3D Printing with Robotic Arm

USING A ROBOTIC ARM TO CREATE MORE SOPHISTICATED 3D PRINTS

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Thanks to all!

Abstract

The development of 3D printers over the last 10 years has been amazing and now it is possible to make your own printer with 50% of the parts printed on another machine. That brought the cost down several times. But current machines are limited by volume. One way to overcome that constraint is to use a robotic arm. Robotic manipulation and 3D printing are closely related, but they have remained mostly separate until now.

The aim of this project is to join 3D printing and robotics together, to make 3D printing more flexible and to remove limits. To make it possible, in this project the following main aspects have been developed: designing and 3D printing the extruder's housing and filament guidance system, mounting the created part onto the robotic arm, programming software to control the necessary hardware like the stepper motor or cooling system, adapting provided software to our system to translate G-code to Rapid code. Finally, the system developed consists of a 3D extruder mounted onto an ABB robotic arm capable of printing 3D models.

The project has been developed using different hardware and software. The most remarkable hardware used is ABB IRB-1200 90/5 robotic arm, MiniFactory and Ultimaker 3D printers, Diabase flexion extruder, Arduino board and some Arduino shields. The software used has been SolidWorks, Repetier-Host for MiniFactory, CuraEngine, Arduino Software and ABB RobotStudio. Therefore, in this project, brief and basic information about these technologies has been included.

Abbreviations

3D	Three Dimensional
ABS	Acrylonitrile Butadiene Styrene
AC	Alternating Current
AM	Additive Manufacturing
CDPR	Cable-Driven Parallel Robots
DC	Direct Current
DOF	Degrees Of Freedom
EPS	European Project Semester
FDM	Fused Deposition Modelling
IAAC	Institute for Advanced Architecture of Catalonia
PA	Polyamide
PC	Polycarbonate
PEEK	Polyether ether ketone
PLA	Polylactic acid
PTFE	Polytetrafluoroethylene
PS	Polystyrene
PVAc	Polyvinyl Acetate
PWM	Pulse Width Modulation
STL	Stereolithography
WAAM	Wire Arc Additive Manufacturing

Table of Content

ACKNOWLEDGEMENTS .... **I**

ABSTRACT .... **II**

ABBREVIATIONS .... **III**

TABLE OF CONTENT .... **IV**

TABLE OF FIGURES .... **VII**

TABLE OF TABLES .... **X**

CHAPTER 1 .... **1**

INTRODUCTION **1**

1.1 European Project Semester 1
1.2 The Team 2
1.3 Brand Identity 4
1.4 Project Motivation 5
1.5 Project Target 5
1.6 Socio-Economic Environment 6
1.7 Document Structure 8

CHAPTER 2 .... **9**

STATE OF THE ART **9**

2.1 MX3D 9
2.2 RamLab 10
2.3 IAAC 10
2.3.1 TerraPerforma 11
2.3.2 Material 12
2.3.3 Mini builders 12

CHAPTER 3 .... **14**

TECHNOLOGICAL CONCEPTS **14**

3.1 Additive Manufacturing (3D Printing) 14
3.1.1 3D Printing Technologies 15
3.1.1.1 Powder Bed Fusion 15
3.1.1.2 Directed Energy Deposition 15
3.1.1.3 Material Extrusion 15
3.1.1.4 Vat Photopolymerization: 15
3.1.1.5 Binder Jetting: 16
3.1.1.6 Material Jetting: 16
3.1.1.7 Sheet Lamination: 16

3.2 Fused Deposition Modelling (FDM) 16
3.2.1 Extruders *17*
3.2.2 Materials *19*
3.2.3 Filament thickness *21*
3.2.4 Bed material *21*
3.3 3D Printing Software 22
3.3.1 G-code *22*
3.3.2 Repetier - Host *22*
3.4 Slicers 23
3.5 ABB Robot 24
3.5.1 Robotic arms *24*
3.5.2 ABB IRB-1200 90/5 .... *25*
3.5.3 Robot Software *27*
3.5.3.1 ABB RobotStudio *27*
3.5.3.2 Rapid Code *29*

CHAPTER 4 30

3D PRINTING TOOL DESIGN AND MOUNTING 30
4.1 Prototype 30
4.2 Final Design 31
4.2.1 Design Approach *31*
4.2.2 Chosen Hardware *33*
4.2.2.1 Extruder *33*
4.2.2.2 Cooling System *34*
4.2.2.3 Drive System *37*
4.2.2.4 Electronics *37*
4.2.3 Housing Design *39*
4.2.4 Guidance System Design *41*
4.2.5 Printing Bed *43*
4.2.6 Additional Parts *43*
4.3 Complete 3D Printing Tool 45

CHAPTER 5 47

SOFTWARE PROGRAMMING 47
5.1 Software for the Tool. Arduino 47
5.2 Robotics Software. Rapid Code 50
5.3 Communication Arduino – Robot 57
5.4 Slicer Configuration 58
5.5 Robot Studio Simulation 61

CHAPTER 6 62

TESTING AND RESULTS 62
6.1 Stepper Motor Driver 62
6.2 Temperature control 64
6.3 Slicer profile - Printing Bed 65
6.4 Guidance System 67
6.5 3D Printing Results 68

CHAPTER 7 71

CONCLUSION **71**
CHAPTER 8 .... **74**
DISCUSSION **74**
CHAPTER 9 .... **76**
SUGGESTIONS **76**
BIBLIOGRAPHY **77**
APPENDIX A: PROJECT MANAGEMENT **80**
A.1 Strength-finder 80
A.2 Belbin Roles 82
A.3 Planning 83
A.3.1 Gantt Diagram 84
A.4 Project Budget 85
A.5 Risk Management 86
A.6 Stakeholders Analysis 89
APPENDIX B: ASSEMBLY MANUAL **95**
APPENDIX C: INSTALLATION MANUAL **102**
APPENDIX D: OPERATING MANUAL **106**
APPENDIX E: WIRING SCHEMATIC **113**

Table of Figures

Figure 1. Brainstorm logo and brand name 4
Figure 2. Final logo 4
Figure 3. MX3D bridge 9
Figure 4. RamLab's Propeller (Alexandrea, 2017) 10
Figure 5. TerraPerforma, 3D printing with clay 11
Figure 6. Material, antigravity additive manufacturing 12
Figure 7. Mini builders 13
Figure 8. FDM Extruder 17
Figure 9. Direct and Bowden tube feeding 18
Figure 10. Repetier Host working screen 23
Figure 11. Robot Arm Design Configurations 24
Figure 12. Rotational axes 25
Figure 13. General dimensions 25
Figure 14. Tool flage schematic 26
Figure 15. User connections 26
Figure 16. Home tab RobotStudio 27
Figure 17. Controller tab RobotStudio 28
Figure 18. Rapid tab RobotStudio 28
Figure 19. Prototype extruder 31
Figure 20. Cable clips 32
Figure 21. Flexion extruder 33
Figure 22. Heating element and thermistor 34
Figure 23. 40x40 mm axial & 50 mm blower fans 34
Figure 24. Cooling tests with different shrouds 35
Figure 25. Narrow-airflow shroud 36
Figure 26. Blower fan mounting 36

Figure 27. Stepper motor 37
Figure 28. Mounting bracket...37
Figure 29. Arduino Uno & stepper motor controller shield..38
Figure 30. Motor driver shield & cooling components...38
Figure 31. 12V power supply...38
Figure 32. Housing design process...39
Figure 33. 3D printing parts 40
Figure 34. Housing design 40
Figure 35. Housing design features...41
Figure 36. Cable guides + mirrored versions...41
Figure 37. Power supply holder + cable guide 42
Figure 38. Filament spool holder + filament guide 42
Figure 39. Printing bed 43
Figure 40. Fan spacer and standoff...44
Figure 41. Stepper motor spacer 44
Figure 42. Reinforced housing and reinforcement 44
Figure 43. Assembled tool..45
Figure 44. Different rendered views 45
Figure 45. Actual 3D-printing tool...46
Figure 46. Arduino flowchart module 1 48
Figure 47. Arduino Flowchart module 2 49
Figure 48. Arduino Flowchart module 3 50
Figure 49. Flow chart of provided robot software...52
Figure 50. General flow chart Robot Program 53
Figure 51. Flow chart of the G0 command 55
Figure 52. Flow chart of the G1 command 56
Figure 53. Ideal (serial) communication 57
Figure 54. Minimal communication 57
Figure 55. Slicer profile – Speed and Quality 59
Figure 56. Slicer profile – Structures...59
Figure 57. Slicer profile - Extrusion 60
Figure 58. Slicer profile – Filament 60
Figure 59. Simulation of the robot software...61

Figure 60. Stepper motor driver variables 62
Figure 61. Step-multiplier test 63
Figure 62. Temperature control variables 64
Figure 63. Test pieces 66
Figure 64. Adhesion problem 67
Figure 65. Guidance system test 68
Figure 66. Extruding without movement 68
Figure 67. First layer printed 69
Figure 68. Lateral view of the firsts pieces printed – 0,4mm and 0,2mm 70
Figure 69. Upper view of the firsts pieces printed – 0,4mm and 0,2mm 70
Figure 70. Bigger and more complex figure 70
Figure 71. Belbin Roles results 82
Figure 72. Gantt project diagram 84
Figure 73. Expected cost vs actual cost 85
Figure 74. Power - Interest Grid 90
Figure 75. Stakeholder Power - Interest Grid 91

Table of Tables

Table 1. 3D printing technologies 15
Table 2. Working range 25
Table 3. Results of cooling tests 35
Table 4. G-code commands used in the software 50
Table 5. General flow chart robot program variables 54
Table 6. Slicer profiles test 66
Table 7. Task breakdown 83
Table 8. Risk Assessment Matrix 87
Table 9. Explanation of Risk Ranking 88
Table 10. Stakeholders strategies 91
Table 11. Communication documents 93
Table 12. Communication Responsibilities 94
Table 13. Bill of Materials 95

Chapter 1

Introduction

The present report is about a EPS project where the purpose is to combine 3D printing and robotics, making it possible to print in 3D with a robotic arm.

1.1 European Project Semester

European Project Semester is a programme offered by eighteen European universities in twelve countries throughout Europe to students who have completed at least two years of study. EPS is created with engineering students in mind, but other students who can support the project with their field of study are also welcome to participate.

The EPS programme is specially meant to address the design requirements of the degree and prepare engineering students with all necessary skills to face the challenges of today's world economy. The programme is a mixture of project related courses and project organized and problem based learning. The students get to work in international and typically interdisciplinary teams of 3 – 6 students on their projects. And most of the time the projects are interdisciplinary too. Some of the projects are done in cooperation with commercial companies and industries, other projects are more academic and commissioned by the Research and Development Department of the designated university. (Hansen, 2016)

A main aim is that the students understand how they learn in the most efficient way and to take responsibility for their learning and their project work. Besides that, they also develop their intercultural competences, their communication skills and the interpersonal skills. The language for all oral and written communication during the semester is English.

The EPS programme is an experience which helps students to grow up as engineers and individuals as well. Changing the personal approach of projects and the way of collaborating in a team and the mentality of working at all should be the outcome of this project semester.

They expect that the students who are taking part in this programme are determined to pursue their goals of amplifying their level of career and collaborate in teams with people from all over the world. With the reason in mind to learn about different countries as well as get to know new people and create new connections.

In short, EPS is a unique way of developing yourself with others that are also willing to develop themselves. It also provides a continuous exchange of ideas and knowledge with people from diverse cultures, backgrounds and languages.

1.2 The Team

Our multicultural team consist of four members:

Job Trommelen, Tilburg, The Netherlands.

Computer Science student at Avans University of Applied Sciences.

"I like to challenge myself and meet new people that are as motivated as I am to discover new things and learn about new subjects. I'm really interested in programming Embedded Systems because there are no boundaries and it is the perfect way to challenge yourself. Besides learning about programming and Embedded Systems I want to learn more about doing business and starting my own company and also Project Management.

I love to see more of the beautiful world we are living on and I can't wait to discover all of the hidden treasures our world has to offer. I think you have to work hard and after that you can play hard."

Juan Carlos García Pozo, Madrid, Spain.

Graduated in Industrial Electronics and Automatic Engineering and studying Industrial Engineering Master at Carlos III university in Madrid.

"My favourite study field is the automatic, but I want to discover other fields because the knowledge takes no place and I need to take advantage of my last student stage to do it. We must to be openminded to discover the future.

I really enjoy discovering new places and cultures. The world is too beautiful to remain always in the same place."

Luc Richters, Enschede, The Netherlands.

Mechanical engineering student at Saxion University of Applied Science in Enschede. Former Advanced Engineering student at University of Twente.

"I like to study everything that moves and to find out how it works. I also like to write small programs for Arduino's and Lego Mindstorms. In my free time, I often try to build new machines or contraptions with the use of Lego Technic and to make these motorized. The process of building these machines takes a lot of trial and error.

I joined the EPS program because of the possibility to see more of the world and to get to know more people in different countries."

Poonam Khatti, Amberg, Germany.

Mechanical engineering student at Ostbayerische Technische Hochschule Amberg-Weiden.

"I am a 23-year-old Indian, currently living and studying in Germany. I like extending my limits, move out of my comfort zone and make things happen. I find that the harder I work the more luck I seem to have.

Mechanics has always fascinated me, like working on Robots for Industrial manufacturing, coil binding technology, using CAD software to create 3D design and new technologies like Digital manufacturing. Currently working on Additive manufacturing in EPS and how it differs from subtractive manufacturing and advances in it gives me new insights.

Travelling for me is going to new places and being adventurous. I travel to seek other states, other lives, other souls."

1.3 Brand Identity

The logo is intended to be the “face” of a company. It’s a graphical display of a company’s unique identity.

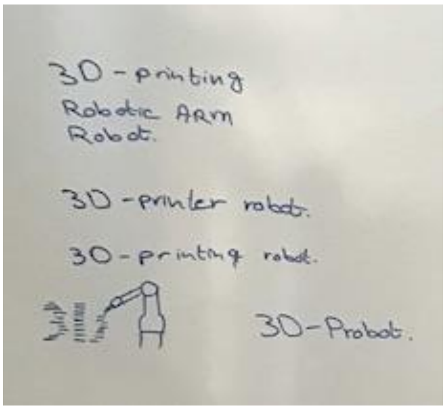


Figure 1. Brainstorm logo and brand name

According to the project description, the logo should include the concept of 3D printing and a robotic arm. The design was thought up in such a way that a robot (blue colour) is printing “3D” layer by layer, so you can see layers in the logo (orange colour).

The idea was to create a logo that is unique and comprehensible to potential customers. Through colours, fonts, and images it provides essential information about our company that allows customers to identify with the company’s core brand.

3D PROBOT

Figure 2. Final logo

The brand name chosen is “Probot”. It was chosen as it is a combination of the two phrases 3D-printing and robotic arm.

1.4 Project Motivation

In recent years the evolution in 3D printing has been fascinating and every time new possibilities appear. Endless opportunities to build and create things and shapes that were previously impossible. However, 3D printing is also a perfect technology for fixing the previously unfixable, when producing spare parts either is not viable or is prohibitively expensive. (Kuneinen, 2013)

The work and research fields opened are huge: medical, dental, aerospace, automotive, jewellery, art, architecture, fashion and even food. (Petch, n.d.)

Until now a 3D printer has been a box capable to print layers in 2D. With the inclusion of the robotics in this field the opportunities grow even more. The two main aspects of this merge are the increase of the printing surface, which now is the robot's reach instead a box with specific dimensions, and the possibility of 3D printing using 3D positions and different orientations instead of layer by layer.

This merge is not too developed yet. Only a few models of robots have been used with this purpose and most are desktop robots, therefore the present project is innovative and may be the start of an important and much longer and larger project.

1.5 Project Target

The main target of the current project is to attach a 3D printing system to an ABB robotic arm enabling the printing of horizontal layers. Achieving, at first, a larger printing surface and more freedom for future improvements.

To reach the final goal it is necessary to accomplish some steps:

- Designing and 3D printing the housing for the extruder and the parts necessary for the filament guidance system
- Mounting the developed parts on the robotic arm
- Programming the controller for the required hardware like the stepper motor or the cooling system
- Adapting the already created software to our system to translate G-code to Rapid code
- Testing and improving the results obtained

The target of this project is not to achieve to 3D print with different orientations. The goal is to achieve horizontal layer printing with a robotic arm.

The system obtained is very flexible and can be used with other ABB robotic arms as the created parts can be attached to the robotic arm easily. The connection is standard and the creation of a simple connection piece would be enough to make it possible. The controller is attached to the housing part and the software can be used with any computer that has the required platform (ABB RobotStudio) or directly on the robot. Although it was not a project target, it is an interesting point.

To sum up, the project target is to create a system capable to 3D print layer by layer in an ABB robotic arm, which serves as a base for future improvements in this field like printing with 3D positions and in addition could be attached to other ABB robotic arms.

1.6 Socio-Economic Environment

The society and technology advances in a lot of fields, one of the most surprising fields is 3D printing.

3D printing is already having an effect on the way that products are manufactured. The nature of the technology permits new ways of thinking in terms of the social, economic, environmental and security implications of the manufacturing process with favourable results. (Petch, n.d.)

One of the key factors behind this statement is that 3D printing has the potential to bring production closer to the end user and/or the consumer, thereby assembly lines and supply chains can be reduced or eliminated for many products. Designs, not products, would move around the world as digital files to be printed anywhere by any printer that can meet the design parameters. Products could be printed on demand without the need to build-up inventories of new products and spare parts. (Campbell, Williams, Ivanova, & Garrett, 2011)

This could have a major impact on how businesses, the military and consumers operate and interact on a global scale in the future. The aim for many is for consumers to operate their own 3D printer at home, or within their community. Currently, there is some debate about whether this will ever come to pass, and even more rigorous debate about the time frame in which it may occur. (Petch, n.d.)

Manufacturing could be pulled away from “manufacturing platforms” like China back to the countries where the products are consumed, reducing global economic imbalances as export countries’ surpluses are reduced and importing countries’ reliance on imports shrink.

A given manufacturing facility would be capable of printing a huge range of types of products without retooling and each print could be customized without additional cost. (Campbell, Williams, Ivanova, & Garrett, 2011)

The effect of 3D printing on the developing world is a double-edged sword. One example of the positive effect is lowered manufacturing cost through recycled and other local materials, but the loss of manufacturing jobs could hit many developing countries severely, which would take time to overcome.

The developed world would benefit perhaps the most from 3D printing as the growing aged society and shift of age demographics has been a concern related to production and work force. Also, the health benefits of the medical use of 3D printing would cater well for an aging western society.

3D printing would have the potential to create new industries and completely new professions, such as those related to the production of 3D printers. There is an opportunity for professional services around 3D printing, ranging from new forms of product designers, printer operators, material suppliers all the way to intellectual property legal disputes and settlements. Piracy is a current concern related to 3D printing for many intellectual property holders.

3D printing is also emerging as an energy-efficient technology that can provide environmental efficiencies in terms of both the manufacturing process itself, utilising up to 90% of standard materials, and, therefore, creating less waste, but also throughout an additively manufactured product's operating life, by way of lighter and stronger design that imposes a reduced carbon footprint compared with traditionally manufactured products. (Petch, n.d.)

The model calculations show that 3D printing contains the potential to reduce costs by 170-593 billion Dollar US, the total primary energy supply by 2.54-9.30 Exa-Joules and CO_2 emissions by 130.5-525.5 Mega tonnes by 2025. The large range within the saving potentials can be explained with the immature state of the technology and the associated uncertainties of predicting market and technology developments. The energy and CO_2 emission intensities of industrial manufacturing are reducible by maximally 5% through 3D printing by 2025, as it remains a niche technology. If 3D printing was applicable to larger production volumes in consumer products or automotive manufacturing, it contains the (theoretical) potential to absolutely decouple energy and CO_2 emission from economic activity. (Gebler, Schoot Uiterkamp, & Visser, 2014)

1.7 Document Structure

The present report has been structured in the next chapters:

- **Introduction**: In this chapter, a presentation and the main general aspects of the project are exposed: European Project Semester, the team, project motivation, project target, socio-economic environment and document structure.
- **State of the Art**: In this chapter, the current progress made in the joining of 3D printing and robotics are exposed.
- **Technological General Concepts**: In this chapter, the main technologies that this project involves, as well as the main characteristics and functionalities of the hardware and software used in the project are exposed.
- **3D Printing Tool Design and Mounting**: In this chapter, the hardware used in the tool, as well as the process of designing, printing the necessary parts (housing and guidance system) and the set mounting on the robotic arm are explained.
- **Robotic Arm and Tool Programming**: In this chapter, the translation between G-code and Rapid code will be discussed, as well as other programming aspects of the robotic arm and the programming for the tool controller are explained.
- **Testing and Results**: In this chapter, all the tests done after the system had been developed are shown. The analysis and results of these tests are also explained.
- **Conclusions and Future Lines:** In this chapter, the conclusions are collected after the end of the project, summarizing which concepts have been more determinant. An exposition of possible improvements of the model and future lines are also exposed.
- **Bibliography**: Finally, all the bibliography used throughout the writing of the report is listed.

In addition, an annexe of the project management has been included, which includes the workshops knowledges, planning and project budget.

Chapter 2

State of the Art

In the recent years some 3D printing projects using robotics have appeared working with different materials. The technology used in the projects, shown in the state of the art, is material extrusion.

2.1 MX3D

MX3D develops ground-breaking robotic additive manufacturing technology, innovate by constantly creating new strategies and software solutions to print a large variety of metal alloys in virtually any size and shape. In close collaboration with global industrial partners, engineers and software experts make Robotic 3D Metal Printing available to industry.

MX3D is 3D printing a fully functional stainless-steel bridge to cross one of the oldest and most famous canals in the centre of Amsterdam, the Oudezijds Achterburgwal. MX3D equips typical industrial robots with purpose-built tools and develops the software to control them. The unique approach allows to 3D-print strong, complex and graceful structures out of metal. The goal of the MX3D Bridge project is to showcase the potential applications of the multi-axis 3D printing technology. (MX3D, 2017)

Figure 3. MX3D bridge

2.2 RamLab

RamLab is an initiative of three founding partners: Port of Rotterdam, Innovation Quarter and RDM Makerspace to achieve its vision of manufacturing certified metal parts on demand through Additive Manufacturing. RamLab's main focus is on Wire Arc Additive Manufacturing (WAAM) technology. The lab currently has two WAAM systems at its disposal. (RamLab, 2017)

RamLab printed the first ship's propeller with a nickel, aluminium and bronze alloy which weighs 400 kilograms and has a 1.30 metre diameter. (Port of Rotterdam, 2017)

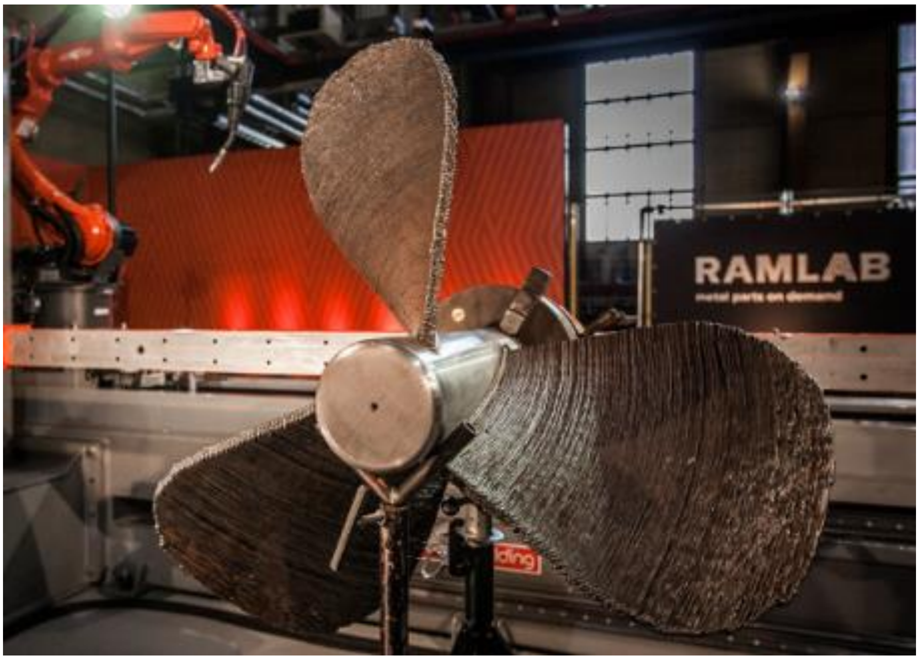


Figure 4. RamLab's Propeller (Alexandrea, 2017)

2.3 IAAC

The Institute for Advanced Architecture of Catalonia (IAAC), based in Barcelona, has been exploring and investigating the potentials of additive manufacturing applied to the architectural field, therefore implemented on a larger scale. With the interest of further developing the potentials of this technique on the large scale, and in view of the environmental and economic crisis, IAAC has been investigating the possibility of onsite additive manufacturing and fabrication with local and 100% natural materials. (Institute for Advanced Architecture of Catalonia, 2017)

2.3.1 TerraPerforma

The project TerraPerforma focuses on large scale 3D printing, the influence of additive manufacturing on building with a traditional material (unfired clay) and climatic performative design. The project combines three various postures of 3D Printing: robotic fabrication, onsite printing and printing with clay.

While 3D printing has given the possibility to create complex geometries, the intelligence of the design comes from the optimisation strategies, the creation of performative shapes becoming easier to achieve.

During TerraPerforma, a series of tests were carried that explore the possibility to optimise design according to different performance parameters. The development of the project started by researching climatic phenomena and material behaviour.

The team also had the opportunity to work within Tecnalia, experimenting with the CoGiro robot, a Cable-Driven Parallel Robot (CDPR) owned by Tecnalia and LIRMM-CNRS. Its original point of design resides in the way the cables are connected to the frame, called the configuration of the CDPR, which makes is a very stable design, hence the team was able to manufacture the biggest monolithic piece done within the research.

For the final prototype of TerraPerforma, it was concluded that a modular approach would be the best, mainly due to the difficulties of bringing a robot in the outdoor and to face hard climatic conditions. The modules are parametrically conceived so that they have optimum performance depending on solar radiation, wind behaviour and structural 3D printing reasoning, both by their own and as a whole design. The facade was conceived as a gradient in both horizontal and vertical directions, having various radiuses of self-shading, in order to optimise east and west sun. (Institute for Advanced Architecture of Catalonia, 2017)

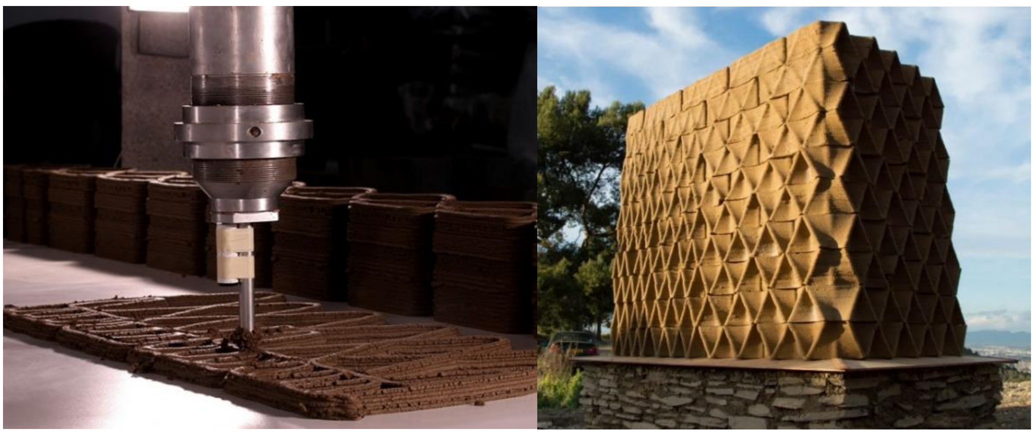


Figure 5. TerraPerforma, 3D printing with clay

2.3.2 Material

Conventional methods of additive manufacturing have been affected both by gravity and printing environment. Creation of 3D objects on irregular, or non-horizontal surfaces has so far been treated as impossible. By using innovative extrusion technology, the effect of gravity can be neutralized during the printing process. This method gives a flexibility to create truly natural objects by making 3D curves instead of 2D layers. Unlike 2D layers that are ignorant to the structure of the object, the 3D curves can follow exact stress lines of a custom shape. (Institute for Advanced Architecture of Catalonia, 2017)

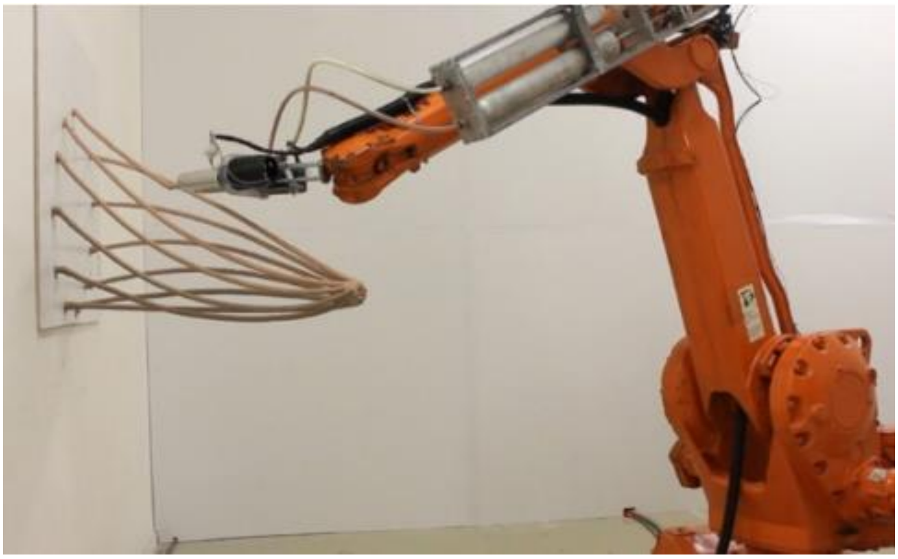


Figure 6. Material, antigravity additive manufacturing

2.3.3 Mini builders

This project develops a family of small-scale construction robots, all mobile and capable of constructing objects far larger than the robot itself. Moreover, each of the robots developed was to perform a diverse task, linked to the different phases of construction, finally working together towards the implementation of a single structural outcome.

Specifically, a family of three robots was developed, each robot linked to sensors and a local positioning system. These feed live data into a piece of custom software allowing control of the robot’s movement and deposition of the material output: fast setting artificial marble.

The first robot, the Base Robot, lays down the first ten layers of material to create a foundation footprint. Sensors mounted inside the robot control direction, following a predefined path. Traveling in a circular path allows for a vertical actuator to incrementally adjust the nozzle height for a smooth, continuous, spiralling layer. The advantage of laying material in a continuous spiral is that it allows for constant material flow, without having to move the nozzle up at intervals of one layer.

To create the main shell of the final structure the second robot, the Grip Robot, attaches to the foundation footprint. Its four rollers clamp on to the upper edge of the structure allowing it to move along the previously printed material, depositing more layers.

Controlled by custom software the robot follows a predefined path, but can also adjust its path to correct errors within the printing process. Rotational actuators control height above the previous layer to maintain a consistent layer. (Institute for Advanced Architecture of Catalonia, 2017)

Figure 7. Mini builders

Chapter 3

Technological Concepts

3.1 Additive Manufacturing (3D Printing)

3D printing, also known as additive manufacturing(AM), refers to processes used to create a three-dimensional object in which layers of material are formed under computer control to create an object. Objects can be of almost any shape or geometry and are produced using digital model data from a 3D model. STL is one of the most common file types that 3D printers can read. Thus, unlike material removed from a stock in the conventional machining process, 3D printing or AM builds a three-dimensional object by laying down successive layers of a specific material until the entire object is created. Each of these layers represents a thinly sliced horizontal cross section of the eventual object.

