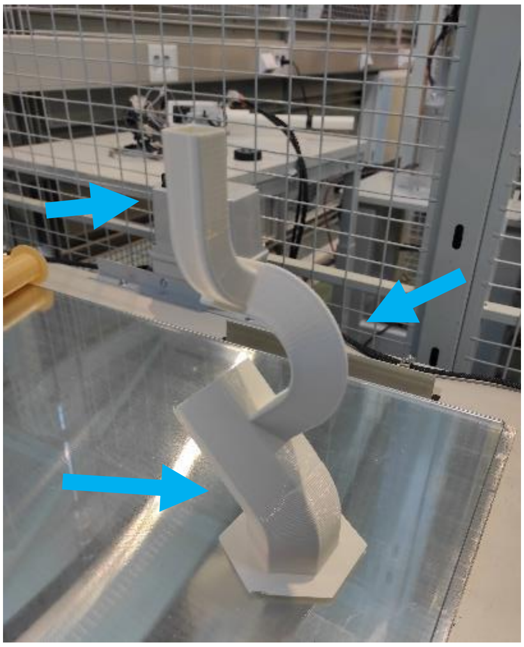


Figure 27: Test model printed with the arm

Additionally, thanks to the work done on the software side by the team, this model was printed using a variable layer orientation. The object consists of three tubes, marked by arrows in Figure 27. During the printing, the extruder was always perpendicular to the section of the tubes and adapted to the model curvature. Notice that the three sections are not continuous. That is because they have been printed in separate stages one after the other.

6 Discussion

In this chapter, the results will be discussed and evaluated according to the initial set objectives. The work done will also be compared to the previous setup and other published work. Finally, the limitations of the study, consistencies and inconsistencies will be considered.

The first objective was to replace the old control electronics, formed by multiple boards, with a single compact board. This has been successfully achieved using the MKS Gen 1.4 board which unifies almost all the functions of the previous system. The only drawback is that it still requires an external adaptor for communication with the robot controller.
As for the second objective, it has been fully completed. The new wire is more compact than the previous plastic tube that guided all the individual cables and more flexible. This makes it easier to hook the cable around the robot while still enabling unconstrained mobility. Additionally, as it can be seen in Figure 26c the new connector is significantly smaller than the previous one and does not take up so much space in the tool.

Finally, regarding the third objective, the probe has been installed and can be controlled from the new microcontroller board. The code has been adapted to output the required signals for the mounting arm servo and the sensor probe. Also, the routines to start probing were created together with the rest of the team. In the same line, the auto levelling system has been tried in different prints and proved to work without problems.

Other projects described in the literature review use their own controller system. For now, the TB RAM project does not pretend to create and manufacture its controller. Instead, it is easier to use an existing product from the market, like the proposed board. However, it is not an option to be discarded, as it would suit better the product needs but implies additional development costs.

Concerning consistencies and inconsistencies, it must be pointed out, as mentioned before, that an additional communications adaptor is still required. Added to the fact that the new board now includes two LEDs and its respective current limiting resistors, the final control box has now more component count than the previous one (6 in the new vs 3 in the old). However, the LEDs are an improvement over the previous version and are not necessary for the controller to work, whereas the three boards used before were a must for the configuration. Moreover, LEDs and resistors are an extremely common component and do not add much complexity. On the other hand, the outcomes of the project are a clear improvement and its development has been extensively reasoned in the previous chapters, making them consistent with the objectives and other work done.

To sum up, the objectives are successfully achieved and there is an evident improvement in the setup. The cabling is cleaner, the space used by the connectors in the extruder has been reduced and the calibration process is much easier thanks to the new sensor. As a result, the 3D printer is closer to a final product.

7 Conclusions

3D printing is still a developing field and a lot of research is being carried. As seen in the literature, an effort is being made to integrate it into the large-scale manufacturing industry and is likely to have a significant impact in the future. The results of this thesis and the whole TB RAM project are part of this effort.

The work done in this project has increased the reliability and simplicity of the 3D printer. The control system has been replaced with a more compact board that reduces the number of core components needed. The cabling and connectors were upgraded with a single multi-wire cable and a smaller connector. Additionally, an automated bed levelling probe has been implemented for easier initial calibration. As a result, the system is now easier to reproduce as the components are widely available and easy to assemble. This makes the project to be closer to a final product that could be production-ready. Furthermore, taking into account the improvements made by the other team members, the printer finally achieved the ability to print in multiple orientations.

