Final Report

European Project Semester Spring 2024

Project name: **3D Printer Design**
Date: 20/06/2024

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And to the additional members of the jury; To EPS Local coordinator **Mourad Benoussaad**, and to the project management supervisors of the other EPS projects **Beth Newick** and **Khanh Nguyen**. Thank you for taking the time to review our report.

Finally, a thank you to all the faculty here at ENIT and the members of the outgoing departments of each member's home university. To **Manuelle Denisse** for helping us integrate and expand our language skills while working abroad. To **Karen Sautet** for her continuous assistance throughout the semester.

3dB wishes to extend our utmost appreciation to all mentioned. The experience and skills gained while working on these projects will be taken forward throughout our careers.

3dB,
Tarbes, 20th of June 2024.

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Glossary

CAD	Computer-Aided Design
EPS	European Project Semester
EniOne	3D-Printing laboratory on the second floor of building C. Students have used this lab for several years for various EPS projects.
Kinematics	The movement style of a 3D printer
PTFE	**P**oly**t**etra**f**luoro**e**thylene also known as Teflon
WBS	Work Breakdown Structure
Prismatic Joint	A singular degree-of-freedom joint constructed of two interconnecting parts which slide together along a common axis.
Electromechanical	An advanced discipline of engineering which encompasses the fusion of electrical and mechanical engineering.
Height-Sensor	A mechanical switch which is pressed signalling to the controller when the printing head reaches the end of its range.
Parallel Kinematics	An end-point connected to independently moving arms to control the position of a common point.
PLA	Polylactic Acid – a common material (thermoplastic polyester) used for 3D printing.
Torque	Rotational Force.
Bearing	A circular mechanical part with connected inner and outer sections which allow for rotation of two individual pieces.
Accelerometer	Electronic device used to measure the rate of change of an objects position.
Tensile Strength	Measurement of the maximum amount of stress a material can receive while being stretched or pulled before breaking.
Yield Strength	Measurement of the maximum stress a material can receive before it loses the ability to return to its original shape.
Ductility	Material's ability to be stretched or deformed without breaking.
Malleability	Material's ability to be hammered or pressed into shape without cracking.
Nut	A type of fastener with a threaded hole.
Brinell Hardness	A measured value determining the strength of a material under constant load.
Alloy	A combination of two different types of metals.
Threading	To create an internal helical groove to allow a screw to be neatly inserted.
Infill Density	The amount of material used to fill the volume of a 3D printed part. The higher the value, the denser the part will be.
Axial Load	A force applied to the axis of an object.
Variable Cross-Section	When the cross-section of a material changes width along its length.
Digital Studio	Specialised CAD environment with software tools for creating designs.
Mechatronics	An interdisciplinary field of engineering that combines principles from mechanics, electronics, computer science, and control engineering.

1 Introduction

This project was executed over the Spring 2024 EPS . The semester took place within *L'École Nationale d'Ingénieurs de Tarbes* (ENIT), established in 1963. EPS began in 1995 to provide students with the opportunity to work in multidisciplinary environments. This report will outline the entire project, explaining the specific challenges faced and the solutions to overcome them. The first section will introduce the team members and outline the context and scope of the project.

1.1 Meet the Team

This semester, the team (3dB), as presented below in *Table 1* has a complementing range of skills relative to this project:

Table 1. Team introduction.

		
Benjamin J. Livingstone	Etienne Foissard	Ikechukwu Danromy Omodolor Omodia
Electrical Power Engineering	Mechatronics Engineering	Mechanical Engineering
Glasgow Caledonian University	The Hague University of Applied Sciences	University of Polytechnics Catalonia, Vilanova i la Geltrú

1.2 Project context

In this section, the project will be introduced alongside an introduction to the machines the team has been working on. This semester, 3dB was invited to work on 3D printer design.

1.2.1 3D Printing

3D printing, which can also be known as additive manufacturing (AM), is a technique that enables the creation of three-dimensional objects to be constructed based on CAD models. Unlike traditional subtractive methods – which involve taking a block of material and cutting or drilling sections to create a specific shape or size – 3D printing is a method of AM that constructs objects layer by layer.

This method of manufacturing provides various advantages, including the production of complex geometries, and the ability to rapidly prototype and customise designs.

1.2.2 EniOne

In the EniOne lab located at ENIT, students have developed 3D printers for the university over several EPS projects. There have been three distinct types of kinematics used for these 3D printers in the EniOne lab: Delta, Tripteron, and Cartesian. During this semester (Spring of 2024), 3dB has worked on Tripteron and Cartesian 3D printers which will be explained in chapters 1.2.3 and 1.2.4 respectively.

This semester, instead of building a new machine from scratch, 3dB will focus on redesigning two existing machines in the lab for future projects within the university.

The following sections will introduce each of these machines and outline the challenges faced this semester. Project management will be later explained in Chapter 2 and all engineering problems will be explained in more detail with provided technical solutions to the problems in Chapter 3.

Figure 1. The EniOne lab

1.2.3 The Tripteron 3D printer

A Tripteron 3D printer uses a type of parallel kinematics which consists of three limbs (X, Y and Z) which work together to perform highly accurate and dexterous tasks. The idea was first patented in 2004 [3] and has since been tested for high-precision assembly operations for manufacturing. However – despite being an intriguing concept – due to various limitations [4], its practical applications are mostly limited to research, education, and hobbyist projects.

The EniOne Tripteron 3D printer was first built in the Fall of 2023 by a previous EPS team, aiming to develop a 3D printer utilising Tripteron kinematics. This printer was designed to be stylish for conference demonstrations and to attract attention during ENIT's open days, aiming to engage and inspire prospective students with its innovative design.

In the previous semester, there was insufficient time to enable full printing functionality. At this stage, the Tripteron 3D printer is currently capable of drawing on a piece of paper. This was achieved through a structure composed of aluminium profiles, motors, rails, and arms holding the printing head.

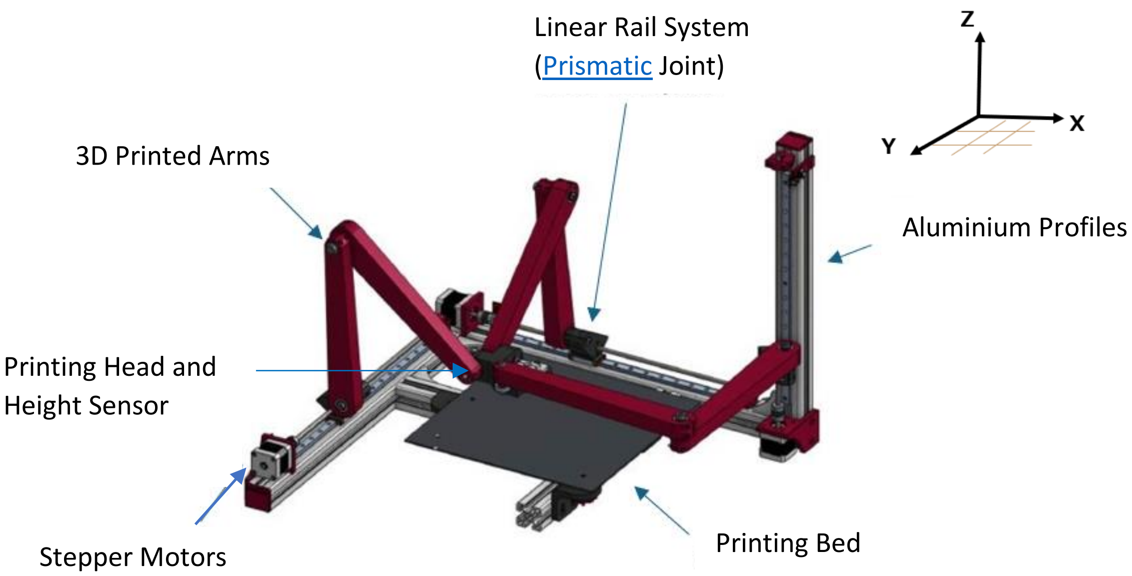

Figure 2. The Tripteron 3D Printer - CAD Model [2]

At the start of this semester, various issues were identified with the machine:

Instability of the arms and printing head – Clear unwanted displacement in the printing head is observed when the arms move in the direction of each axis. A short video is available to further illustrate the problem:

https://youtu.be/Pa9s2CJwtrA?si=W5lAQ4t-xEle9F2F

The machine does not stay within its intended range – The printing bed of the machine is 300x300mm with an additional 10mm of space at each edge. The software used to control the motors does not effectively stop the motion at each end-point of the printing bed. There are mechanical switches – also known as end-stops – which detect the base of the arm and stop the motors however they are loosely connected and do not work effectively. This can cause damage and overheating to the motor.

Loose Wiring – The electrical components have been connected below an expected standard of safety. Having loose wiring in electromechanical machines can create hazardous environments due to potential electric shocks or users tripping over the cables. Over time, the cabling of the height sensor has disconnected which suggests insecure connection points.

1.2.4 The Cartesian 3D printer

Cartesian 3D printers are more straightforward in their design. The printing head is attached to a horizontal sliding mechanism which is moved up and down the Z-axis to create the layers. Unlike a typical Cartesian 3D printer that uses three motors for its axes, this larger model uses four motors for the Z-axis, two for the X-axis, and one for the Y-axis. The Cartesian 3D printer has been in the EniOne lab for six years without usage.
Last year, an intern at the University – Julián Jaramillo Perez – designed a concept for a compression-chamber for a 3D printer which would take marine plastic waste and process the material into small discs.
At the end of the previous semester, it was proposed by a professor at ENIT that the momentarily abandoned Cartesian machine could be used as a support for the marine-plastic 3D printer. The chamber itself has a maximum load of 60kg and has dimensions of 50cm width, 60cm depth and 51cm height. Given these dimensions, it was determined that the Cartesian is large enough to fit inside the compression chamber with the additional 3D printing components while providing spatial manoeuvrability to potentially print rows and/or columns of discs. This semester, the secondary aspect of this project was to ensure that the Cartesian printer can support the additional weight requirements.

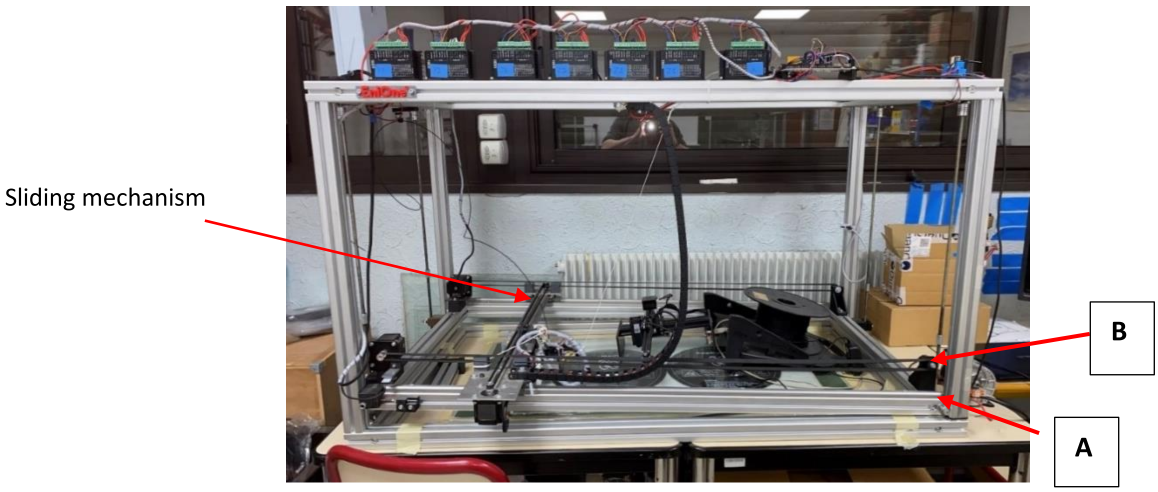

Figure 5. Cartesian 3D Printer - Photographed

There were clear structural issues which needed to be repaired; The supporting profiles [A] had become disconnected and over time the brackets [B] which were previously made from PLA had degraded.

The compression chamber, as shown in *Figure 4,* has an induction motor for which the torque is transferred to the chamber via a gear system. When the axis of the motor rotates, the gears cause rotation of a mechanical press within the chamber. A mixture of various plastics is heated to a suitable temperature and the transferred force is used to compress the material into discs.

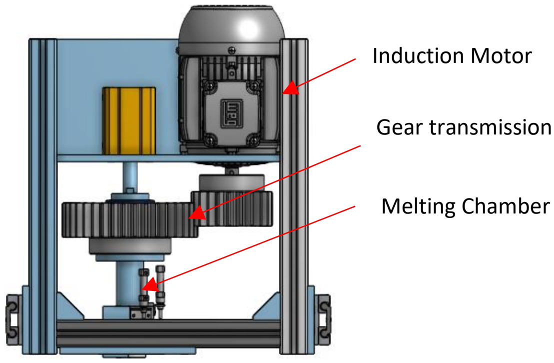

Figure 7. Compression-Chamber - CAD Model - Julián Jaramillo Perez

1.3 Project Objectives

In this section, the objectives of this project will be explained with reasoning as to why these decisions were made.

1.3.1 Specifying the objectives

During this semester, the two main objectives were as follows:

1. Installing 3D printing capabilities for the Tripteron 3D printer.
2. Restore functionality to the Cartesian machine.

Objective 1:
Typical 3D printers have an expected accuracy of around 0.3mm. Reducing the Tripteron 3D printer's unwanted displacement to be equal to, or less than, the typical 3D printer's accuracy should ensure adequate stability for precise printing.

The plans to achieve this were as follows:

Plan A: Redesign the arm connected to the Z-axis. The arm must be designed to provide a more rigid movement of the printing head.

Reasoning: Upon visual inspection during the analysis phase, it was clear that most of the displacement comes from a lack of rigidity in the Z-arm. It must first be proven that a machine of this style cannot function effectively with 3D-printed arms before considering alternative solutions.

Plan A is explained in more detail in the *Technical Solutions* section (*Page 34*).

If plan A was unsuccessful at reducing the displacement, the following alternatives would be considered:

Plan B: Additional structural profiles and an additional Z-arm to provide the necessary rigidity.

Plan C: Manufacturing the arms from metal.

Objective 2:
The Cartesian machine needed to be repaired to a working state so it could be used to carry the compression chamber of around 60 kilograms. To support this additional load, brackets were redesigned to be manufactured from aluminium. Structural profiles were to be reconnected and wiring was to be tested before testing the functionality of the Cartesian machine.

1.3.2 Structuring the objectives

Working on two projects within one semester presented significant challenges regarding planning and executing the semester. The original plan was to work on the Tripteron machine first. Then, upon completion, begin focusing on the Cartesian.

It was decided this method would be insufficient from a project management perspective. Any delays in manufacturing or ordering parts would hinder the ability to progress continuously throughout the semester. It was later agreed to work on both machines simultaneously to minimize this critical risk.

1.4 Stakeholders

The stakeholders of this project are as follows:

- Client: ENIT
- Technical supervisors:
  - François Grizet
  - Foued Abroug
- Project management supervisor:
  - Philippe Fillatreau
- 3dB Members (Benjamin, Etienne, Danromy)
- EPS coordinator:
  - Mourad Benoussaad
- End-Users:
  - Students coming to visit the university during the summer open day.
- EPS teachers:
  - Philippe Fillatreau (Project Management)
  - Chantal Barutau (Library Skills)
  - Manuelle Denisse (FLE)
  - Andrew Ghio (Communications)

Additional stakeholders for the Cartesian 3D printer:

- Intern:
  - Julián Jaramillo Perez
- Supervisor of the intern:
  - Jérémy Fraisseix
- Technacol:
  - www.technacol.com

2 Project management

Following the context of the project and the description of each machine, this section will outline the project requirements and the limits and exclusions. Following these will be the Work Breakdown Structure (WBS)

The Work-Breakdown-Structure (WBS) will include the deliverables, Gantt chart, milestones, workload estimations and risk management.

2.1 Project requirements

The project requirements for this semester are shown in the table below. Almost all existing requirements from previous semesters [2] for each machine were maintained. The only change was the size allocation for the Tripteron. If necessary, the height and width of the Tripteron could change to incorporate new structural designs.

Table 2. Project requirements table

No.	Both	Tripteron	Cartesian
1	Maintain original styles of kinematics and functionality.	Reduce unwanted displacement to a measured value of 0.3mm to provide sufficient accuracy for 3D printing.	2 completed designs for upper brackets.
2	Resolve hazardous wiring and ensure the safety of functionality.	Install a 3D printer head.	Common lower bracket design for each corner.
3	Standard 230V operation.	Install a spool holder for 1kg filament.	Maintains original size.
4	A maximum budget of €1000, excluding already available parts.	Maximum size 750x800x1000mm [X, Y, and Z].	Functional movement of each axis [X, Y, and Z].
5	Onshape CAD must be used for all solutions.	Maximum visibility of parts for showcasing to prospective students.	It should support a load of 60kg.
6		An emergency stop must be installed.	
7		This 3D printer should include a user guide.	

2.2 Limits and exclusions

The limits and exclusions apply to both machines unless it is specified which machine a limit or exclusion pertains to.

2.2.1 Limits

- The total price of the ordered and printed parts must not exceed the €1000,- budget.

2.2.2 Exclusions

- Remove the vibrations completely from the Tripteron machine.
- Create a casing for the Tripteron machine.
- Hiding all the wiring.
- SolidWorks CAD software must not be used.

2.3 Work Breakdown Structure

Given the complexity of having two projects in one semester, it was agreed that the WBS would be divided into two separate theoretical and physical prototypes with an encompassing Management and EPS documentation section as can be seen in Figure 5. In Figure 6, the tasks of deliverables one and two for the Tripteron 3D printer are depicted, while Figure 7 showcases the tasks of deliverables five and six for the Cartesian 3D printer. Figures 8 and 9 display the tasks for the Management and EPS documents, respectively.

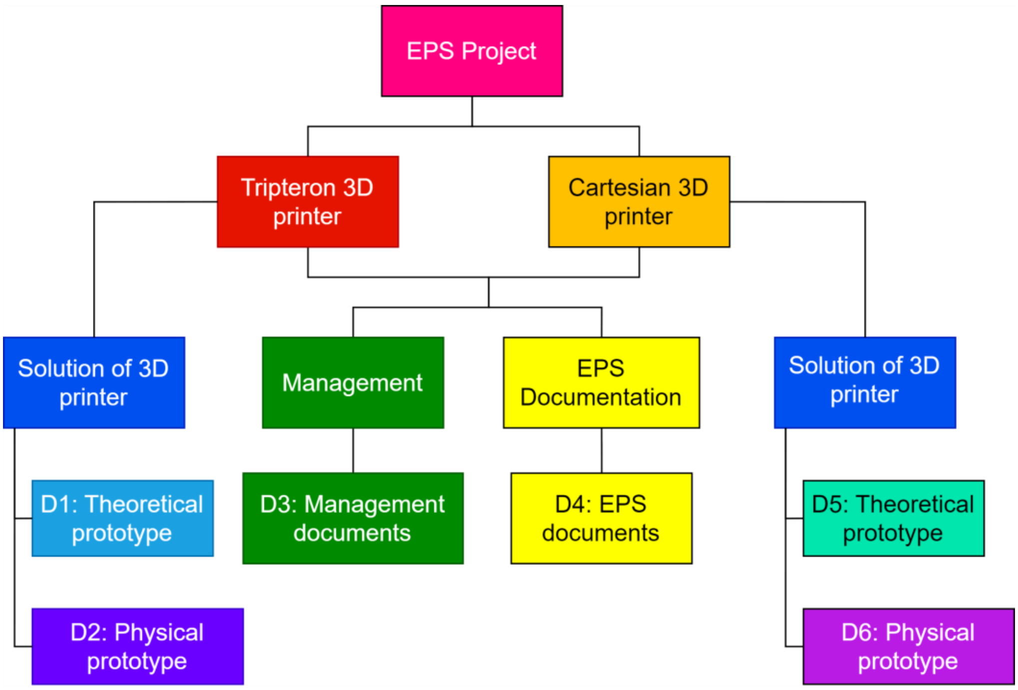

Figure 8. Global WBS.