3D printing is the opposite of subtractive manufacturing which is cutting out / hollowing out a piece of metal or plastic with for instance a milling machine.

3D printing enables you to produce complex (functional) shapes using less material than traditional manufacturing methods.

Primary areas of use: Prototyping, specialized parts (aerospace, military, biomedical engineering, dental), hobbies and home use, future applications (medical, buildings and cars).

3D Printing uses software that slices the 3D model into layers (0.2mm thick or less in most cases). Each layer is then traced onto the build plate by the printer, once the pattern is completed, the build plate is lowered and the next layer is added on top of the previous one. (European Social Fund Malta 2007-2013, 2013).

There are different 3D printing methods exposed below.

3.1.1 3D Printing Technologies

Table 1. 3D printing technologies

Process Type	Ex. Companies	Materials	Market
Powder Bed Fusion	EOS (Germany), 3D Systems (US), Arcam (Sweden)	Metals, Polymers	Direct Part, Prototyping
Directed Energy Deposition	Optomec (US), POM (US)	Metals	Direct Part, Repair
Material Extrusion	Stratasys (Israel), Bits from Bytes (UK)	Polymers	Prototyping
Vat Photopolymerization	3D Systems (US), Envisiontec (Germany)	Photopolymers	Prototyping
Binder Jetting	3D Systems (US), ExOne (US)	Polymers, Glass, Sand, Metals	Prototyping, Casting Molds, Direct Parts
Material Jetting	Objet (Israel), 3D Systems (US)	Polymers, Waxes	Prototyping, Casting Patterns
Sheet Lamination	Fabrisonic (US), Mcor (Ireland)	Paper, Metals	Prototyping, Direct Part

3.1.1.1 Powder Bed Fusion

An additive manufacturing process in which thermal energy selectively fuses regions of a powder bed.

3.1.1.2 Directed Energy Deposition

An additive manufacturing process in which focused thermal energy is used to fuse materials by melting them as they are being deposited.

3.1.1.3 Material Extrusion

An additive manufacturing process in which material is selectively dispensed through a nozzle.

3.1.1.4 Vat Photopolymerization:

An additive manufacturing process in which liquid photopolymer in a vat is selectively cured by light-activated polymerization.

3.1.1.5 Binder Jetting:

An additive manufacturing process in which a liquid bonding agent is selectively deposited to join powdered materials.

3.1.1.6 Material Jetting:

An additive manufacturing process in which droplets of build material are selectively deposited.

3.1.1.7 Sheet Lamination:

An additive manufacturing process in which sheets of material are bonded to form an object.

3.2 Fused Deposition Modelling (FDM)

Fused deposition modelling (FDM) is an additive manufacturing technology commonly used for modelling, prototyping, and production applications. It is the technique chosen for our 3D printing parts.

The model or part is produced by extruding small flattened strings of molten material to form layers as the material hardens immediately after extrusion from the nozzle.

A plastic filament or metal wire is unwound from a coil and supplies material to an extrusion nozzle which can turn the flow on and off. There is typically a worm-drive that pushes the filament into the nozzle at a controlled rate.

The nozzle is heated to melt the material. The thermoplastics are heated past their glass transition temperature and are then deposited by an extrusion head.

Myriad materials are available, such as Acrylonitrile Butadiene Styrene ABS, Polylactic acid PLA, Polycarbonate PC, Polyamide PA, Polystyrene PS, lignin, rubber, among many others, with different trade-offs between strength and temperature properties.

During FDM, the hot molten polymer is exposed to air. Operating the FDM process within an inert gas atmosphere such as nitrogen or argon can significantly increase the layer adhesion and leads to improved mechanical properties of the 3D printed objects. (Lederle, Meyer, & Brunotte, 2016)

FDM technique is open to different extruders, materials, filament thickness and bed materials.

FDM technique is used in the current project.

3.2.1 Extruders

The 3D extruder is the part of the 3D printer that ejects material in liquid or semi-liquid form to deposit it in successive layers within the 3D printing volume. In some cases, the extruder serves only to deposit a bonding agent used to solidify a material that is originally in powder form. (sculpteo.com, n.d.)

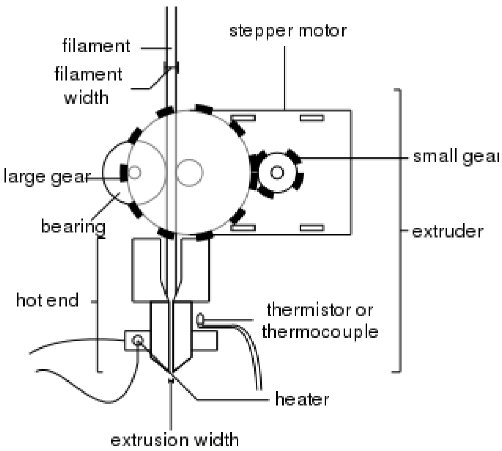


Figure 8. FDM Extruder

To extrude molten plastic filament, the "cold end" forces the raw material into the hot end. The feeding filament should then go through the "hot end" of the extruder with the heater and out of the nozzle at a reasonable speed. The extruded material falls onto the build platform (sometimes heated) and then layer by layer onto the part as it is built up.

The cold end is usually the bulk of the extruder. In some designs, the cold end is split into two parts; one part does the driving of the filament that is stationary and connected to the carriage portion. The driver is a motor that rotates a knurled, hobbled or toothed pinch wheel against a pressure plate or bearing with the filament forced between them. Some form of cooling, keeps the cold end cold, usually a fan.

The cold end is connected to the hot end across a thermal break or insulator. This must be rigid and accurate enough to reliably pass the filament from one side to the other, but still prevent much of the heat transfer. The materials of choice are usually PEEK plastic with PTFE liners or PTFE with stainless steel mechanical supports or a combination of all three. A hot end is frequently joined to the cold end using a “groove mount” where the thermal break or insulator is part of the hot end assembly and the cold end body is provisioned with a cylindrical recess.

The hot end is the active part of the 3D printer that melts the filament. It allows the molten plastic to exit from the small nozzle to form a thin and tacky bead of plastic that will adhere to the material it is laid on. The molten plastic exits the heating chamber through the hole at the tip. The hole in the tip (nozzle) has a diameter of between 0.1mm and 1.0mm with typical size of 0.5mm with present generation extruders. Outside the tip of the barrel is a heating means, either a wire element or a standard wire wound resistor. The heat required is of the order of 20W with typical temperatures around 150 to 250 degrees Centigrade. For feedback control of the nozzle temperature, a thermistor is usually attached close to the nozzle, though a thermocouple may serve with suitable control hardware. High temperature materials are needed here. These include metals, cements and glues, glass and mineral fibre materials, PEEK, PTFE and Kapton tape. (reprap.org, 2015)

Attending to the feeding there are two different extruders: Direct and Bowden. With the direct approach, the extruder itself is typically mounted directly on top of the hot end and the filament is directly inserted.

On the other hand, with the Bowden approach the hot end is physically separated from the extruder. Typically, the extruder is mounted on the back or interior of the 3D printer. The “remote” extruder works in the same manner as the direct extruder: it grasps the filament and pushes. However, the difference is that the filament must travel a distance through a tube to finally arrive at the hot end. (Stevenson, 2015)

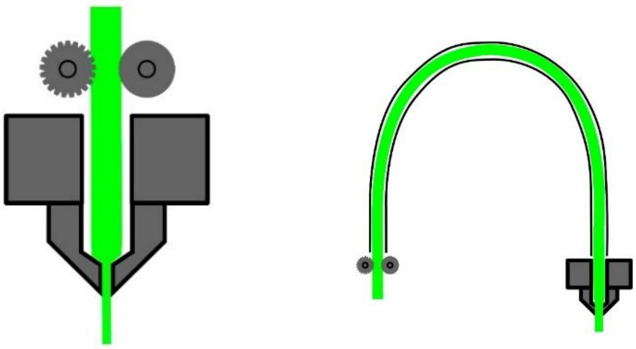


Figure 9. Direct and Bowden tube feeding

3.2.2 Materials

There are many materials that are being explored for 3D Printing, however the two dominant plastics are ABS and PLA. Both ABS and PLA are known as thermoplastics; that is, they become soft and mouldable when heated and return to a solid when cooled.

Both ABS and PLA do best if, before use or when stored long term, they are sealed off from the atmosphere to prevent the absorption of moisture from the air.

Moisture laden ABS will tend to bubble and spurt from the tip of the nozzle when printing; reducing the visual quality of the part, part accuracy, strength and introducing the risk of a stripping or clogging in the nozzle. ABS can be easily dried using a source of heat (preferably dry).

PLA responds somewhat differently to moisture, in addition to bubbles or spurting at the nozzle, may have discoloration and a reduction in 3D printed part properties as PLA can react with water at high temperatures and undergo de-polymerization. PLA can also be dried, but it is important to note that this can alter the crystallinity ratio and will possibly lead to changes in extrusion temperature and other extrusion characteristics.

Both ABS and PLA can create dimensionally accurate parts. However, there are a few points worthy of mention regarding the two.

For most, the single greatest hurdle for accurate parts in ABS will be a curling upwards of the surface in direct contact with the 3D Printer's print bed. A combination of heating the print surface and ensuring it is smooth, flat and clean goes a long way in eliminating this issue.

For fine features on parts involving sharp corners, such as gears, there will often be a slight rounding of the corner. A fan to provide a small amount of active cooling around the nozzle can improve corners but one does also run the risk of introducing too much cooling and reducing adhesion between layers, eventually leading to cracks in the finished part.

Compared to ABS, PLA demonstrates much less part warping. For this reason, it is possible to successfully print without a heated bed and use more commonly available "blue" painters tape as a print surface. Ironically, totally removing the heated bed can still allow the plastic to curl up slightly on large parts, though not always.

PLA undergoes more of a phase-change when heated and becomes much more liquid. If actively cooled, much sharper details can be seen on printed corners without the risk of cracking or warping. The increased flow can also lead to stronger binding between layers, improving the strength of the printed part.

In addition to a part being accurately made, it must also perform in its intended purpose.

ABS as a polymer can take many forms and can be engineered to have many properties. In general, it is a sturdy plastic with mild flexibility (compared to PLA). Natural ABS before colorants have been added is a soft milky beige. The flexibility of ABS makes creating interlocking pieces or pin connected pieces easier to work with. It is easily sanded and machined. Notably, ABS is soluble in Acetone allowing one to weld parts together with a drop or two, or smooth and create high gloss by brushing or dipping full pieces in Acetone. Compared to PLA, it is much easier to recycle ABS.

Its strength, flexibility, machinability, and higher temperature resistance make it often a preferred plastic by engineers and those with mechanical uses in mind.

PLA is created from processing any number of plant products including corn, potatoes or sugar-beets, PLA is considered a more 'earth friendly' plastic compared to petroleum based ABS. Used primarily in food packaging and containers, PLA can be composted at commercial compost facilities. It won't bio-degrade in your backyard or home compost pile however. It is naturally transparent and can be coloured to various degrees of translucency and opacity. Also, strong and more rigid than ABS, it is occasionally more difficult to work with in complicated interlocking assemblies and pin-joints. Printed objects will generally have a glossier look and feel than ABS. With a little more work, PLA can also be sanded and machined. The lower melting temperature of PLA makes it unsuitable for many applications.

In summary, the ABS strength, flexibility, machinability, and higher temperature resistance make it often a preferred plastic for engineers, and professional applications. The additional requirement of a heated print bed means there are some printers simply incapable of printing ABS with any reliability.

For PLA, the wide range of available colours and translucencies and glossy feel often attract those who print for display or small household uses. Many appreciate the plant based origins. When properly cooled, PLA seems to have higher maximum printing speeds, lower layer heights, and sharper printed corners. Combining this with low warping on parts make it a popular plastic for home printers, hobbyists, and schools. (Chilson, 2013)

3.2.3 Filament thickness

Both materials ABS and PLA need to be prepared to feed the extruder. Solid plastic filaments are created with this purpose and the basic difference is the thickness. There are two possibilities: 3mm or 1,75mm.

By using 1.75mm filament, the torque required from a stepper motor is three times less than with 3mm filament. This reduction in torque means a smaller direct drive system can be used, and since the drive system is smaller, the inertia of an entire print axis is reduced. This means smaller, faster printers than can also print better at low layer heights. In addition, heating less mass will always take less time.

That’s not to say there aren’t advantages to 3mm filament. If a printing with large nozzles or high feed rates is required, a larger filament is a good option. However, 3mm filament is a little less resistant to bending.

The difference between 1.75 and 3mm filament is only a choice in engineering trade-offs, neither one is better, but each offers a few advantages. (Benchoff, 2015)

3.2.4 Bed material

The bed material needs to satisfy two somewhat contradictory goals: The bed material must stick to the plastic coming out of the extruder; otherwise, the partially-printed part will slide around. Then, the next layer of the part won't be aligned, having a failed print.

The bed material must not stick too strongly to the plastic coming out of the extruder. Otherwise you'll create perfectly-printed parts that are impossible to remove from the bed without damaging the bed, the part or both. (reprap.org, 2016)

It is difficult to have good results printing directly onto various metal surfaces like copper, brushed aluminium, and bare glass.

Kapton Tape is useful as a build surface as hot, extruded plastic adheres to it easily and cooled parts can be peeled from the tape without damaging the part or the Kapton tape.

Blue Painter's Tape is a cheaper alternative to Kapton tape. The light wax surface allows hot, extruded plastic to adhere to the surface well. Unlike Kapton tape, it can be more difficult to remove cooled parts from the blue painter's tape which leads to small rips.

A simple solution especially good for PLA is mixing a white PVAc based glue like Elmer's Glue-All or School Glue. The ratio is about 1-part glue to 10 parts waters.

People at the 3D printing group of Brazil have discovered that a solution of 1:10 jelly to water adhere both PLA and ABS if the heated bed is over 60°C, the bond is really strong and the part pops itself up when the print is finished and the bed cools down. (reprap.org, 2017)

3.3 3D Printing Software

To work, the 3D printer needs specific commands for the movements and set/reset the different tools included like fans, heated bed or the extruder among others.

3D printers use G-code to make it possible. This code is generated by specific software through a 3D model.

3.3.1 G-code

G-code (also called RS-274), is the common name for the most used numerical control programming language. It is used mainly in computer-aided manufacturing to control automated machine tools

G-code is a language in which people tell the computerized machine tools how to make something. The "how" is defined by G-code instructions provided to a machine controller (industrial computer) that tells the motors where to move, how fast to move, and what path to follow. (Oberg, Jones, Horton, Riffel , & Green , 1996)

3.3.2 Repetier - Host

Repetier is the specific software for 3D printers. This software allows the connection between computer and 3D printer. Also, it transfers the G-code between both.

Repetier includes basic tools like a work screen, where the progress in the 3D impression can be followed, and tools for scaling or rotating the object. There are different tabs: slicer selection and some print settings, preview (where some information like estimated time and necessary layers or filament can be seen), manual control and Z axis calibration.

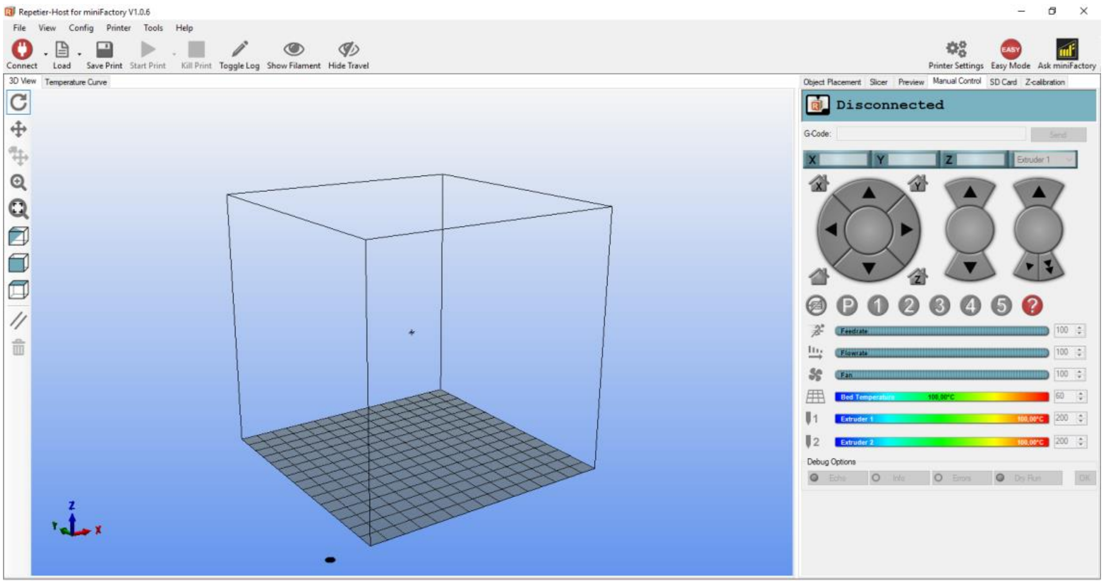


Figure 10. Repetier Host working screen

3.4 Slicers

A slicer takes a 3D model and translates it into individual layers. The slicer then generates the G-code that the printer will use for printing. (Schneider, 2016)

In the slicer, there is the printer and filament configuration. This configuration is important to make a quality piece. A slicer program allows to calibrate printer settings for several types of "areas to print", the most important are: movement speed (printing or travelling), layer height, infill structure and quality, support structure, extrusion parameters (speed, nozzle diameter), filament diameter, print and bed temperatures and cooling (fan speed).

To sum up, the slicer transforms a 3D model into layers and generates the G-code. This information is used by Repetier to make a 3D printing preview and to provide the G-code to the printer.

3.5 ABB Robot

This chapter will provide information about robotic arms in general and about the articulated ABB IRB-1200 90/5 model specifically.

3.5.1 Robotic arms

Robotic arms are mechanical devices that resemble the human arm. These mechanical arms can be programmed to do various tasks. Robotic arms are often used to perform tasks that are either harmful to humans, unsafe, unpleasant or highly repetitive. A few examples of these tasks are: material handling, welding, painting and assembling. These tasks are often programmed using a teach and repeat technique where the operator/programmer uses a portable device to teach the robot its task. This is done by going through the motions that the robot will need to make.

There is a wide range of shapes, sizes and configurations available. The most significant differences between robotic arms are the number of joints (and thus degrees of freedom (DOF's)), the reach and the maximum load that the robotic arm can handle. Another important part is the configuration of the arm. Different configurations are shown in *Figure 11.* Robot Arm Design Configurations

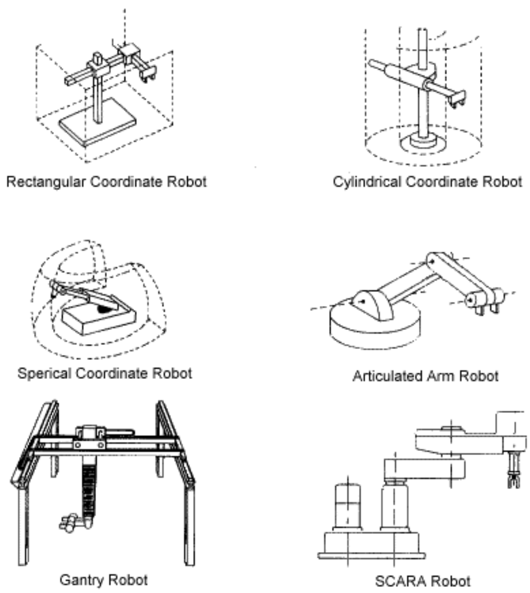
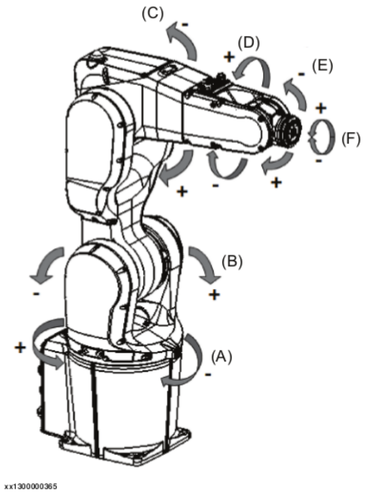


Figure 11. Robot Arm Design Configurations

Most robotic arms are driven by electrical motors, either AC or DC. It is often the case that these motors are servo motors that have sensors installed to determine the position of the joints. In the case of larger articulated arm robots, it is common that the electrical motor on the second axis is accompanied by a gas spring to reduce the load on the motor. (Occupational Safety and Health Administration, n.d.)

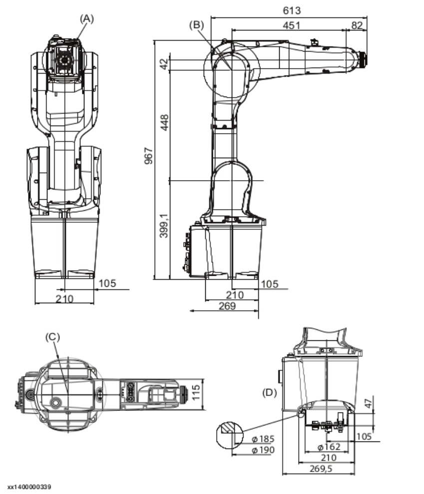
3.5.2 ABB IRB-1200 90/5

The articulated robotic arm that will be used for this project is the IRB-1200 90/5 from ABB. This is a compact 6-axis industrial robot. The 90/5 model has a reach of 90 cm and a maximum combined weight of the end effector and payload of 5kg. The 6 rotational axes are shown in *Figure 12*. In *Figure 13* the size of the robot is shown.



Posi-tion	Description	Posi-tion	Description
A	Axis 1	B	Axis 2
C	Axis 3	D	Axis 4
E	Axis 5	F	Axis 6

Figure 12. Rotational axes



Pos	Description
A	Minimum turning radius axis 4 R=79 mm
B	Minimum turning radius axis 3 R=111 mm
C	Minimum turning radius axis 1 R=138 mm
D	Valid for option Robot cabling routing, 966-1 From below

Figure 13. General dimensions

Table 2 shows the range of movement for each axis.

Table 2. Working range

Location of motion	*Type of motion*	*Movement freedom*
Axis 1	Rotation motion	+170° to -170°
Axis 2	Arm motion	+130° to -100°
Axis 3	Arm motion	+70° to -200°
Axis 4	Wrist motion	+270° to -270°
Axis 5	Bend motion	+130° to -130°
Axis 6	Turn motion	Default: +400° to -400° maximum revolution: ±242

Figure 14. Tool flage schematic shows the dimensions of the flange onto which the tool will be mounted. In the case of this project, the tool in question will be a support frame for the extruder and nozzle of a 3D-printer.

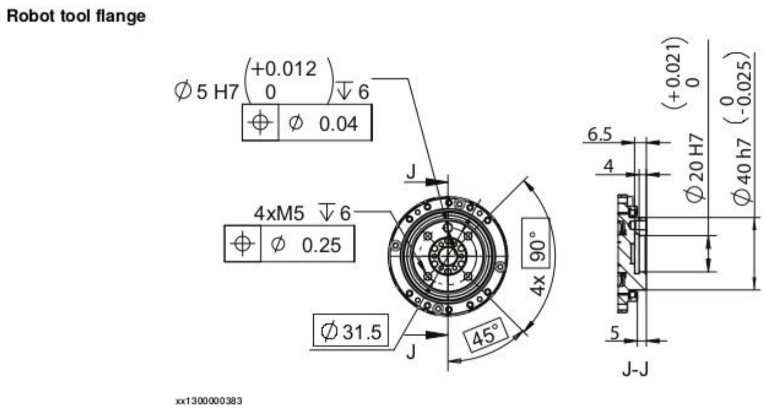
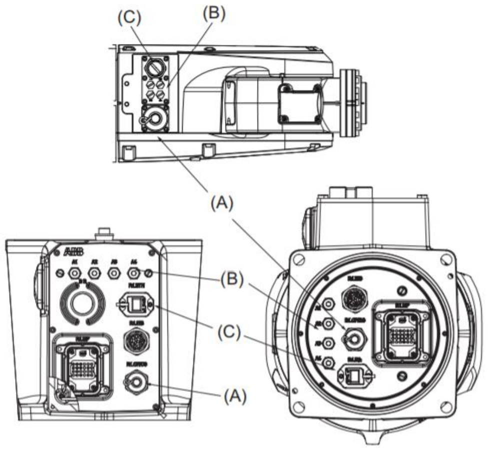


Figure 14. Tool flage schematic

Figure 15 shows the multiple ways to transmit data to the tool. The robotic arm has three connection points, two at the base of the robot and one on position D (*Figure 12*) There are 10 connections for user power that can each handle a maximum of 49V / 500mA. Additionally, there is an ethernet connection with 8 data lines and there are four pneumatic lines that can go up to a pressure of 5 bar. (ABB, 2017)



Position	Connection	Description	Number	Value
A	(R1)R4.CP/CS	Customer power/signal	10	49 V, 500 mA
B	Air	Max. 5 bar	4	Inner hose diameter 4 mm
C	(R1)R4.Ethernet	Customer Ethernet	8	100/10 Base-TX

Figure 15. User connections

3.5.3 Robot Software

Before the robot can do certain tasks, it needs to be programmed. The programs that make the robot move are made with special software called an Integrated Development Environment (IDE). ABB Robots have their own IDE, RobotStudio. With RobotStudio, programming can be done visually or by using a programming language that is made for robots. ABB developed their own programming language, RAPID Code. This chapter will discuss how ABB RobotStudio is used and will give an introduction in RAPID Code.

3.5.3.1 ABB RobotStudio

ABB RobotStudio is downloadable from the ABB site. However, a license is needed for RobotStudio. The Research and Development department of the local universities in Vaasa have a joint building for research and all kind of facilities for technology studies called Technobotnia. Since there are several ABB robots in the building, the licenses server provides a license that can be used on a laptop.

With RobotStudio the user can create virtual stations with one or more robots that can be selected from the ABB Library. The benefits of making a virtual station is that a physical robot is not needed to program it since RobotStudio has virtual controllers that can be used to simulate the behaviour of a physical robot. If the program is finished it is possible to connect to a physical controller and transfer the program that was created in the virtual station to the controller and run it on the physical robot. *Figure 16* shows the window where the robot can be programmed visually and import different robots and geometries.

Figure 16. Home tab RobotStudio

In *Figure 17* the controller window is shown, where request write access can be required to transfer the program from the virtual controller to the physical controller through a network.

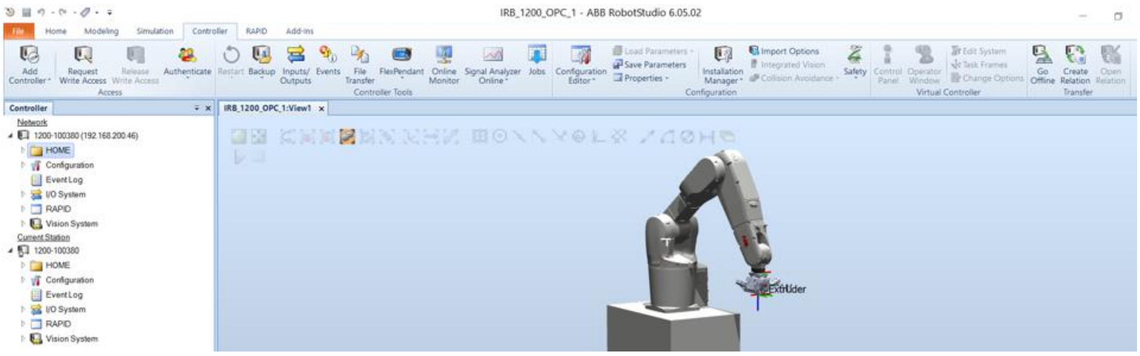


Figure 17. Controller tab RobotStudio

Besides programming the robot visually, it is also possible to program the robot with the RAPID Code programming language. In fact, RobotStudio always creates RAPID Code, even if the robot is programmed using the visual interface. It is possible not only to change the generated code in the RAPID tab but also to write robot programs from scratch. The RAPID tab includes functions that give the programmer the ability to debug the program per line of code. In *Figure 18* the RAPID interface is shown.

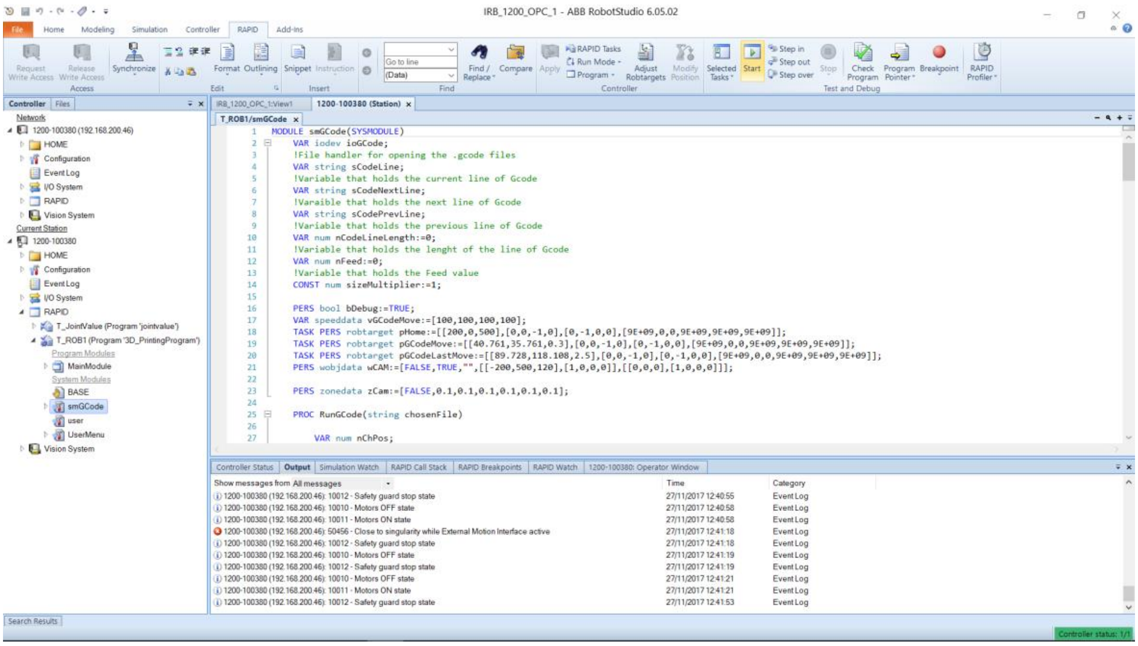


Figure 18. Rapid tab RobotStudio

3.5.3.2 Rapid Code

RAPID is a high-level programming language used to control ABB industrial robots. The code was introduced by ABB Group in 1994 to replace the ARLA programming language. The language features routine parameters:

- Procedures – used as a subprogram.
- Functions – returns a value of a specific type and are used as an argument of an instruction.
- Trap routines – a procedure that responds to interrupts
- It supports multi-tasking and it is possible to create modular programs with it.

Chapter 4

3D Printing Tool Design and Mounting

4.1 Prototype

The following prototype was made to test printing with the robotic arm. It is made from parts, sourced from a RepRap Mendel type 3D-printer, which are attached to a 3D-printed frame that connects it to a mounting plate on the robotic arm. The parts were originally used in a Bowden-type extruder. The tube was shortened so that everything could be fitted to a small frame. It was not possible to print with the prototype because a stepper motor driver and a heating element were missing. These parts were ordered for the final design but never used for the prototype. This was because all the parts arrived at the same time which made the prototype superfluous.