However, there are some improvements to be done. One of the problems still to be resolved is the slow communication between the extruder controller and the robot computer. The current configuration has a delay in the response time which difficult the accuracy of the extrusion. More optimization has to be done in the communication protocol or find a way to control the extruder directly from the robot controller.

Finally, developing a single custom board should be further considered as has been suggested in the previous section. It would enable the control system to be customized and adapted to the project needs. As explained in the Discussion chapter, an adaptor is still needed for the RS232 communication. This adaptor could be integrated into the board making the design more compact.

To sum up, this project is a step forward for the tool to become a final product but there are still point that requires more work to be done. These points may be used in future investigations or by the TB RAM project itself and may certainly improve the extruder system, contributing to the overall AM industry.

8 References

3D Insider (2017) *History of 3D Printing Timeline: Who Invented 3D Printing - 3D Insider*. Available at: https://3dinsider.com/3d-printing-history/ (Accessed: March 18, 2021).

3D Printing (2021) *What is 3D printing? How does a 3D printer work? Learn 3D printing*. Available at: https://3dprinting.com/what-is-3d-printing/#sla (Accessed: May 5, 2021).

ABB (2021) *IRB 1200 | ABB Robotics - Industrial Robots | ABB Robotics*. Available at: https://new.abb.com/products/robotics/industrial-robots/irb-1200 (Accessed: May 6, 2021).

Academy of EMC (2021) *EMC Design Guidelines | Academy of EMC*. Available at: https://www.academyofemc.com/emc-design-guidelines (Accessed: April 29, 2021).

Ahlers, D. (2018) *3D Printing of Nonplanar Layers for Smooth Surface Generation*.

Airwolf 3D (2019) *3D Printing - Truths and Myths of 3D Printing with Support Material | Airwolf 3D*. Available at: https://airwolf3d.com/3d-printing-support-material/ (Accessed: May 4, 2021).

AMFG (2019) *How the 3D Printing Hardware Market is Evolving in 2020 - AMFG*. Available at: https://amfg.ai/2019/10/22/how-the-3d-printing-hardware-market-is-evolving-in-2019/ (Accessed: May 7, 2021).

Antclabs (2014) *BLTouch V3.1 | antclabs*. Available at: https://www.antclabs.com/bltouch-v3 (Accessed: April 23, 2021).

Arduino (2018) *What is Arduino? | Arduino*. Available at: https://www.arduino.cc/en/Guide/Introduction (Accessed: May 6, 2021).

Arduino (2021a) *Arduino - PinMapping2560*. Available at: https://www.arduino.cc/en/Hacking/PinMapping2560 (Accessed: April 23, 2021).

Arduino (2021b) *Arduino Mega 2560 Rev3 | Arduino Official Store*. Available at: https://store.arduino.cc/arduino-mega-2560-rev3 (Accessed: May 12, 2021).

Arduino (2021c) *Arduino Uno Rev3 | Arduino Official Store*. Available at: https://store.arduino.cc/arduino-uno-rev3 (Accessed: May 6, 2021).

Atmel *et al.* (2015) “Atmel ATmega640/V-1280/V-1281/V-2560/V-2561/V,” *Linux-Magazin*, (November), p. 66. Available at: https://ww1.microchip.com/downloads/en/DeviceDoc/ATmega640-1280-1281-2560-2561-Datasheet-DS40002211A.pdf.

Bandyopadhyay, A., Gualtieri, T. PL. and Bose, S. (2015) “Global Engineering and Additive Manufacturing,” in Bandyopadhyay, A. and Bose, S. (eds) *Additive Manufacturing*. 1st edn. CRC Press, pp. 1–18.

BCN3D Technologies (2020) *Best 3D Printer Extruders: Basic Buyer’s Guide - BCN3D Technologies*. Available at: https://www.bcn3d.com/3d-printer-extruders-a-basic-guide/ (Accessed: May 4, 2021).