2.3.1 Tasks

The tasks relative to each deliverable are shown in this section:

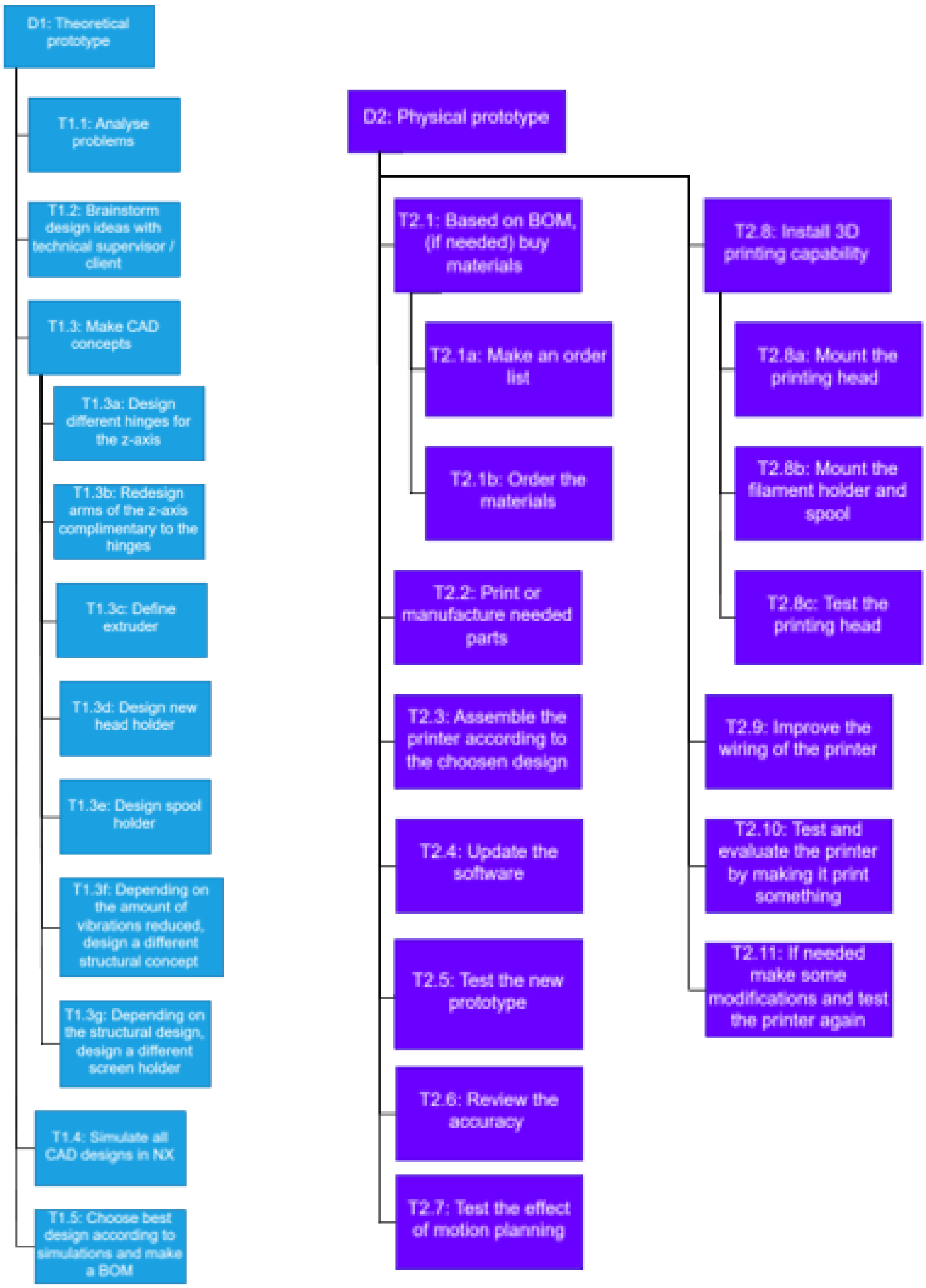

Figure 9. Theoretical and Physical prototypes for Tripteron.

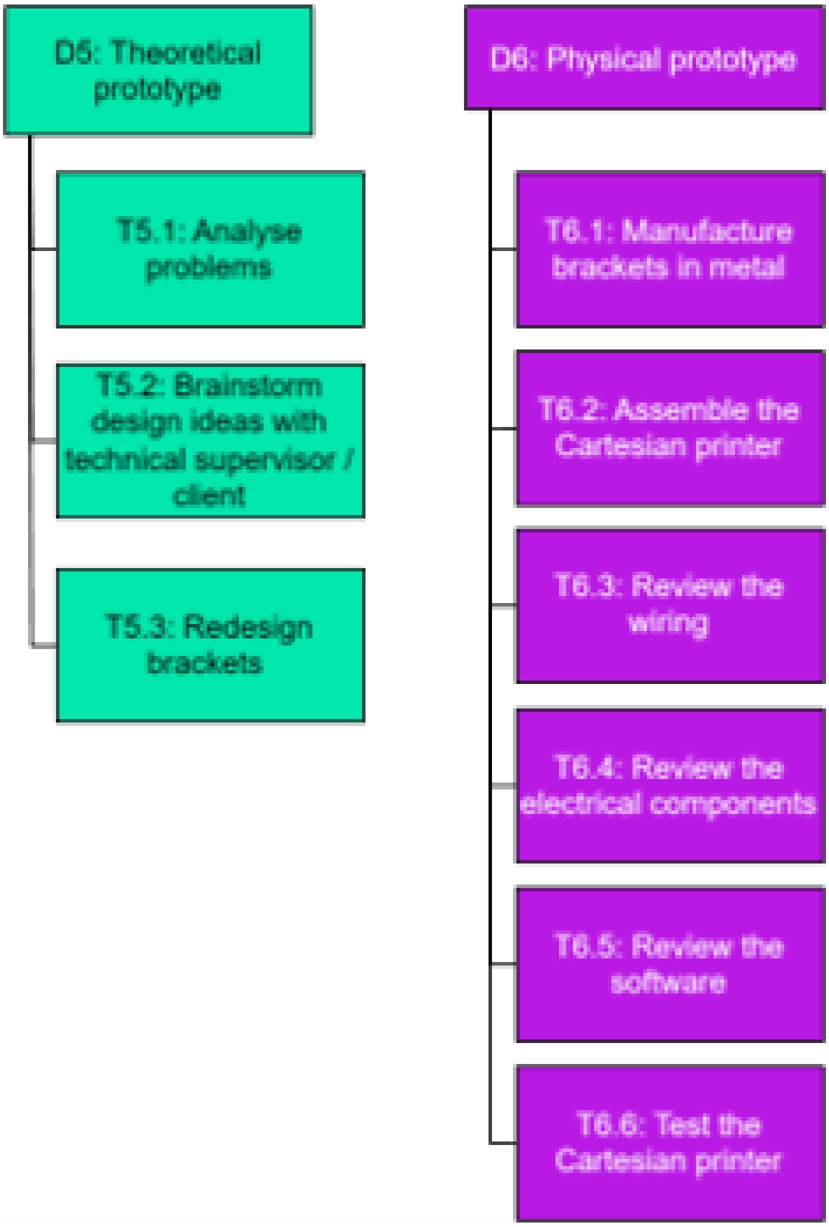

Figure 10. Theoretical and Physical prototypes for Cartesian.

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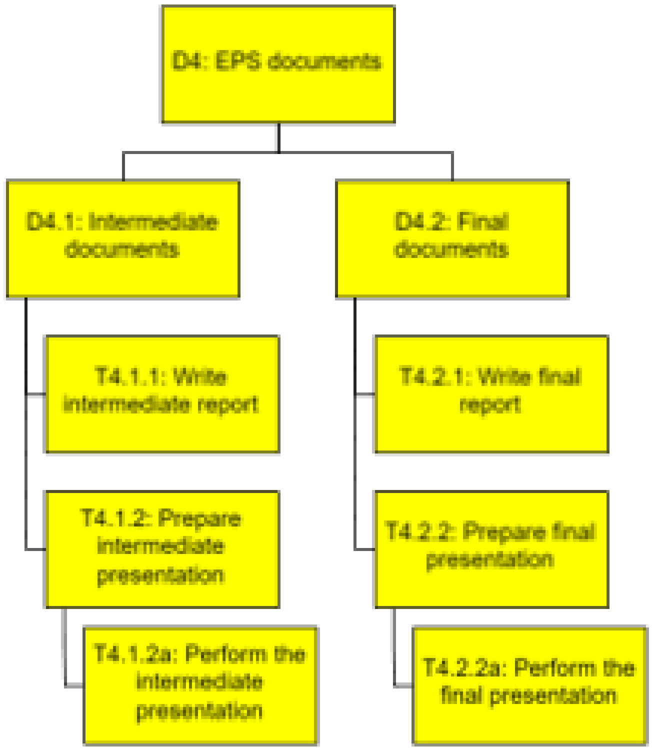


Figure 8. EPS Documents.

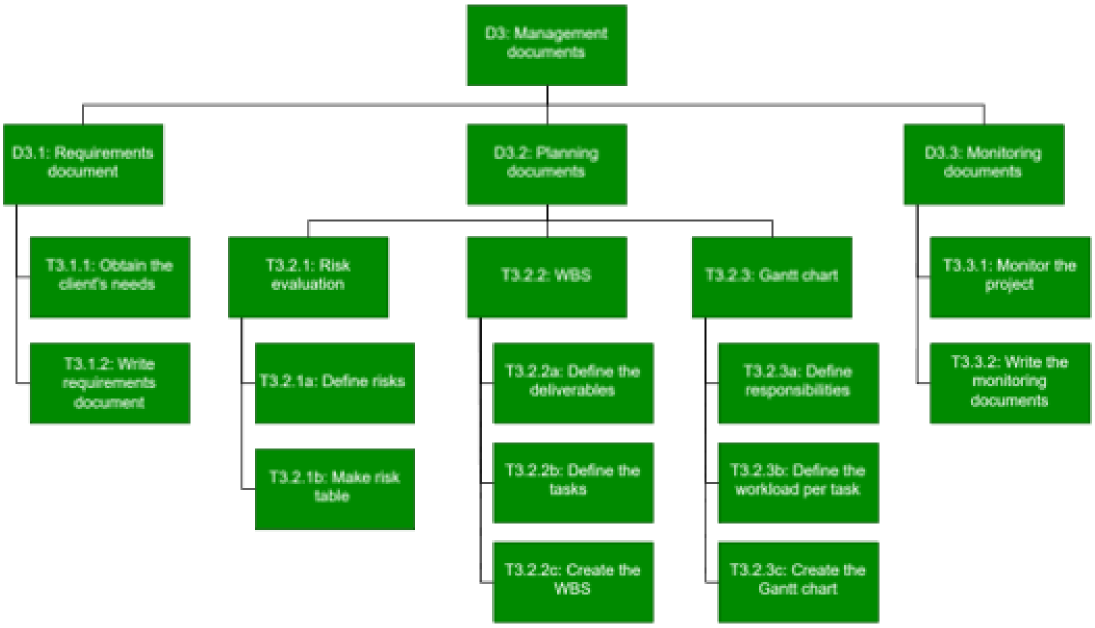


Figure 9. Project Management Documents.

2.4 Deliverables

For this project, the main deliverables are of the Tripteron machine are shown below.

- **D1: Theoretical prototype**
    - A. A concept design in OnShape
    - B. Simulation of the concept in NX
- **D2: Physical prototype**
    - 3D printer assembly
    - Software update required
    - Wiring of 3D printer enhancement
    - 3D printer testing and evaluation
- **D3: Management documentation:**
    - D3.1: Requirements document.
    - D3.2: Planning documents.
        - Risk evaluation
        - WBS
        - Gantt diagram
    - D3.3: Monitoring documents.
- **D4: EPS documents:**
    - D4.1: Intermediate documents.
        - Intermediate report.
        - Intermediate presentation.
    - D4.2: Final documents.
        - Final report.
        - Final presentation.

For the Cartesian machine, the documentation and management deliverables are identical. However, the Theoretical and Physical prototypes are different hence they are numbered D5 and D6.

- **D5: Theoretical prototype**
    - Bracket redesign
- **D6: Physical prototype**
    - Machine assembly
    - Software, electrical components and software review
    - Machine testing

2.5 Milestones

Before explaining the tasks required for each deliverable, the milestones for this project are as shown in the table below.

Table 3. Milestones

05/03/2024	Meeting technical supervisor	
02/04/2024	Submit requirement document	**D3.1**
03/04/2024	Kick-off meeting review	
05/04/2024	Submit intermediate report for review.	**T4.1.1**
08/04/2024	Redesign Z arm and hinge [Tripteron]	**T1.3A**
18/04/2024	Intermediate report	**T4.1.1**
22/04/2024	Begin practical work	
25/04/2024	Intermediate review	**T4.1.2**
06/05/2024	Final Testing Tripteron	**T2.5**
11/05/2024	Begin Cartesian Testing	**T6.6**
03/06/2024	Final Safety and 60kg Operation Checks [Cartesian]	**T6.6**
20/06/2024	Final report	**T4.2.1**
27/07/2024	Final review	**T4.2.2**

2.6 Gantt chart

The Gantt chart reflects the decision to work on both machines simultaneously. Before the April holiday, the team divided our attention between **theoretical (★)**, **project management (★)** and document writing. During the **prototype phase (★)** an exceptionally long period was expected for the manufacturing and printing stage of the project due to potential delays.

Project Start Date:	04/03/2024
Project Name:	3DB EPS

Theoretical	Start	Duration
Analyse	04/03/2024	3
Brainstorm	08/03/2024	3
Measure	29/04/2024	3
CAD	18/03/2024	21
Hinges (T)	18/03/2024	6
Arms (T)	24/03/2024	6
Brackets (C)	30/03/2024	6
Simulate	01/04/2024	6
BOM	06/05/2024	2
Print / Manufacture	22/04/2024	30
Assembly	21/05/2024	5
Test & Measure	27/05/2024	5
60kg Load Test	03/06/2024	1
Project Documents	18/03/2024	21
Requirements	20/03/2024	4
Risk	24/03/2024	4
WBS	28/03/2024	10
Monitoring	02/04/2024	6
Intermediate Report	05/04/2024	14
Final Report	03/06/2024	14
April Holiday	08/04/2024	14

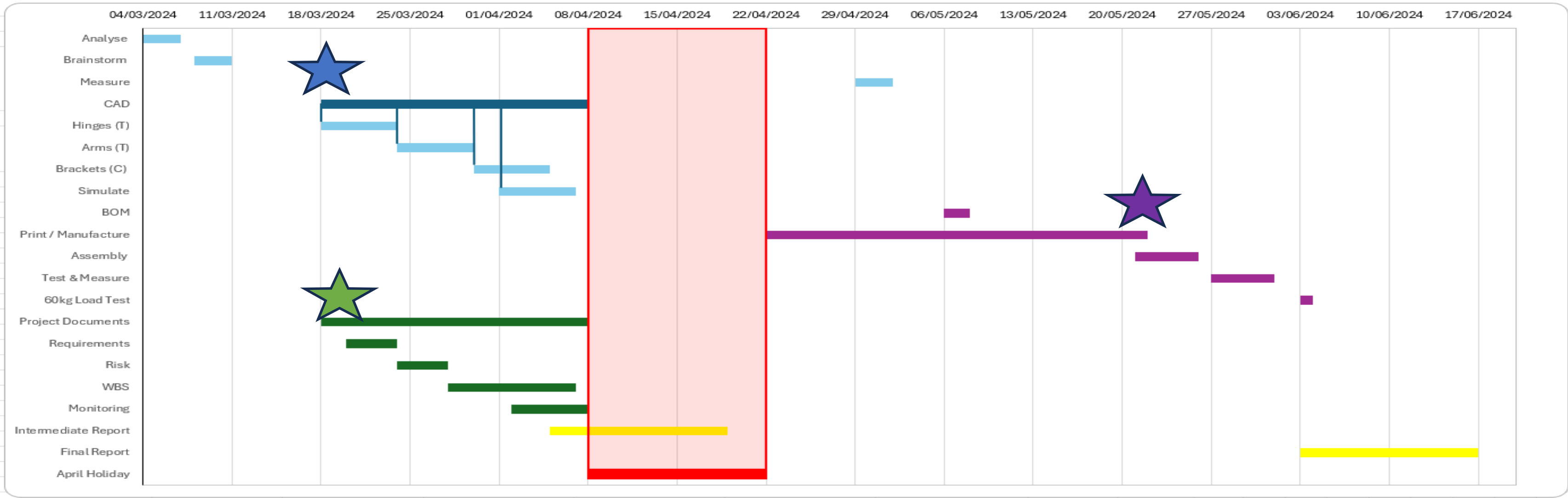


Figure 10. Gantt Chart

2.7 Workload estimation

In Table 6, the workload estimation for each task and deliverable of each 3D printer is provided. The column labelled 'fixed work', measured in hours, represents the total number of hours estimated by the entire group for a specific task or deliverable. It should be noted that while this figure reflects the collective effort, individual group members may not necessarily allocate the same amount of time to each task. The fixed work hours per (sub-)task are based on the previous report and our experiences in similar projects throughout each team members studies.

The way the team has divided the responsibilities of each task is by considering academic backgrounds, strengths and weaknesses of each member. For example, team member Benjamin Livingstone is studying electrical engineering so he was responsible for most of the electrical-related tasks such as task T6.4: Review the electrical components (see Table 7). Team member Ikechukwu Danromy Omodolor Omodia is studying mechanical engineering so he was responsible for most of the CAD designing and physical work-related tasks such as task T1.3a: Design different hinges for the z-axis (see Table 6). Lastly, team member Etienne Foissard is a mechatronics engineer. Since this is a broad study, he was responsible for some electrical, software, CAD design and physical work-related tasks such as T1.3e: Design spool holder; T2.4: Update the software; T6.3: Review the wiring (see Tables 6 and 7).