The prototype can be seen in the *Figure 19* with the numbers representing the following parts:

1. frame
2. stepper motor
3. drive system
4. heatsink
5. cooling fan
6. hot end
7. mounting holes

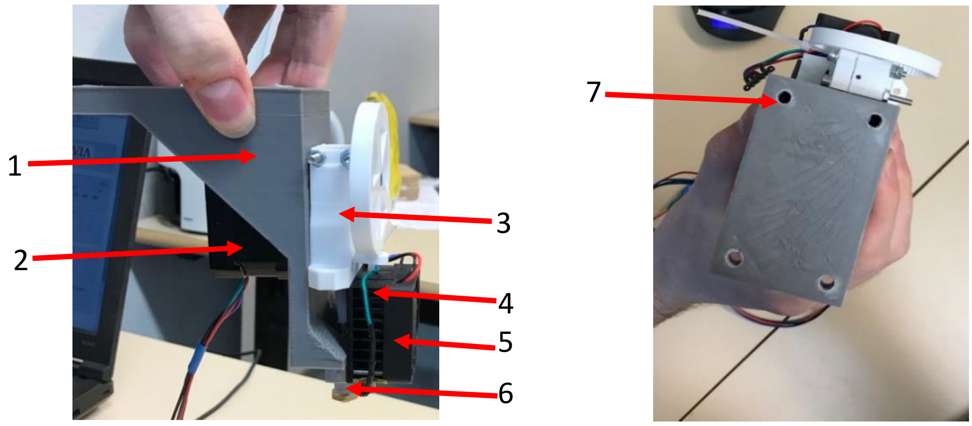


Figure 19. Prototype extruder

4.2 Final Design

The final design for the extruder was put together at about the same time as the prototype was assembled. It consists mostly of parts sourced from online stores and some parts that can be 3D-printed.

4.2.1 Design Approach

The first part of designing the 3D-printing tool was to determine the necessary hardware. The parts that were chosen will be set forth in *4.2.2 Chosen Hardware* and the reason for the choices will also be explained.

The next part was to design a frame, later called a “housing”, that holds all the hardware together and can be attached to the robotic arm. This housing was designed using the Solidworks CAD/CAM software and was designed specifically to be 3D-printed.

All the chosen hardware parts were also replicated in Solidworks to smoothen the process of designing the housing. This was quite a challenge because technical drawings could not be found for every piece of hardware. Some dimensions had to be estimated even if the technical drawing was found because these were not shown. The largest challenge was to replicate the Flexion extruder in Solidworks as this is a very complex part and no technical drawings exist of it. It was finally accomplished by using the high-resolution pictures from the site at which it is sold and measuring the dimensions by hand. As most digital parts are at least partly based on assumptions and estimations, these should not be regarded as completely correctly sized.

After all the hardware had been digitized the parts were used to determine the general shape of the housing. A part of the design is also based on the Printrbot Simple

Metal 3D-printer. Then, all the parts and the housing were combined in a large assembly. The different hardware parts were moved about to determine the best placement and afterwards holes were designed in the housing so that all the parts could be attached to it. Finally, some unnecessary material was removed as there were no more parts that needed to be attached and the smaller volume of the housing would reduce the printing time.

The final part of designing was to create the parts necessary for keeping the cables and filament tube organized on the robotic arm and to prevent them from snagging. These parts were loosely based on the cable clips that can be seen in *Figure 20* and redesigned to be 3D-printed with a rigid plastic. A holder was also designed to attach the power supply to the robotic arm. Additionally, some spacers were designed. These spacers are used for:

- Keeping the axial fan at the correct distance from the flexion extruder block
- Keeping the stepper motor at the correct distance from the mounting bracket
- Keeping the housing at the correct distance from the robotic arm

Figure 20. Cable clips

Of course, some small mistakes were made in the design but luckily these were minor and easily fixed. The mistakes include:

- 1 Misaligned hole for attaching the Arduino.
- Holes for attaching to robotic arm were too large to fit the bolts.
- Assuming PWM (Pulse Width Modulation) works with stepper motors
- Cable holders did not hold cables
- Power cable was shorter than expected

The misaligned hole has not been fixed as this is not deemed necessary because two bolts hold the Arduino in place well when a third bolt is used as a guidance pin.

The oversized holes were tapped to one size larger (M7 instead of M6) and helicoid metal thread inserts were used to bring them back to the standardized M6 size. The threads are a lot more durable now because the bolts are bolted in the metal insert instead of the soft plastic.

To issue of the clashing voltages of the cooling fans and the stepper motor was a bit more problematic. At first it was assumed that PWM could be used to lower the voltage for the stepper motor. To remove any chance of mishaps a second motor driver shield and a 5V output step down converter were put on backorder.

The cable holders did not hold the cables correctly because the cables lined up with the slit designed to put the cables in. The design was mirrored to resolve this.

A holder was designed for the power supply to attach it to the robotic arm.

4.2.2 Chosen Hardware

4.2.2.1 Extruder

The Flexion High Temperature retrofit kit (shown in *Figure 21*) was chosen because of the capability of printing materials that have higher melting points than the standard ABS and PLA materials. This will facilitate the printing of Nylon variants and flexible PUR materials. The kit also includes a standard hot end for printing ABS and PLA. Additionally, a total of 6 nozzles, 2 each with aperture sizes of 0.3, 0.4 and 0.5 mm, are included in the kit.

Figure 21. Flexion extruder

As this extruder kit does not include a heating element or a thermistor for controlling the temperature these were chosen separately based on the compatibility with the extruder and the price. These parts are shown in *Figure 22.*

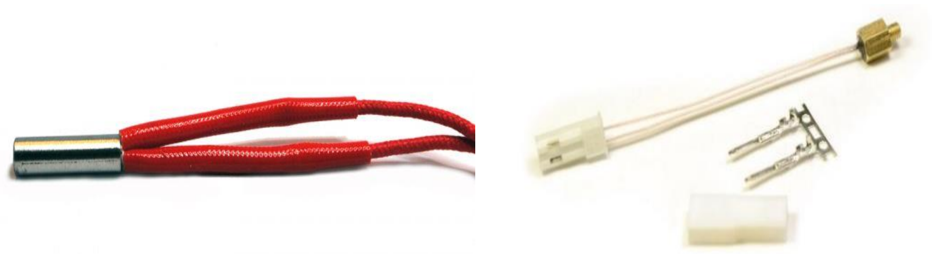


Figure 22. Heating element and thermistor

4.2.2.2 Cooling System

3D printing can require cooling to limit warping and to create a good-looking surface finish. If the filament is not cooled enough when printing large unsupported overhangs, it will sag and thus not bond together.

There are two main types of fans used on 3D printers, an axial fan that is almost always of a size of 40x40 mm or a blower fan with a diameter of 50 mm. These are shown in

Figure 23.

Figure 23. 40x40 mm axial & 50 mm blower fans

According to tests done by Desi Quintans, the best option between these two fans is the 50-mm blower-style fan. Desi Quintans also tested the effect of diverse types of fan shrouds. As can be seen in *Table 3*, the largest difference in appearance comes from using a blower fan. The differences between the various fan shrouds when using the blower fan are not that big except when using the nozzle shroud or when the blower is mounted almost horizontally and very close to the printing bed. (Quintans, The effects of fan types and fan shrouds on overhangs and warping in 3D printing, 2015)

Table 3. Results of cooling tests

Fan type	Shroud style	Warping (% change in height)	Overhang visual appearance								Summed score	Weighting (overhang ÷ warping)
			10°	15°	20°	25°	30°	35°	40°	45°		
Blower	Open	1.54	0	1	2	2	2	2	2	2	13	8.44
Blower	Funnel	2.05	0	1	2	2	2	2	2	2	13	6.33
Stock	Funnel	2.15	0	1	2	2	2	2	2	2	13	6.04
Blower	Surrounding	2.21	0	1	2	2	2	2	2	2	13	5.87
Blower	Naked (high)	2.38	0	1	2	2	2	2	2	2	13	5.46
Blower	Nozzle	3.72	0	1	2	2	2	2	2	2	13	3.50
Blower	Naked (low)	3.92	0	1	2	2	2	2	2	2	13	3.32
Stock	Nozzle	4.31	0	1	2	2	2	2	2	2	13	3.02
Stock	Naked	7.68	0	1	2	2	2	2	2	2	13	1.69
Stock	Open	7.71	0	0	0	0	1	2	2	2	7	0.91
None	Naked	27.17	0	0	0	0	0	0	2	2	4	0.15

According to his findings, best choice would be to use a 50-mm blower fan with an open shroud as this will yield the best results regarding warping.

Additional research was done by Desi Quintans to determine the effect of using two blower fans to cool the plastic. These tests were also done to find out which combination of different fan shrouds gives the best results in print quality. The results of the tests can be seen in *Figure 24* where a higher score means a higher quality print. The conclusion of this research is that using two blower fans results in the highest print quality. One of these fans should use an open shroud or no shroud at all and the other fan should use a narrow-airflow shroud. (Quintans, cooling tests 2, 2016)

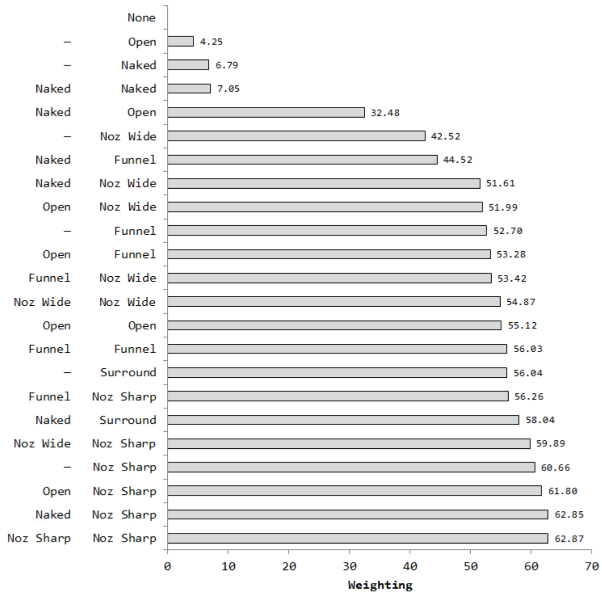


Figure 24. Cooling tests with different shrouds

Based on this research, the decision was made to use two blower style fans for cooling the print. Also, a narrow-airflow shroud was designed to fit. This shroud can be seen in *Figure 25.* Narrow-airflow shroud*.*

Figure 25. Narrow-airflow shroud

In addition to the fan shroud, mounting brackets for the blower fan are also necessary. The mounting block shown in *Figure 26* was chosen because of the possibility of 3D-printing it.

Figure 26. Blower fan mounting

The mounting block for the hot-end of the extruder must be cooled as well. This is to protect the stepper motor from overheating. The fan chosen for this task is a 40x40 mm axial fan with a thickness of 20 mm. This thicker version of fan can move more air in a given amount of time and will thus increase cooling capability. The extruder has been designed to fit this type of fan and thus it was chosen.

4.2.2.3 Drive System

To be able to 3D-print with the extruder a motor is necessary. The extruder is designed to fit on a NEMA-17 type stepper motor as shown in *Figure 27*. The final design will be using a stepper motor that works with 5.3V, 0.85A. This model was chosen because torque increases as voltage lowers and this voltage is the lowest that is compatible with the stepper motor controller.

Figure 27. Stepper motor

To connect the motor as rigidly as possible to the other parts a metal mounting bracket was chosen. The specific bracket is shown in *Figure 28***.**

Figure 28. Mounting bracket

4.2.2.4 Electronics

To control the different fans, the stepper motor and the heating element, an Arduino Uno was chosen. Additionally, two types of shields (extension modules) were chosen to be fitted onto the Arduino. The first type shield is a stepper motor driver shield that can control up to two stepper motors or up to four DC motors depending on the configuration. It will be used to control both fans and the stepper motor. The second type is a high-current motor driver shield that will be used to power the heating element. Additional parts were chosen to keep the components on this shield cool to improve the lifespan and reduce the risk of burns. The Arduino, the shields and the cooling parts are shown in *Figure 29* and *Figure 30.*

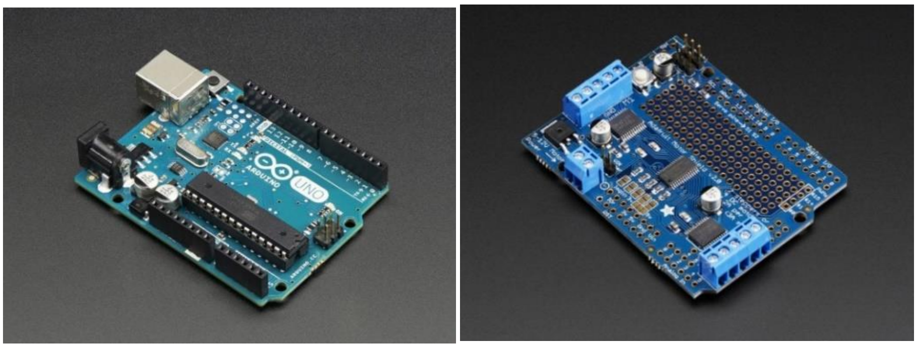


Figure 29. Arduino Uno & stepper motor controller shield

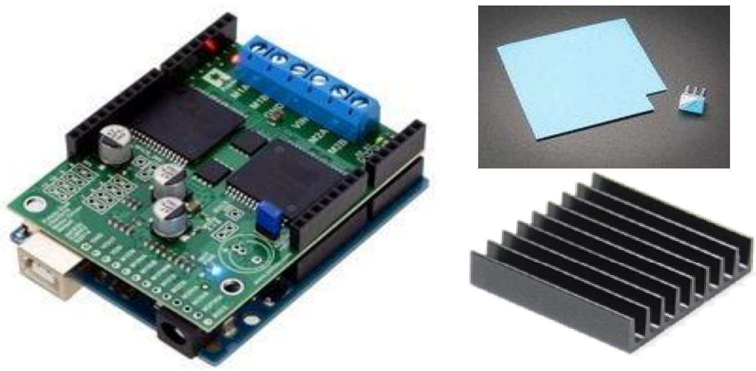


Figure 30. Motor driver shield & cooling components

The last electronical part is the 12V power supply. This part is necessary to power the different 12V electronics like the fans and the Arduino shields. The 60W model was chosen because of the high-power demand by the heating element (40W). The power supply is shown in

Figure 31. 12V power supply

.

Figure 31. 12V power supply

4.2.3 Housing Design

The housing is designed so that it can be 3D-printed and to hold all the necessary parts. In *Figure 32* it is possible to see the process used to design the part. The shape in the first step (top left) is based on the "Printrbot Simple Metal" and the sizes are changed a bit to fit all the necessary parts. In the second step, (top right) mounting holes for the stepper motor bracket were added and excess material has been removed. The third step adds mounting holes and airflow holes for the filament-cooling fans. It also adds the mounting holes used to attach the complete assembly to the robotic arm. The final step adds holes for mounting the stack of the Arduino and the shields. This step also adds a hole and a cut-out for the Bowden tube that is used to prevent the filament from snagging. This cut-out makes it possible to mount the housing flush to the robotic arm.

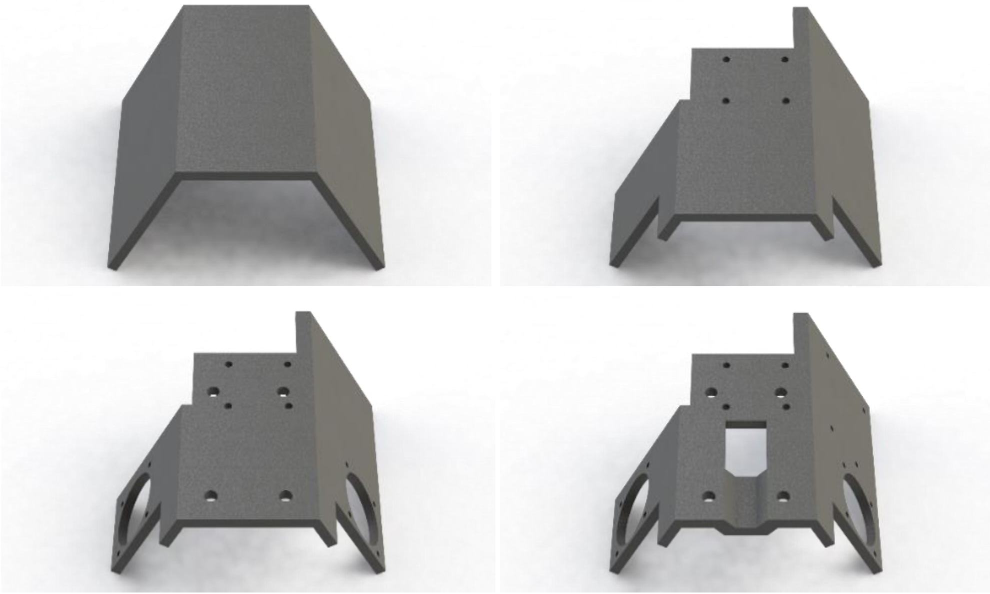


Figure 32. Housing design process

The housing was turned into three smaller parts to make the 3D-printing quicker and to use less support material. These parts can be seen in *Figure 33*.

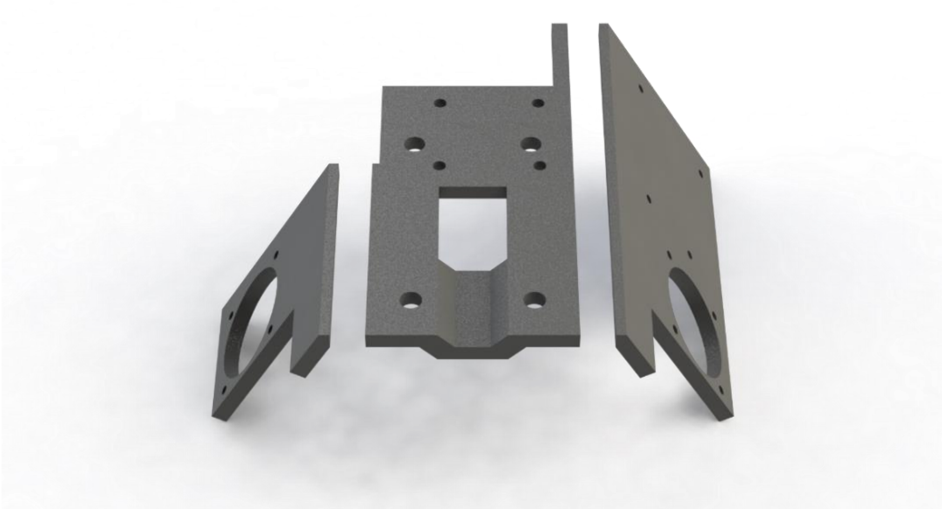


Figure 33. 3D printing parts

Figure 34 and *Figure 35* show the housing in larger detail. The numbered parts relate to the following features:

1. Openings for airflow from fans & mounting holes for fan mounts / shroud
2. Place and mounting holes for Arduino microcontroller and shields

3. Four large mounting holes for attaching to the robotic arm (fitted with helicoil thread inserts)
4. Mounting holes for bracket that holds the stepper motor and extruder
5. Opening and channel for filament to enter the extruder

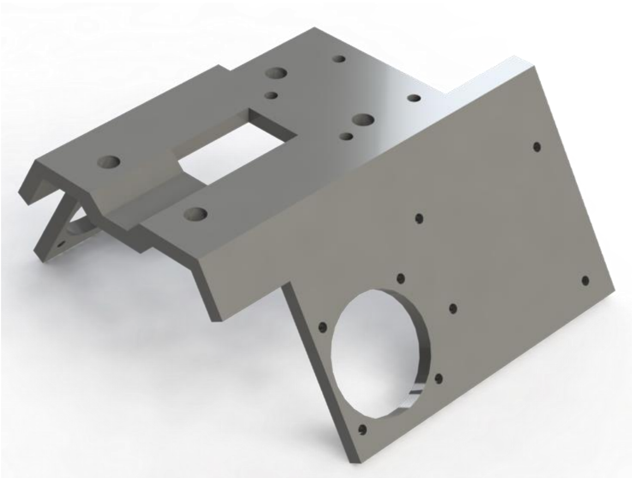


Figure 34. Housing design

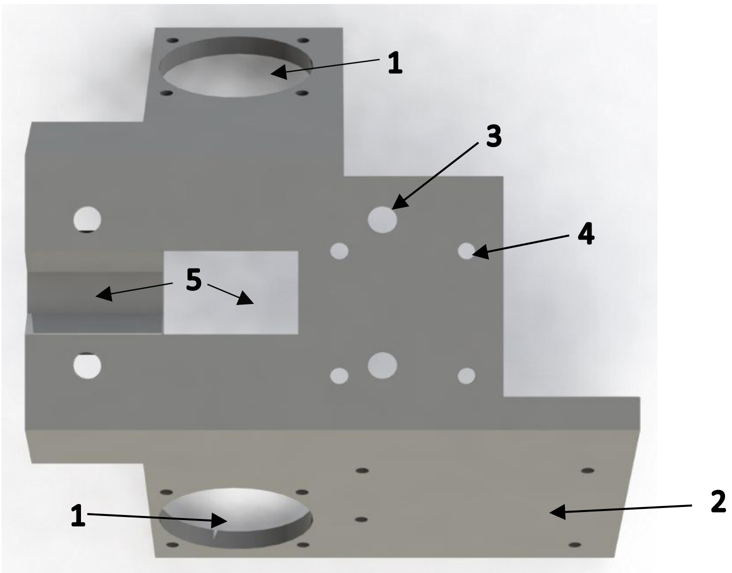


Figure 35. Housing design features

4.2.4 Guidance System Design

A guidance system was necessary to prevent the different cables and the Bowden tube from snagging or getting stuck. Two parts were designed to fit on the robotic arm and to guide the cables. The narrow guide is used twice, and the wide guide is used once. The red parts in *Figure 36* were designed first. It was however not considered how the cables would be situated. The cables lined up with the slot for two of the three guides and they tended to pop out. Mirrored versions were designed and 3D-printed to stop this.

Figure 36. Cable guides + mirrored versions

When the power supply arrived, it became apparent that the cable was shorter than expected. This meant that the power supply had to be mounted on the arm itself and not situated somewhere on/under the stand for the robotic arm. A holder was designed for the power supply. This part can be seen in *Figure 37***.** A cable guide was glued on top as the power supply would use the same mounting holes as that cable guide and it would interfere with the cables otherwise.

A holder for the filament spool was also designed. It was specially made to fit the fencing and to fit wide spools. Additionally, a guide for the filament was made to prevent the filament from unnecessary unspooling. This guide also reduces the risk of the filament getting stuck on the spool. These parts are shown in *Figure 38*.

Figure 37. Power supply holder + cable guide

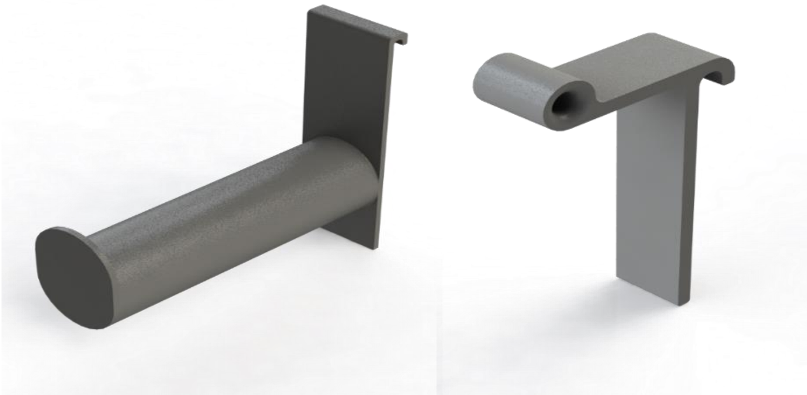


Figure 38. Filament spool holder + filament guide

4.2.5 Printing Bed

The printing bed consists of a glass plate that is carefully levelled and attached to the table. It can be expanded in the future to fit larger prints and it is also possible to use heating elements to create a heated bed. *Figure 39* shows the way the printing bed is attached to the table. It was not possible to reach the location of the plate with clamps and the tape holds it in place securely.

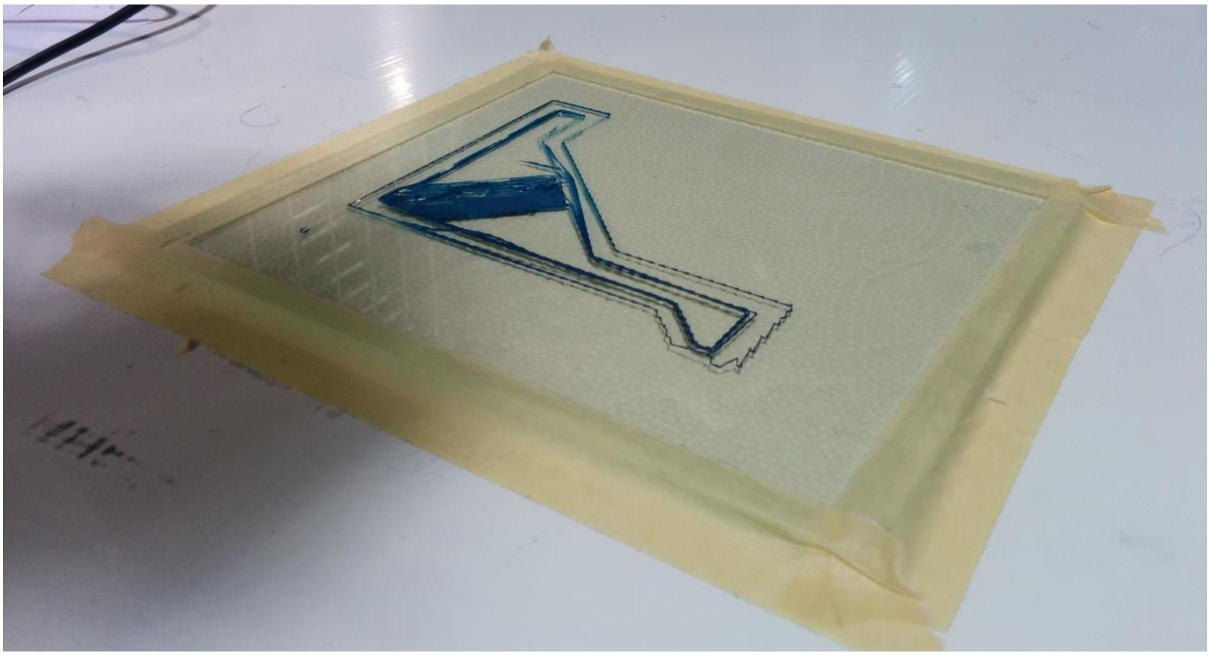


Figure 39. Printing bed

4.2.6 Additional Parts

Some additional parts were also necessary so that the whole 3D-printing tool assembles well. Two spacers were necessary to keep the axial fan at the correct distance from the extruder mounting block and the stepper motor. Four standoffs were made to fit between the 3D-printing tool and the mounting plate on the robotic arm and to create some space between the two. This space was necessary as shorter screws were not available and to alleviate the sharp bend that the filament had to make. The spacer and standoff can be seen in *Figure 40*.

A spacer was also designed to fit between the stepper motor and the mounting bracket. This spacer was necessary to fill the gap that was created by the standard-length screws. The spacer is shown in *Figure 41*.

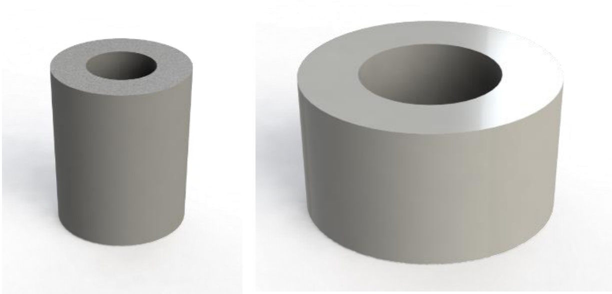


Figure 40. Fan spacer and standoff

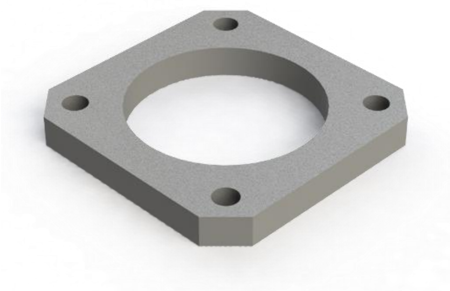


Figure 41. Stepper motor spacer

Figure 42. Reinforced housing and reinforcement shows a necessary addition to the housing. A plate is added to the housing to reinforce it and to reduce the stress on the glued seams. This reinforcement will be glued in place and is designed to have enough clearance with all the other parts. No other pictures include this reinforcement as it was a last-second addition.

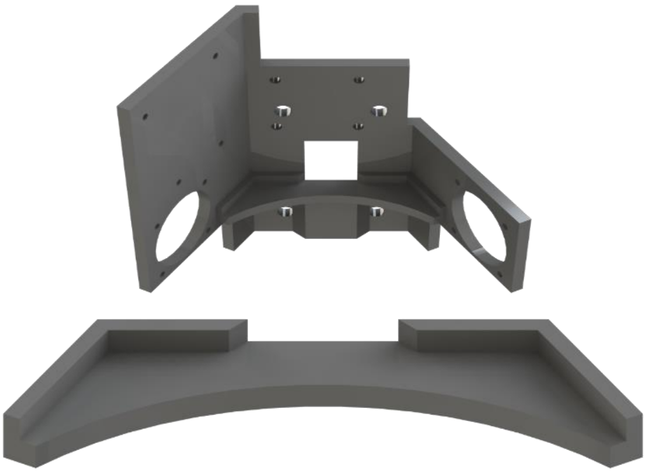


Figure 42. Reinforced housing and reinforcement

4.3 Complete 3D Printing Tool

Figure 43 and *Figure 44* show the assembled 3D-printing tool in a rendered image. A few parts were left out in these pictures. The large block on top is the mounting plate that is attached to the robotic arm. *Figure 45.* Actual 3D-printing tool shows the assembled tool mounted on the robotic arm.