Bigtree-tech (2021) *BIGTREETECH SKR MINI E3 V2.0 - BIQU products BIGTREETECH SKR MINI E3 V2.0*. Available at: https://www.bigtree-tech.com/products/bigtreetech-skr-mini-e3-v2-0-32-bit-control-board-integrated-tmc2209-uart-for-ender-3.html (Accessed: May 12, 2021).

Branch Technology (2020) *BRANCH TECHNOLOGY*. Available at: https://www.branch.technology/ (Accessed: May 9, 2021).

Chua, C. K. and Leong, K. F. (2017) *3D printing and additive manufacturing : principles and applications*. 5th edn. Edited by A. Yun. Singapore: World Scientific.

Cuellar (2019) *How 3D Printing Works – 3DMaker Engineering*. Available at: https://www.3dmakerengineering.com/blogs/3d-printing/how-3d-printing-works (Accessed: May 3, 2021).

Daniels, L. (2020) *Managing the product requirements definition process*, *Paper presented at Project Management Institute Annual Seminars & Symposium, Houston, TX*. Available at: https://www.pmi.org/learning/library/product-requirements-definition-process-foundation-1894 (Accessed: April 28, 2021).

Dine, A. and Vosniakos, G. C. (2018) "On the development of a robot-operated 3D-printer," in *Procedia Manufacturing*. Elsevier B.V., pp. 6–13. doi: 10.1016/j.promfg.2018.10.004.

EG Projects (2020) *Controlling Servo Motor with Stm32f103 microcontroller using stm32cubemx code configurator by STMicroelectronics and keil uvision 5 ide for cortex m1 series microcontrollers*. Available at: https://www.engineersgarage.com/electronic-projects/interfacing-servo-motor-with-stm32/ (Accessed: April 23, 2021).

Forge Labs (2020) *FFF vs. FDM - What Is The Difference? | Forge Labs*. Available at: https://forgelabs.com/fff-vs-fdm-what-is-the-difference/ (Accessed: May 3, 2021).

Formlabs (2021a) *3D Printing Guide: Types of 3D Printers, Materials, and Applications*. Available at: https://formlabs.com/3d-printers/ (Accessed: March 27, 2021).

Formlabs (2021b) *SLA vs. DLP: Guide to Resin 3D Printers | Formlabs*. Available at: https://formlabs.com/blog/resin-3d-printer-comparison-sla-vs-dlp/#How%20Do%20DLP%203D%20Printers%20Work%3F (Accessed: May 5, 2021).

Fysetc (2014) *FYSETC F6 - FYSETC WIKI*. Available at: https://wiki.fysetc.com/F6_V1.3/ (Accessed: May 12, 2021).

Fysetc (2019) *FYSETC S6 - FYSETC WIKI*. Available at: https://wiki.fysetc.com/FYSETC_S6/ (Accessed: May 12, 2021).

Gebhardt, A., Kessler, J. and Thurn, L. (2019) *3D Printing: Understanding additive manufacturing*. 2nd edn. Edited by M. Smith. Munich, Germany: Hanser Pulbishers.

Hitec RCD (2002) "General Servo Information," p. 2. Available at: https://hitecrcd.com/files/Servomanual.pdf.

Hullette, T. (2018) *Direct Drive vs Bowden Extruder Setup: The Differences | All3DP*. Available at: https://all3dp.com/2/direct-vs-bowden-extruder-technology-shootout/ (Accessed: May 11, 2021).

Jan Galba, M. and Reischle, T. (2015) "Additive Manufacturing of Metals Using Powder-Based Technology," in Bandyopadhyay, A. and Bose, S. (eds) *Additive Manufacturing*. 1st edn. CRC Press, pp. 97–142.

Jin, Y. an *et al.* (2014) "Optimization of tool-path generation for material extrusion-based additive manufacturing technology," *Additive Manufacturing*, 1, pp. 32–47. doi: 10.1016/j.addma.2014.08.004.

Khan, M. S. and Dash, J. P. (2019) "Enhancing Surface Finish of Fused Deposition Modelling Parts," in Kumar L. Jyothish and Pandey, P. M. and W. D. I. (ed.) *3D Printing and Additive Manufacturing Technologies*. Singapore: Springer Singapore, pp. 45–57. doi: 10.1007/978-981-13-0305-0_5.