Table 4. Workload estimation for Tripteron 3D printer

Tripteron 3D printer	**Type**	**Task codes**	**Dependency Finish-Start**	**Fixed work (hours)**	**Responsible**
Theoretical prototype	Deliverable	D1		**118**	
Analyse problems	Task	T1.1		10	BL
Brainstorm design ideas with technical supervisor / client	Task	T1.2	T1.1	15	BL
Make CAD concepts	Task	T1.3	T1.2	50	ID
Design different hinges for the z-axis	Sub-task	T1.3a		40	ID
Redesign arms of the z-axis complimentary to the hinges	Sub-task	T1.3b		7	ID
Define extruder	Sub-task	T1.3c		3	EF
Design new head holder	Sub-task	T1.3d	T1.3c	6	ID
Design spool holder	Sub-task	T1.3e		2	EF

Depending on the amount of vibrations reduced, design a different structural concept	Sub-task	T1.3f		45	ID
Depending on the structural design, design a different screen holder	Sub-task	T1.3g		3	BL
Simulate all CAD designs in NX	Task	T1.4	T1.3	35	ID
Choose best design according to simulations and make a BOM	Task	T1.5	T1.4	5	BL
Physical Prototype	Deliverable	D2		**127**	
Based on BOM (if needed), buy materials	Task	T2.1	T1.5	14	EF
Make an order list	Sub-task	T2.1a		13	EF
Order the materials	Sub-task	T2.1b	T2.1a	1	EF
Print or manufacture needed parts	Task	T2.2	T1.5	10	BL
Assemble the printer according to the chosen design	Task	T2.3	T1.5, T2.2	25	ID
Update the software	Task	T2.4		15	EF
Test the new prototype	Task	T2.5	T2.3, T2.4	12	BL
Review the accuracy	Task	T2.6	T2.5	2	BL
Test the effect of motion planning	Task	T2.7	T2.3, T2.4	5	BL

Install 3D printing capability	Task	T2.8	T2.3	8	BL
Mount the printing head	Sub-task	T2.8a		2	EF
Mount the filament holder and spool	Sub-task	T2.8b		2	ID
Test the printing head	Sub-task	T2.8c		4	BL
Improve the wiring of the printer	Task	T2.9		6	BL
Test and evaluate the printer by making it print something	Task	T2.10	T2.6, T2.7, T2.8	20	BL
If needed make some modifications and test the printer again	Task	T2.11	T2.10	10	ID

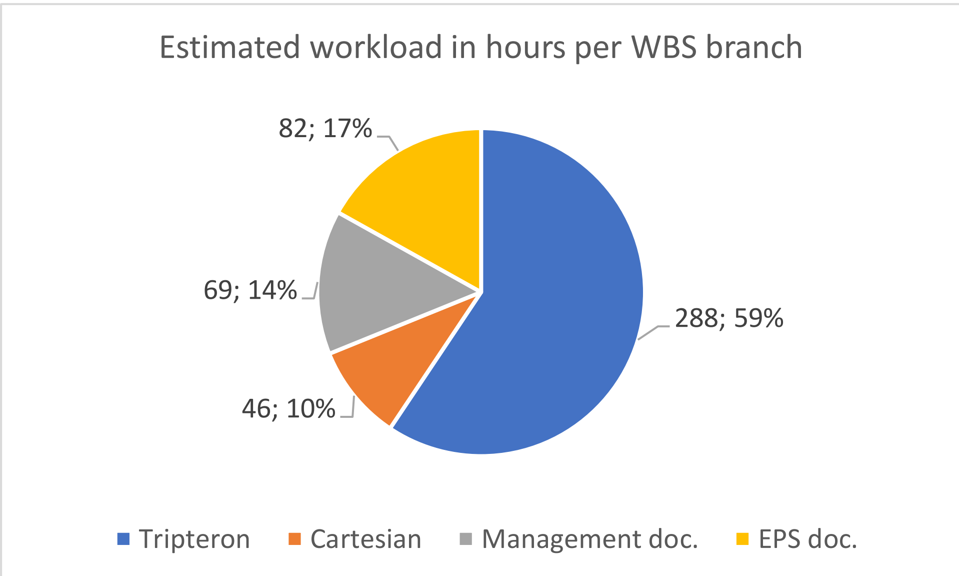
Table 5. Workload estimation for Cartesian 3D printer

Cartesian 3D printer	**Type**	**Task codes**	**Dependency Finish-Start**	**Fixed work (hours)**	**Responsible**
Theoretical prototype	Deliverable	D5		**18**	
Analyse problems	Task	T5.1		10	BL
Brainstorm design ideas with technical supervisor / client	Task	T5.2	T1.1	5	ID
Redesign brackets	Task	T5.3	T1.2	3	ID
Physical Prototype	Deliverable	D6		**28**	
Manufacture brackets in metal	Task	T6.1	T1.5	Outsourced	EF
Assemble the Cartesian printer	Task	T6.2		6	EF
Review the wiring	Task	T6.3	T2.1a	3	EF
Review the electrical components	Task	T6.4	T1.5	3	BL
Review the software	Task	T6.5	T1.5, T2.2	6	ID
Test the Cartesian printer	Task	T6.6		10	EF

Table 6. Workload estimation for Management and EPS documents

Management documents	Deliverable	D3		**69**	
Requirements document	Sub-deliverable	D3.1		15	
Obtain the client's needs	Task	T3.1.1		10	EF
Write requirements document	Task	T3.1.2		5	BL
Planning documents	Sub-deliverable	D3.2		29	
Risk evaluation	Task	T3.2.1		10	EF
Define risks	Sub-task	T3.2.1a		5	EF
Make risk table	Sub-task	T3.2.1b	T3.2.1a	5	EF
WBS	Task	T3.2.2	T3.1.3	14	EF
Define the deliverables	Sub-task	T3.2.2a		4	BL
Define the tasks	Sub-task	T3.2.2b	T3.2.2a	4	EF
Create the WBS	Sub-task	T3.2.2c	T3.2.2a, T3.2.2b	6	EF
Gantt chart	Task	T3.2.3		5	BL
Define responsibilities	Sub-task	T3.2.3a	T3.2.2	1	All
Define the workload per task	Sub-task	T3.2.3b	T3.2.2	2	EF
Create the Gantt chart	Sub-task	T3.2.3c	T3.2.2, T3.2.3a, T3.2.3b	2	BL
Monitoring documents	Sub-deliverable	D3.3		25	
Monitor the project	Task	T3.3.1		15	ID
Write the monitoring documents	Task	T3.3.2	T3.3.1	10	BL

EPS documents	Deliverable	D4		**82**	
Intermediate documents	Sub-deliverable / Milestones	D4.1		41	
Write intermediate report	Task	T4.1.1		30	BL
Prepare intermediate report	Task	T4.1.2	T4.1.1	10	BL
Present the intermediate presentation	Task	T4.1.2a	T4.1.2	1	All
Final documents	Sub-deliverable / Milestones	D4.2		41	
Write final report	Task	T4.2.1	T4.1.1	30	BL
Prepare final presentation	Task	T4.2.2	T4.2.1	10	BL
Present the final presentation	Task	T4.2.2a	T4.2.2	1	All



2.8 Risk Management

The following section will discuss the risks of the project and how the team has actively prevented those risks from occurring.

The major risks of our project are as follows:

1. [Tripteron] Inadequate rigidity from printed/plastic arms, potentially rendering hinge redesign ineffective and thereby proving a necessity of metallic arms.
2. [Global] Not meeting the expectations for both machines.

The minor risks have been assessed using the 5M-tool.

1. Man
    - Lack of knowledge in 3D printing.
    - A team member or supervisor cannot work due to sickness/absence.
    - Insufficient communication between team members.
    - Lack of responsibility/ownership of a deliverable/task.
    - Technical Supervisor François Grizet in China for the early stages of the project.
2. Media
    - Limited access to school due to a global pandemic or an environmental disaster.
    - Loss of documents.
3. Machine
    - Short circuit due to loose/poor of insulation wires.
    - Exposed or extraneous conductive parts.
    - Electrical components become defective after connection.
    - Motors unexpectedly become overloaded.
    - A bug in the software and/or a defective electrical component(s) leads to breaking of a mechanical component.
    - Not safe for use.
    - Ordered components are delayed.
    - Practical results don't match expectations based on simulations.
    - Unable to complete the secondary objective for the Cartesian machine.
4. Management
    - Poor strategic planning.
    - Development starts too late due to design decision making.
    - Failure in talent management.
    - Unable to begin practical work prior to Intermediate Review.
5. Mission
    - Losing sight of the objectives and deliverables.
    - Difference of opinion leading to suboptimal results.
    - Unable to strategize and plan for two projects in one semester.

In Table 3 the risk matrix can be found. This is a tool used to give the risks, defined at the beginning of this chapter, a risk index from 1 to 25. This is done by defining the odds of the risk happening as well as the impact of the risk on the project. With the help of Table 7, a risk index can then be given to that risk. Additionally, by referring to the legend provided in Table 8, the significance of each colour within the risk matrix can be determined.
The risk table, found in Table 9, provides each risk with a corresponding risk index, along with preventive measures and suggested corrective actions in case the risk occurs.

Table 7. Risk matrix.

Impact / **Odds**	Negligible (1)	Minor (2)	Moderate (3)	Major (4)	Severe (5)
Rare (1)	1	2	3	4	5
Unlikely (2)	2	4	6	8	10
Possibly (3)	3	6	9	12	15
Probably (4)	4	8	12	16	20
Almost certainly (5)	5	10	15	20	25

Table 8. Legend of the risk matrix.

Colour	**Meaning**
	Very low risk
	Low risk
	Medium risk
	High risk
	Extreme risk

Table 9. Risk table.

Category	**Risk**	**Odds (1-5)**	**Impact (1-5)**	**Index**	**Preventive measures**	**Corrective measures**
Man	Lack of knowledge in 3D printing	2	3	6	Ensure that students get involved in robotics education and training to acquire knowledge	Seek guidance from supervisors to acquire specific skills necessary to overcome any knowledge gaps.
	A team member or supervisor cannot work due to sickness/absence	3	4	12	Standard hygienic measures	Utilise work from home options
	Insufficient communication between team members	1	5	5	Make use of communication channels as team meetings and project	Organise team buildings activities to improve communications

					management to facilitate regular and transparent communications	and trust among team members
	Lack of responsibility/ownership of a deliverable/task	2	4	8	Make clear expectations every week regarding deadlines, quality standards for each task or deliverable.	Provide clarifications and guidance to ensure everyone understands what is required of them.
	François Grizet in China for the early stages of the project.	5	2	10	N/A	Focus on defining priorities and objectives for the first machine until recieving further guidance on the Cartesian.
Media	Limited access to school due to a global pandemic or an environmental disaster	1	5	5	Not applicable.	Unforeseeable.
	Loss of documents	1	4	4	Put every document online with autosave on and have a copy on an external hard drive.	Rewrite the document or retrieve from external hard drive.
Machine	[Tripteron] Inadequate rigidity from printed/plastic arms, potentially rendering hinge redesign ineffective and thereby proving a necessity of metallic arms.	2	5	10	Have the hinge and arms redesign be simulated prior to usage.	Do research on a different solution to the Tripteron kinematics. This may involve using metallic arms.
	Short circuit due to lose or poorly insulated wires	1	5	5	Ensure that electrical wiring and equipment are installed according to safety standard.	Replace and repair damaged wires with new ones.
	Exposed or extraneous conductive parts	1	5	5	Ensure the entire build is in accordance with safety standards.	Visual inspection and fault testing.

	Electrical components become defective after connection	2	3	6	Revise the connections to check if they are well connected as well as testing the components.	Replace the electrical component.
	Motors unexpectedly become overloaded	2	4	8	Comparing the calculated maximum loads on the axes and motors.	Decrease the load on the axis.
	A bug in the software and/or a defective electrical component(s) leads to breaking of a mechanical component	3	3	9	Check/Test the software and every electrical component before testing the printer.	Correct the bug and/or replace the electrical as well as the broken mechanical component.
	Not safe for use	1	5	5	Testing the 3D-printer and make sure there is a working emergency stop.	Assess, eliminate hazards and test the printer again.
	Ordered components are delayed	3	3	9	Order the needed components as early as possible.	Reorder from another supplier.
	Practical results don’t match expectations based on simulations.	2	4	8	Verifying expectations with technical supervisors.	Verify that the simulation settings are correct. If so, try to understand why. If there is enough time, reassess and redesign potential solutions to reduce the vibrations.
Management	Poor strategic planning	2	4	8	Develop and monitor a Gantt chart and WBS to keep ahead of schedule. Plan a scheduled period every week to confirm all tasks are up to date.	Allocate extra work hours to catch-up on anything missed.
	Development starts too late due to design decision making	2	4	8	Minimise the amount of designs, include brainstorming	Allocate extra work hours to catch-up on anything missed.

					sessions to establish our ideas before the design phase.	
	Failure in talent management	1	4	4	Continually assess our skills/strengths and their utilisation.	Ask guidance from technical supervisors and project manager.
	Unable to begin practical work prior to Intermediate Review.	5	2	10	Efficiently manage and optimize the utilisation of allocated lab time.	Focus on the project management and define a clear plan for after the holidays.
Mission	[Global] Not meeting the expectations for both machines.	3	4	12	Work on both project simultaneously.	Presenting our best findings and explanations of why the expectations were unattainable. And redefine the expectations with technical supervisors.
	Losing sight of the objectives and deliverables	1	5	5	Gantt chart and WBS revision. Having a clear and defined end-goal to work towards.	Allocate extra work hours to work on the objectives and deliverables.
	Difference of opinion leading to suboptimal results	2	4	8	Discuss opinions pre-emptively and arrange for resolutions so that the client is satisfied.	Arrange meetings with technical supervisors, project manager and client to resolve conflicting opinions.
	Unable to strategize and plan for two projects in one semester	3	5	15	Discuss with supervisors the balance / workload and available options.	Discuss with the supervisors to prioritize one project.

This semester, the risks were prevented with effective project management and consistency throughout the semester. Effectively managing our time, reviewing our progress and planning schedule has prevented any severe risks from occurring.

3 Technical Solutions

This section will discuss the solutions to the problems for each machine. Focusing on the considerations made for all designs and then elaborate on each of the solutions.

3.1 Design for Manufacturing and Assembly (DFMA)

DFMA is a critical aspect of engineering that integrates design and manufacturing considerations for the optimisation of assembly. For this project, most parts were manufactured or 3D printed here at ENIT. However, for large-scale projects, where parts may need to be manufactured thousands of times, small inaccuracies or inconsiderate mistakes can compound to enormous losses of time and resources.

A crucial part of this project was to ensure that each designed part could be easily manufactured or printed without technical difficulties or confusion. So that in later stages, there would be minimal downtime for manufacturing delays.

The following sections of this report will outline the technical challenges faced for each machine and how DFMA was considered at each point of the solutions stage.

3.2 The Challenges (Tripteron)

As mentioned previously, the team assessed the lack of strength to come from the Z-arm. The initial visual analysis of the problem identified clear torsion and slight flexion of the supporting arm (shoulder to elbow) and flexion of the forearm (elbow to wrist).

3.2.1 Torsion

Torsion is defined as the twisting of an object under an applied force. While in a static position, the torsion of the supporting arm is clear through visual inspection alone. This suggests the load is too much for the current design of the arm.

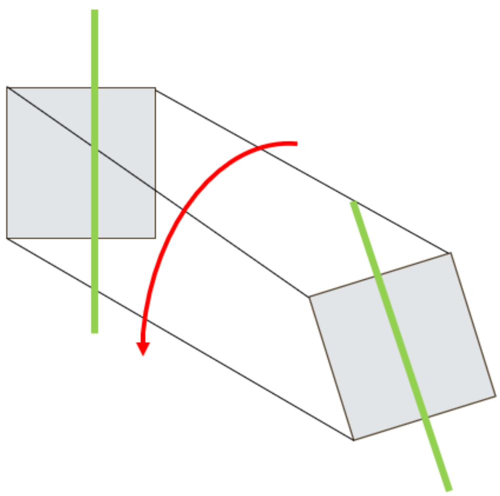


Figure 11. Graphical representation of Torsion.

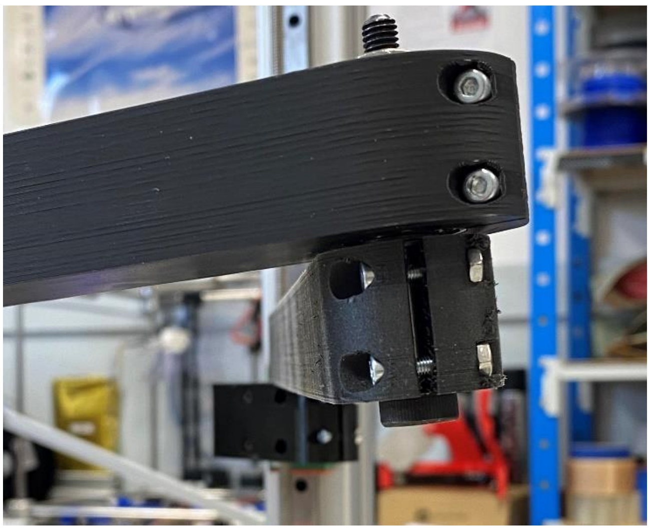


Figure 12. Photographic representation of Torsion.

3.2.2 Flexion

Flexion is defined as the bending of a joint or limb. As shown below, the printing head was too heavy for this design. The previous design of the arm was not strong enough for its purpose.

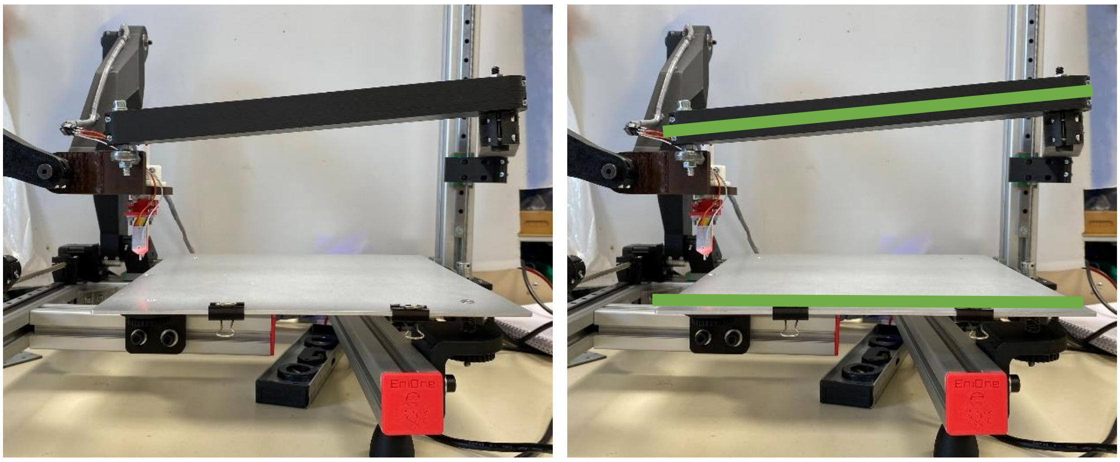


Figure 13. Photographic representation of Flexion.