Figure 43. Assembled tool

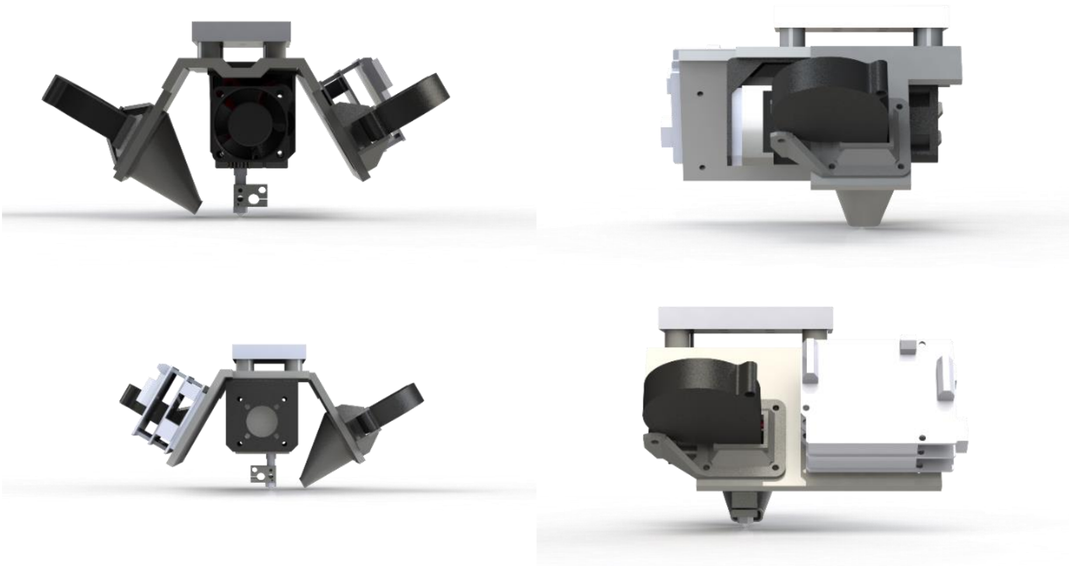


Figure 44. Different rendered views

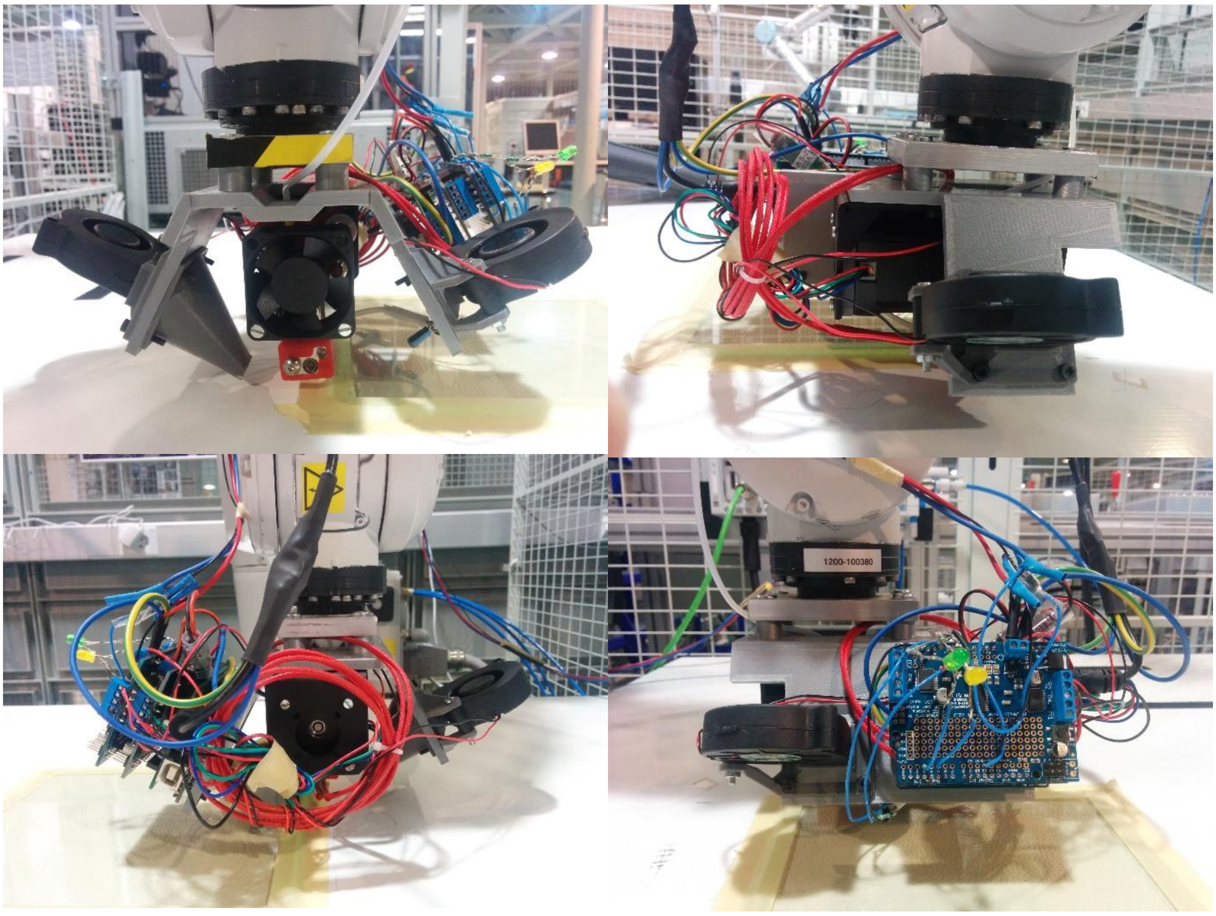


Figure 45. Actual 3D-printing tool

Chapter 5

Software Programming

In the 3D printer programming, there are two different parts well differenced that at the end must be connected by a communication module to exchange the data required. These two parts are the software for the different elements mounted in the tool, programmed using Arduino software, and the software developed for the robot in Rapid code, responsible for the G-code translation.

In the present chapter, the software developed is presented using flowcharts for a better understanding. Including at the end a simulation of the whole station in RobotStudio.

5.1 Software for the Tool. Arduino

The software programmed in Arduino includes the stepper motor, thermistor, heating element and the cooling system. The software created is time based, it means that at first, a time counter starts, and the different parts of the software systematically start when they are required.

The software is divided in three modules, one for each kind of hardware. First, the program starts with the stepper motor module. This module calculates the steps that must be done and the time between each step (extrusion speed), based on the data from the Gcode converter. In each execution, the current position is saved to compare with the next data from the Gcode. Once the calculation has been done, the software executes each step in the time required until the calculated number of steps is reached.

The second module is the temperature control module. When the module starts, the output from the thermistor is obtained and compared with the calibration table of the sensor, giving the correct temperature and making an interpolation if is necessary. The temperature obtained is the input of the PID regulator. The PID input is compared with the PID setpoint (desired temperature) and the heating element is turned on or off depending this comparison.

Finally, the third module is in charge of the fans. If the current speed is different from the needed speed, it will be updated. All the modules are shown in the flowcharts below.

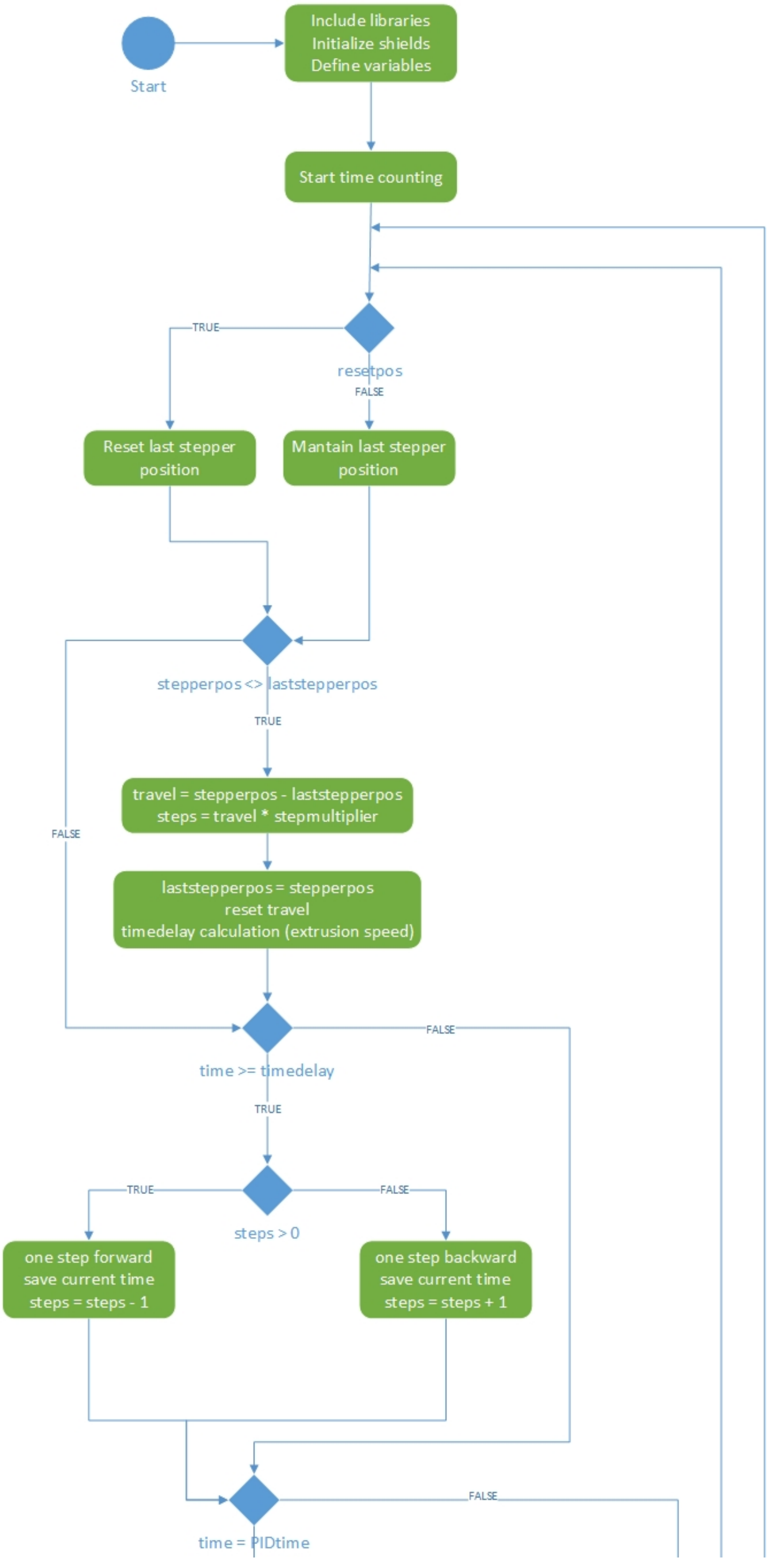


Figure 46. Arduino flowchart module 1

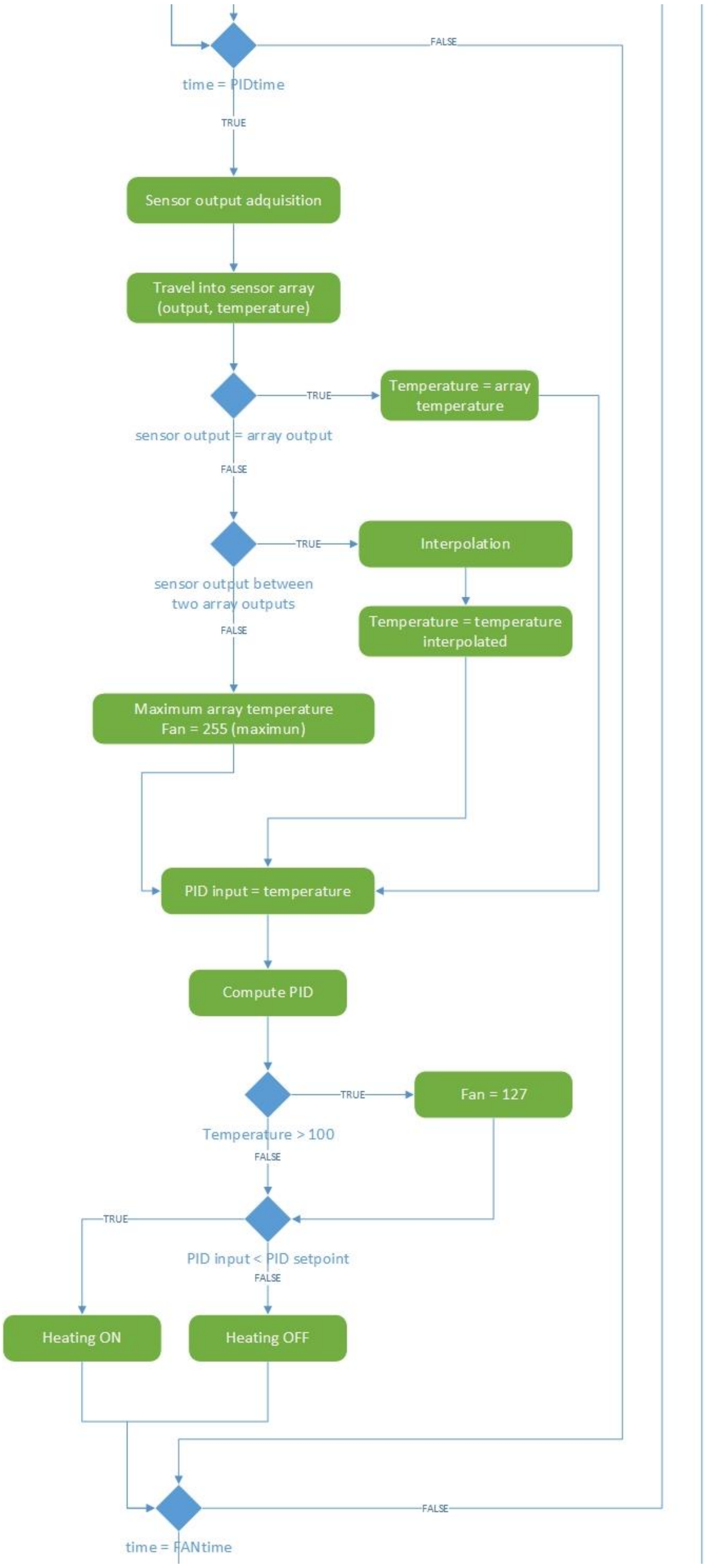


Figure 47. Arduino Flowchart module 2

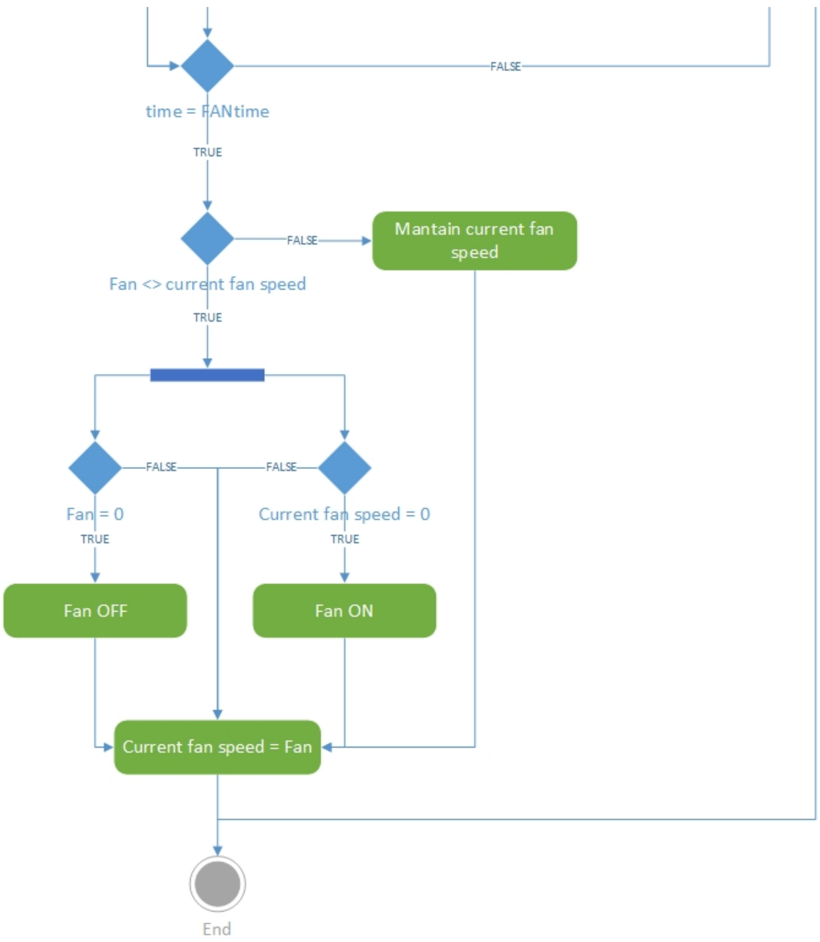


Figure 48. Arduino Flowchart module 3

5.2 Robotics Software. Rapid Code

For the robot programming, there was a Pack and Go file created that included a virtual station and the corresponding code for RobotStudio. The code included the basics for reading a certain G-code file and searching for lines that contains a G1 command. The software has been expanded to be able to read more commands that are useful for the robot. The G0 command is added as this command contains the travel movements and those are essential to making prints the same way as a 3D-printer. In *Table 4* all the commands used in the software are shown.

Table 4. G-code commands used in the software

G-code Command	*Command Values*	*Description*
G0		*Travel Movement, it moves the*

		printer to a certain position without printing. *G0 X45 Y18 Z0.3*
	X	The X coordinate of the Travel Movement
	Y	The Y coordinate of the Travel Movement
	Z	The Z coordinate of the Travel Movement
G1		*Linear Movement, it moves the printer to a certain position in a straight line*
	X	The X coordinate of the Linear Movement
	Y	The Y coordinate of the Linear Movement
	Z	The Z coordinate of the Linear Movement
	F	The F value represents the speed at which the printer moves
	E	The E value represents the extrusion in mm/min. The extruder's stepper motor will rotate.
G28		*Perform Homing Routine. It will move to a certain position before printing and after it finished printing.*
M109		*Turns on/off the heating element and waits until the heating is done. It has two parameters but in this project, they are not used.*
M104		*Turns on/off the heating element and continues to the next command.*

The commands G28, M109, M104 normally have parameters that are used by the 3D-printer. However, in this project these parameters are not used due to there being only a one-way communication. This will be explained in *5.3 Communication Arduino – Robot*. The parameters would hold which extruder should turn on in case of a dual-extruder, and the specified temperature.

The provided software is shown below in *Figure 49*.

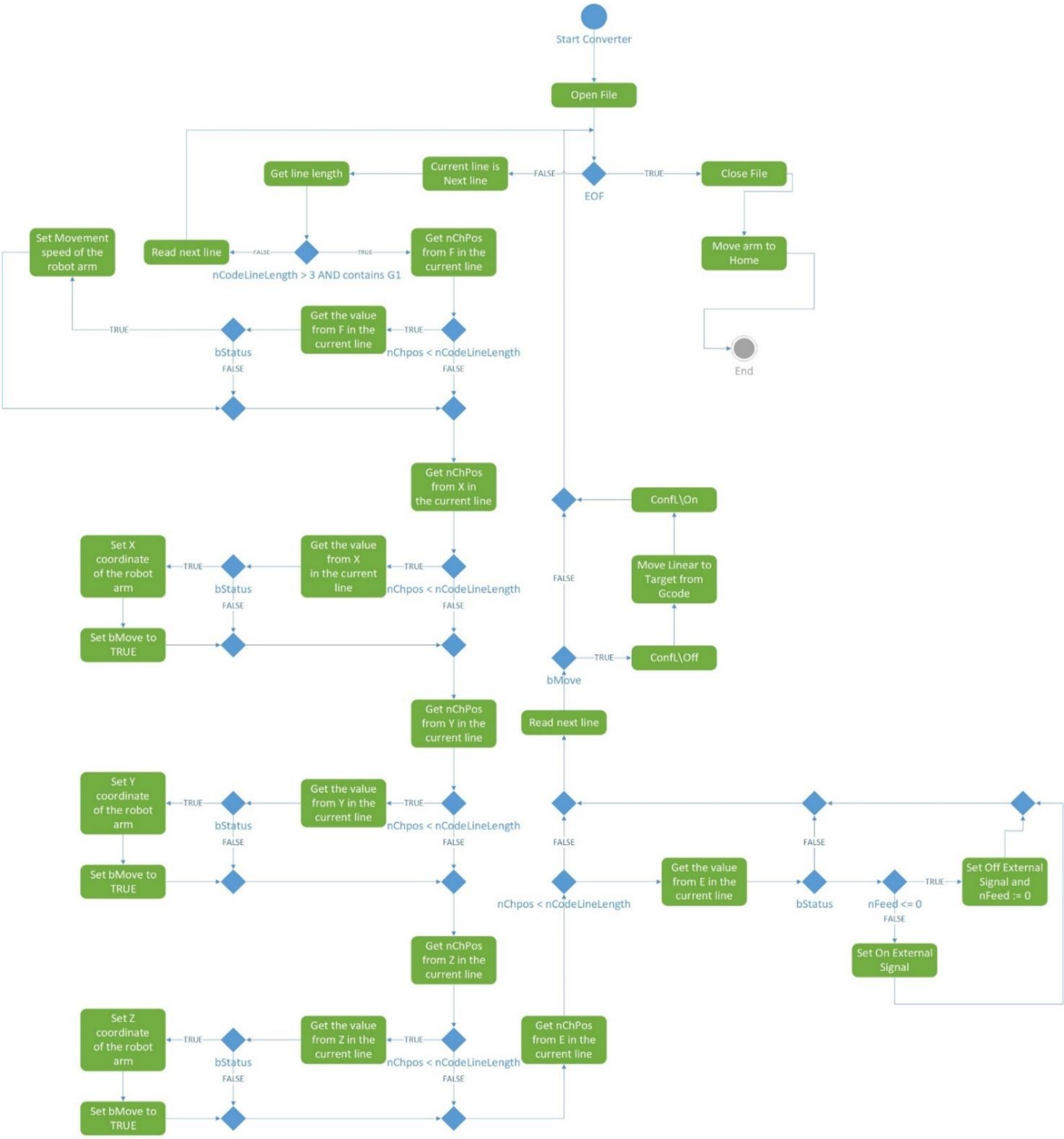


Figure 49. Flow chart of provided robot software

This code needed to be extended since it would keep extruding and the travel movements were not included so the original path would not be followed. In the provided code, the robot is moved to the home position after it closed the file. It did not use the G28 commands that are found in the G-code file. This would cause problems in the beginning of the print as it would start from the last position of the previous printing and this could cause a “position out of reach” error. For this reason, the G28 command is included in the converter, making the software more robust and more usable for future extensions.

Besides including additional commands to the program a user interface (UI) is also developed. This UI prints out all the G-code files that are located in the G-code folder on the robot and enables the operator to choose which one to print. This creates a more user-friendly program. In *Figure 50* a global diagram of the software for the robot is shown.

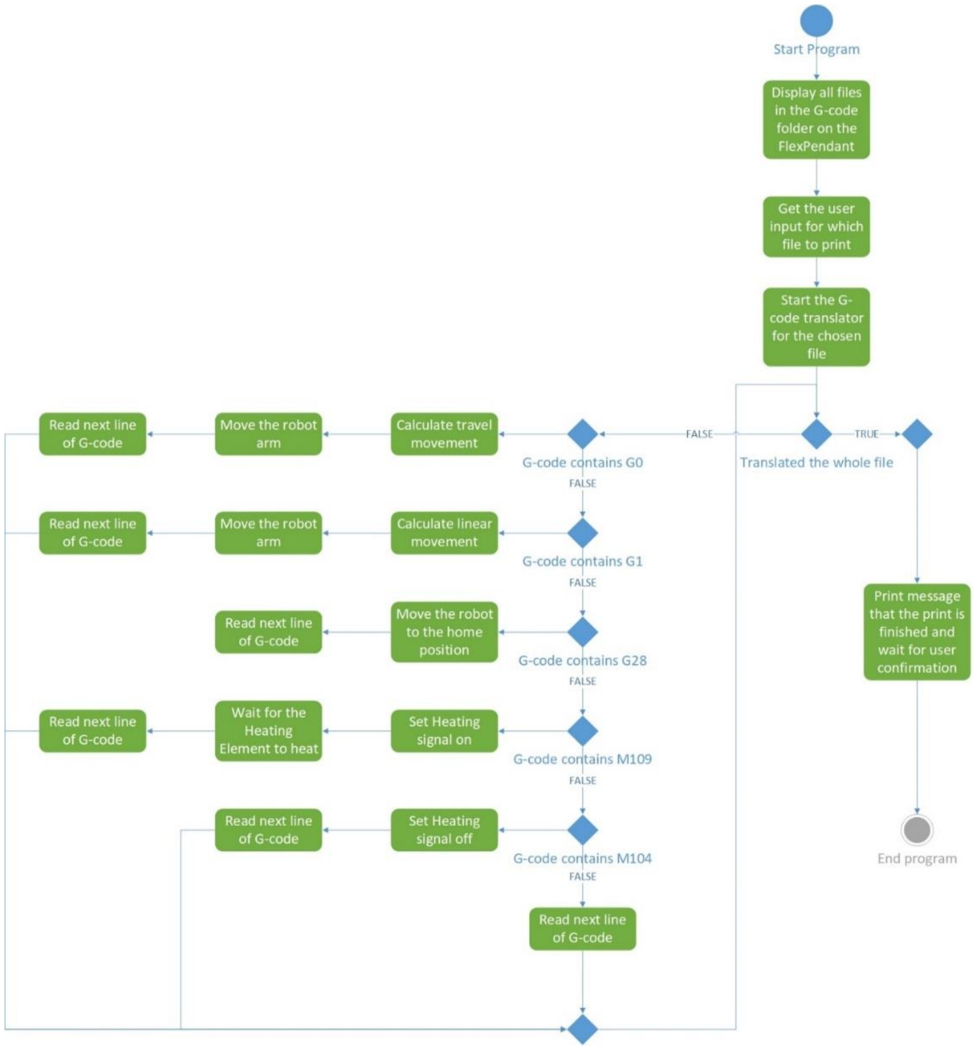


Figure 50. General flow chart Robot Program

The algorithm for G1 and G0 are more complex than the others. They are shown in more detail in *Figure 51* and *Figure 52*. Also, in *Table 5* the function of each variable can be seen.

Table 5. General flow chart robot program variables

Variable name	*Description*
nCodeLineLength	This holds the size of the current string in a number
nChPos	This holds the position of the letter that is searched for.
nSpeed	A variable that stores the temporary speed value that is found after the F in G-code
nX	A variable that stores the temporary X value that is found after the X in G-code
nY	A variable that stores the temporary Y value that is found after the X in G-code
nZ	A variable that stores the temporary Z value that is found after the X in G-code
bStatus	Contains the boolean that is returned from the conversion function. It indicates if the value is usable or not.
bMove	Contains the boolean that indicates if the robot arm should move. Because not all G1 commands are for the movement. (To move the extruder only)
nozzleUp	Contains the boolean that indicates if the robot should move with MoveL or MoveJ because if the Z value changes too much it will give an error that a certain coordinate is outside reach.

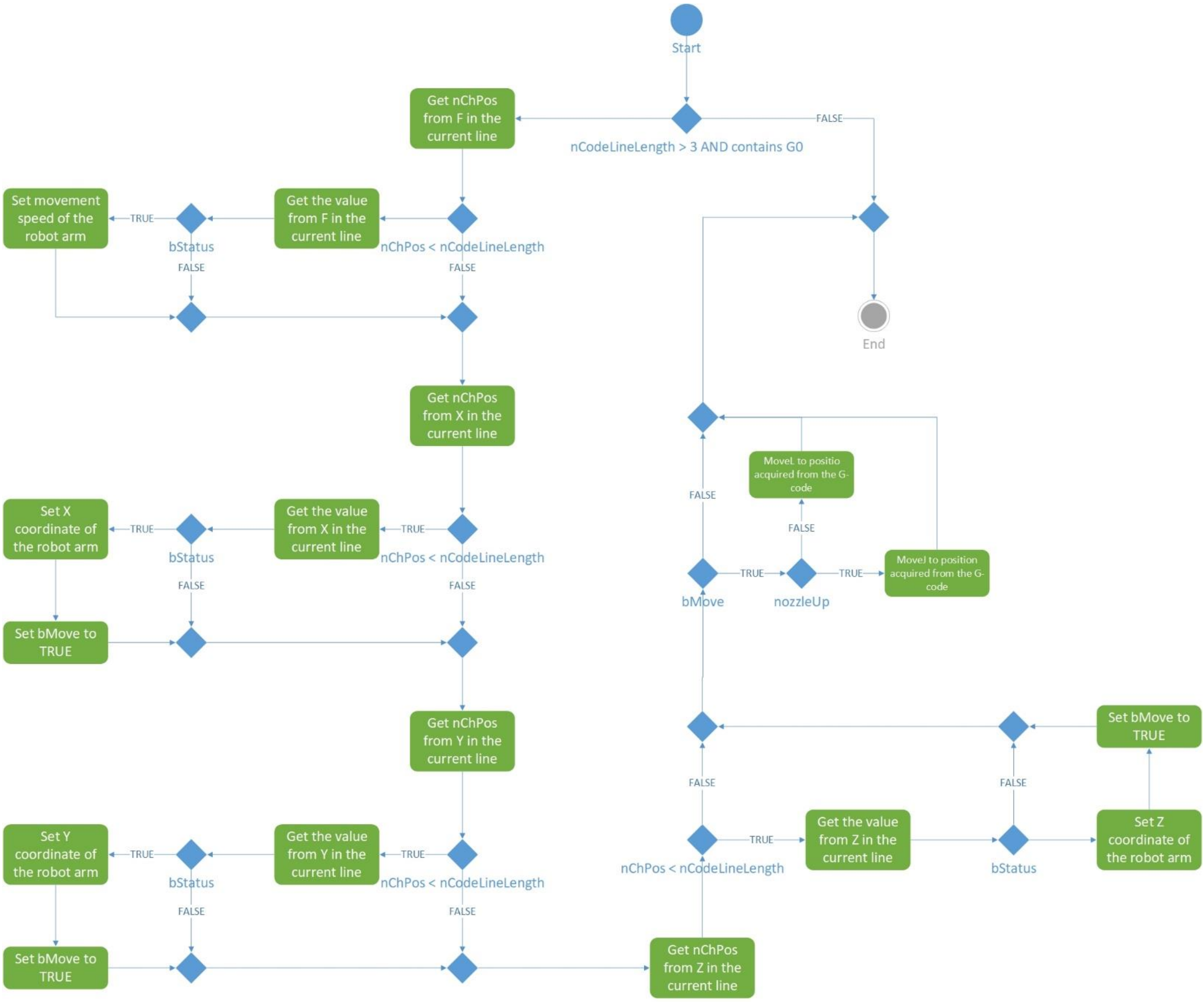


Figure 51. Flow chart of the G0 command

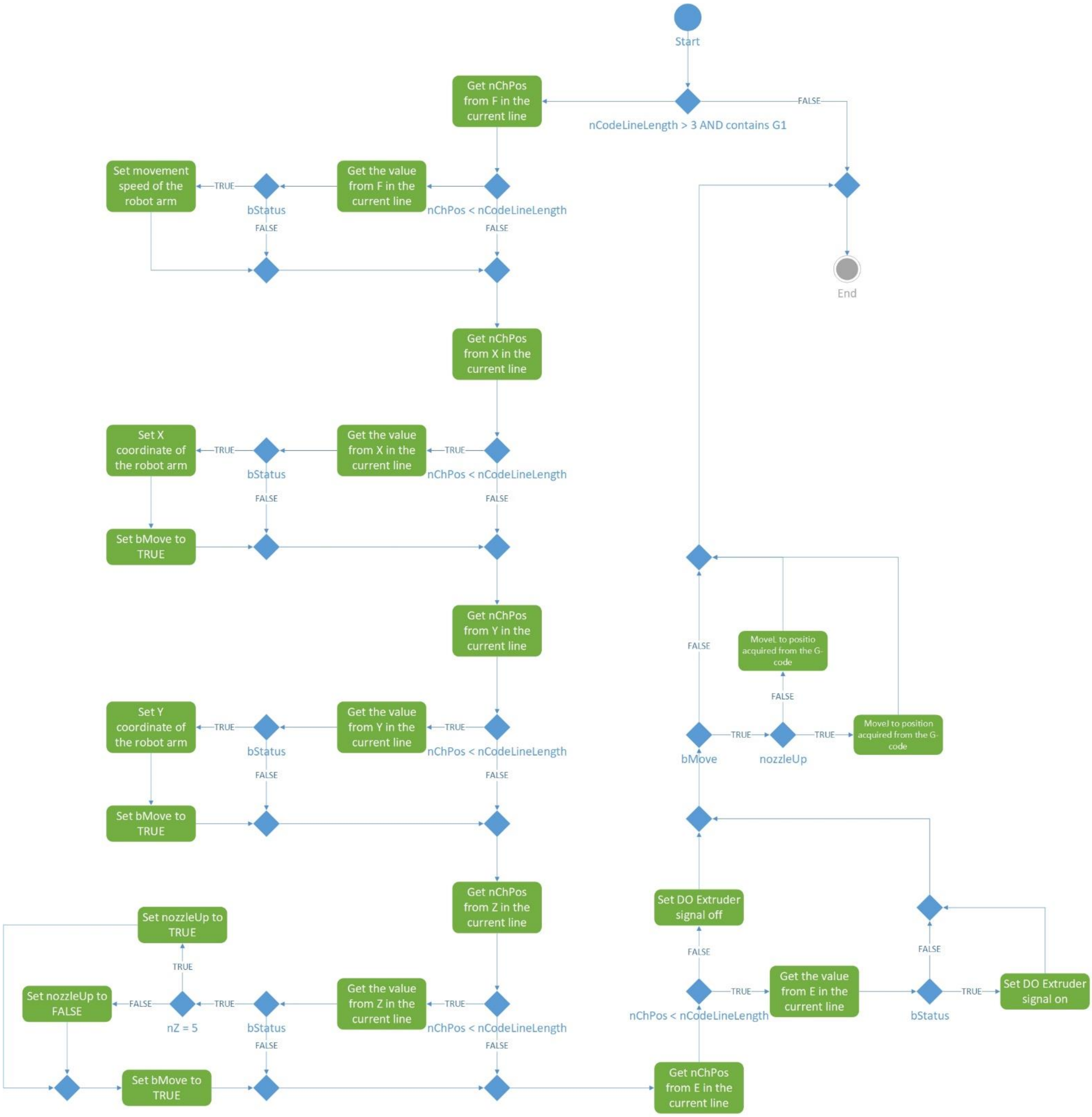


Figure 52. Flow chart of the G1 command

5.3 Communication Arduino – Robot

The programs for the Arduino and the G-code to Rapid code converter have been written based on the assumption that two-way communication between the Arduino and the robotic arm was possible. In practice however, it was not possible to make this two-way communication work because of several factors:

1. ABB did not respond to questions about how the commands for serial communication work or about the way the serial interface would be connected.
2. The ABB manuals only stated that serial communication could be used but had no explanation as to how it should be used / connected.