Kramer, T. R., Proctor, F. M. and Messina, E. (2000) *The NIST RS274NGC Interpreter-Version 3*. Gaithersburg, MD.

KUKA (2020) *Additive manufacturing and industrial 3D printing | KUKA AG*. Available at: https://www.kuka.com/en-de/products/process-technologies/3d-printing (Accessed: May 9, 2021).

Library of Congress (2019) *STL (STereoLithography) File Format Family*. Available at: https://www.loc.gov/preservation/digital/formats/fdd/fdd000504.shtml (Accessed: April 30, 2021).

Llewellyn-Jones, T., Allen, R. and Trask, R. (2016) "Curved Layer Fused Filament Fabrication Using Automated Toolpath Generation." doi: 10.1089/3dp.2016.0033.

Monolithicpower (2021) *Stepper Motors: Types, Uses and Working Principle | Article | MPS*. Available at: https://www.monolithicpower.com/en/stepper-motors-basics-types-uses (Accessed: May 11, 2021).

Monroe Engineering (2020) *The 3 Basic Steps of 3D Printing - Monroe Engineering*. Available at: https://monroeengineering.com/blog/the-3-basic-steps-of-3d-printing/ (Accessed: April 30, 2021).

MX3D (2021) *MX3D | Introducing the advantages of 3D metal printing to new high-impact industries*. Available at: https://mx3d.com/ (Accessed: May 8, 2021).

O'Connell, J. (2020) *FDM 3D Printers Explained: Cartesian, Delta, CoreXY, & More | All3DP*. Available at: https://all3dp.com/2/cartesian-3d-printer-delta-scara-belt-corexy-polar/ (Accessed: May 4, 2021).

Oxman, N. *et al.* (2013) "Freeform 3D printing: Towards a sustainable approach to additive manufacturing," *Green Design, Materials and Manufacturing Processes - Proceedings of the 2nd International Conference on Sustainable Intelligent Manufacturing, SIM 2013*, pp. 479–483.

Pick3dprinter (2019) *3D Printer Heated Bed - Everything About Heated Beds - Pick 3D Printer*. Available at: https://pick3dprinter.com/3d-printer-heated-bed/#do-i-need-a-heated-bed (Accessed: May 4, 2021).

Polytechnique (2021) *PS 2 - Triangle Mesh Processing and Simplification*. Available at: http://www.lix.polytechnique.fr/~maks/Verona_MPAM/TD/TD2/ (Accessed: April 30, 2021).

Ralph (2017) *Mainboard anschließen – drucktipps3d.de*. Available at: https://drucktipps3d.de/mainboard-anschliessen/ (Accessed: April 29, 2021).

Reprap (2018) *MKS GEN - RepRap*. Available at: https://reprap.org/wiki/MKS_GEN (Accessed: May 12, 2021).

Reprap (2021) *G-code - RepRap*. Available at: https://reprap.org/wiki/G-code (Accessed: May 3, 2021).

Sanladerer, T. (2020) *3D Printing Basics 1 – Tom's 3D printing guides and reviews*. Available at: https://toms3d.org/2020/06/12/3d-printing-basics/ (Accessed: May 3, 2021).

Sertoglu, K. (2021) *The Free Beginner's Guide - 3D Printing Industry*. Available at: https://3dprintingindustry.com/3d-printing-basics-free-beginners-guide/ (Accessed: March 18, 2021).

Shaqour, B. (2016) "Developing an Additive Manufacturing Machine," p. 107. Available at: https://www.researchgate.net/publication/317974747_Developing_an_Additive_Manufacturing_Machine.

Simplify3D (2019a) *Ultimate 3D Printing Materials Guide*. Available at: https://www.simplify3d.com/support/materials-guide/ (Accessed: May 4, 2021).

Simplify3D (2019b) *Ultimate Materials Guide - 3D Printing with Carbon Fiber*. Available at: https://www.simplify3d.com/support/materials-guide/carbon-fiber-filled/ (Accessed: May 5, 2021).

Stevenson (2016) *Variable Layer Slicing for The Ember 3D Printer: Good Idea or Not? « Fabbaloo*. Available at: https://www.fabbaloo.com/blog/2016/11/16/variable-layer-slicing-for-the-ember-3d-printer-good-idea-or-not (Accessed: April 30, 2021).