Any solution to the arm should overcome both the issues of torsion and flexion. It was agreed that the issues of torsion were due to insufficient width of the supporting arm and that the flexion was due to insufficient height of the forearm.

3.2.3 Stress

In physics, stress (σ) is defined as a force (F) being applied to a cross-sectional area (A):

$$\sigma = \frac{F}{A}$$

To solve the problems of torsion and flexion in each section of the Z-arm, a plausible solution was to increase the cross-sectional area of each arm. Based on the above formula, increasing the area would reduce the stress.

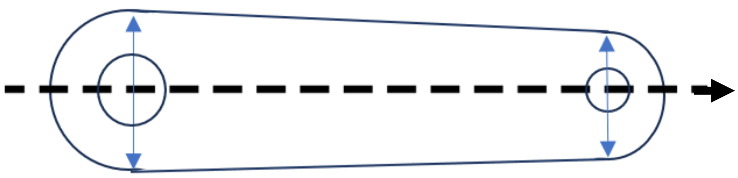


Figure 14. Illustration of Variable Cross-Section

The previous designs for each arm had more width at the sides closer to the Z-axis, as illustrated in the image below. This variable cross-section led to increased stress at the front end of each arm. The comparative values of the dimensions of the new arm are shown in the table below. 70mm of height was added to the forearm. 95mm of height was added to the supporting arm with an additional 130mm of width. The additional material in both the X and Y planes adds to the rigidity of the arm and reduces the impact of both flexion and torsion forces. The measurements of the old and new versions of the Z-arm components can be found in Table 10.

Table 10. Measurements of old and new versions of the Z-arm.

Version	Forearm (mm)		Support-Arm (mm)		Shoulder (mm)	
V1 – Fall 2023	W: 42	H: 25	W: 40	H: 25	W: 72.65	H: 32
V2 – Summer 2024	W: 30	H: 95	W: 170	H: 120	W: 35	H: 96

3.3 Designing a New Arm for the Tripteron.

Initial concept drawings considered the reduction of excess materials and the ability to easily 3D print the designs. A crucial balance between having enough material to provide the support while not so much as to be too heavy or cause a collision with other sections of the machine was considered throughout.

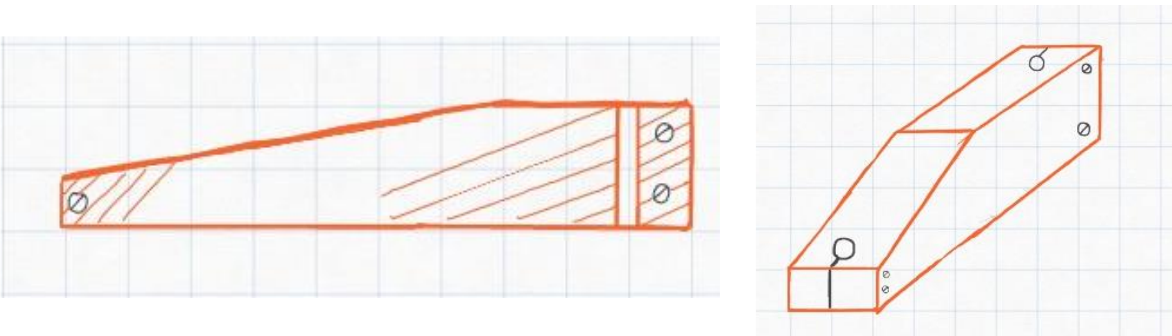


Figure 15. Initial Concept drawings for Forearm.

The weight of the printing head would become redundant if the forearm had sufficient material at the elbow joint to support the load. Additional weight towards the printing-head side could be reduced, saving excess material. A triangular shape was chosen towards the printing-head side with a rectangular shape closer to the elbow. This is because most of the flexion in the forearm is closest to the elbow joint, so more height was needed there.

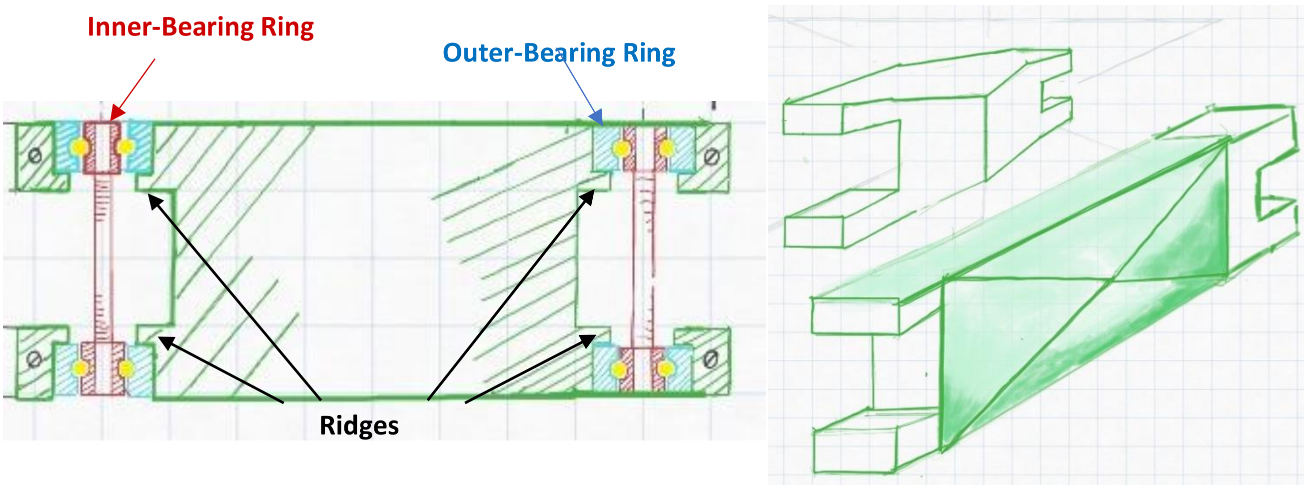


Figure 16. Initial concept drawing for supporting arm.

The supporting arm was designed with consideration of fitting bearings so that they would be secure and easy to install. It was necessary to also consider the ease of rotation of the inner bearing ring while keeping the outer bearing ring fixed to the arm. Extending the material across the width of the arm would reduce the torsion by providing additional strength across the horizontal plane. Ridges were added to the internal side of each bearing to prevent the complete assembly of the bearing and shaft from moving up and down.

The following sections will outline how all the considerations were imagined during the CAD process.

3.3.1 Forearm

The first step of designing the Z-arm was defining the distances between each hinge. The first requirement of this project was to maintain all kinematics. Thus, regardless of the width or height of each arm, the distance between each joint would remain the same. The distance from the ball-joint at the wrist to the shoulder-joint was measured at 300mm and the distance from the shoulder to the elbow was 290mm. It was crucial to keep these measurements so as not to change the kinematics of the printer.

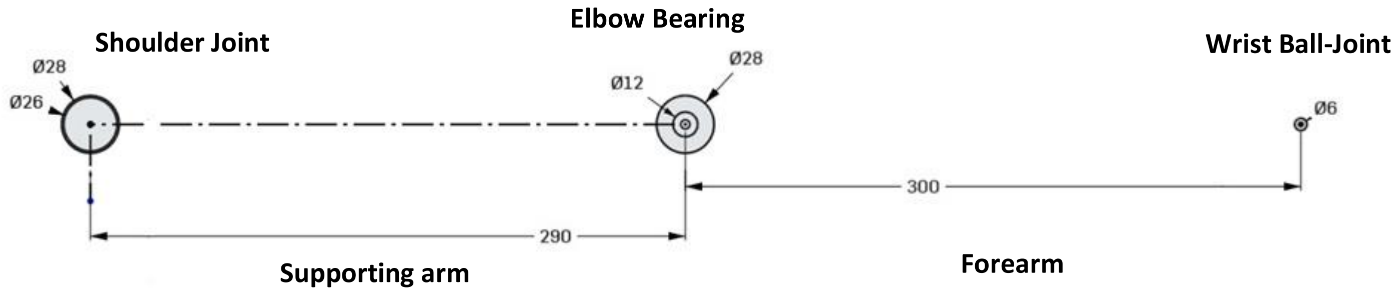


Figure 17. Onshape dimensions between each joint.

Four bearings with 28mm outer and 12mm inner diameter were chosen because there were already two in the EniOne lab available and the solutions could be designed to utilise existing materials. The slots for the shoulder bearings on the supporting arm were designed with a 2mm rim of material to stop them from moving due to axial load. Once the dimensions were accurately prepared, the designs for each arm went ahead. The forearm was designed with a 12mm diameter aluminium cylinder fixed within the elbow bearings and a 6mm aluminium cylinder at the wrist. The material around each hole would be tightened with screws to create a secure fixing around the bearings so additional holes were included around the fixings at each end of the arm. With DFMA in mind, the distances between the cylinder and the external edges were determined to provide enough strength without unnecessary use of material.

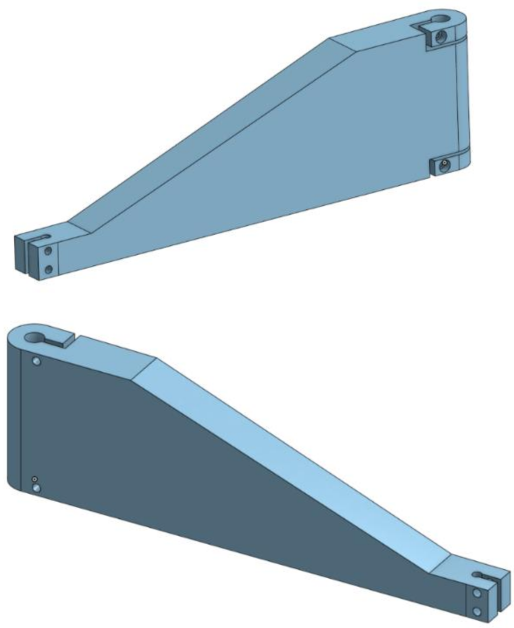


Figure 18. CAD Models – Forearm.

3.3.2 Supporting Arm

With DFMA in mind and while considering the necessity of having additional material at the sides for the reduction of torsion. A triangular protrusion was designed for each side of the supporting arm. This solution was able to simultaneously increase the rigidity of the arm while minimising the use of materials. Due to the layer-by-layer method of 3D printing, problems would occur while 3D printing this piece if the angle (ɸ) of the material protruded beyond 45°. This is because there would be no support for the additional material and it would ultimately collapse.

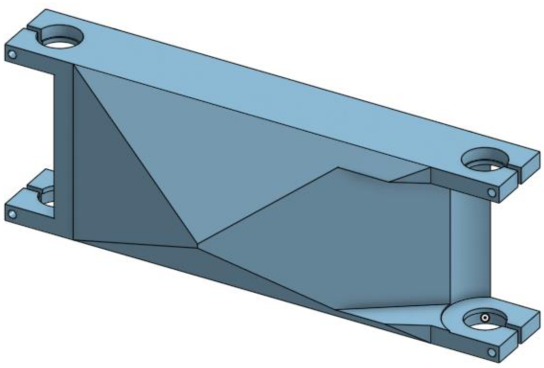


Figure 19. Trimetric view of Supporting-Arm

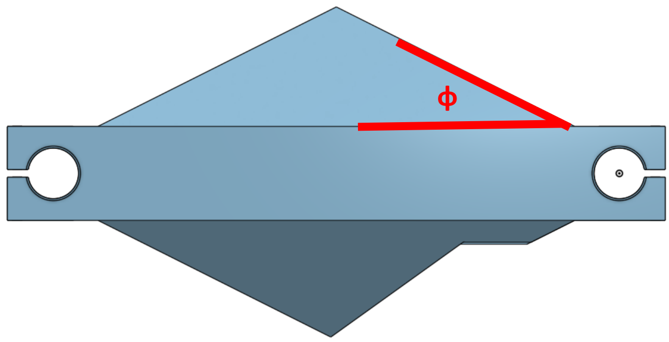


Figure 20. Top-down view of Supporting-Arm

3.3.3 Shoulder Attachment

Due to the new dimensions, the shoulder was redesigned to incorporate the new height, width of the supporting arm, and the new diameter of the axis.

The design was made to utilise two sliding rails along the Z-axis for additional support at the base of the arm. It also provides enough strength around the axis to hold it in place while allowing the screws to tighten. The rounded edge allows for rotation within the supporting arm. The vertical hole closest to the sliding rails allows the screw axis to pass through, enabling the entire Z-arm to move up and down.

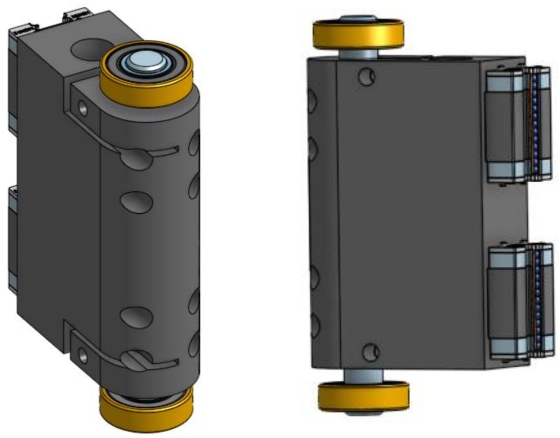


Figure 21. CAD model of Shoulder

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3.3.4 Digital Assembly

After completing the shapes and dimensions for each section of the arm, the final assembly phase began. Each part was integrated into the same digital studio which allowed for testing the angles for potential collisions. The final assembly consists of each section of the arm as shown below.

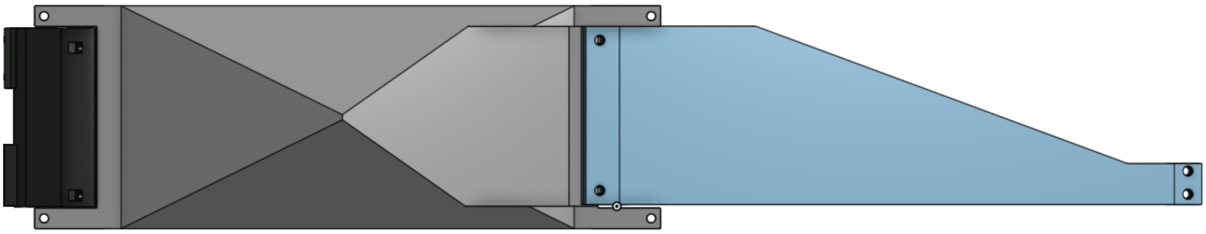


Figure 22. CAD model of Entire assembly.

A collision was observed in the assembly when the arm rotated to a gap between the fore- and supporting arm of approximately 26° at its maximum position. To prevent this collision, material was removed from the final shape of the supporting arm which can be seen in Figures 24 and 25.

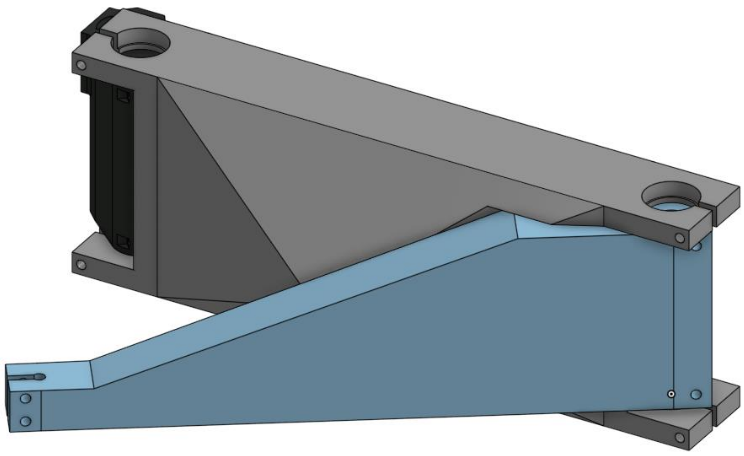


Figure 23. CAD model representation of angle.

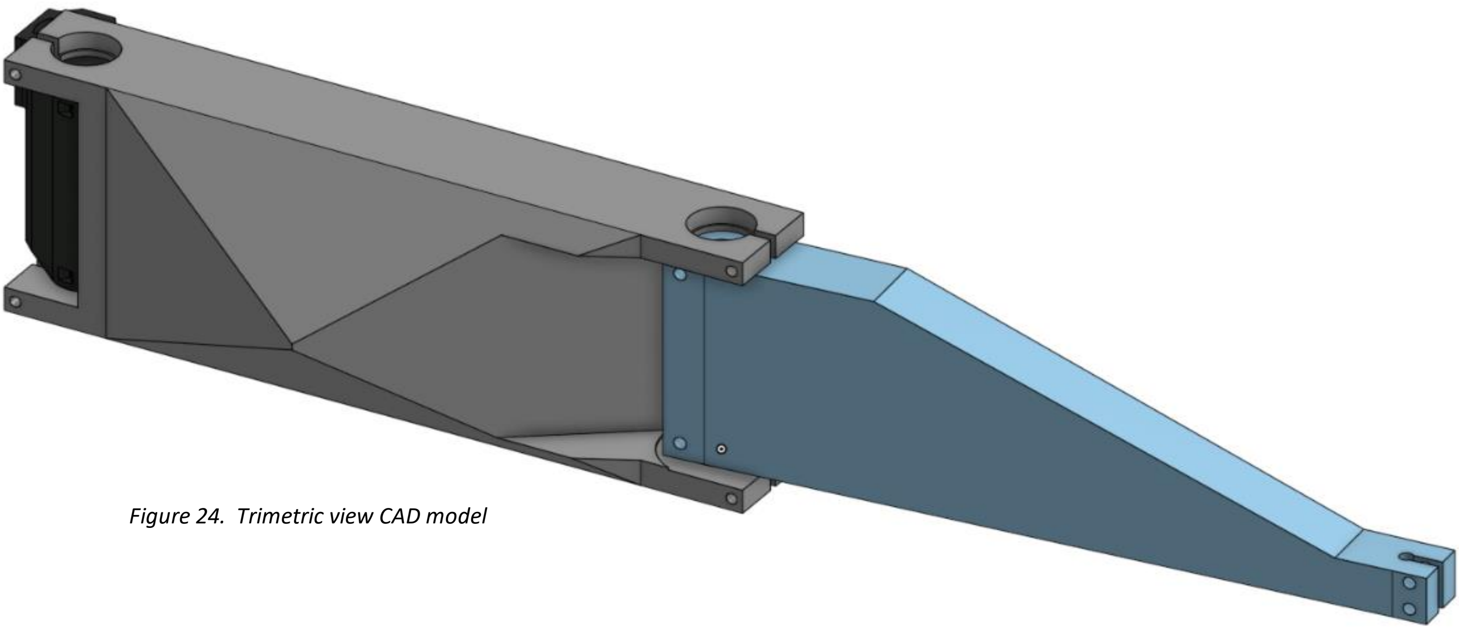


Figure 24. Trimetric view CAD model

3.4 Measurable Displacement Analysis (Tripteron)

To determine the difference in displacement between the previous arms and the new arms, an accelerometer was used to provide a graphical representation of the unwanted motion of the arms.