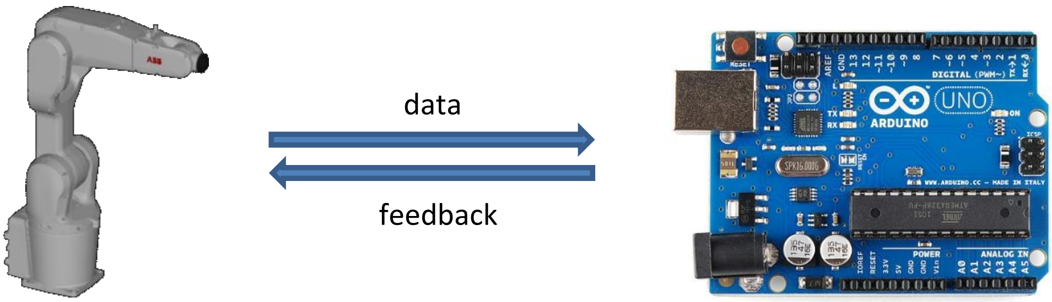


Figure 53. Ideal (serial) communication

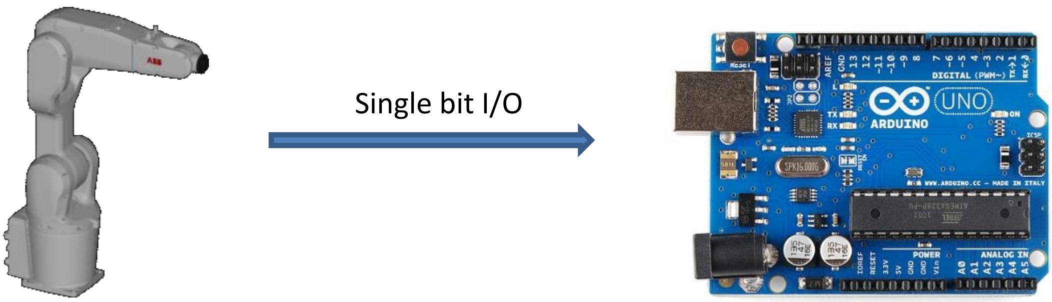


Figure 54. Minimal communication

Serial communication is preferred because it would enable the use of feedback as can be seen in *Figure 53*. This feedback would be used to send a signal to the robotic arm to tell it when the heating element is up to temperature or when there is a failure in one of the shields. It will also enable changing printing speeds (for infill), changing temperatures, changing layer height, changing fan speeds and keeping track of the extruder position.

Currently, single bit I/O is used. This means that the robotic arm only sends single bits to the Arduino. There is no feedback for this system. This can be seen in *Figure 54.*

Minimal communication**.** Two data lines are used. One for enabling/disabling the heating element and one for the stepper motor. The Arduino reads the inputs (should the heater / stepper be on?) and then uses this as a master switch for enabling these functions. The program still controls the heater by means of a PID-controller so that it does not overheat but the target temperature is hardcoded at 205°C for PLA. Feedback for when the desired temperature is reached is currently done by means of a LED. This means that the operator needs to manually allow the program to continue when the LED indicates that the desired temperature has been reached. The speed for the stepper motor is also hardcoded in the program. This means that every printing operation must be done at the same speed. The extruder speed is currently set at 40 mm/s.

5.4 Slicer Configuration

Due to the type of communication and the printing bed used, it is essential to set a standard slicer profile that makes it possible to work with the 3D printer. This slicer profile generates the G-code where all the printing characteristics (shown in *3.4 Slicers*) are included. The main two aspects considered to make this profile are that all the printing movements must be at the same speed and there is no heating for the printing bed.

The profile chosen is shown below, which has been obtained through the test developed in *6.3 Slicer profile - Printing Bed*.

Figure 55 shows the speed fixed at 40 mm/s for all movements and the layer height at 0,4mm.

Figure 56 shows the thickness in the walls of the figure and the percentage of infill, the characteristics of the support (it needs to be different for different pieces), the characteristics of the first line, made to purge the material before starting the printing (skirt) and the characteristics of the raft, made like the base of the piece to support it if is necessary.

Figure 57 shows the parameters for the retraction and multi extruder settings, which are not necessary in this project, and the cooling settings.

Figure 58 shows the characteristics of the filament, the nozzle and printing bed temperature and the cooling settings. Is important to set minimum layer time at 0 to avoid changes in the movement speed.

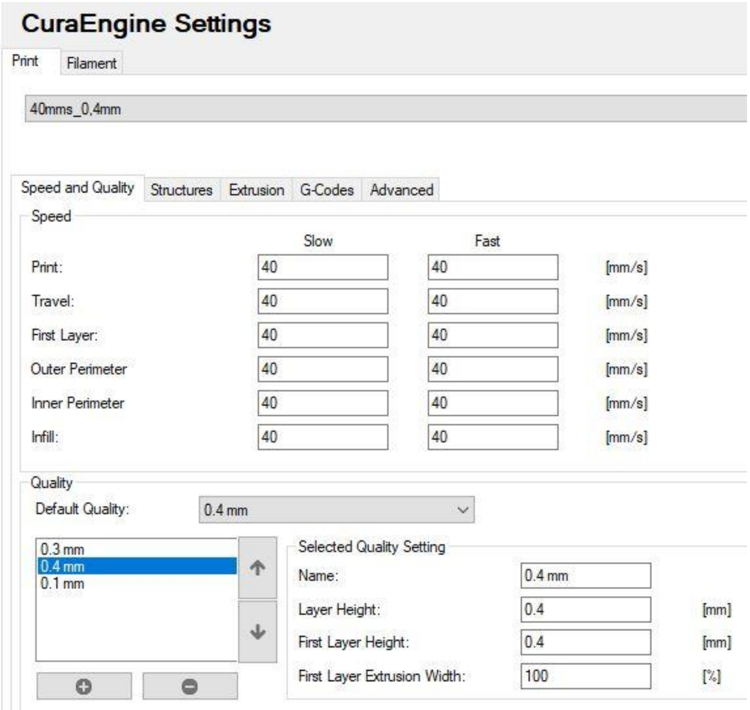


Figure 55. Slicer profile – Speed and Quality

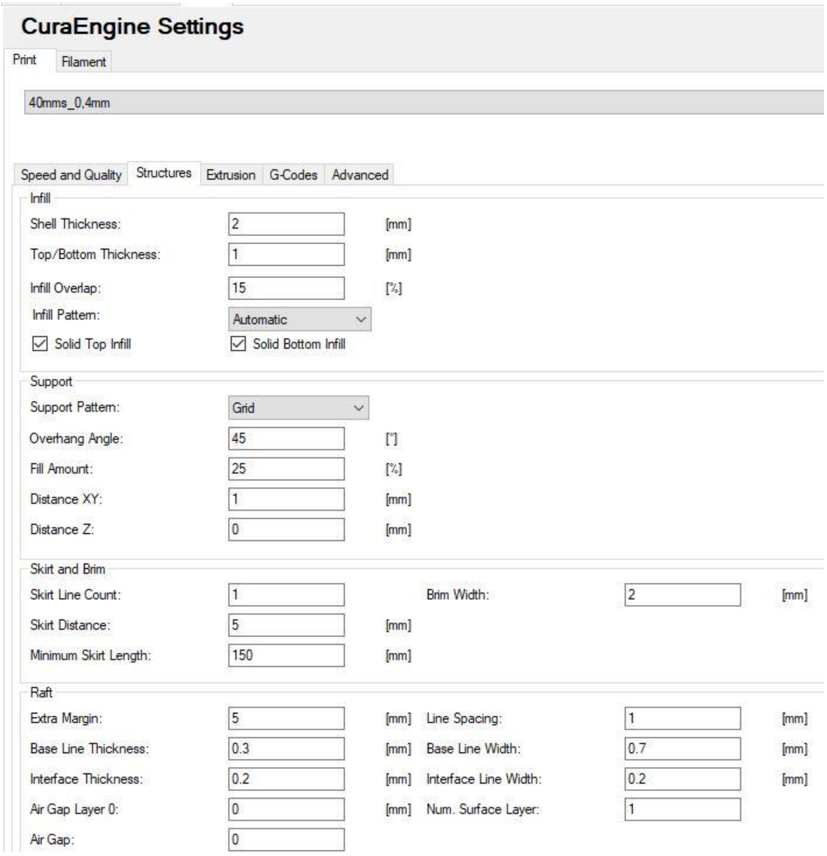


Figure 56. Slicer profile – Structures

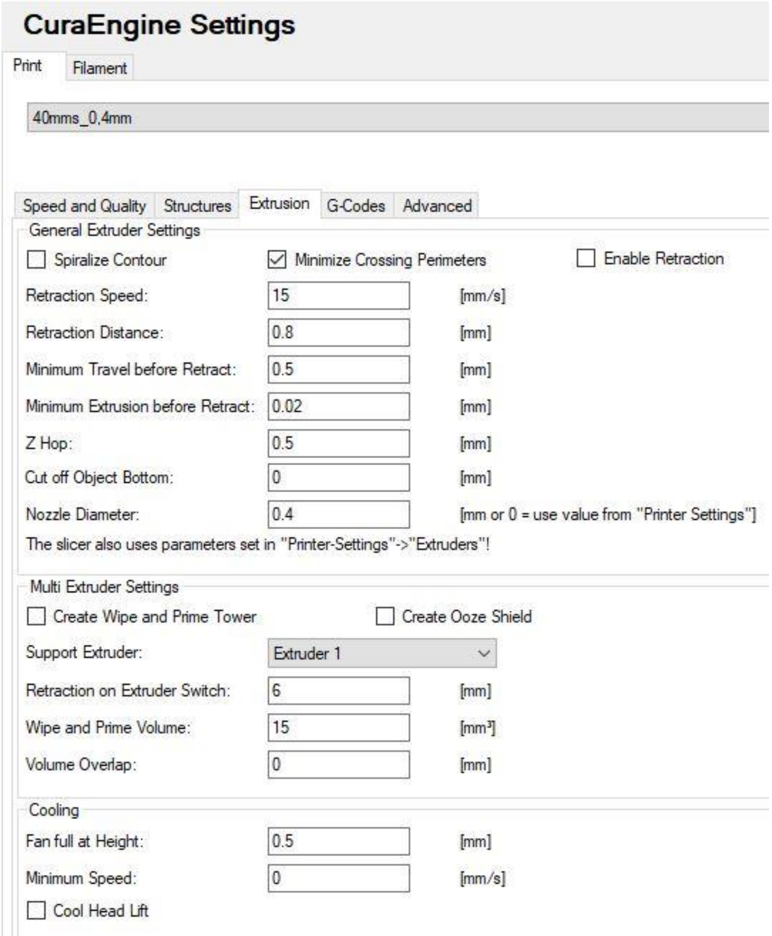


Figure 57. Slicer profile - Extrusion

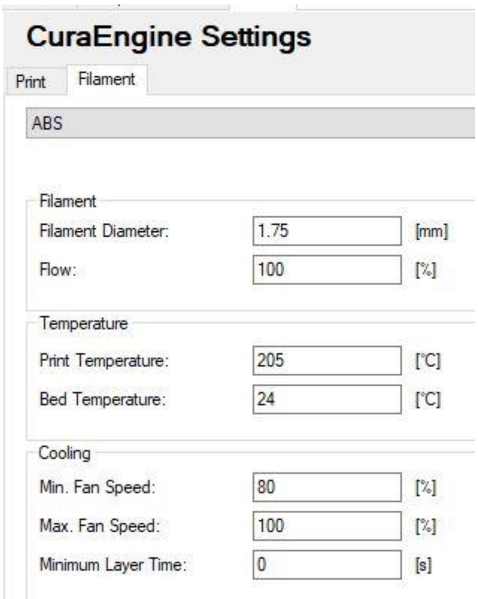


Figure 58. Slicer profile – Filament

5.5 Robot Studio Simulation

RobotStudio has a simulation feature that allows the user to simulate the developed robot program on a virtual robot before uploading the software to the physical robot. This feature is powerful since the user does not need a physical robot to develop the software and it speeds up the progress of developing. The most important benefit is that if the software contains faults, the robot will not be damaged.

During this project, the simulation feature is used to test the conversion from G-code to robot movements. A feature that the user can use during the simulation is tracking the path of the tool that is currently used. The feature proved to be useful during this project due to enabling the programmer to see the virtual printed layers in the simulation view. In *Figure 59* the path followed is shown with the white traces. Besides testing if the conversion worked correctly. It is also possible to test the user interface.

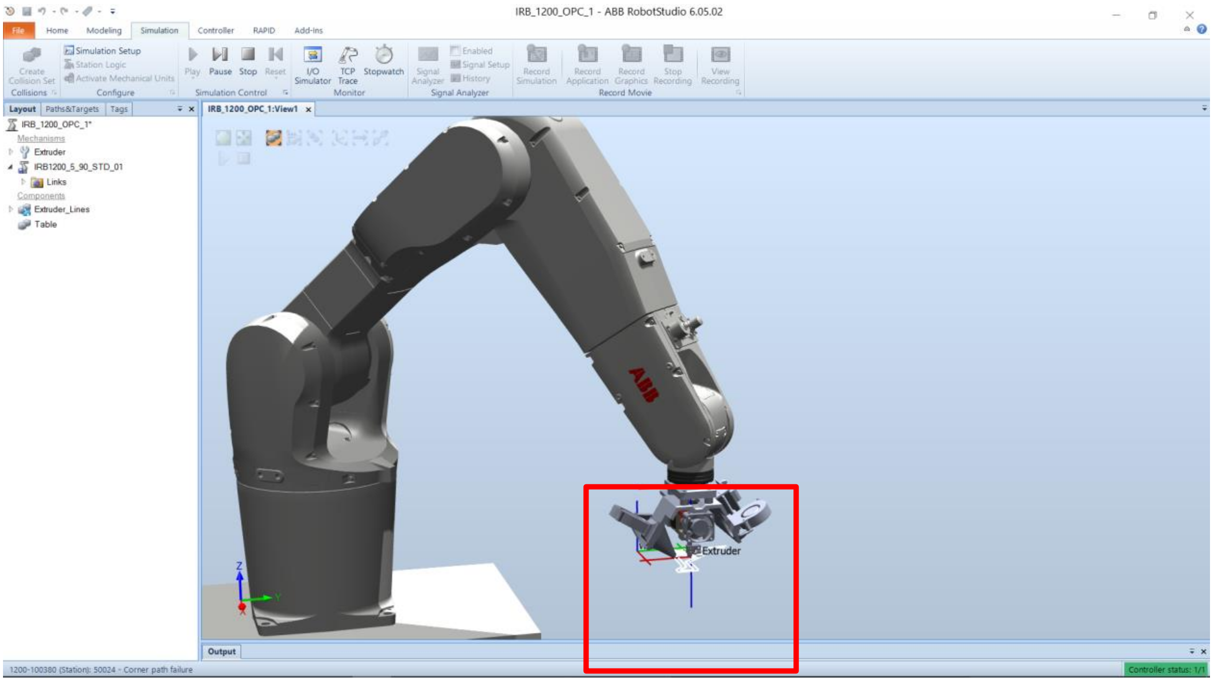


Figure 59. Simulation of the robot software

Chapter 6

Testing and Results

In this project, there are several parts produced and to make sure that in the end the parts work as they are supposed to, they will be tested. Testing the parts as soon as they are finished prevents that unforeseen problems occur during or after assembly of all the parts. In this chapter, the parts that are tested will be discussed and the results of the tests are displayed.

6.1 Stepper Motor Driver

The stepper motor driver allows the stepper motor operation. In his code, the next variables have been used:

```
// variables for stepper control
int feed; // horizontal displacement speed
float stepperpos; // actual stepper position
bool resetpos; // from the comunication module
float laststepperpos; // saves the previous stepper position
float stepmultiplier = 5.9; // tested value
int step2multiplier = 590; // stepmultiplier*100 for faster calculations
int steps;
float travel;
long previousmillis = 0;
long timedelay;
int LH = 2; // layer height in mm*10
int NW = 4; // nozzle width in mm*10
long FR = 875L; // filament radius in microns
int pi = 31416; // pi *10000
int extruderpin = 0;
```

Figure 60. Stepper motor driver variables

The target of this test is to extrude the correct amount of filament and doing it with the correct speed in each case. The G-code provides the length of filament that must be extruded in mm. This length needs to be translated to steps. For this reason, it is necessary to use the step-multiplier.

The step-multiplier is a constant value that multiplied by the length of filament needed in mm is equal to the number of steps required for the stepper motor. This value was fixed at 5,9 that means 1mm is equivalent to 5,9 steps.

The test to determine the step-multiplier is based on trial and error, changing the value until 1mm was obtained. Every time that the step-multiplier value was changed, the filament extruded was measured until the length was exactly 1mm.

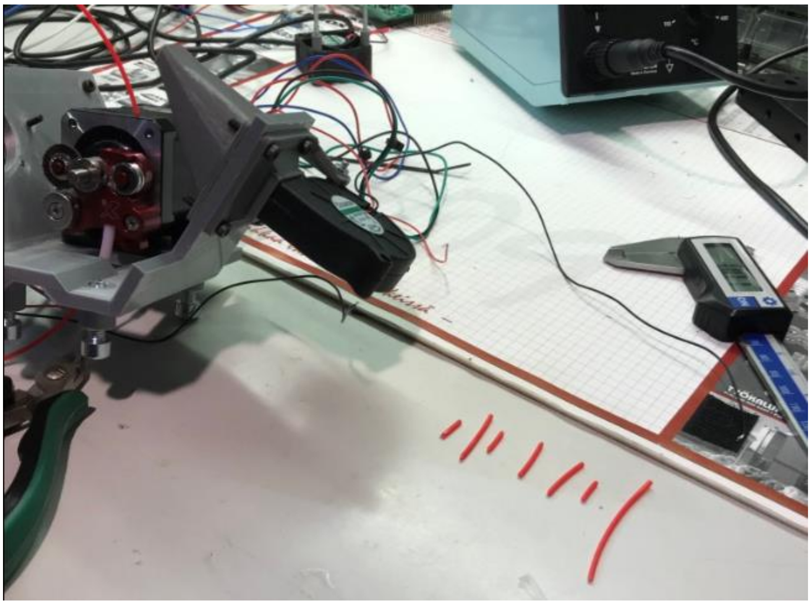


Figure 61. Step-multiplier test

Once the step-multiplier is obtained, the second parameter to determine is the extrusion speed in $steps/s$. This speed is calculated applying the equality between the volume of the filament that get out of the extruder and the volume of the layer extruded with this filament, as well as the horizontal displacement speed of the nozzle (feed):

$$V_F = \pi \cdot {F_r}^2 \cdot F_l$$

$$V_L = L_l \cdot L_h \cdot N_w$$

Relating these two volumes:

$$td\left[\frac{s}{mm}\right] = \frac{{F_r}^2[mm^2] \cdot \pi}{feed\left[\frac{mm}{s}\right] \cdot L_h[mm] \cdot N_w[mm]}$$

Lastly, applying the step-multiplier:

$$td\left[\frac{s}{step}\right] = td\left[\frac{s}{mm}\right] \cdot stepmultiplier\left[\frac{mm}{steps}\right]$$

Where:

$V_F = Filament\ volume$

$F_r = Filament\ radius$

$F_l = Filament\ length$

$V_L = Layer\ volume$

$L_l = Layer\ length$

$L_h = Layer\ heigth$

$N_w = Nozzle\ width = Layer\ width$

$td = Time\ delay = Seconds\ between\ each\ step$

$feed = {}^{L_l}/_{S} = Horizontal\ displacement\ speed\ of\ the\ nozzle$

The parameter "time delay" obtained allows the stepper motor to make each step in the time that is required.

6.2 Temperature control

The temperature control software allows measuring the temperature in each instant and heating the nozzle through PID control when this is required. The next variables have been used in the code:

```
//variables for temperature control
int sensvalue;  // output from the sensor
int temp;  //real temperature
int i;  //variables to travel throght the array
int x1;
int x2;
int y1;
int y2;
PID tempPID(&input, &output, &setpoint, Kp, Ki, Kd, DIRECT); //PID function
int PIDtime = 200;  //PID control variables
double input, output;
double setpoint = 20500;  //205°C
double Kp = 0.10, Ki = 0.001, Kd = 0;  //PID constants
int analogPin = 2;
int heaterpin = 1;
int ledpin = 3;
```

Figure 62. Temperature control variables

Additionally, an array variable has been used to store the values that correspond with certain temperatures. This table comes indirectly from the data sheet of the thermistor. The original table shows the resistance at certain temperatures. These resistances are then used to calculate the output voltage of a voltage divider and finally transformed into the corresponding digital values for those voltages.

The first test consisted of measuring the ambiance temperature and the small changes that the sensor output showed when it was warmed with the hands. Once the sensor showed the correct values was inserted in the heated block to carry out the heating element and PID control test.

The heating is regulated by PID control. A PID controller is a control loop feedback mechanism widely used in industrial control systems and a variety of other applications requiring continuously modulated control. A PID controller continuously calculates an error value as the difference between a desired setpoint and a measured process variable and applies a correction based on proportional, integral, and derivative terms.

The obvious method is proportional control: the motor current is set in proportion to the existing error. An integral term increases action in relation not only to the error but also the time for which it has persisted. At last, a derivative term does not consider the error (it cannot bring it to zero, a pure D controller cannot bring the system to its setpoint), but the rate of change of error, trying to bring this rate to zero. It aims at flattening the error trajectory into a horizontal line. (Araki)

The heating element and PID control test consisted of heating the block reaching progressively higher temperatures to prevent damaging of the system. This was done until the target temperature required (205°C for PLA) was reached and while testing different values for each constant (Kp, Ki and Kd).

Finally, observing the different behaviours, a PI control was implemented with Kp = 0,1 and Ki = 0,001 that allows the system to reach the desired temperature using approximately 2 amperes.

Once the target temperature is reached the PID controller keeps working to maintain this temperature in the nozzle since the cooling system is working to avoid damage in other parts and would cool down the nozzle.

6.3 Slicer profile - Printing Bed

The printing bed used in the station is a glass printing bed without heating. This last aspect can cause adhesion problems of the deposited material. For this reason, is important to find a slicer profile for which the printing bed has a good behaviour, considering the limitations generated by the communication system as well.

To find out the optimal profile, the printing bed has been tested with different settings in the Mini Factory 3D printer, which use the same printing bed as the one used in the project, while always keeping the heating bed turned off.

The test has been focused in the three main settings that could affect the adhesion of the layer in the printing bed: speed, nozzle temperature and layer height. *Table 6* shows the combinations tested.

Table 6. Slicer profiles test

Shape	*Speed (mm/s)*	*Nozzle Temperature (ºC)*	*Layer height (mm)*	*Result*
Simple	20	220	0,2	OK
Simple	20	205	0,2	OK
Simple	20	220	0,3	OK
Simple	40	220	0,2	OK
Simple	40	205	0,2	OK
Simple	40	220	0,3	OK
Simple	60	220	0,2	OK
Simple	60	205	0,2	OK
Simple	60	220	0,3	OK
Simple	80	205	0,2	OK
Simple	120	205	0,2	OK
Simple	150	205	0,2	OK
Complex	150	205	0,2	OK

As the table show, all the profiles tested worked correctly and without adhesion problems. Concluding that the profile selected can oscillate from 20 mm/s to 150 mm/s for the movements speed, from 205ºC to 220ºC for nozzle temperature and 0,2mm or 0,3mm for the layer height. The pieces made with the different test are shown in *Figure 63*.

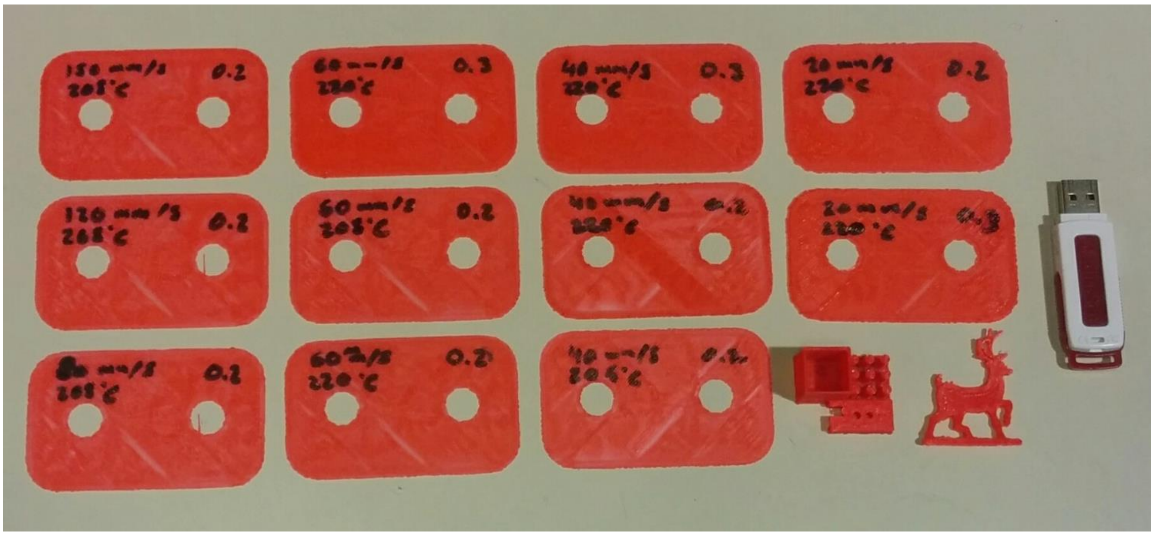


Figure 63. Test pieces

Is necessary to point out that, at the beginning of the test, no result was satisfactory due to the Z axis calibration of the 3D printer. A perfect Z axis calibration is needed to avoid adhesion problems like the one shown in *Figure 64*.

Figure 64. Adhesion problem

6.4 Guidance System

The requirements for the guidance system are holding all the cables required (power cable, communication cable and Bowden tube) without losing any of them or creating tension on it.

The best way to test the system is with a real 3D printing. The system has been tested with all the created pieces, never giving any problems. Never losing cables or creating tension on it. However, the Bowden tube was removed to avoid feeding problems as the constriction in the tube that could be caused by the other cables and by the entry position to the extruder caused too much resistance. Finally, the filament is not held by the guidance system and it was attached to the robot fence, going directly to the extruder.

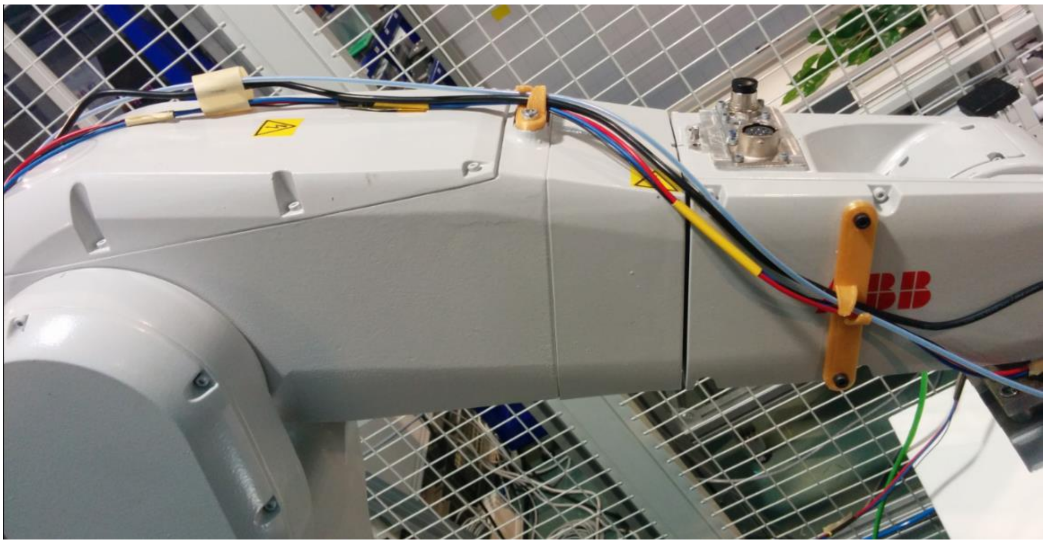


Figure 65. Guidance system test

6.5 3D Printing Results

Once all the parts were tested separately, the whole system was mounted on the station. The first step was extruding some filament without the robot moving, only activating the hardware of the tool. *Figure 66* shows the satisfactory result of the extrusion.