TIA (1997) *Interface Between Data Terminal Equipment and Data Circuit-Terminating Equipment Employing Serial Binary Data Interchange from IHS*. Available at: https://global.ihs.com/doc_detail.cfm?&csf=TIA&item_s_key=00125234&item_key_date=870024&input_doc_number=232&input_doc_title=&org_code=TIA.

Torrado, A. R. and Roberson, D. A. (2016) "Failure Analysis and Anisotropy Evaluation of 3D-Printed Tensile Test Specimens of Different Geometries and Print Raster Patterns," *Journal of Failure Analysis and Prevention*, 16(1), pp. 154–164. doi: 10.1007/s11668-016-0067-4.

Trommelen, J. *et al.* (2017) "3D Printing with Robotic Arm." Available at: https://eps.novia.fi/assets/Sidor/2/1545/Final-Report-3D-Printing-with-Robotic-Arm.pdf.

Twi-global (2021) *What is Arc Welding? - Definition and Process Types - TWI*. Available at: https://www.twi-global.com/technical-knowledge/faqs/what-is-arc-welding (Accessed: May 8, 2021).

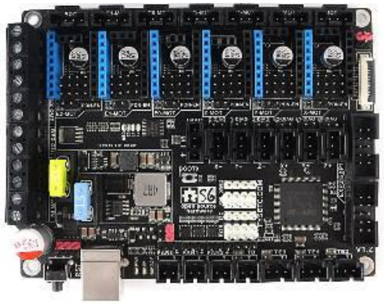
UltiMachine (2018) *Archim2 – UltiMachine*. Available at: https://ultimachine.com/products/archim2 (Accessed: May 12, 2021).

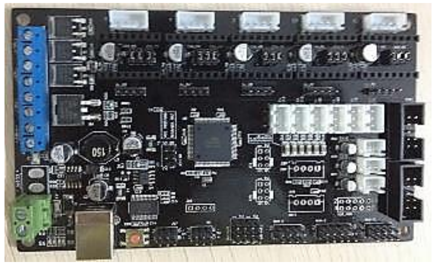
Walker, J. L. and Santoro, M. (2017) “Processing and production of bioresorbable polymer scaffolds for tissue engineering,” in *Bioresorbable Polymers for Biomedical Applications: From Fundamentals to Translational Medicine*. Elsevier, pp. 181–203. doi: 10.1016/B978-0-08-100262-9.00009-4.

Yadav, D. K., Srivastava, R. and Dev, S. (2019) “Design & fabrication of ABS part by FDM for automobile application,” in *Materials Today: Proceedings*. Elsevier Ltd, pp. 2089–2093. doi: 10.1016/j.matpr.2020.02.451.

Yan, C. *et al.* (2021) *Selective Laser Sintering Additive Manufacturing Technology*, *Selective Laser Sintering Additive Manufacturing Technology*. Elsevier. doi: 10.1016/b978-0-08-102993-0.00005-9.

9 Appendix I

Board	Photo	Motor drivers	Input voltage	Servos	Communication	Power output	Arduino IDE	Price	Link
Archim 2		5 integrated	12-24V	0*	USART, SPI, I2C, JTAG, microSD	5A	Yes	140€	https://ultimachine.com/products/archim2
Fysetc S6		6 externals	12-28V	1*	USART, SPI, I2C, microSD	5A	Yes	35€	https://wiki.fysetc.com/FYSETC_S6/

SKR MINI E3		4 integrated	12-24V	1*	USART, SPI, I2C, microSD	5A	Yes	32€	https://www.bigtree-tech.com/products/bigtreetech-skr-mini-e3-v2-0-32-bit-control-board-integrated-tmc2209-uart-for-ender-3.html
MKS GEN1.4		5 externals	12-24V	4	USART, SPI, I2C	5A	Yes	25€	https://es.aliexpress.com/item/32810883738.html?spm=2114.12010612.8148356.17.635711419wsVTl
Fysetc F6		6 externals	12-24V	4	USART, SPI, I2C	5A	Yes	23€	https://wiki.fysetc.com/F6_V1.3/