The Arduino Nano 32 BLE Sense was selected due to its lightweight structure and built-in accelerometer capabilities.

Figure 25. Arduino NANO BLE Sense [www.amazon.fr]

The following video shows the results obtained from the original arm: https://youtu.be/ALH3pSB4KTs

Shown below is a screenshot of the results. At rest, the top graph (Z-axis) sits at a value of one while the bottom graphs (Y- and X-axis) rest at a value of zero. This is because the accelerometer detects the gravitational force applied on the Z-axis and therefore calculates this acceleration differently.

To achieve a maximum unwanted displacement of 0.3mm, the graph would barely move at the end of each motion and be less chaotic throughout its manoeuvrability. Currently, the Z-axis has a displacement of 0.2 on this scale. However, this does not reflect 0.2mm, and without the value of time it's impossible to calculate how much this relates to in millimetres.

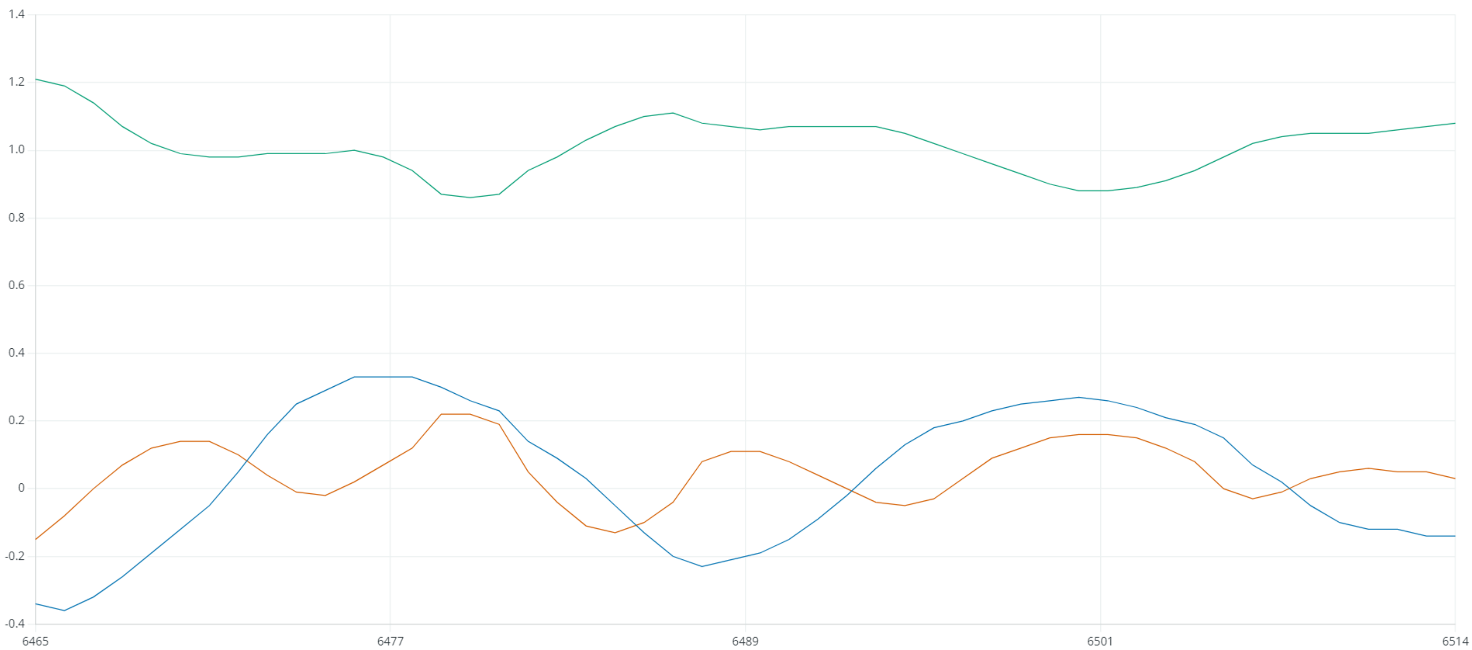


Figure 26. Graph of Displacement.

3.5 Designing and implementing the 3D Printing capability

For any 3D printer, it must contain a part which allows the printing material to be processed and passed onto the printing bed. This is referred to as the 'Extruder'.

A 3D printer extruder exists of two parts: the cold end, and the hotend.

The cold end of a 3D printer extruder is a critical component responsible for guiding and preparing the filament (the thin material which is used in the printer) before it reaches the hotend where it is melted and extruded onto the print bed. The cold end is located at the upper portion of the extruder assembly. Its primary function is to grab the filament, push or pull it, and maintain consistent pressure as it is fed into the hotend.

The cold end comprises the following components to make this work:

Stepper motor: The stepper motor is essential for driving the motion and extrusion of the filament in most modern desktop 3D printers. Since these motors are brushless (meaning the rotating part does not connect and pass electrical current with the non-rotating part) they can offer precise control and full torque at low speeds. They are ideal for accurate filament extrusion. However, additional components are needed to grip and propel the filament towards the hotend.

Gears: In basic extruders, a toothed gear on the motor directly grabs and feeds filament which is known as direct drive. With gearing, the extruders are also used to adjust the torque applied to the filament. Regardless of the type, the cold end includes a filament pathway towards the hotend, along with the motor and gears.

Filament path: A well-defined pathway guides the filament through the cold end. This pathway includes mechanisms that help the material pass alongside spring-loaded bearings. Constriction of the filament path is crucial to prevent issues like deformation while the material passes through the tubing. This is particularly significant when printing with flexible filaments or at high speeds.

3.5.1 Choosing the Extruder

For the selection of the printer head – based on popularity amongst similar projects in the 3D printing community – there were two options: Direct Extruders and Bowden Extruders.

Both serve the same purpose of pushing filament through a heated nozzle. However, the key distinction lies in their placement: direct-drive extruders are mounted on the printhead and directly feed filament into the hotend. In contrast, Bowden extruders are usually attached to the frame, with filament guided through a PTFE tube to the printhead. With direct-drive and Bowden extruders prevalent in most 3D printers, the focus now shifts to comparing their features. This analysis will outline their respective advantages and drawbacks and has helped the team decide which extruder to choose.

3.5.2 Direct Extruders

Direct extruders apply the heat **and** pressure from the printing head. The printing head – also known as the hotend – contains the heating elements and motors which push the material through the nozzle.

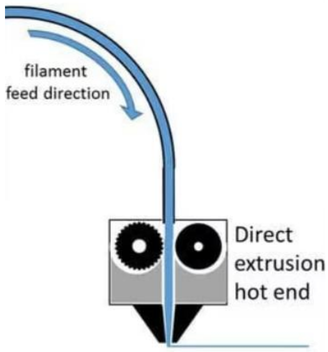


Figure 27. Direct Extruder [6]

Advantages:

- Provides cleaner prints due to its ability to easily reverse the direction of the material.
- Provides accuracy due to the shorter distance between the motor and the printing space.

The critical disadvantage of direct extruders is having additional weight on the printing head. This ultimately contradicts the goals of this project and is why a direct extruder was not chosen.

3.5.3 Bowden Extruders

Bowden extruders reduce weight on the printing head by incorporating a separate part containing the motors. In this project, the main problem was that the arms couldn't support the weight of the printing head. Thus, adding weight to the printing head would worsen the issue of unwanted displacement.

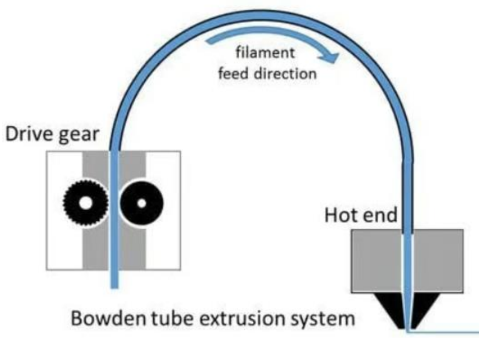


Figure 28. Bowden Extruder [6]

This method was selected so that the drive gear (the motor that creates the force to push the plastic) could be connected to the Z-axis instead of the printing head. In Bowden extruders, PTFE tubing guides the filament to the hotend.

3.5.4 Designing the Bowden extruder holder

This specific Bowden extruder (see Figure 29) was chosen because it was already available in the EniOne lab. Just like the stepper motor (see Figure 30) that is needed to drive the Bowden extruder.

Figure 29. Photo of Extruder

Figure 30. Photo of Stepper Motor

The Bowden extruder system was placed in the middle of the Z-axis to keep the Bowden tube as short as possible. Usually, having a Bowden tube that is too long can cause problems, such as the extruder being unable to retract properly due to the filament stretching and the filament binding at bends. However, since the material being used is PLA, that won't be a problem.

The design made to attach the Bowden extruder system to the Z-axis is quite simplistic (see Figure 27). Using bolts and sliding nuts, it can be easily attached to the Z-arm, and the Bowden extruder and stepper motor can be attached to each other with simple bolts.

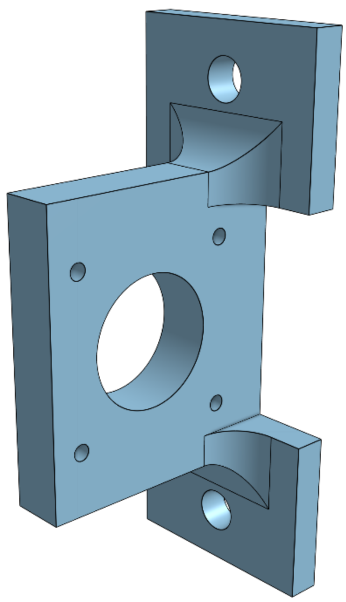


Figure 31. CAD model - Bowden extruder holder.

3.5.5 Designing the printhead

When the Bowden extruder system (cold end of the extruder) pushes the filament through the Bowden tube, the filament arrives at the hotend of the extruder. The chosen hotend is the “Ender 3 MK8 hotend” which can be found in Figure 32.

Figure 32. Hot-End.

Since the previous design was made for holding a pen to demonstrate the kinematics of the design by drawing a shape on a 2D surface, some changes had to be made. A critical factor that had to be kept was the centre point of the pen because this is where the kinematics were built. With this in mind, the centre of the nozzle was designed to be at the same point as the pen's centre. The other components – shown on the next page – such as the ventilator, the fan, the hotend, the height sensor, and the connecting section, are designed around this centre point.

The hotend is used to melt the filament coming from the Bowden extruder. The filament will be melted by the heating element and will exit the hotend through the nozzle. This heating element can reach temperatures of 200°C. To ensure this heat will not interfere with the printing process and the Bowden tube, a direct current (DC) fan is placed on the finned aluminium heat sink (see Figures 35 and 36) to cool down the hotend. During 3D printing, a ventilator is used to cool down the printed filament. It takes air from the side (see the exposed orange part on the side of the ventilator in Figure 36). Attached to the ventilator is a geometric air tube (see Figure 36) that directs the airflow around part of the hotend.

The height sensor (BLTouch) is an automatic level sensor which is used to precisely measure the tilt of the printing bed. This means that if parts of the bed level are higher or lower than zero, the 3D printer will adjust to this height whilst 3D printing. However, for this to work effectively the height sensor’s probe needs to be approximately two millimetres above the lowest point of the hotend. To ensure this feature, slots have been made behind the hotend’s and fan’s screw holes to make this height adjustable. Also, washers can be placed between the connecting section and the height sensor to adjust the height to the hotend’s lowest point.

Figure 33. 3D Probe Sensor

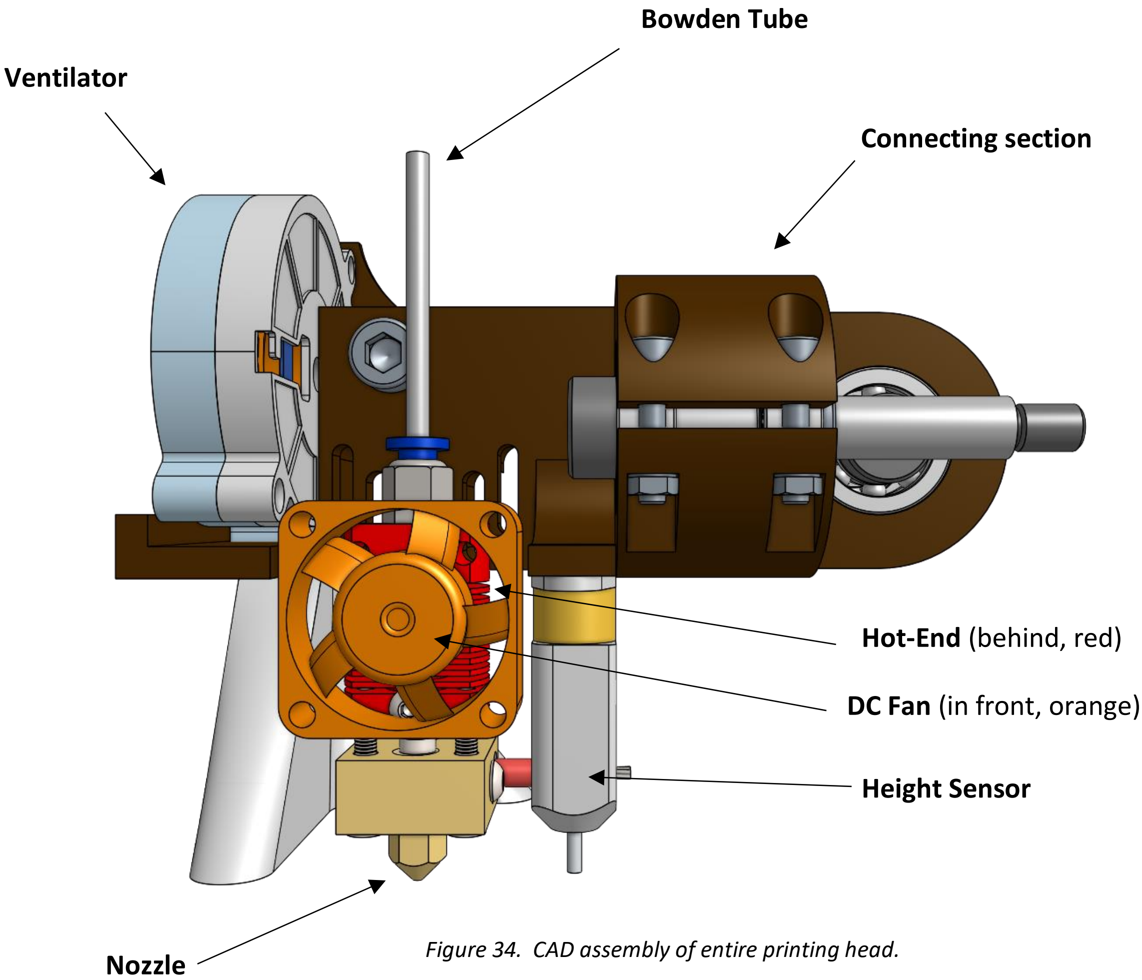


Figure 34. CAD assembly of entire printing head.

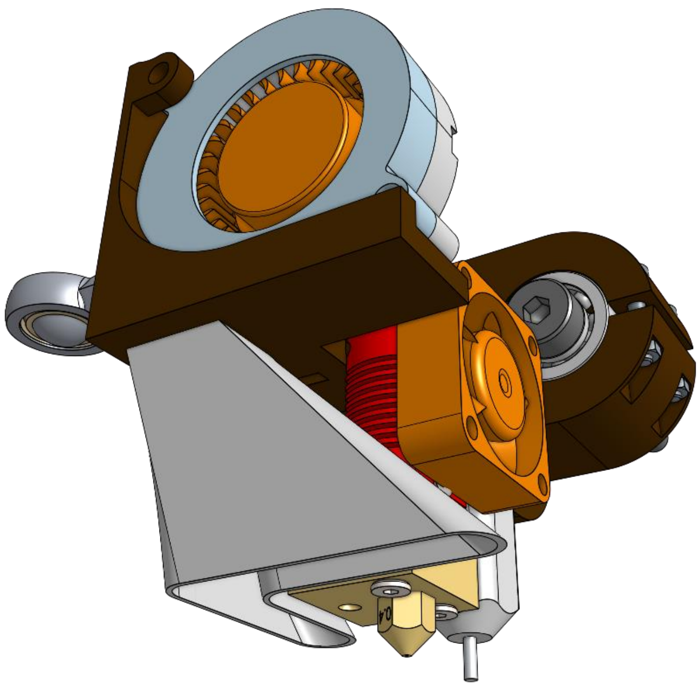


Figure 35. Alternative perspective of entire printing head.

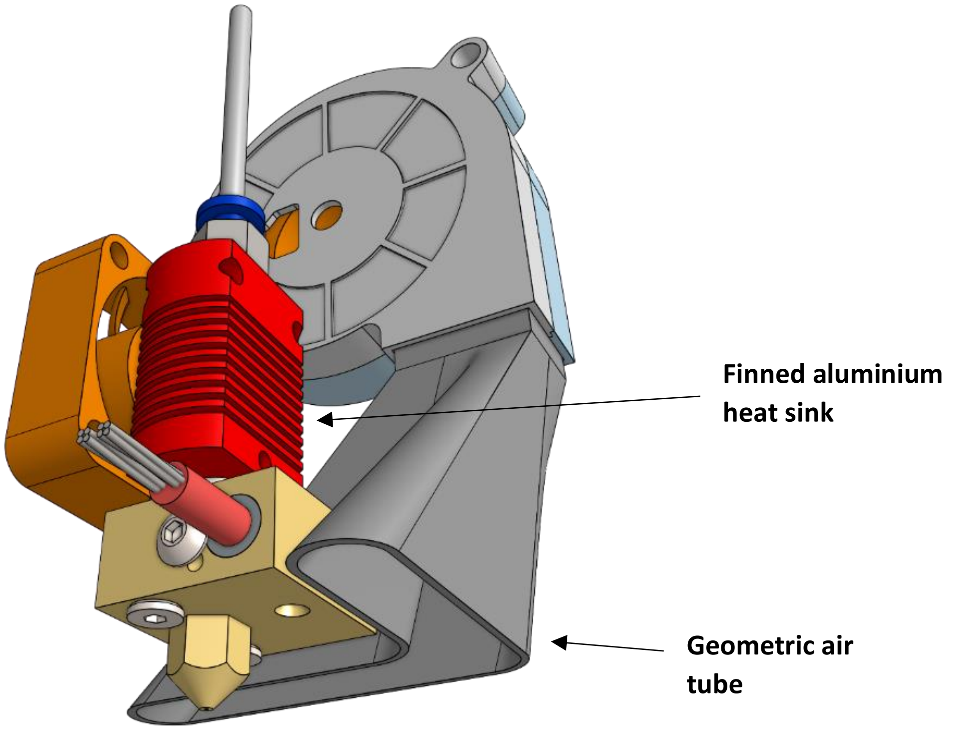


Figure 36. Alternative perspective of entire printing head (2).

3.6 The Challenges (Cartesian)

The main challenge with the Cartesian 3D printer was the strength of the material used for the brackets. The brackets are used to connect the moving inner section to the static outer section while allowing rotation of the threaded rod, as photographed below.