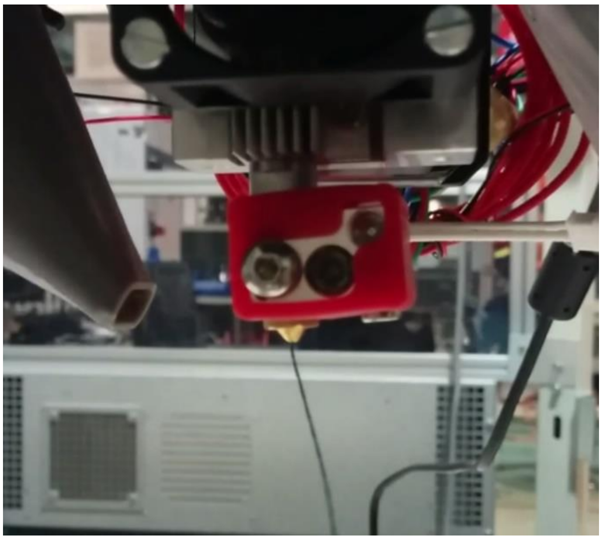


Figure 66. Extruding without movement

The second step of the final test consisted in 3D printing the first layer of a simple model. The main purpose was testing the movements and the behaviour of the printing bed in general, therefore in this step a strict calibration of the bed was not done. The result was a satisfactory behaviour of the robot in the movements, following the paths required and an expected bad adhesion of the layer on the printing bed due mainly to it not being level. *Figure 67* shows the first layer printed with the system.

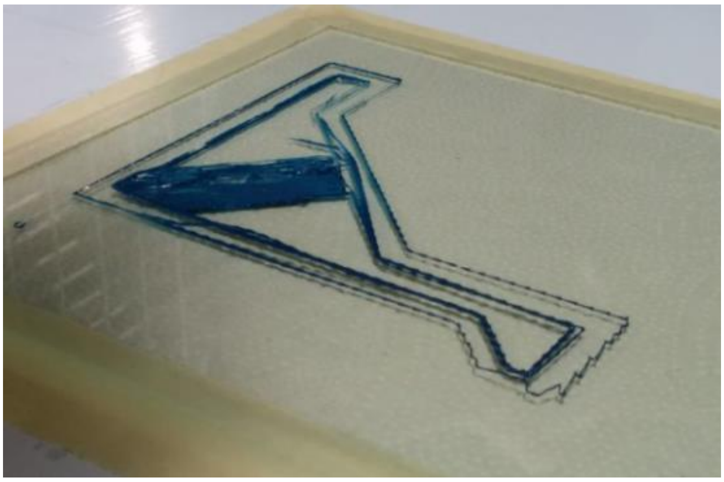


Figure 67. First layer printed

The next step was the 3D printing of a complete simple model without adhesion problems. First, the printing bed was calibrated, measuring with the robotic arm the Z axis offset in each corner and the centre and raising all the points to the height of the highest measured point. Also, a layer of glue was added to the printing bed and the layer height was increased to 0,4mm to improve the adhesion.

On the other hand, an extruding problem was detected when a nozzle blockade was simulated by blocking it off with a spatula. To overcome the problem the Bowden tube was removed to avoid feeding problems and the gear pressure of the stepper motor was increased.

During the testing with these improvements, problems in the robotic movements were detected. The robot stopped in some points, when the movements were too short, and the robot did not move in the Z axis. Finally, these issues were overcome by adding a delay time between each loop of the robotic software, so the robot has time to process these short movements. The problem with the Z axe was solved by improving the character Z searching code.

The first piece with the robotic arm was printed with 0,4mm layer height and to improve the quality, the same piece was tested with 0,2mm layer height. The first piece was not finished totally due to the lack of adhesion in the printing bed. The difference between them is shown in *Figure 68* and *Figure 69*.

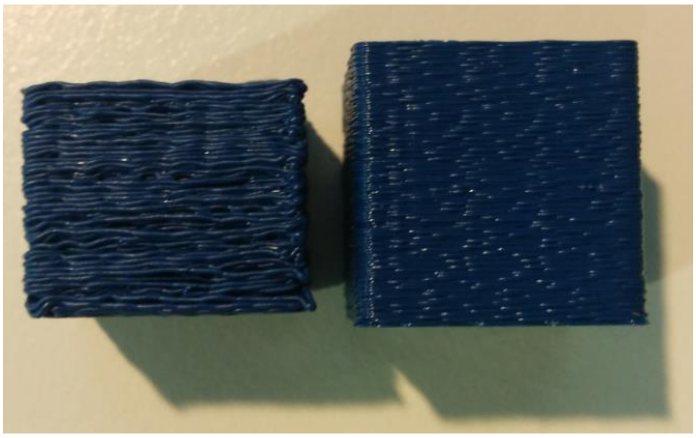


Figure 68. Lateral view of the firsts pieces printed – 0,4mm and 0,2mm

Figure 69. Upper view of the firsts pieces printed – 0,4mm and 0,2mm

As the pictures show the quality is an aspect to improve, due to, for instance, the stepper motor working step by step instead of working with smooth movement or due to the robotic movements.

The last step was printing a bigger and more complex piece. The piece created is shown in *Figure 70*.

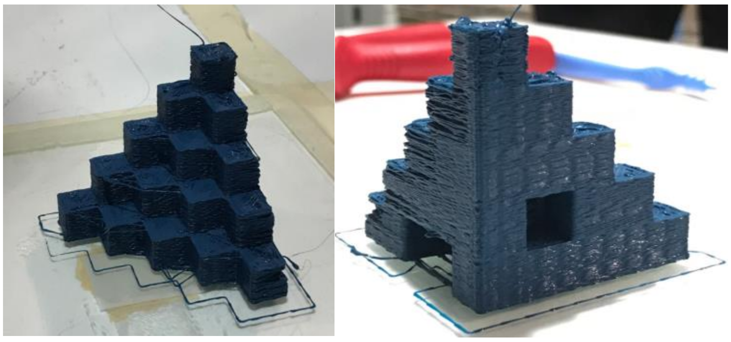


Figure 70. Bigger and more complex figure

Chapter 7

Conclusion

The developed project could be the start point for others related directly with it since this is the first time that a 3D printing tool is mounted directly on a robotic arm in Novia UAS. The EPS semester allows just to start and reach the basic functionality that this project can develop. For this reason, since the start, the project was thought in this direction.

The project fulfils the requirements set at the beginning. Firstly, a functional design, 3D printing and mounting of the tool has been achieved, doing possible the simulation of the tool in the different software like SolidWorks or RobotStudio. Then the software developed for the tool in Arduino and the robot in Rapid has accomplished the required features. Without forgetting about other characteristics developed like the guidance system or the printing bed and all the research needed to find out the best solutions.

Overall, a system with the basic characteristics of a 3D printer has been developed, but in an ideal environment that makes the continuous development of the system possible, both at the hardware level and at the software level.

The team has tested different parts of the 3D-printing system. Based on these tests the group made its conclusions. It contains conclusions about the different subsystems that are tested and one about the system as a whole. First every separate part is discussed and at the end based on the findings of the subsystems a final conclusion is made.

The printing bed was one of the most challenging parts in the project because in the beginning of the project it came clear that a heated bed was not the first solution. To design a heated bed that was large enough to cover the reach of the robot arm was outside our project scope and would cost so much that it did not fit in the project budget. The solution was a printing bed made out of glass with additional techniques to improve the adhesion. During the project, Purple glue was used for making the prints adhere to the printing bed. This solution made it possible to print on the glass bed without heating it. The material used was PLA because other materials would require a heated bed. A heated bed not only improves the adhesion but it also prevents the print from warping, which increases the quality of the print. So, a non-heated bed works up to a certain point. If the user wants better quality and to use different materials a heated bed is necessary.

To guide the filament from the spool to the extruder a guidance system was designed. The filament was not placed on the robot itself. It would restrain the movement of the robot and it would take up around 15% (a spool of 750 grams) of the maximum payload of the robot. This was not the best option, so the spool would be mounted near the robot. The guidance system was first designed with a Bowden tube that would be held tight with clips mounted on the robot arm. During the first tests, it turned out that the Bowden tube created too much friction on the filament and that the extruder was not able to pull it through the tube. Now there is a temporary solution without a Bowden tube. This system is mounted on a fence near the robot. Because it is mounted on the fence it is a temporary solution because this solution is not portable to different robots in different environments. Ideally the filament guidance would follow the same way as the cables. The communication cable and power cable are also guided to the extruder by the clips on the robot. The cables were hanging alongside of the robot, the guidance system was designed to prevent this but failed. The guidance system could be redesigned or additional parts could improve the current version. For instance, an extra mounting point on the robot arm would resolve the problem.

Extruding with the designed extruder proved to be working as supposed. The filament comes out regular and the fans cool down the filament and the tube between the heating element and gears. The extruder controller works correctly. It reacts to the input of the robot and is able to control the stepper motor and heating element. The PID controller used for the heating element could be improved because currently the time to reach the designated temperature is approximately 2 – 5 minutes. By fine tuning the PID controller the time to heat the heating element could be decreased. During this project, the communication between the robot and Arduino was limited. As a result, the speed of extruding was limited at exactly 40mm/s which increased the printing time. If there was an opportunity to communicate between the robot and Arduino with a protocol it would have solved the problem of a fixed extruding speed. Not only the extruding speed could be changed but also the speeds of the fan and the temperature of the heating element. During testing, it turned out that the design of the extruder was functional and it fulfilled the expectations. The only downside was that during testing the extruder broke down because the shroud of the fan kept hanging behind the print. This was not a case of bad design but failure of the RAPID program. And the space between the mounting and the housing of the extruder could be increased. During testing, it turned out that the tight space between the mounting and housing caused friction on the filament. And that caused the extruder sometimes not to grip the filament.

The G-code to RAPD converter was most of the time tested with simulations in RobotStudio. During tests with the robot arm it turned out that the converter was not working. The robot arm was not moving in the Z-direction but only moving in X and Y-direction. The problem was in the converter when it was trying to take the Z-value from the G-code file. The converter was looking for a space character. However, the Z-value was always located at the end of a line. At the end of each line there is a different character than a space character. Namely an end of line character ("\0D"). Because of this the converter was not able to correctly convert the value to a numeric value which caused the robot not moving in the Z-direction. This problem was not discovered during the simulation because the program was working fine when simulating. The virtual robot was moving in the Z-direction so they were only discovered later in the project. Besides the problem with the conversion the RAPID program was working as supposed. The User Interface could be improved to add more functionality to it. One useful feature would we a calibration menu for the printing bed.

During one of the tests the team tried to print a circular object. During the test, the robot arm was having difficulties to make the circular movements. This is understandable because the G-code consists only linear movements. The robot cannot move such close distances without hiccups. With other models, this behaviour was visible as well. The time that is was standing at the same place was significantly less than the object with curves in it.

At last, the team can conclude that 3D-printing with a robot arm is possible. The system that was created contains basic functionality. The system could be extended and improved upon.

Chapter 8

Discussion

The results of the different tests are promising and printing with a 3D-robotic arm is possible. However, this chapter will go over the different aspects of the project where the project team thinks it could be done better for the next time.

The planning could have been done better because we did not take into account the delivery times of the ordered parts. This caused delays and resulted in less time for testing the extruder and the whole system. In the first half of the semester the planning was poorly managed because we did not schedule time for reviewing the Midterm report which resulted in an incomplete and hastily written report. Next time the planning should be made more careful with the whole team. The delivery times should be checked as soon as possible.

For the next time, more care should be taken when designing parts that have to be 3D-printed. Some of the parts did not fit correctly or broke because the design was not made with enough care and because some forces were overlooked.

The robotic arm should be handled with more care and not when the operators are tired. The extruder was bent because manual movements were made in the wrong direction. This could have been prevented if only the control software was used to move the robotic arm.

Better designs for extruder housing could be created and tested before finalizing one design. The housing design works but there is little space near the mounting plate. this was not an expert decision and there is a little friction where the filament rubs against the mounting plate. This mistake could be prevented if suggestions of others were asked.

The printing bed works but it is not an efficient solution. Time has been wasted by the need of cleaning, putting glue on, and heating the bed with a heat-gun every time something needs to be printed. That time could have been used in creating some more products or creating a better rapid code program to test other parts that might not be possible with the current program. This could be prevented with good printing bed options and further research. Again, expert advice or asking for suggestions of others is recommended.

Chapter 9

Suggestions

The future development possibilities for this project are huge, this project can continue being developed in different stages.

At design level, the techniques that use metal like 3D printing material could develop a more resistant and consistent housing for the tool, make it less vulnerable to accidents that can occur with the robot, for example in case of the tool crashing into the printing bed.

The printing bed is one of the important parts of the station. In the present project, a glass printing bed has been implemented making printing with PLA plastic possible. To increase the printing material possibilities, a warmed printing bed would be necessary. This new printing bed would improve the adhesion and avoid the warping in the created models. It is a fundamental requirement to use other printing materials.

However, the most interesting improvements could be done at software level. First of all, the communication improvement between tool and robot is the most important of them. In the present project, a single bit communication has been implemented making basic communication possible. By implementing serial communication without delays, it would be possible to transfer all the data needed for full functionality: more automation and different printing speeds.

Other possible future improvement for this project is 3D printing with 3D positions instead of layer by layer. To make it possible, a full project creating a slicer capable of slicing in 3D, and not layer by layer, would be necessary. Combining these two projects and making standard support structures for the desired models, the advantages created by the robot could be used.

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Appendix A: Project Management

A.1 Strength-finder

1. Analyse and comment on the Talent Theme Profile of your team.

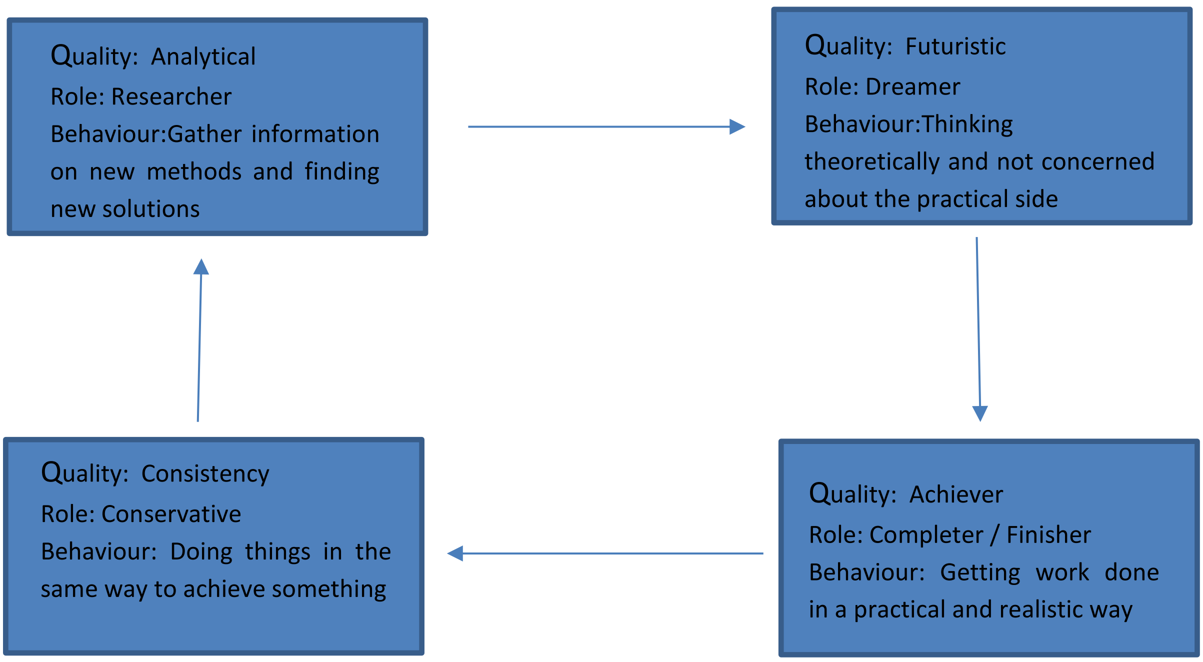
- We are a heavily strategic thinking team.
- We have no influencers.
- We have some executioners in our group.
- We have some relationship building qualities in our team like Developer, Harmony and Positivity.

2. What would be the one or two core strengths of your team?

- Input
- Achiever

3. Elaborate on this and come up with an Ofman Core Quadrant for the team as a whole.

We have already made two versions of the Ofman Core Quadrant this is our third version and every team member think this is the best one we have made. Also, we modified the Core Quadrant a bit. The reason for this is that with the extra information we have added there is a better understanding of our Core Quadrant.



Talent – Our core talent is analytical and a researcher has this talent and the most import thing for a researcher is gathering information and find new methods to solve problems and also finding new solutions for a certain problem.

Pitfall – The quality where we define our pitfall by is futuristic because if you do too much research and only think about the information and what the future could hold for you than you become a dreamer. A dreamer thinks about things in a theoretical way and is not concerned about the practical side of an idea or problem.

Challenge – Our challenge is to achieve things in a practical way. This is our challenge because our Pitfall is Futuristic. The role that belongs to this challenge is a finisher, someone who get things done. We think this is in balance because two of our members have the Achiever Talent in their Top-5.

Allergy – Our allergy is when people are stuck in their current methodology and are not willing to look for new methods. These people are afraid of widening their horizon. Because our team are very open-minded and are always searching for new opportunities we think it's not a good idea if we have to work with people that are doing things in the same way to achieve what they want.

4. Tell us how you are going to cherish and / or develop this team core strength even more.

We will search for new research methods and reflect on how we have done our research.

5. What is your team main challenge?

- Take care of the information we use and manage that we use only relevant information, especially for the team members with Input as Talent.

- Getting work done in a practical and realistic way, we have two members with Achievers, so they should take the lead in this challenge.

6. How are you going to deal with its pitfall and allergy?

- Being practical and realistic in our solution to solve a certain problem.

- We will have daily meetings and during these meetings we will reflect on our progress and if it's needed we will change our direction and way of working until we are able to work in a practical way.

- Dealing with problems in a positive way, and try to utilize our Talents for finding problems.

A.2 Belbin Roles

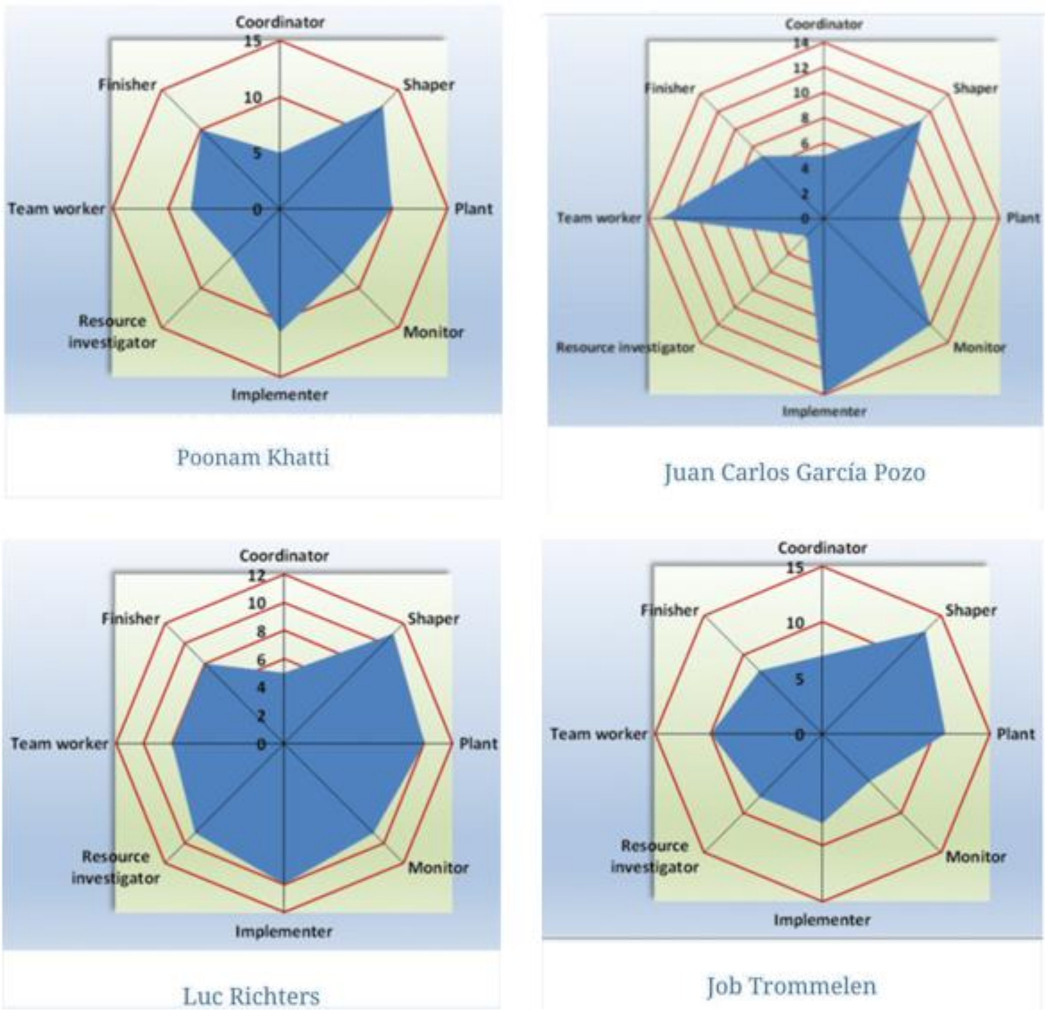


Figure 71. Belbin Roles results

There are very different Belbin roles in our group. All the team members have shaper in their results. A shaper provides the necessary drive to ensure that the team keeps moving and does not lose focus or momentum. The work better under pressure and are have courage to overcome obstacles.

The Implementer is quite strong in the group. These people are practical and turn ideas into actions. The practical work during the project should not be an obstacle because all the group members are able to do the practical work with ease.

The shortcoming roles in the group are Coordinator and Finisher. A coordinator makes sure that the team's objectives are reached and delegate the work that needs to be done. A finisher makes sure that the work is complete and without errors. This could be a risk at the end of the project because none of the members is capable of searching out the errors and polishing everything up.

A.3 Planning

The project has been divided in different phases, which are explained below:

Phase 1: Initial research and documentation

I. 3D Printing and robotic arm
II. Software: SolidWorks, Repetier, Slicers and RobotStudio
III. Required additional hardware for the tool and ordering

Phase 2: Project development

I. Designing and printing necessary parts
II. Assembling the extruder
III. Developing software for Arduino
IV. Adapting Translation G-Code to Rapid Software

Phase 3: Testing the 3D printer

I. Test and documentation of it
II. Improvements

Phase 4: Elaborating the report and presentation

I. Redaction of the report
II. Correction and making up
III. Preparing the presentation

Table 7. Task breakdown

PHASES	*EMPLOYED HOURS*
Initial research and documentation	450
Project development	720
Testing the 3D printer	375
Elaborating the report and presentation	375
TOTAL	**1920**

A.3.1 Gantt Diagram

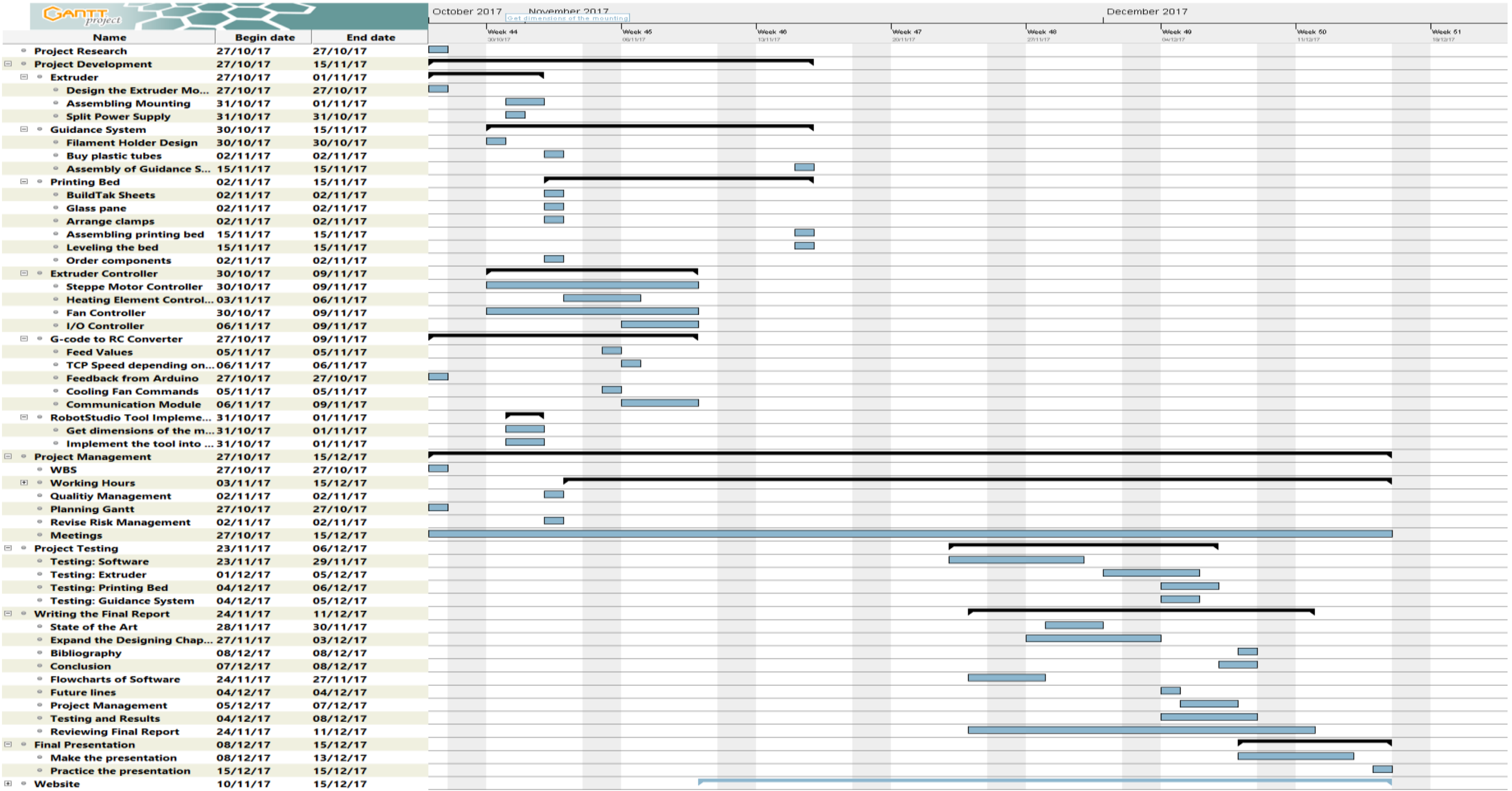


Figure 72. Gantt project diagram

A.4 Project Budget

Figure 73. Expected cost vs actual cost

A.5 Risk Management

During the project there are a lot of possible risks that can occur. Because the fact that risks occur during a project it is important to assess those risks before starting with the project. That is when Risk Management comes in. The goal of Risk Management is to determine risks that can occur during the project and estimate how these risks will affect the project. After the project knows which risks are able to show up an action-plan can be made. By doing this kind of management it is possible to spot early problems in the project and to anticipate on these problems before they become severe. Below is a list shown that is created during a brainstorm session about the possible risks during the first half of the project.

Outcome of the brainstorm session about possible risks:

- Stakeholders fail to support project
- Estimates are inadequate
- Conflicts between team members
- Project team misunderstand requirements
- Loss of information and/or damaged files
- Design fails peer review
- Training is inadequate
- Learning curves – delays
- Technology components aren't fit for purpose
- Unclear scope
- Under communication
- Sickness
- Bad scheduling
- Clashing programming
- Trips
- Lack of motivation
- Bad work distribution
- Lack of management control

With this list the project team can make a Risk Matrix shown in *Table 8*.

Table 8. Risk Assessment Matrix

		Severity			
		NEGLIGIBLE small/unimportant; not likely to have a major effect on the operation of the event	**MARGINAL** minimal importance; has an effect on the operation of event but will not affect the event outcome	**CRITICAL** serious/important; will affect the operation of the event in a negative way	**CATASTROPHIC** maximum importance; could result in disaster; WILL affect the operation of the event in a negative way
Probability	**LOW** This risk has rarely been a problem and never occurred at a college event of this nature			Project team misunderstand requirements Training is inadequate Lack of motivation	Loss of information and / or damaged files Stakeholders fail to support project Design fails peer review
	MEDIUM This risk will MOST LIKELY occur at this event		Conflicts between team members	Bad scheduling Bad work distribution Technology components aren't fit for purpose	Unclear scope Lack of management or control
	HIGH This risk WILL occur at this event, possibly multiple times, and has occurred in the past	Sickness	Estimated hours are inadequate Trips Clashing programming	Under communication Learning curves – delays	

Table 9. Explanation of Risk Ranking

LOW	**MEDIUM**	If the consequences to this event/activity are LOW / MEDIUM, your group should be OK to proceed with this event/activity. It is advised that if the activity is MEDIUM, risk mitigation efforts should be made.
HIGH		If the consequences to this event/activity are HIGH, it is advised that you seek additional event planning support.
EXTREME		If the consequences to this event/activity are EXTREME, it is advised that you **do not hold** this event without prior consultation with Risk Management

1. **Lack of management or control** Risk: EXTREME
   Causes: To ignore the importance of planning

   Solutions: To evaluate the several aspects of project management and keep focus on it

2. **Unclear scope** Risk: EXTREME
   Causes: Unclear information/misunderstanding about project or objective

   Solutions: Good documentation, clear information, clear objectives. Valuable information administration

3. **Loss of information/ damaged files** Risk: HIGH
   Causes: Human mistake or system failures

   Solutions: To manage the resources with care and making backups systematically

4. **Stakeholders fail to support the project** Risk: HIGH
   Causes: Lack of time/ motivation/ interest

   Solutions: To keep compromised with the project, scheduling time for the project in your timetable. Proactivity

5. **Design fails peer review** Risk: HIGH
   Causes: The stakeholder in reviewing charge/ other team members ignore the importance of reviewing work done.

   Solutions: Person in charge/ other team members have to make reviews of the others/ own work.

A.6 Stakeholders Analysis

Our first brainstorm was about the two different groups of stakeholders:

Major Stakeholders: Members of the project (We), project coach (Rayko Toshev), EPS coordinator (Roger Nylund).

Minor Stakeholders: ABB Robot, KUKA and other 3D printing companies.

The second brainstorm was more adequate and we used some questions to determine our stakeholders.

- Who are affected by this project?
- Who have influence on this project?
- Who has the power to determine certain key parts of our project?
- Who may have interest in our project?

We finally came to the following list of potential stakeholders:

- Roger Nylund
- Rayko Toshev
- Mika Billing
- The team
- Novia UAS R&D Department
- RamLab
- Repetier
- Hanna Latva
- ABB
- KUKA
- MiniFactory
- Fillament Supplier
- StarElec Oy
- MX3D
- CuraEngine

After we have made a list of the potential stakeholder we have to prioritize them. We do this by using a Power / Interest grid as shown below.