As mentioned in previous sections, PLA was used which is a material prone to degradation. This gives it an inherent brittleness and makes it prone to cracking and breaking under prolonged stress. Especially considering the increase of 60kg load. This is particularly problematic for connecting brackets, which are subject to repeated vibrations in a Cartesian 3D printer.

Figure 37 below shows one of the previous brackets made from PLA, highlighting areas where the material has begun to deteriorate. These visible signs of cracking show that any new material should be durable for long periods.

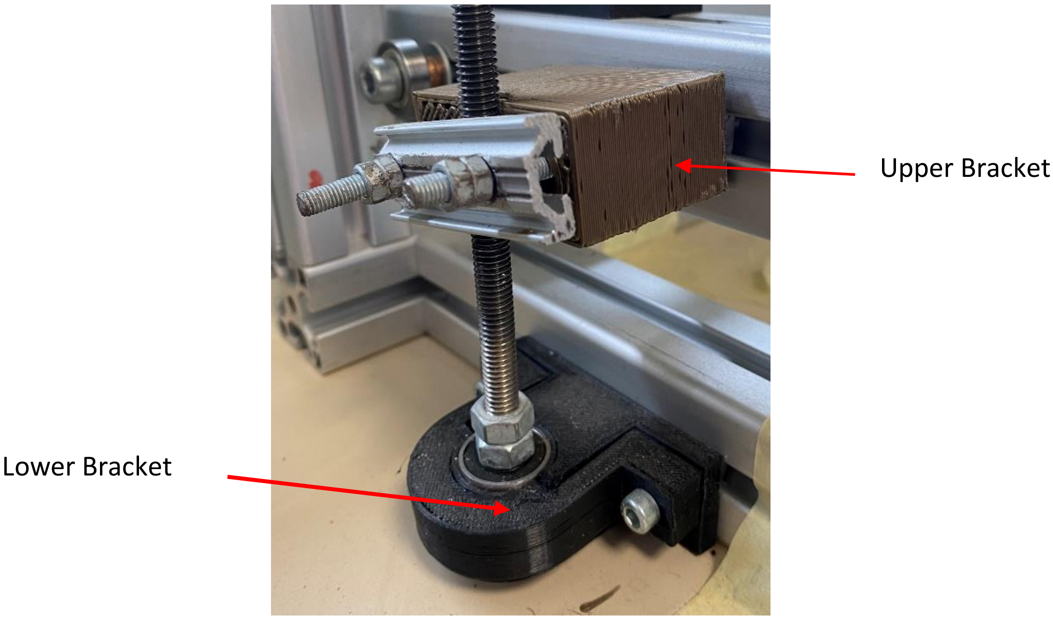


Figure 37. Old brackets.

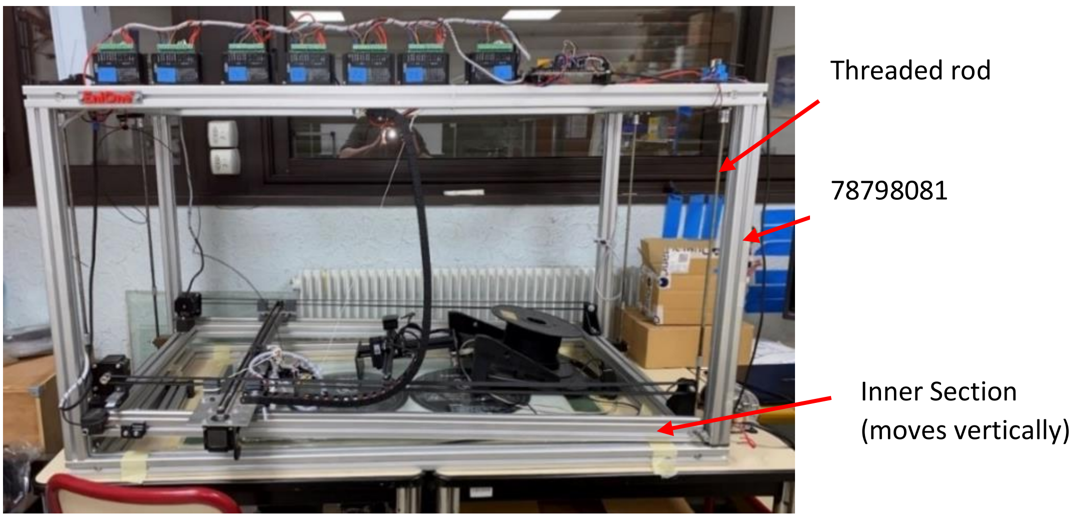


Figure 38. Cartesian photographed.

3.6.1 Comparison of Material Strengths

In this subsection, the considered materials will be displayed alongside the methods used for selection. To determine the strength of each material, the value of Megapascals were compared. Megapascals are a measurement of a materials resistance to stress (N/mm^2) . Newtons (N) are a measurement of force. If holding an apple in your hand, the force of gravity would exert roughly 1N of force. Having a value of Megapascals provides information on the value of newtons (N) of force acting on an area (mm^2).

A suitable material to solve the problem should have high resistance to forces and be able to retain its shape under large loads. A copper-bronze alloy was chosen based on the characteristics shown below.

The table below shows the values of MPa in 2 potential materials for the brackets in comparison with PLA.

Table 11. Properties of potential materials

Property	PLA	Copper-Bronze	Aluminium
Tensile Strength	50-70 MPa	210-370 MPa	90-600 MPa
Yield Strength	48-60 MPa (approx.)	70-210 MPa	35-550 MPa
Characteristics	Rigid, brittle	Ductile, malleable	Lightweight, Versatile.

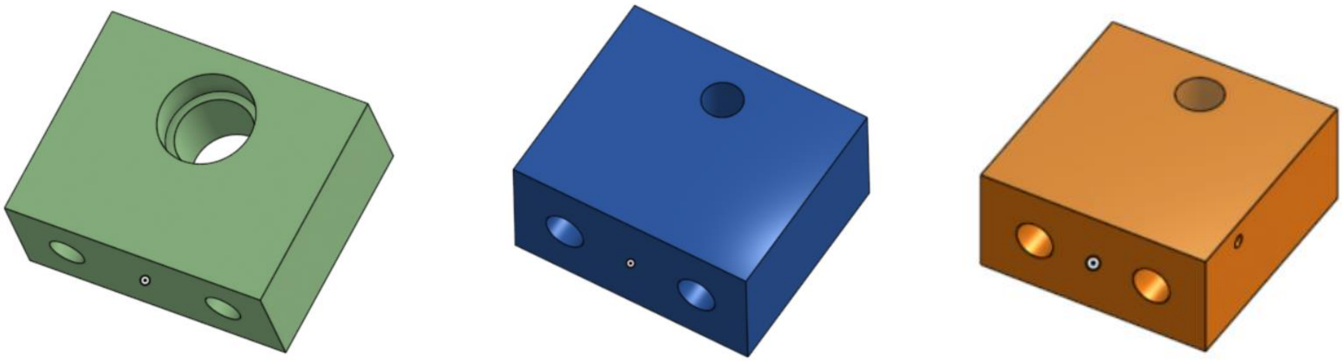
3.7 Designing a New Bracket for the Cartesian

This section will explain the two design phases for the Cartesian brackets and why a critical project management decision was made throughout this process. Three separate brackets were necessary to design. Firstly, because all four corners share a common lower bracket (**Design 1**). Three of the four corners share a common upper bracket (**Design 2**) except for one part on the front-left corner which guides the movement of the inner section along the Y-axis. This corner part needed its own design for an upper bracket (**Design 3**) because it sits closer to the frame and has a different connection. These three designs can be found in Figure 39.

3.7.1 The Original Copper-Bronze Alloy Design

A copper-bronze alloy was the original choice of material due to its strength advantages and high machinability, meaning it can be easily cut, shaped and drilled. Copper also has low friction with steel, meaning any new copper parts could easily slide over the existing steel screws.

Designs were made for this material choice which would allow the threaded rod to rotate within each part exclusively for **Design 2** and **Design 3**. This is because the threaded rod rotates with the inner-ring of the bearing while the outer-ring is fixed within each design.



Design 1 **Design 2** **Design 3**

Figure 39. Original design.

3.7.2 Budget constraints

The quote for the copper-bronze alloy was requested from the manufacturer as shown below. The quoted price was €1,146.00 which exceeded the budget allocation of €1000,-.

Customer correspondent: ABROUG FOUED
Your reference :

Designation	Number	Dimensions	Quantity	u	Unit price	Amount excluding tax
BRONZE UE12-FLAT DIM 65 X 52 LG 700	1		1	u	710.00	710.00
IF NEEDED CCPU (WE CAN HAVE IT ONLY TO ORDER)						
ANALYSIS CERTIFICATE 3.1			1	u	185.00	185.00
PARTICIPATION SHIPPING COSTS			1	u	60.00	60.00
DELIVERY 18 DAYS EXCEPT SALE						

Amount excluding tax	VAT rate 20%	Amount including tax
€955.00	191.00	**€1,146.00**

Figure 40. Quote for copper-alloy.

It was then considered that aluminium could provide all the same benefits for a potentially lower price. Aluminium was readily available in the university and significantly more cost-effective. This change substantially reduced the budget, as it was only necessary to account for the tools for manufacturing. A second quote was made as shown below.

V / Réf :

Référence	Poste	Description	Qté	Délais	P.U. net	MT HT	TVA
11640000400		1164 - FORET LONG HSSCo TiAlN DIN340S Ø4,00x78x119	2	48h	8,78	17,56	20,00
11050001600		1105 - FORET HSSCo DIN338N Ø16	2	48h	27,02	54,04	20,00
11050000420		1105 - FORET HSSCo DIN338N Ø4,2	5	48H	1,36	6,80	20,00
22520005008		2252 - TARAUD MACH. HSSE VAP DIN371/ C R35 HUNIX M5x80 6H	2	48H	10,76	21,52	20,00
N30N3701200		ecoKEN N30N.37 D12x22x83 Z3 K-CROM	2	DISPO	31,63	63,26	20,00
N30N3700500		ecoKEN N30N.37 D5x10x50 Z3 K-CROM	2	DISPO	9,35	18,70	20,00

Devis gratuit. Les prix TTC sont établis sur la base des taux de TVA en vigueur à la date de remise de l'offre. Toute variation de ces taux sera répercutée sur les prix.

Taux	Base HT	Montant TVA
20,00	181,88	36,38

Mode de règlement : VIREMENT 30 J FDM LE 15

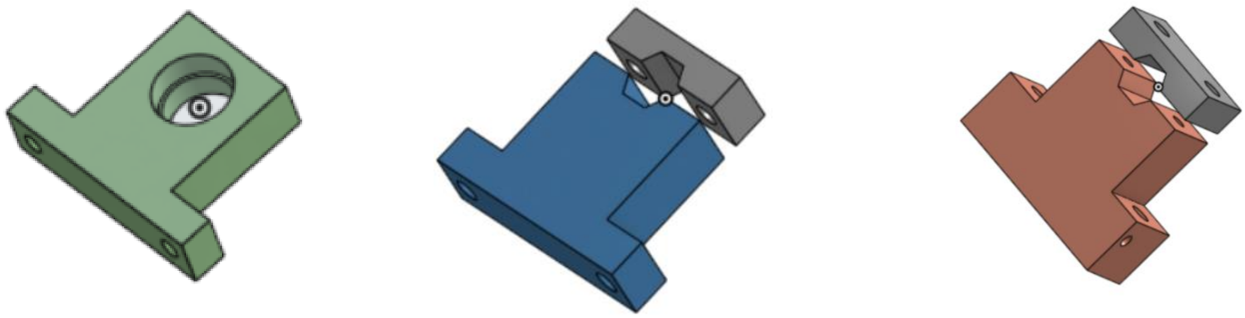
Total HT	181,88
Remise 0,00%	0,00
Total HT remisé	181,88
Port HT	0,00
Total HT Net	181,88
Total TVA	36,38
Total TTC	218,26
Acomptes	0,00
Net à payer	218,26 €

Figure 40b. Quote for aluminium tools.

3.7.3 New Aluminium Design

Consequently, it was decided to revise the initial design and change the material for manufacturing the holder. Due to the new choice of material, a change in design was necessary because an aluminium part could not be used the same way. This is because the friction between aluminium and steel is greater than the friction between copper and steel [9]. This increase in friction would cause faster deterioration of the threading inside the aluminium.

The following designs were created for the new aluminium brackets.



Design 1 **Design 2** **Design 3**

Figure 41. New aluminium design.

As with the previous design. **Design 1** is the lower bracket for all four corners. **Design 2** is the design for the three common upper brackets and **Design 3** is the design for the unique front-left bracket.

The design was changed for the lower bracket because the original plan was to manufacture new screws at ENIT. It was decided to use shorter screws already in the lab. Thus, the lower bracket was designed with shorter sections at each side to incorporate the existing materials. The problem with the original designs for the upper brackets was that the circle inside the aluminium would cause deterioration of the aluminium due to it having a lower Brinell Hardness (BH) value [7]. Aluminium works well for applications requiring a lightweight, lower-strength material with strong corrosion resistance. However, due to its inherent weakness relative to copper, a redesign was necessary.

Separating the parts for **Design 2** and **Design 3** into two sections provided multiple advantages: Being able to spread the load across multiple screws would reduce the stress at the fixed point around the thread. The stress would mostly be applied to the screws, which could be retightened or replaced. This would provide longevity to the part. For the upper brackets, having two separate pieces locked together with screws would compensate for the reduction of strength in aluminium. Where the separate pieces connect, a hexagonal design was incorporated to allow a hexagonal nut (see Figure 42) to stay in place while the threaded rod rotates inside the nut.

Figure 42. Hexagonal Nut.

3.7.4 Orthographic Drawings (Cartesian)

Orthographic projection is a universally followed method of representing a three-dimensional object in two dimensions. The method is to show the necessary perspectives for manufacturing. The object can be displayed from front, side, top and/or bottom perspectives, depending on how the part will most effectively be explained or manufactured. This is important because manufacturers rely on them to understand and interpret the specifications of the part they need to create. The drawings in this section were sent to the LGP building to be manufactured, after ensuring that each piece fits together correctly in the final assembly.

Detailed orthographic projections were created to facilitate the manufacturing process. These projections were then submitted for a new budget assessment.

Figure 43 below illustrates the lower bracket (**Design 1**) which would be mounted in all four corners of the printer.

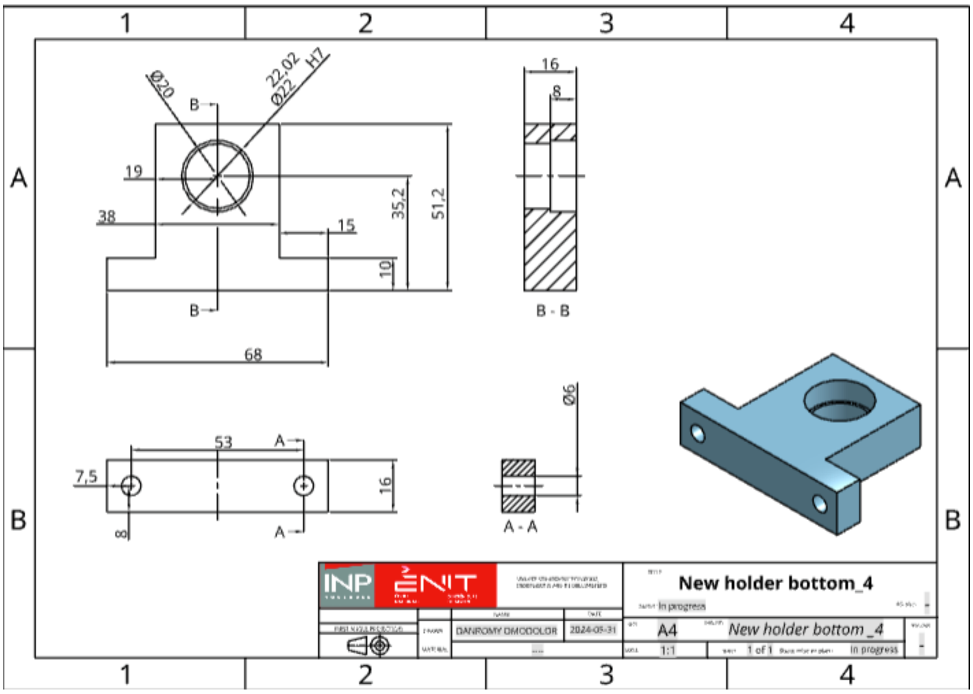


Figure 43. Orthographic drawings for Design 1

As shown in Figure 44, a second part was manufactured so that the hexagonal nut could be held in place with screws.

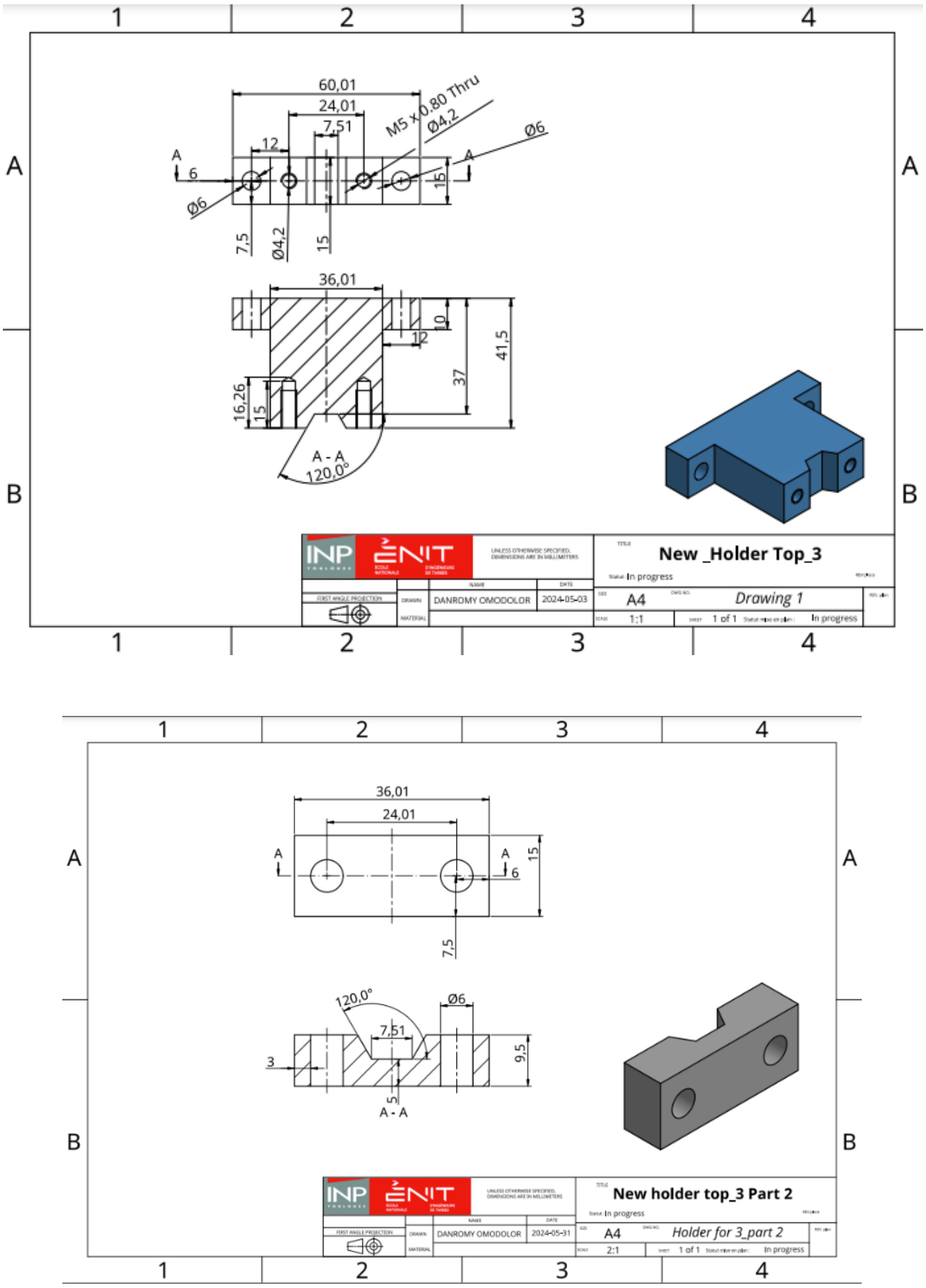
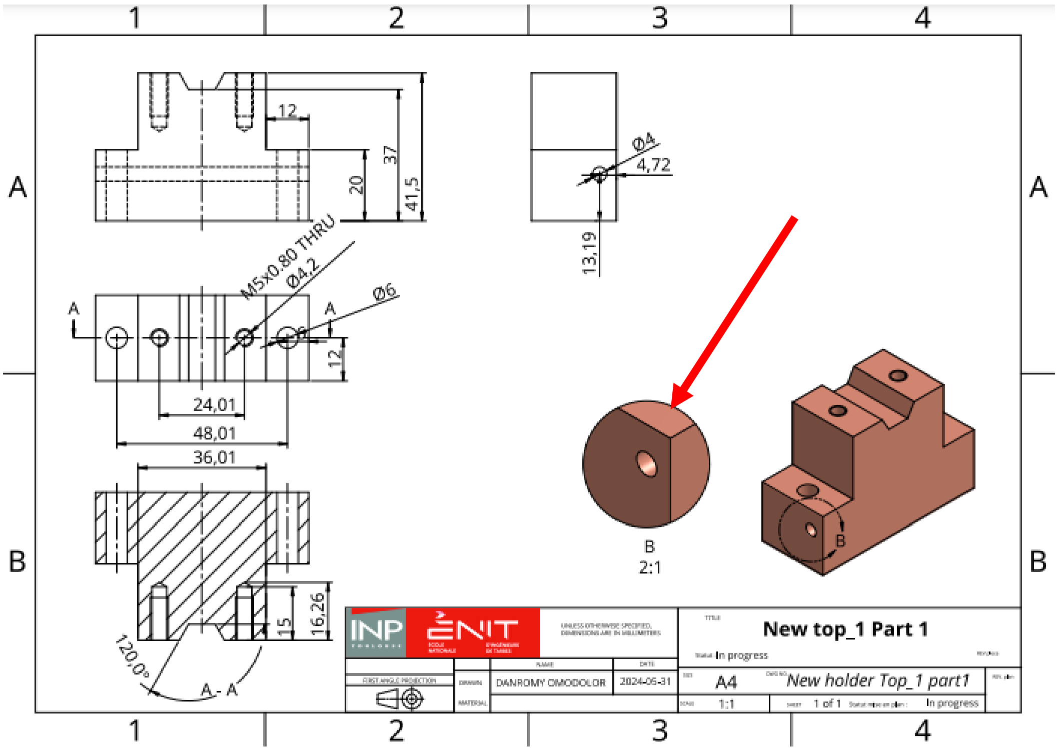


Figure 44. Orthographic drawings for Design 2.

Design 3 is similar to **Design 2** in its shape however it was made thicker to include a hole which holds a screw through the bracket (as shown with a red arrow in Figure 45). The hole allows the part to be connected to the inner section of the machine. The main function of this connection is to guide the inner section along its vertical axis.



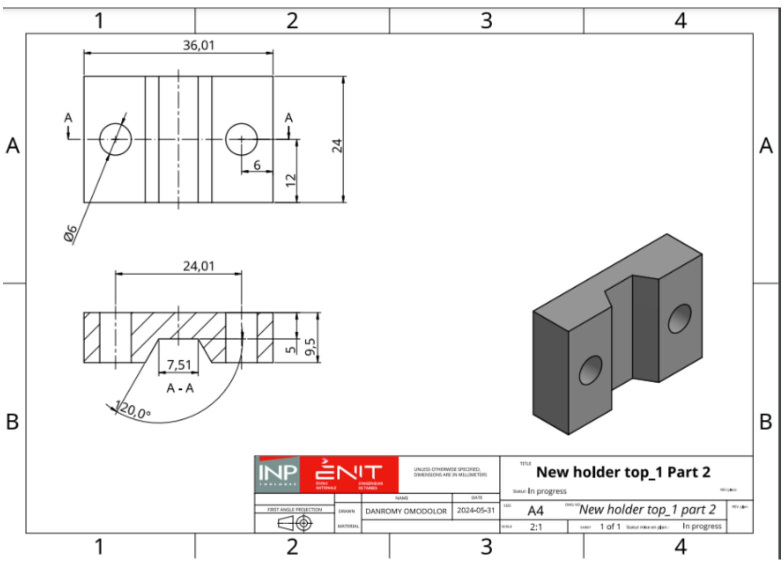


Figure 45. Orthographic drawings for Design 3.

3.8 Manufacturing

The manufacturing process of this project will be explained in this section. It will firstly cover the 3D printing of required parts for the Tripteron before discussing the metal manufacturing for the Cartesian.

3.8.1 Converting CAD models to printable files

Any 3D model can be 3D printed, but it must first be translated into a format which a 3D printer can understand. CAD models are saved as "*Standard Tessellation Files*" (or STL files) which convert a 3D model into a computable formula which can be sent to a **3D slicing software**.

A 3D slicing software is a type of specialised program which takes the .STL file and translates it into specific instructions known as G-code. The G-code gives specific instructions to the 3D printer, telling it where to go, when to stop, where to begin printing and when to move up to the next layer. Customary settings like the amount of infill density inside the part or the option to 3D print with support will also be included.

3.8.2 Supporting large bodies in 3D printing

Due to the layer-by-layer method that 3D printing utilises, there is often a requirement for support material to be printed inside a specific shape [8]. The supporting arm has two extruding sections for the bearings on either side. During the printing process, if these sections were not supported sufficiently with additional material, they would fall. The tree-support method was chosen because it typically uses less material when creating supports for extruding sections of 3D-printed parts.

In the late 15^{th} century, Leonardo Da Vinci hypothesized what is now known as "*Da Vincis Rule of Trees*" which states that for a tree to support itself and withstand its environment, the width of the trunk must be equal to, or greater, than the sum of the branches.

In Figure 46, the tree support which was created for the supporting arm of the Tripteron 3D printer is shown. This tree was used to support the extruding sections at each side of the supporting arm. The trunk of the tree is too thin, which caused it to snap off during the final hours of a 28-hour-long printing process.

Figure 46. Tree-Supports.

3.8.3 Supporting-Arm Print First Attempt

Due to this critical failure, 2 days were lost at the end of this project. Throughout the final hours of the 28-hour printing process, the roof section began to split and the entire 760g of material was wasted. During the assessment, it was agreed that the arm was too heavy and the second attempt should be lighter (as explained in the next section). Shown below are images of the first attempt.

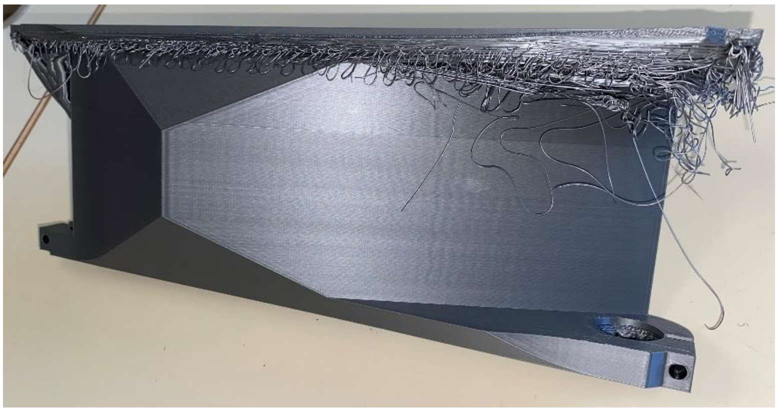


Figure 47. First-attempt.

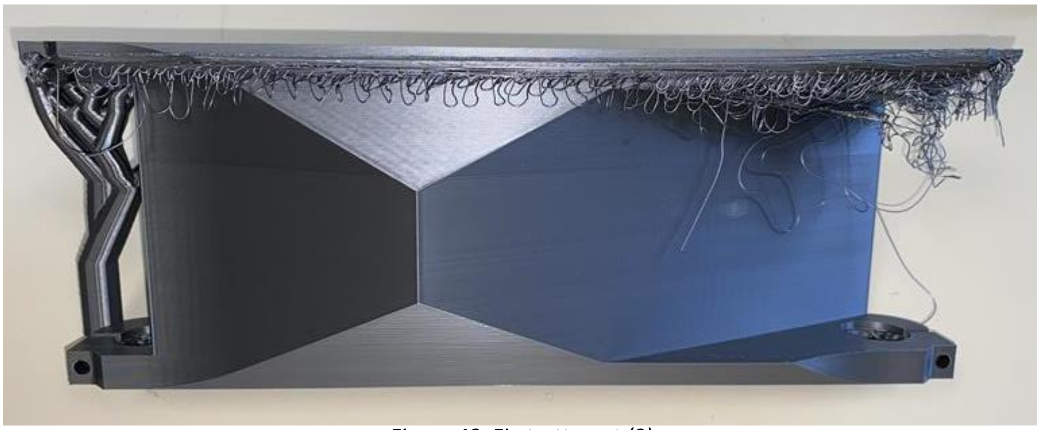


Figure 48. First-attempt (2).

3.8.4 Supporting-Arm Print Second Attempt

A decision was made to reduce the infill density so that the second attempt would be lighter in weight, which resulted in a considerable reduction of printing time. The original infill density was 20%. For the second attempt, it was reduced to 8%. This reduced the printing time by almost half (18 hours) and the weight to 364g however the second attempt also failed. As shown in Figures 48 and 49, a similar problem occurred.

It was assumed that this occurred due to positional failures of the 3D printer. Perhaps the size of the model was too large for the dimensions of the printer. While attempting to print, the printer gave the option of rescaling the arm. However, due to the arm being designed with the dimensions of the original joints, this option wasn't used. In the images below, it's highlighted with a red arrow where the branches of the tree have been printed at different coordinates. This suggests at least one of the printer's motors has lost its calibration causing it to print at different coordinates.

A video (32s) of the printing process shows the point of failure (28s): https://youtu.be/ihku0aarAkM

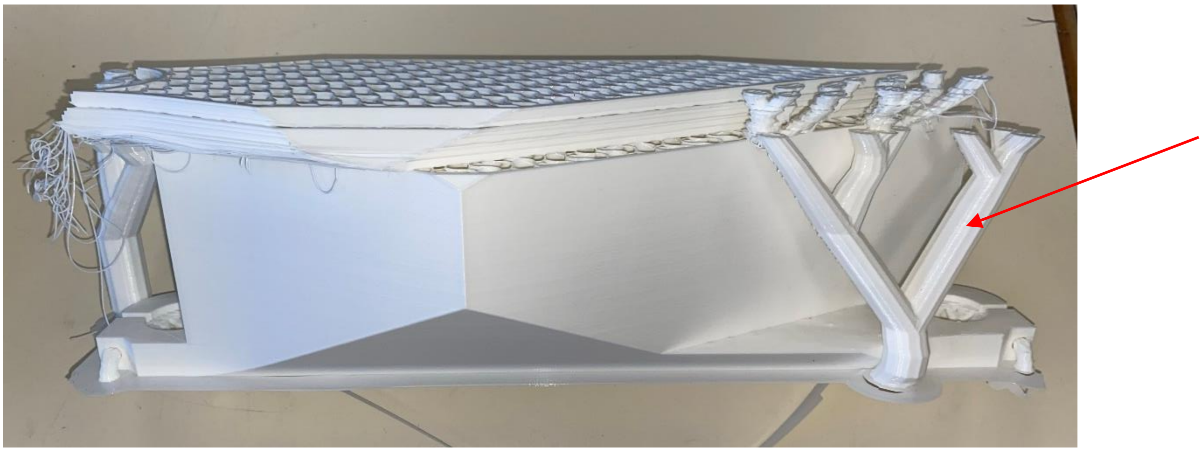


Figure 49. Second-attempt.

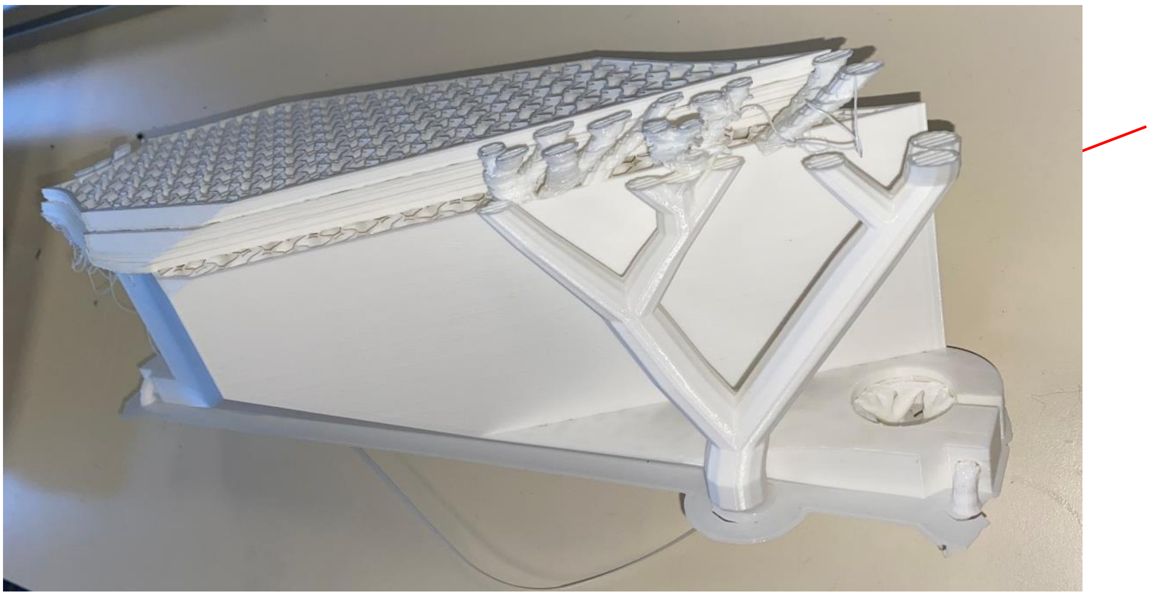


Figure 50. Second-attempt (2).

3.8.5 Supporting-Arm Print Third Attempt

As shown below, the third print was a success. Initial testing confirmed the bearings were able to sit tightly in the allocated space without falling through.

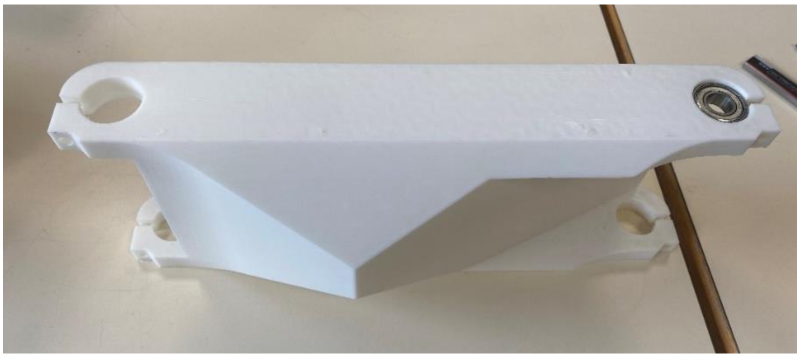


Figure 51. Third-attempt.

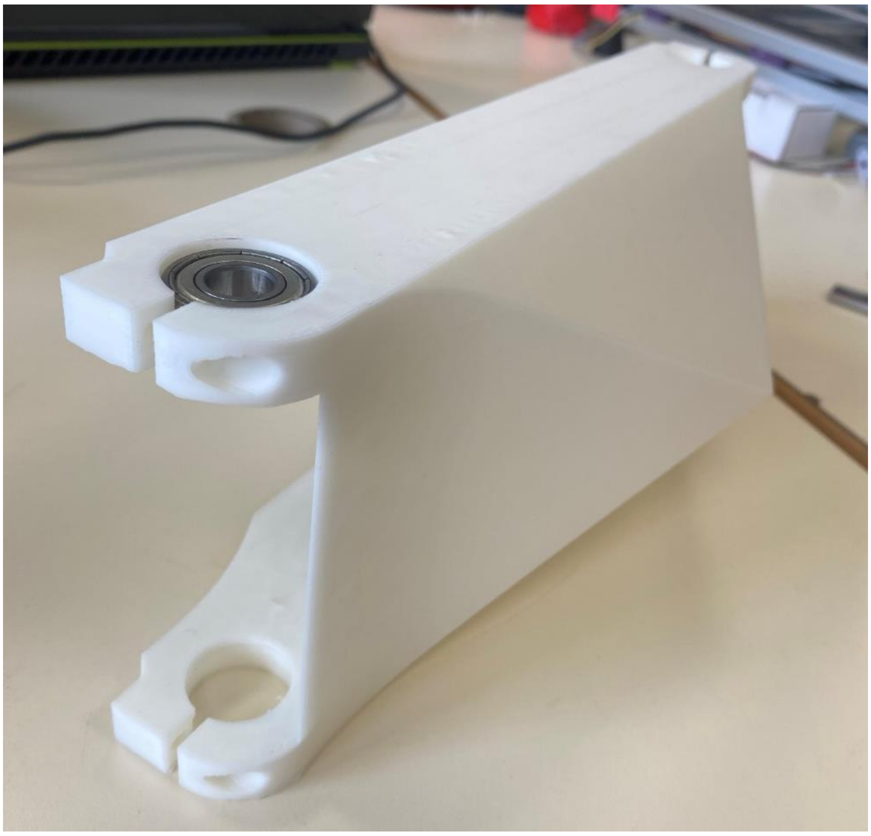


Figure 52. Third-attempt (2).

Figure 53. Shoulder Joint.