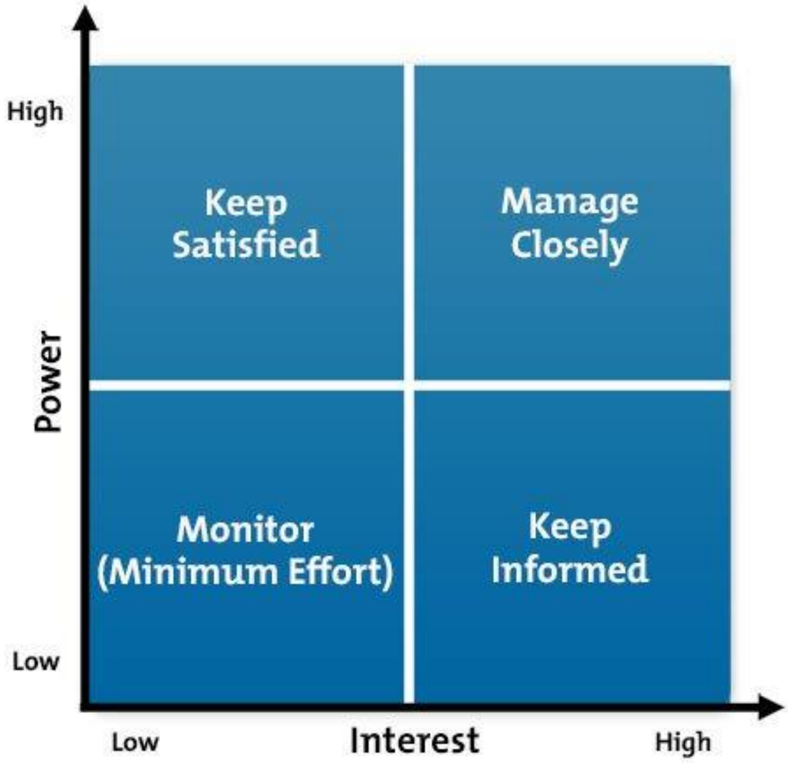


Figure 74. Power - Interest Grid

The grid is divided in four different squares. In the top-left corner there is “Keep Satisfied” what means that the stakeholder has power but no real interest in the outcome of the project. The project team is supposed to meet their requirements. In the bottom-left corner there is “Monitor” which means that the project team should check on these stakeholders a minimal amount. Then there is “Keep Informed” who have a high interest in the project, however they have not so much influence as the stakeholders in the “Manage Closely” square where the key stakeholders are located.

With the list of potential stakeholders and the Interest/ Power grid the project team prioritized the stakeholders and the result is shown below.

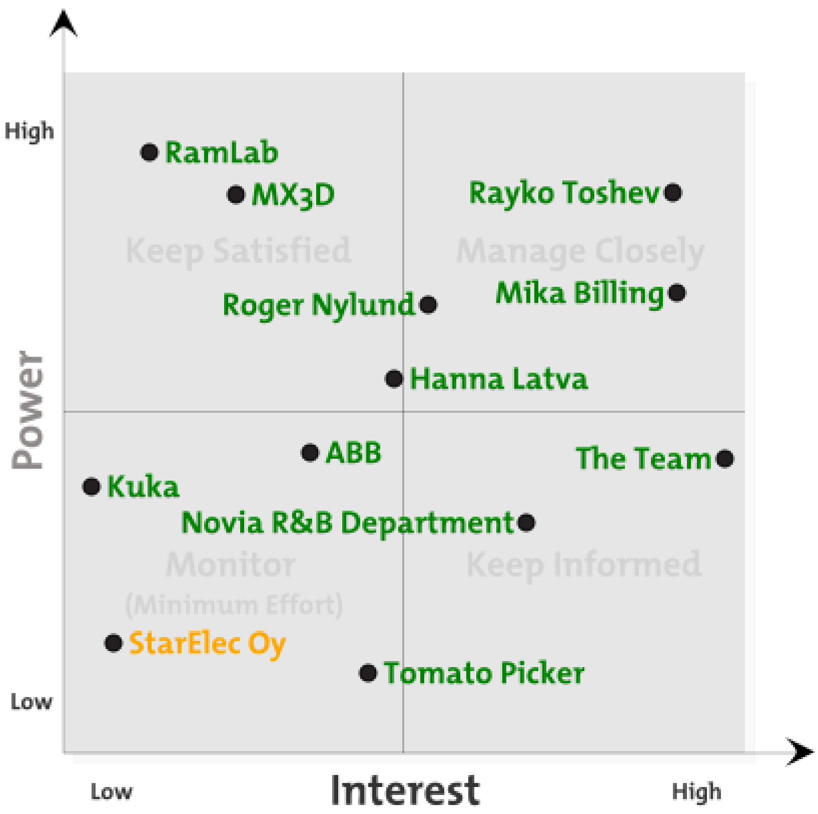


Figure 75. Stakeholder Power - Interest Grid

This grid is useful for visualizing the stakeholders, but it does not tell us what the aim of the stakeholder is and how the project team should handle these stakeholders. In *Table 10* this important information is added.

Table 10. Stakeholders strategies

STAKEHOLDER	AIM OF STAKEHOLDER	POWER	INTEREST	ACTION	WIN-WIN STRATEGY
ROGER NYLUND	Guide our project group and learn PM	High	High	Manage Closely	Make sure that we do all our PM tasks and if we have questions about PM ask him for help.
RAYKO TOSHEV	Project supervisor, make sure that the intended result is accomplished	High	High	Manage Closely	Make sure we have enough meetings with him to make sure that the project is heading the right way. Show the progress we made weekly to check if we are on schedule and we

					don’t lose the scope of our project.
MIKA BILLING	Guide the project on with the practical aspects.	High	High	Manage Closely	Ask for workshops twice a month and ask for help if we have some questions about the ABB robot or the converter program.
HANNA LATVA					
THE TEAM	The people that are executing the project	Low	High	Keep Informed	Have weekly meetings to get updates about the project. Make a schedule and divide tasks. If there are changes or important information, make sure that everyone gets the information they need.
NOVIA UAS R&D DEPARTMENT	Commission different project in different field of studies to expand their knowledge and work together with local businesses and industries.	Low	Low	Monitor	Make sure that our project is perfectly documented and follows the guidelines that Novia gives. As the project develops and we create an interesting end result we can profit from this because it will attract more stakeholders and people that are interested in our work. We as team can expand our network that can help us to find future jobs.

With this information a communication plan is created that tells the project team which kind of documents will be created and how the communication between stakeholders will take place.

Table 11. Communication documents

TYPE OF DOCUMENTS		DESCRIPTION
REPORTS	Midterm Report	Includes parts of PM, conducted research, state of the art, current progress, conclusions, future action planning
	Final Report	Include everything from the Midterm report, final product, testing and results. Conclusion and lessons learned, recommendations
AGENDA MINUTES		See the Agenda Minutes Template located in the Agendas folder
MINUTES OF MEETINGS		See the Minutes of Meetings Templated located in the Minutes folder
PROJECT PLAN	Scope Management	Includes Project Description, Project Objectives, Mission and Vision statements, Project Requirements, Project Deliverables and milestones, WBS
	Time Management	Project schedule, Responsibilities
	Human Resource Management	Staffing plan
	Cost Management	EVA, Project Budget, Cost breakdown structure, budget follow-up
	Communication Management	Stakeholders Analysis, Project Communication Plan
	Quality Management	Quality plan, Quality Assurance and control
	Risk Management	Risk Assessment matrix, Mitigation strategies, Risk Elimination, Risk Monitoring and control
	Change Management	Change Control Log, Project Change Action-plan,
	Project handover / Lessons Learned	Includes each team member's lessons learned, closing and handover plan
DESIGNS		Includes the designs and models for the 3D-printing module
CODE OF CONDUCT / PROJECT TEAM		Includes rules, team members'

INFORMATION	information
RESEARCH	Includes the conducted research and the essence of the research, information important for the project, state of the art
PRESENTATIONS	
MINUTES OF WORKSHOPS	Include the subjects and additional information about the workshop and the outcomes and learning objectives.

Table 12. Communication Responsibilities

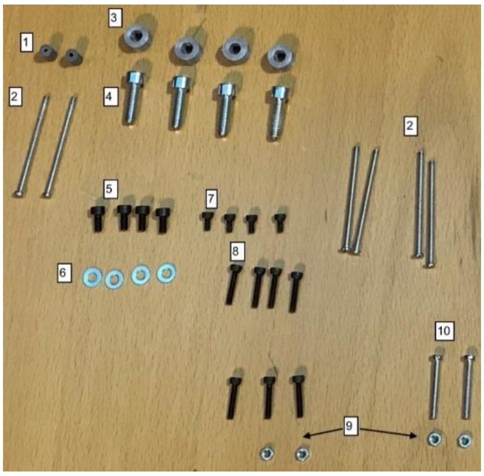
WHO	WHAT	WHEN	MEDIUM	RESPONSIBLE
ROGER NYLUND	Midterm Report	Every two weeks	Personal, Dropbox	Job
	PM Exercises	Weekly	Personal, Mail, Dropbox	Job
RAYKO TOSHEV	Midterm Report	Every two weeks	Personal, Dropbox	Job
	Agenda Minutes	Weekly	Mail, Dropbox	Luc
HANNA LATVA	Midterm Report	Monthly	Mail, Dropbox	Job
THE TEAM	Reports	Daily	Dropbox, Whatsapp	Everyone
	Agenda Minutes	Weekly	Dropbox, Whatsapp, Mail	Luc
	MoMs	Weekly	Dropbox, Mail	Poonam
	Project Plan	Weekly	Dropbox	Job
	Designs	Daily	Dropbox	Everyone
	Code of Conduct	Monthly	Dropbox	Job
	Research	Daily	Dropbox	Everyone
	Presentations	Daily	Dropbox	Everyone
	Workshop Minutes	Every two weeks	Dropbox	Job

Appendix B: Assembly Manual

Table 13. Bill of Materials

Part number:	*Parts*	*Quantity*
1	Spacers for M3X50	2
2	M3X50	6
3	Spacers for M6X20	4
4	M6X20	4
5	M4X10	4
6	Washers for M4X10	4
7	M3X6	4
8	M3X16	7
9	Washers	4
10	M3X26	2
11	Flexion extruder kit	1
12	40x40x20 mm fan	1
13	50 mm fan	2
14	Fan spacer	2
15	Stepper motor	1
16	Blower fan holder	2
17	New shroud	1
18	Motor bracket	1
19	Arduino board	1
20	Adafruit motorshield V2	2
21	Pololu board	1
22	Final extruder frame	1
23	Mounting plate	1
24	Standoff	4
25	Motor spacer	1

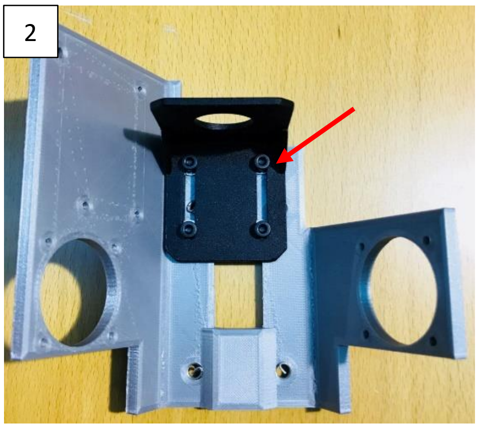
Screws and tools:



Step 1:

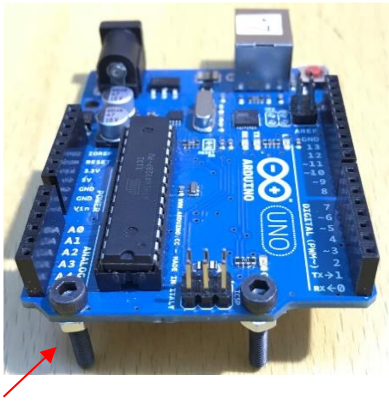
Attaching Mounting bracket

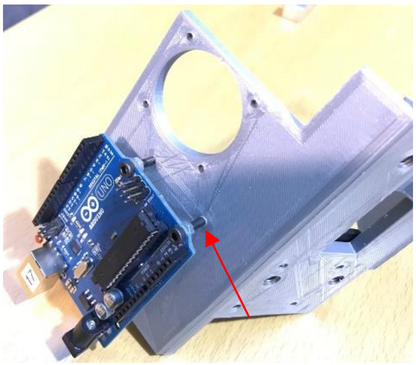
1

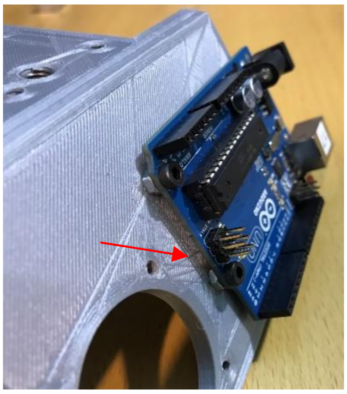

2


1) Final housing design.
2) Attach mounting bracket with four screws: M4X10

Step 2: Attaching Arduino



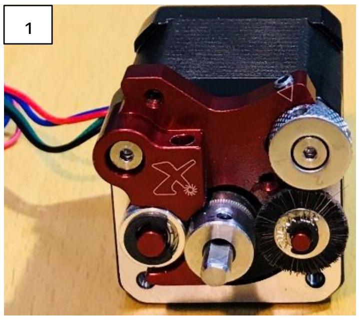


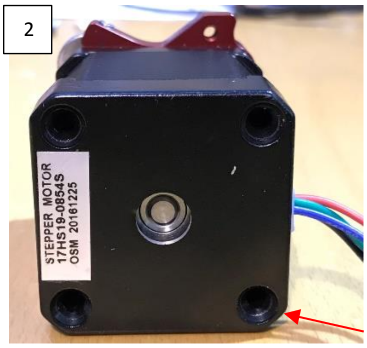


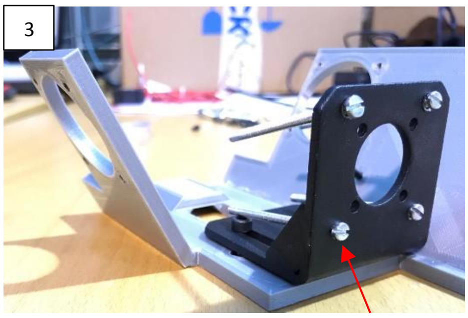
Fix two screws on Arduino with nuts which are used as spacers.

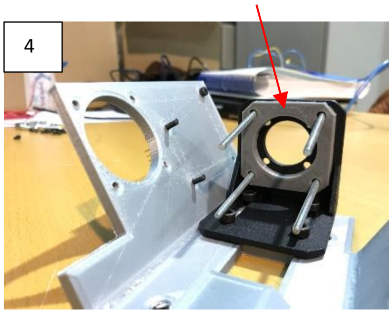
3 Screws: M3X16

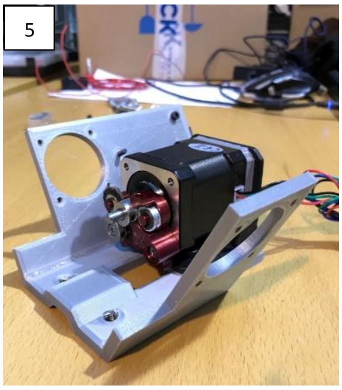
Step 3: Attaching stepper motor





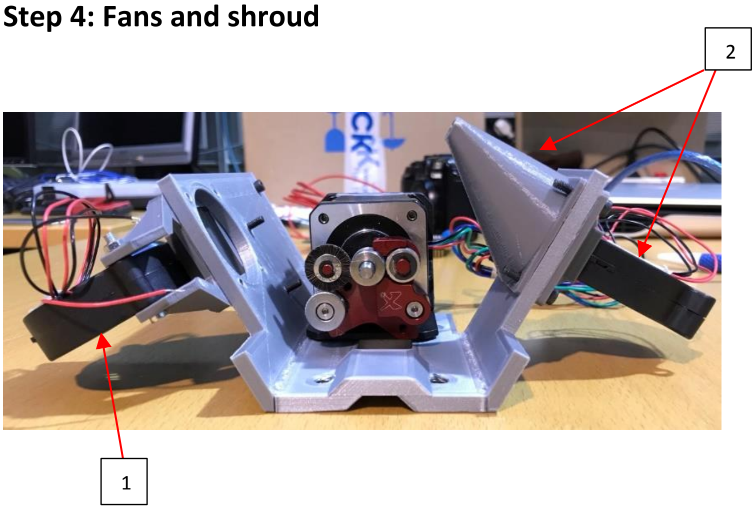






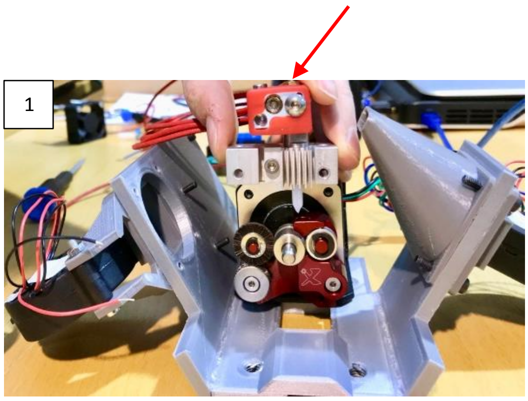
1) Mount Flexion Kit to Stepper motor with instructions from this link: https://flexionextruder.com/support/i3-style-printer/
2) Remove the Screws that are already on Stepper motor.
3) Use four long screws : M3X50. Put the screws in bracket .
4) Attach Spacer (grey) in front of bracket.
5) Fix Stepper motor.

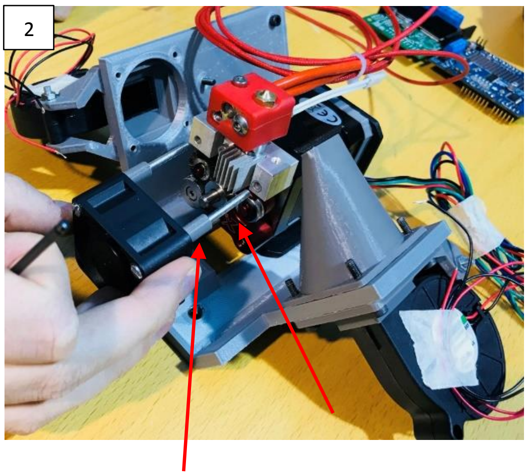
Step 4: Fans and shroud

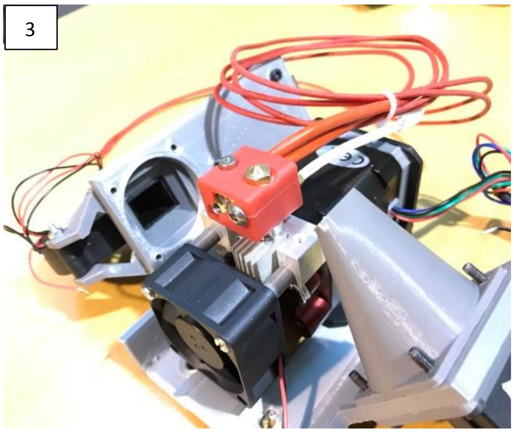


1) Fix the fan on Housing design with 4 Screws:M3X6
2) Fix the second fan with shroud together on other side (opposite to Adruino board). Use four screws:M3X16

Step 5: Heating Element

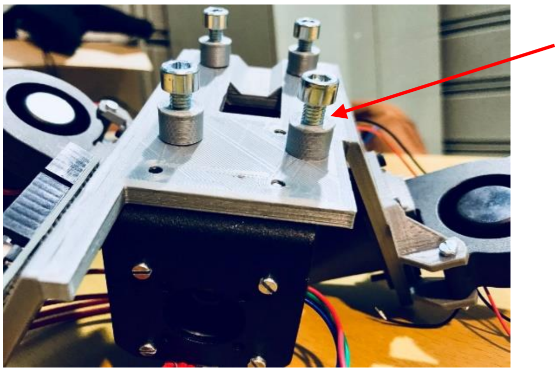






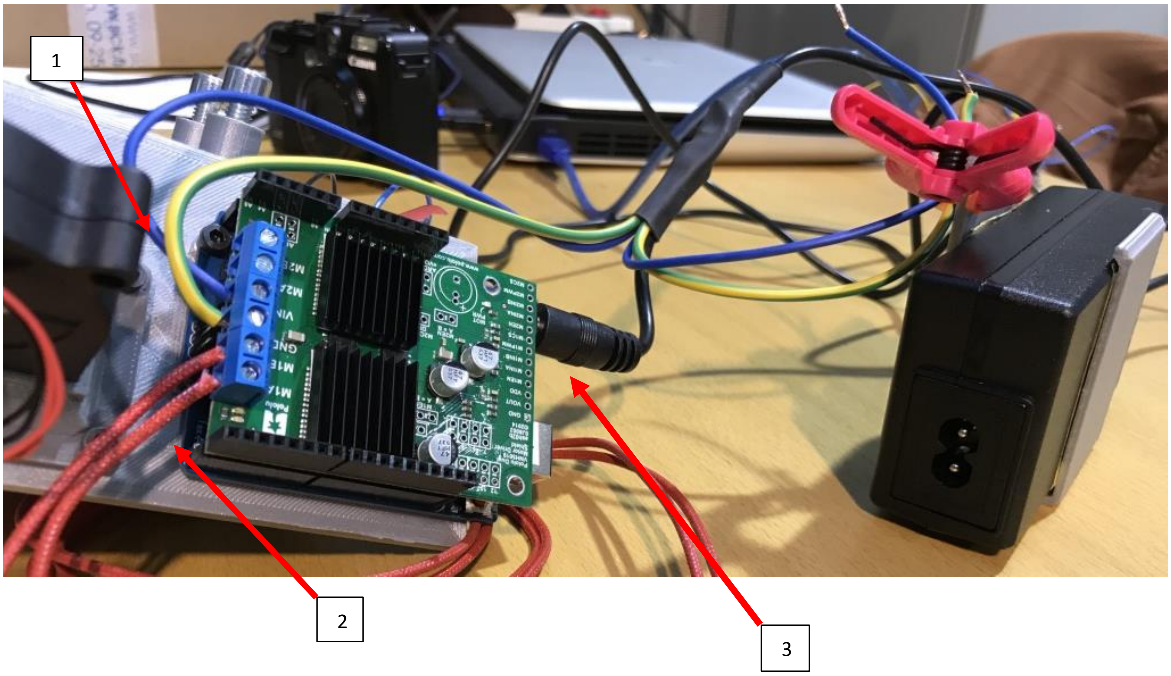
1) Fix the heating element on top (red color).
2) Put black fan in front, use two screws: M3X50. Add spacers on screws.
3) Push screws through heating block and tighten to stepper motor.

Step 6: Upper part



Fix 4 screws on top: M6X20. Add spacers on top.

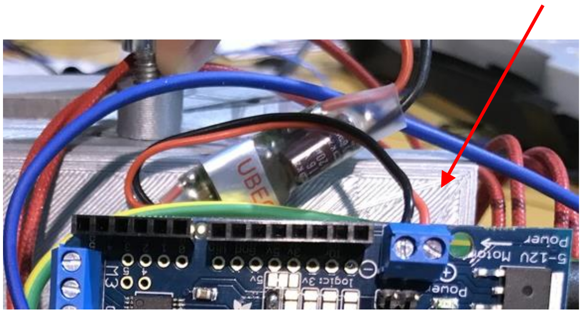
Step 7: Connecting Power supply wire

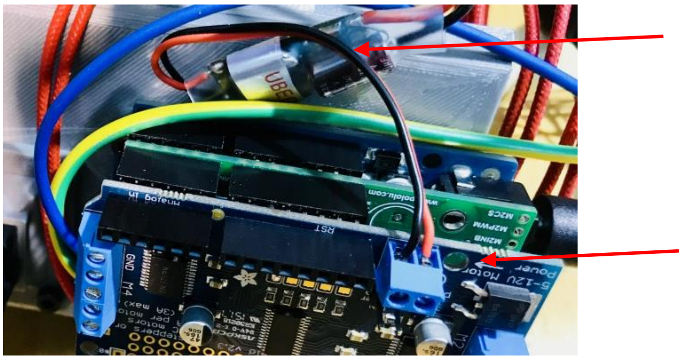


1) Power supply wire.
2) Heating element wires.
3) Connect 5.5 mm Power supply plug on Arduino connection.

Step 8: Adafruit board and wires connection

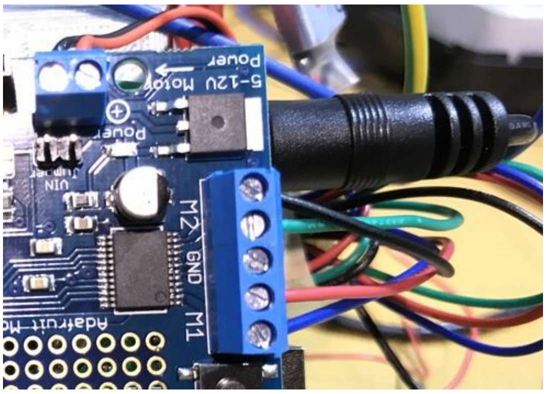
1)

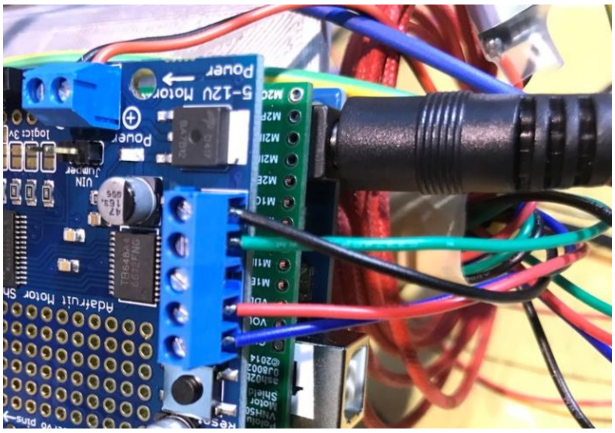




Attach output wires from step-down converter to the power terminal.

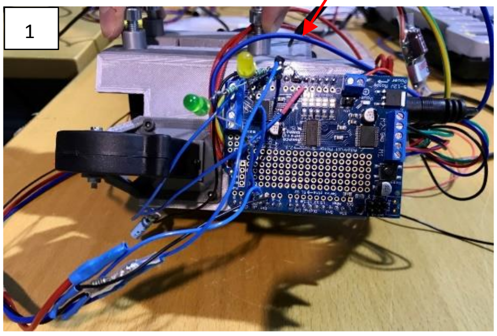
2)

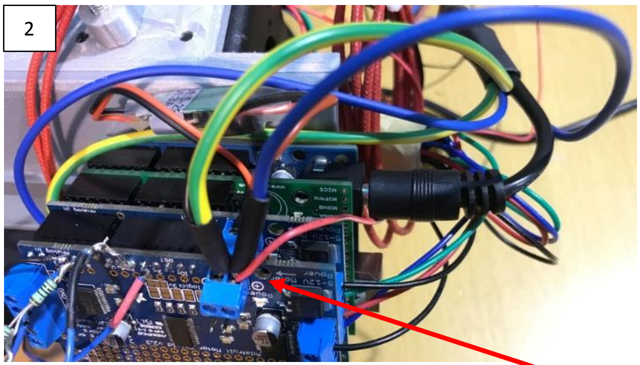


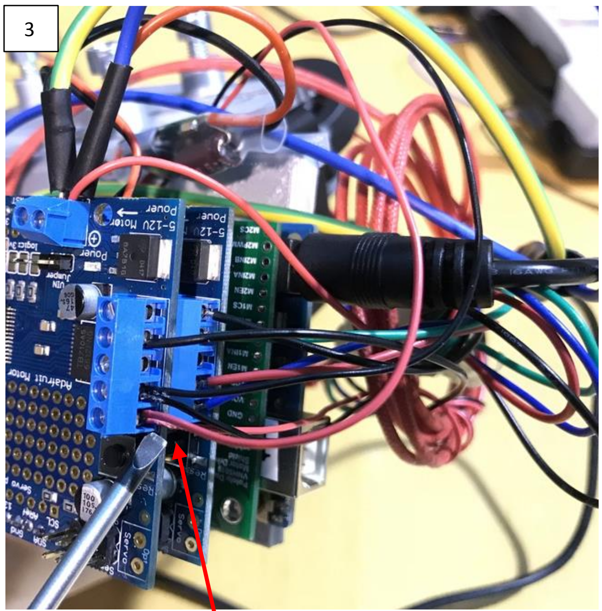


Attach Stepper motor wires on same Adafruit board.

Step 9: Fourth board







1) Adafruit board with some ready connections fixed on top of other board.
2) Attach the power supply wires to second adafruit board as shown, attach red wire from axial fan to same terminal as the blue power wire.
3) Attach black wire from axial fan to centermost M1 connection and attach the wires from the blower fans together to M2 connection as shown.

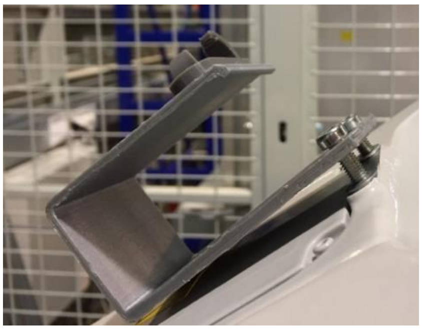
Appendix C: Installation Manual

Step 1: Guidance System:

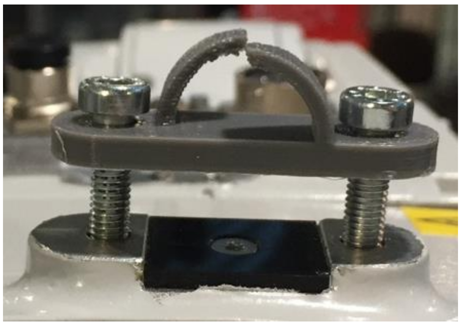
1)

2)

Use 2 Screws: M5X16 with washers

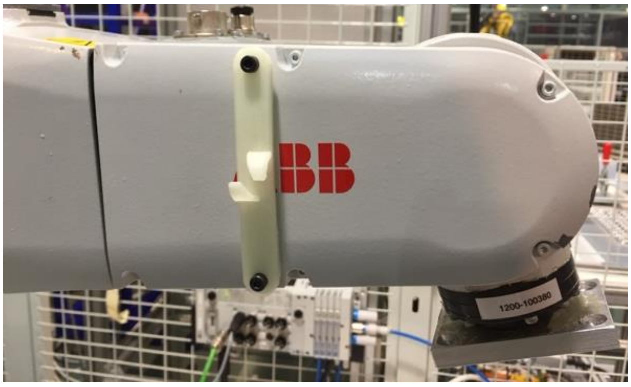


3)



Use 2 Screws: M5X16

4)

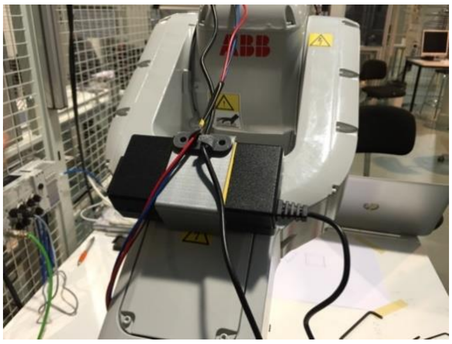


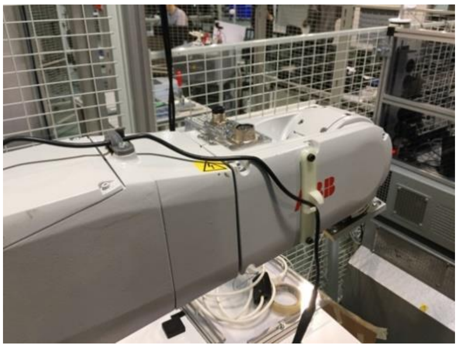
Use 2 Screws: M4X8

Step 2: Power Supply and cables in clips:

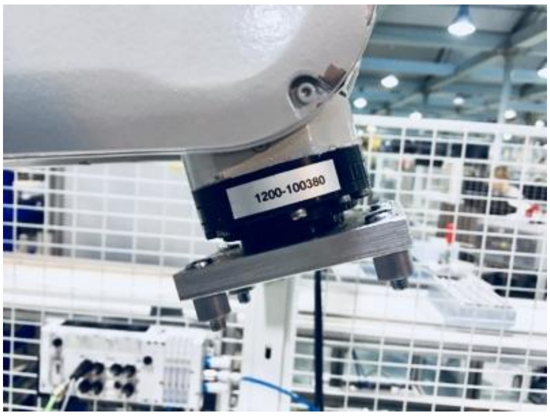
1) Power supply

2) Clips





Step 3: Extruder with 4 bolts

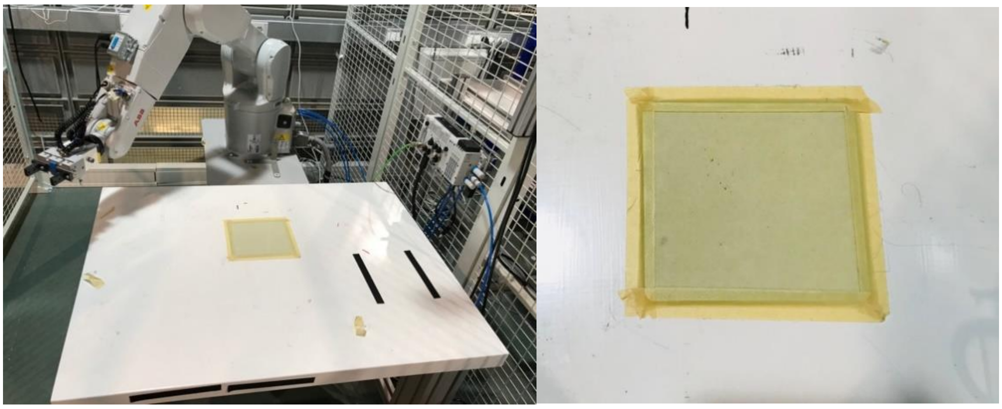


Mount it with fan facing the yellow black tape as shown in photo two.

Step 4: Communication cable

Step 5: Loading filament

Step 6: Placing and tightening Printing bed

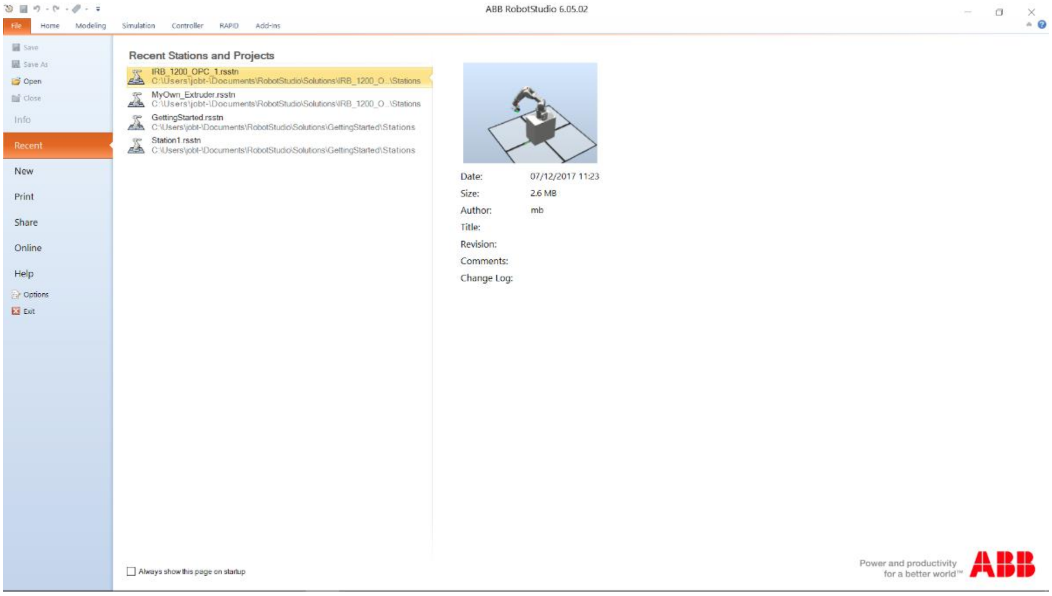


With Painter’s Tape fix the glass plate on the table. The printing bed should be at centre as shown in image.

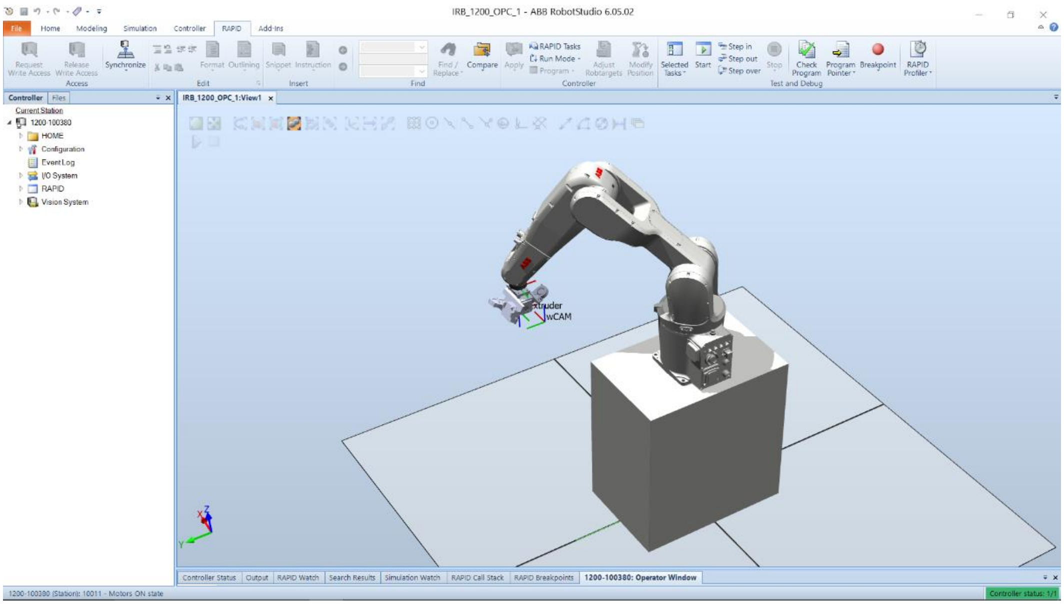
Step 7: Power cable: Put the power cable in plug.

Appendix D: Operating Manual

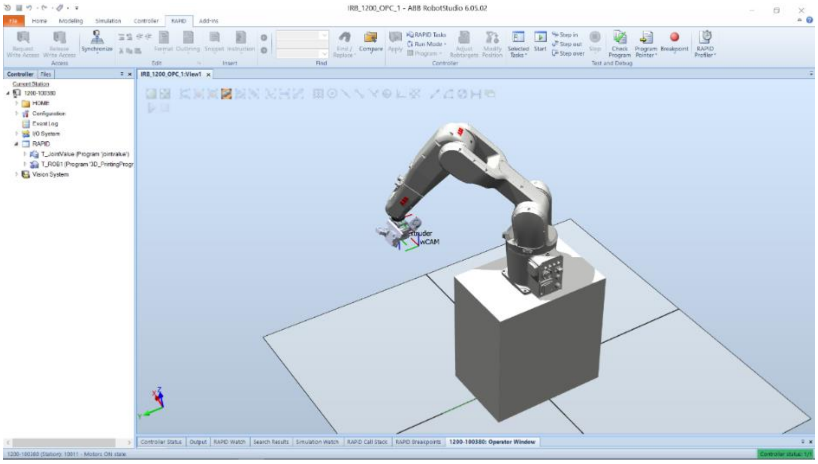
Step 1: Open the *Solution*



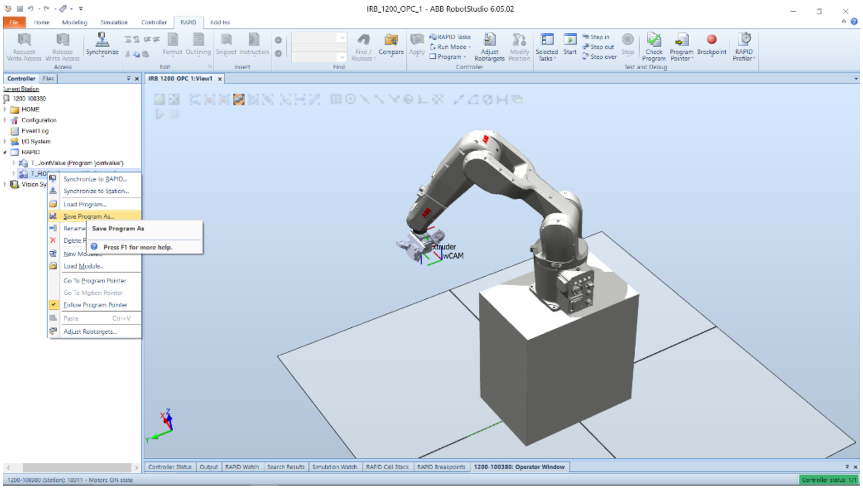
Step 2: Click on the *RAPID tab*

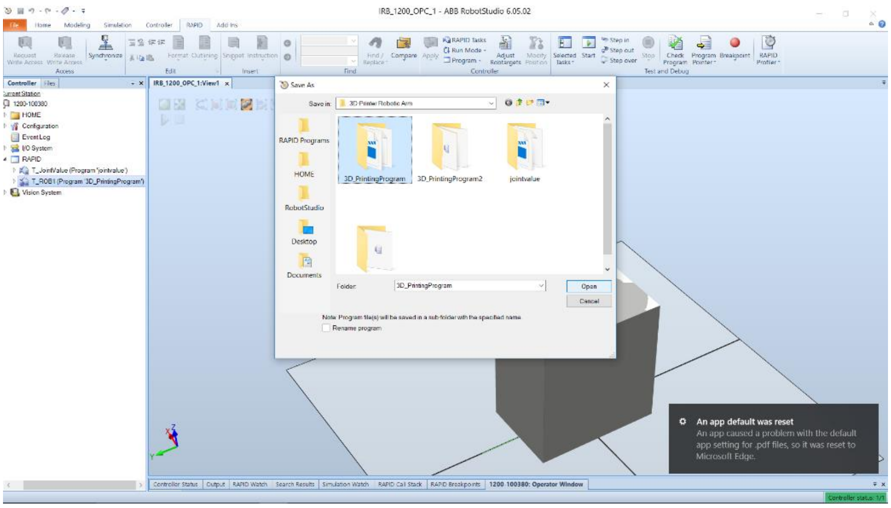


Step 3: Expand the RAPID modules in the *Controller Window*

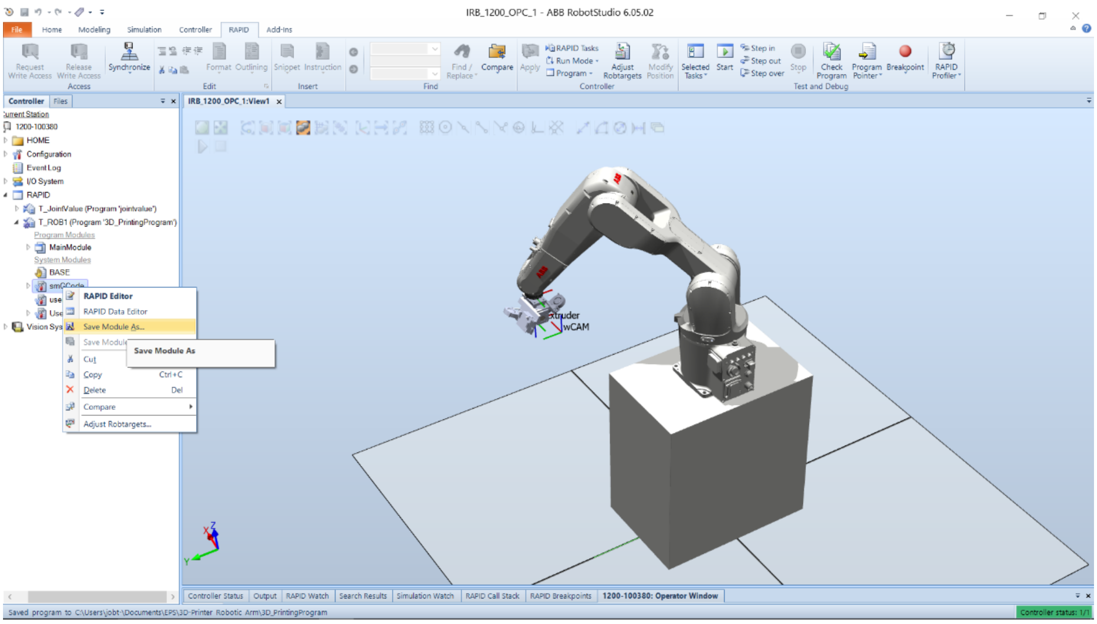


Step 4: Right-click on the *T_ROB program* and click *Save Program As…* and save it on your computer



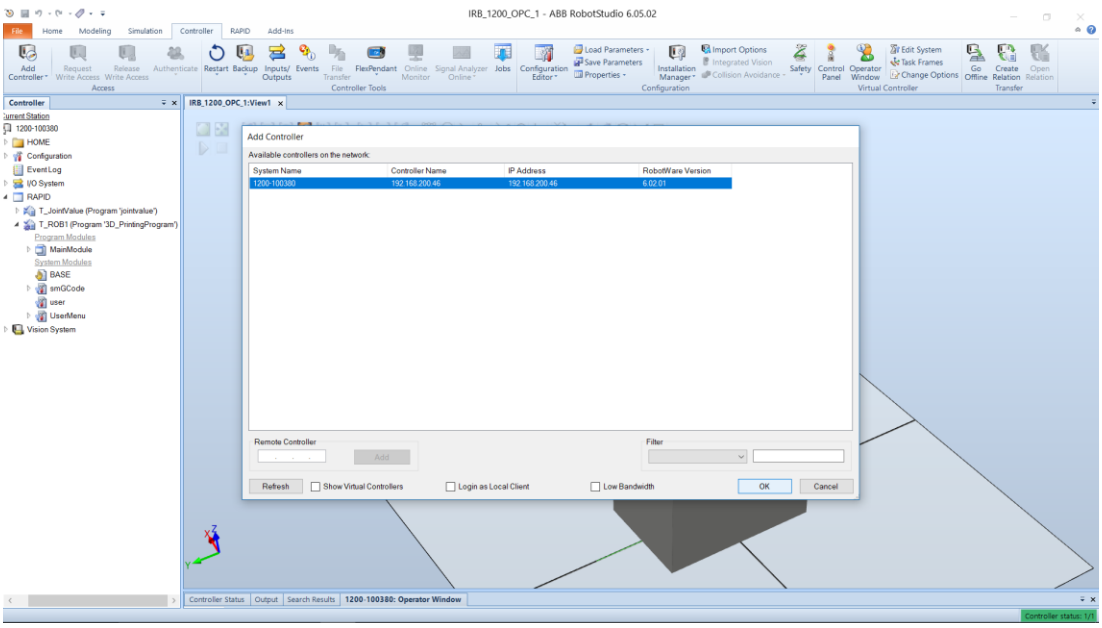


Step 5: Right-click on the System Modules (*smGCode*, *userMenu*) and click *Save Module As…* and save them in the same location as you saved you program folder. (So not in the program folder that was created by the previous step)



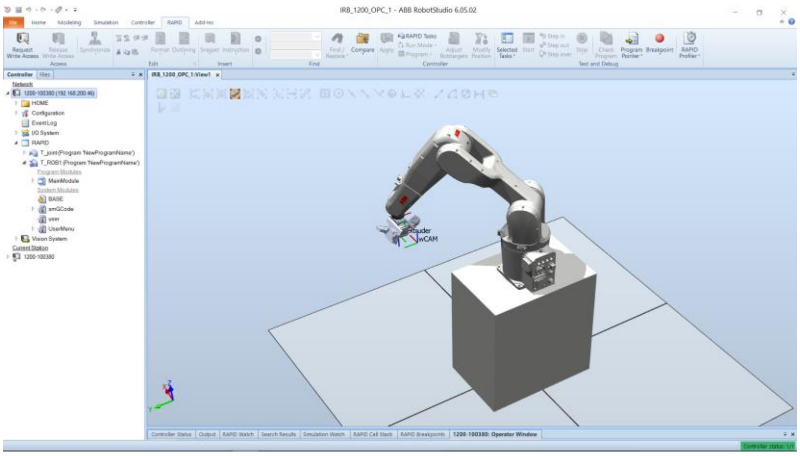
Step 6: Turn on the Robot Controller with the *MAIN SWITCH* and let the Controller start everything up. Connect your computer with the ABB-ROBO wi-fi.

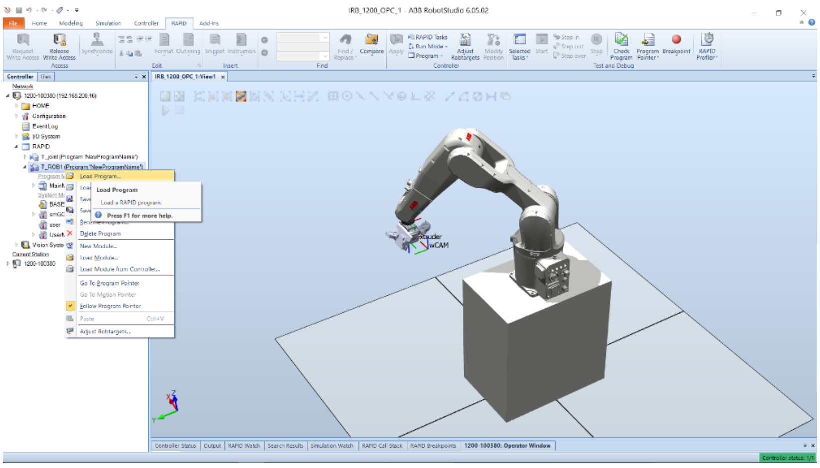
Step 7: In the *Controller tab* click on *Add Controller* and then *Add Controller* again. The IRC5 controller should appear in the list. Select the Controller and press *OK*.

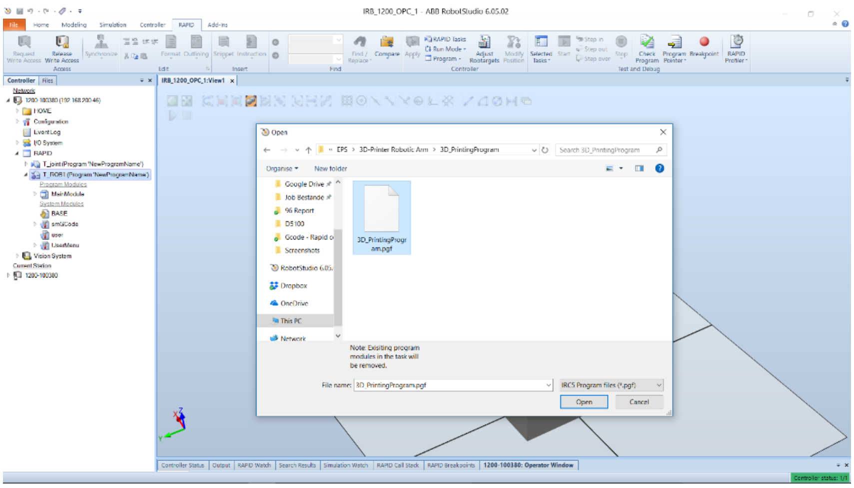


Step 8: If you click on the *RAPID tab* and look in *the Controller Window* the physical robot is displayed.

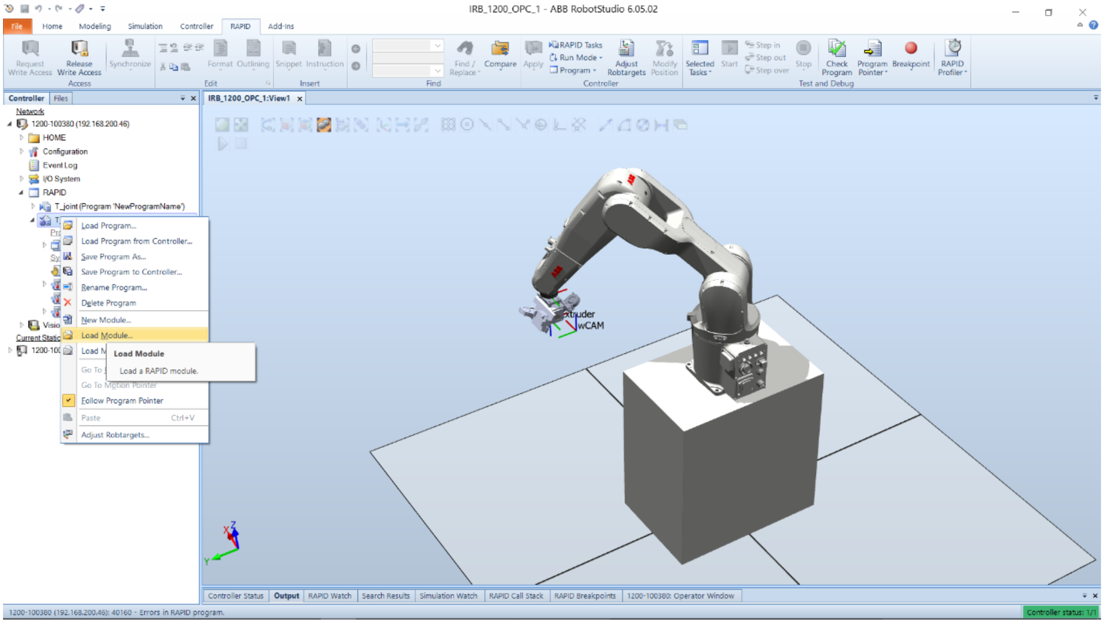
Step 9: Expand the RAPID modules and right-click on *T_ROB program* and click *Load Program…* and load the program you saved during *Step 4*. Make sure that you have requested write access with the *Request Write Access* button in the top-left corner.



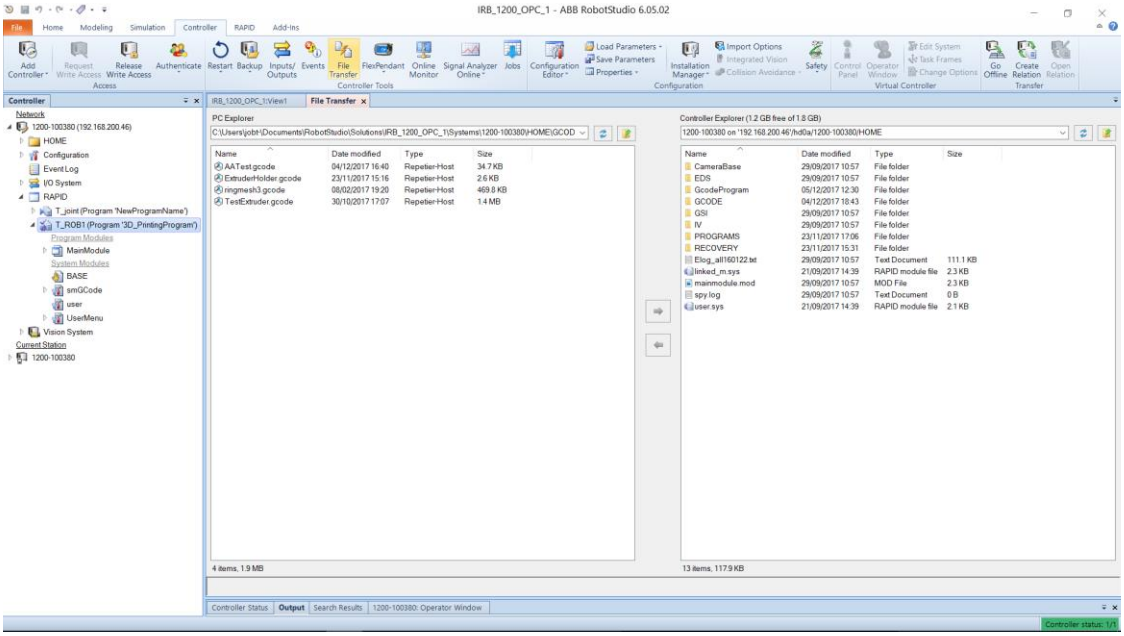




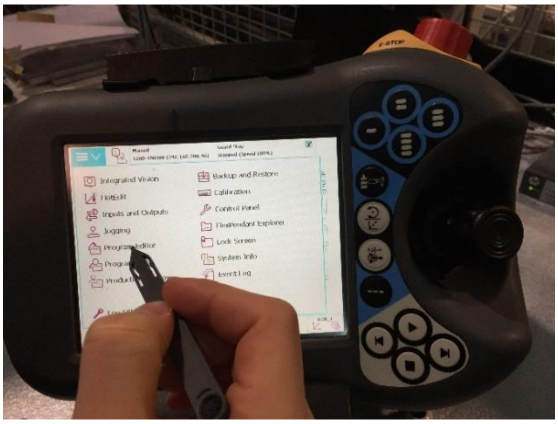
Step 10: Right click again on *T_ROB program* and click *Load Module…* to load the system modules (smGCode, userMenu) that you have during *Step 5*.

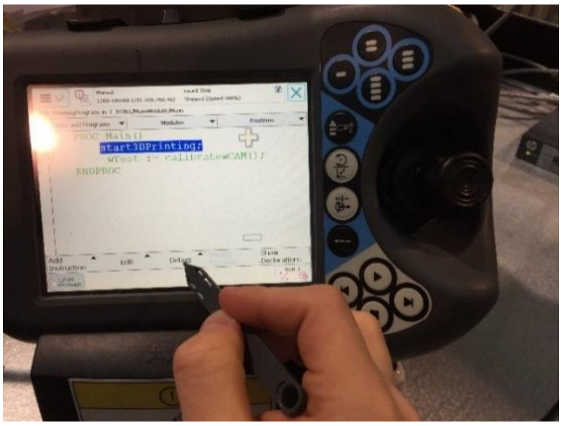


Step 11: To transfer the G-code files from your laptop to the robot controller in the *Controller tab* click *File Transfer* and copy the G-code file(s) you want to print to the *G-code folder*.

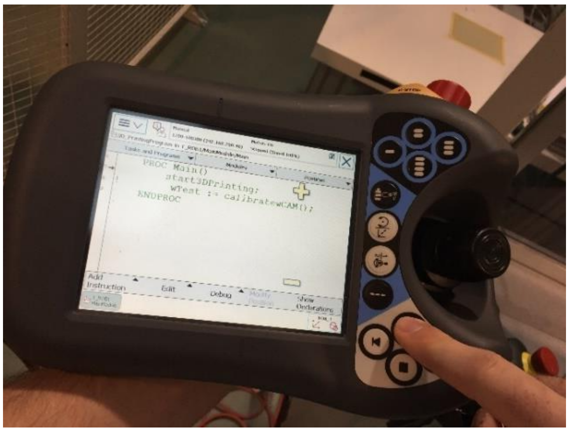


Step 12: Now on the FlexPendant open *Program Editor* and click on the *Debug button* and click *PP to Main*.

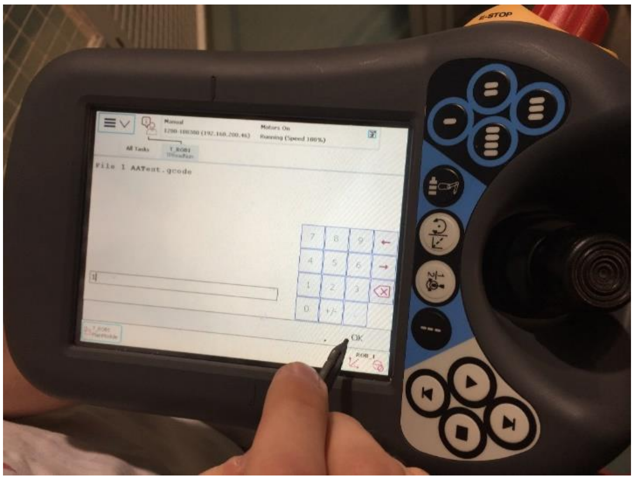




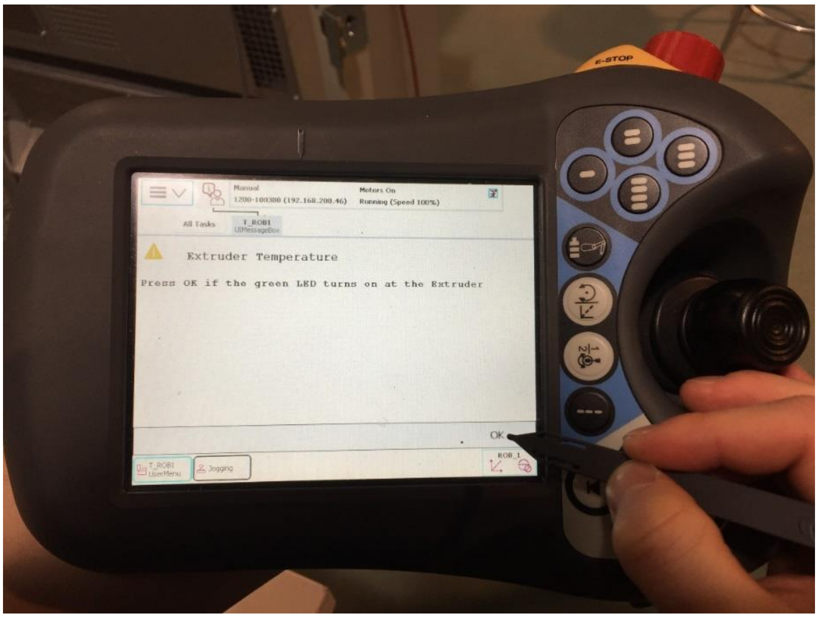
Step 13: Enable the robot with the trigger on the side of the FlexPendant. Press the *Play button* on the FlexPendant.



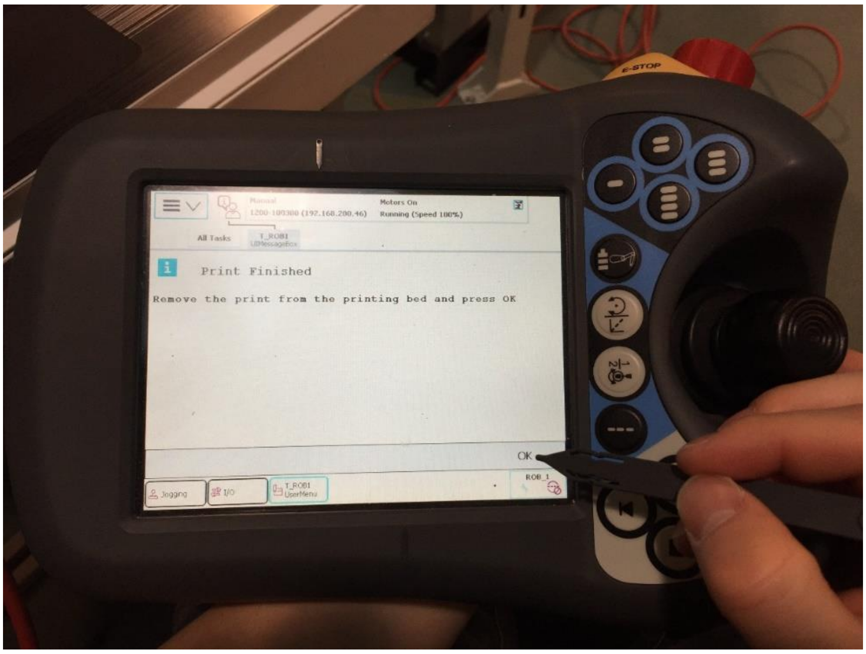
Step 14: The program starts and displays all the files in the G-code folder. Chose the number of the file you want to print.



Step 15: The robot moves first to the Home position and then to the printing bed. It will give a message that you have to press *OK* when the green LED is on.



Step 16: The robot will now start printing the 3D-model after it finishes it will give a message that the print is finished and you can take of the 3D-print. Press *OK* if the print is removed.



Appendix E: Wiring Schematic