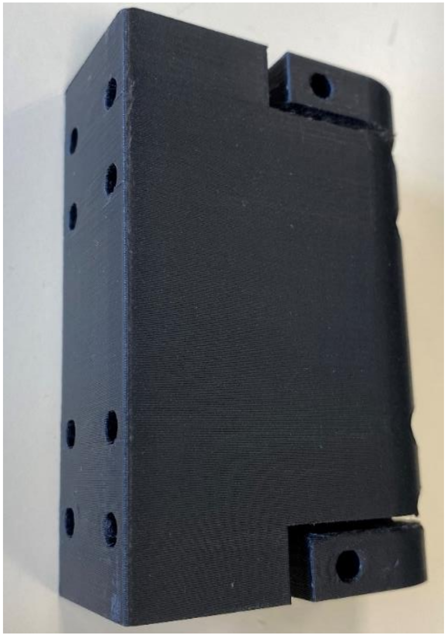


Figure 54. Shoulder Joint (2).

3.8.6 Milling the Brackets for the Cartesian

In the milling workshop of ENIT, the process of creating each bracket for the cartesian started with taking aluminium blocks and cutting the appropriate sections to create the basic shapes for each bracket. Shown in Figure 54 are the blocks before the milling process.

Figure 55. Original blocks of aluminium.

Figure 55 below shows the Haas VF-1 milling machine located in the workshop at ENIT. The machine fastens the part for drilling and moves it in X, Y and Z axes while also being able to rotate the part and change the angle of the part which allows for complex parts to be made in one machine.

Figure 56. Haas milling machine.

Due to the immense heat from the friction, the machine sprays coolant onto the part while drilling, as shown Figure 56 below. This is essential to dissipate heat and maintain the lifespan of parts. It also provides a smoother finish by removing any pieces of debris.

Figure 57. Heat dissipation.

Shown below is a video of the milling process. The first part of the video shows with the coolant spraying and the second part shows without: https://youtu.be/EW_jG7SuBZA

Figure 57 below shows the part with its completed shape before the holes are drilled.

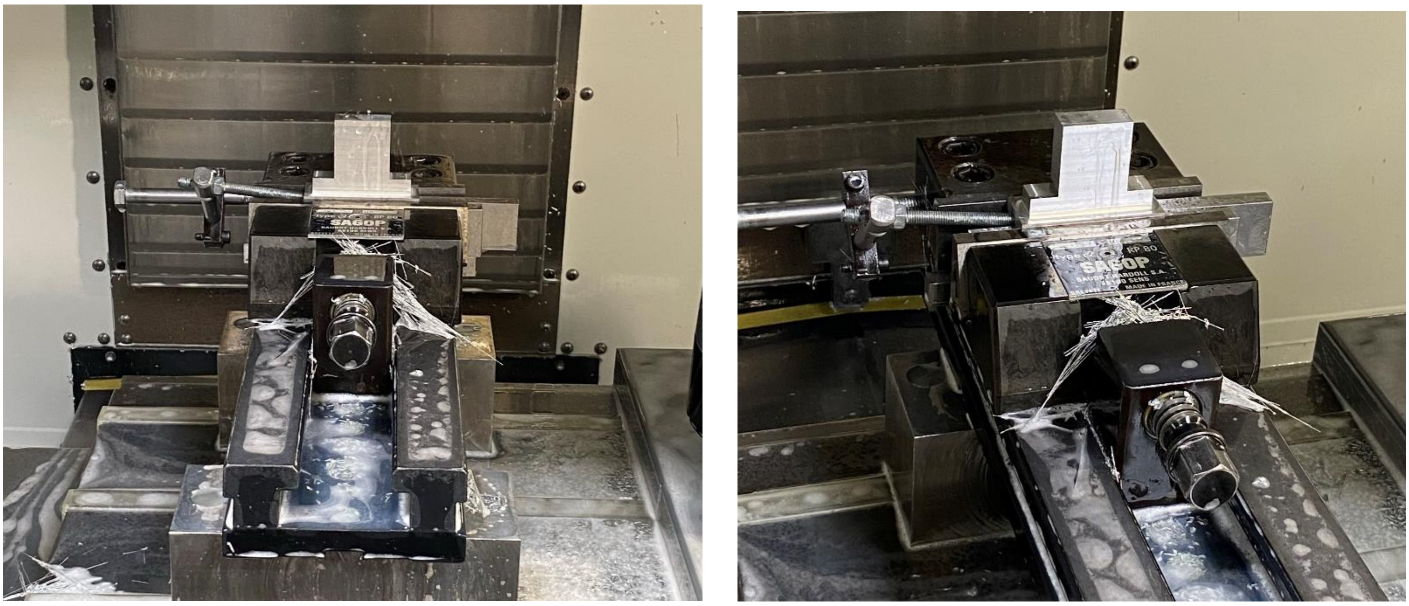


Figure 58. Finished product.

3.9 Assembly

Due to the delays in manufacturing for both the Tripteron and Cartesian machines: At this time, the assembly has not been completed. 3dB expects the manufacturing stage to be completed during the week of the 20th of June which means the assembly will be explained further in the presentation.

The photograph below shows the completed arm attached to the Tripteron. This photograph was taken on 20/06/2024 and the results from the accelerometer will be included in the presentation.

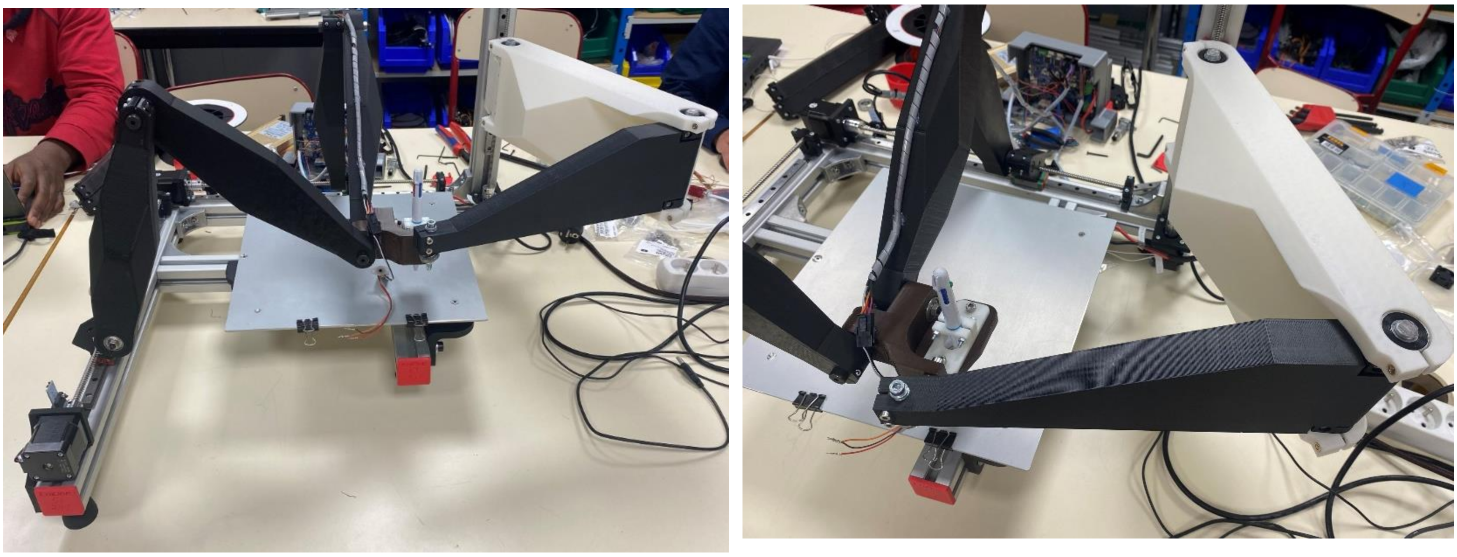


Figure 59. Tripteron arm assembled.

3.10 Electrical Safety and Testing

Electrical safety will be completed after the assembly of both the Tripteron and Cartesian machines. Each machine must be assembled first before testing the electricals and finding the right lengths for each wire.

All Testing will be conducted after the assembly of each machine.

3.11 Bill of Materials (BOM)

The following section will provide the BOM for this project. Some parts were already in the lab for use. The purchased items, printed items, manufactured items, and items already existing within the lab are shown below in different tables. Items will be coloured for the **Tripteron** and **Cartesian** machines.

Table 12. Purchased Items

Name of Part	Quantity	Size Ø: $Diameter$(mm)	Cost (per part) [Total] €	(Supplier) [reference Code]
1164 – FORET LONG	2	Ø4x78x119	17.56	11640000400
1105 - FORET HSSCo	2	Ø 16	54.04	11050001600
1105 - FORET HSSCo	5	Ø4.2	6.80	11050000420
2252 - TARAUD MACH.	2	$M5x80\ 6H$	21.52	22520005008
Eco KEN N30N.37	2	Ø12x22x83	63.26	N30N3701200
Eco KEN N30N.37	2	Ø5x10x50	18.70	N30N3700500
Bearing	2	28		
New Rail	1			
Cylindrical Shaft	2			

Table 13. Printed Items

Name of Part (Weight in grams)	No. of prints	Cost (per part) [Total]
Shoulder (76)	3	(1.90) [5.70]
Forearm (225)	2	(5.60) [11.20]
Supporting arm (365, 446, 760,)	3	(9.20, 11.15, 19.00,) [39.35]
Example: 1kg PLA	1	25.00

Table 14. Manufactured Items

Name of Part	Quantity	Size (mm)	Cost (per part) [Total]€	(Supplier) [Part Code]
Bracket (design 3)	4	51x68		n/a
Bracket (design 1)	3	41.5x60.01		n/a
Bracket holder (design 1)	3	9.5x36.01		n/a
Bracket (design 2)	1	41.5x48.01		n/a
Bracket holder (design 2)	1	9.5x36.01		n/a

Table 15. Existing Items

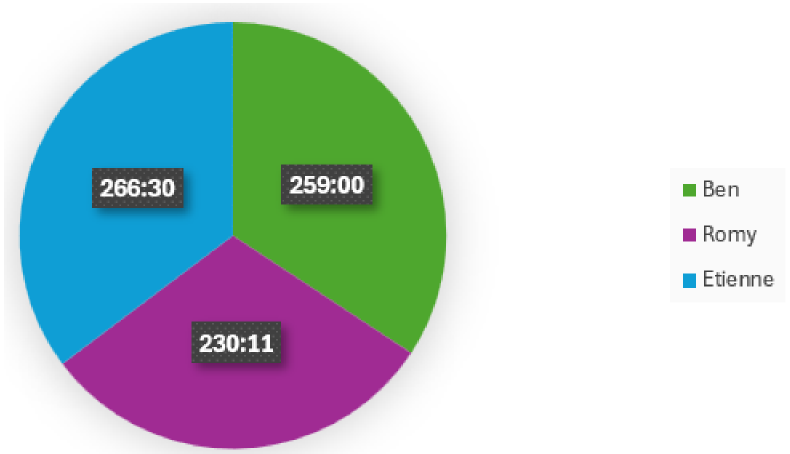
Name of Part	No. of parts ordered	Size	Cost (per part) [Total]	(Supplier) [Part Code]
Bearing	4	Inner diam.: 12mm, Outer diam: 28mm, Thickness: 8mm	1.62	6.48

Print Head	1		6.00	
Extruder	1		16.00	n/a
DC Fan	1		1.90	SD3010S12M
Ventilator	1	n/a	4.00	n/a
Stepper Motor	1		5.00	MT-1704HS168A

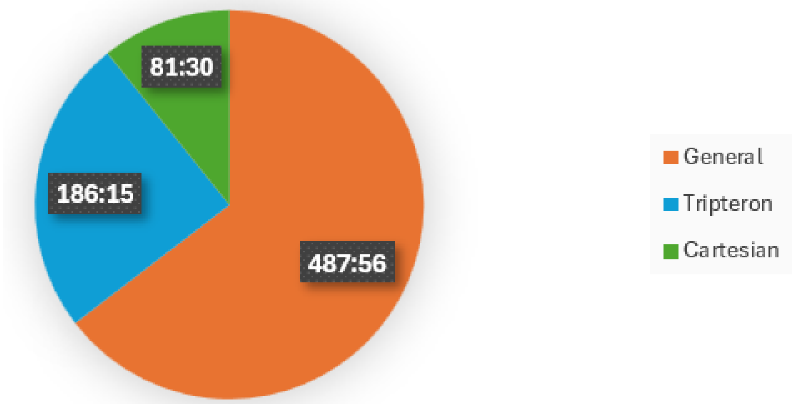
4 Monitoring the project

To ensure milestones were met temporally, various methods were utilised. Weekly recaps within the team to discuss progress and next steps were conducted, alongside regular updates to technical supervisors. To track the project, a logbook was made where each team member put in their hours in the following categories: General, Tripteron 3D printer and Cartesian 3D printer. Under the 'General' category all meetings and global tasks can be written down whereas for the other two categories, it can be more specific. This method provided ongoing data about where the resources were mostly being spent. All previously determined risks were reviewed before each new stage to ensure that the preventative measures were being utilised to the best of the team's ability. In the pie charts below, the total hours spent per team member can be found alongside the allocation of time per each task. General covers EPS and management documents while the work for Tripteron and Cartesian are also separated.

Workhours per Member:



Workhours per Category:



5 Conclusion

3dB had two goals this semester: To install 3D printing capabilities to the Tripteron and to restore functionality to the Cartesian.

At this time, due to considerable delays in the physical prototype phase of the project, the construction of each machine is incomplete. 3dB expects the manufacturing delays to be over and to begin assembly after this report is submitted. The subsequent presentation will include more information about the assembly and testing.

There are considerable implications for the future of these projects. After assembly, 3dB expects the Tripteron to be able to print. This will be confirmed during the presentation.

In future iterations of these projects, the marine-plastic 3D printer could be fitted within the Cartesian machine along with the feeding system currently being designed by SUSTAIN-A-SEA, another EPS team.

5.1 Lessons Learned

During this semester, each member of 3dB has learned not just from supervisors and lecturers here at the university but also from each other within the team. Each of the unique strengths of individual members has improved an aspect of academic inexperience within others.

For example, Benjamin Livingstone had no experience in mechanical drawing but learned from Ikechukwu Danromy Omodolor how to read and draw technical drawings for manufacturing. Etienne Foissard learned about effective cable selection based on Ohm's Law from Benjamin Livingstone. Ikechukwu Danromy Omodolor also made a huge improvement in teamwork and learned from his colleagues how to delegate work effectively and plan for long-term projects.

Thanks to the help from our supervisors and despite many challenges faced this semester, 3dB has been able to provide the necessary solutions to solve both the technical and project management problems faced during this semester.

With the advantage of hindsight, there are some things 3dB would have done differently throughout this project:

5.1.1 Effective design in industry

This year, with no prior experience of DFMA, the team learned the importance of considering the challenges of manufacturing and assembly. Effectively designing with these considerations has been an invaluable skill which will be taken forward in the careers of each member.

5.1.2 Project Life-Cycle management

At the beginning of the semester, 3dB made errors in defining the scope and objectives of the project. Learning about real projects in industry in both the classroom and laboratory helped the team simply and clearly define the project from start to finish and how to execute a project through to the end.

5.1.3 Underestimations

Cost/Resources – At the time of submitting the original designs for the Cartesian brackets. It was assumed that the team had more resources and time to finish the project without many difficulties. Due to the costs coming back over budget, the team had to allocate more resources to redesigning based on the change of material. This greatly affected the team's ability towards the end of the project.

Time – Due to the cost underestimates. The team ultimately lost a lot of time. The team also lost time due to spending too much time designing the arms of the Tripteron on paper. Spending too much time on the conceptual phase took time away from our designing and simulating phases.

Thank you for taking the time to read this report. 3dB looks forward to seeing you again at the presentation.

[END]

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[10] GrabCAD.com [used for 3D modelling of existing parts]

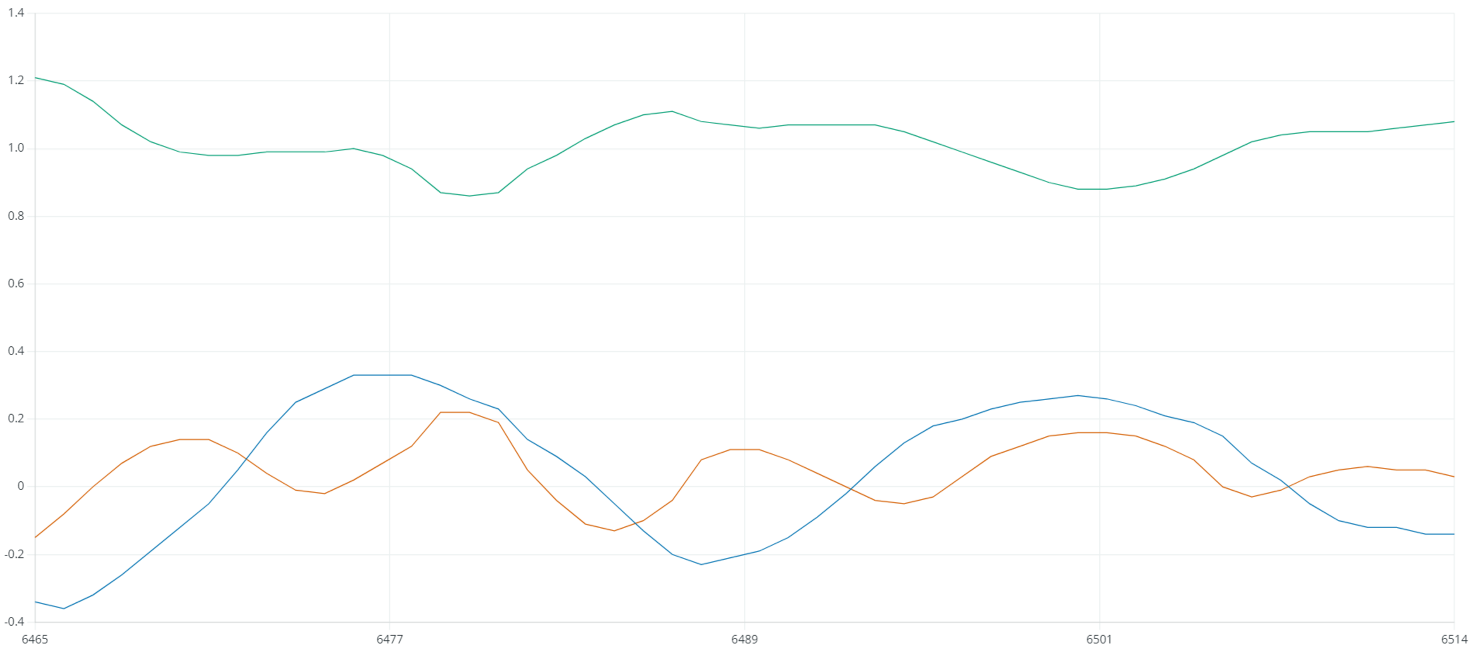
https://grabcad.com/library/ender-3-hot-end-1

https://grabcad.com/library/radial-cooling-5015-fan-50mm-dc12v-1

https://grabcad.com/library/3010-fan-1

Appendix

Appendix 1 – Original Accelerometer Readings:



Appendix 2 – Code for Arduino:

```
#include "Arduino_BMI270_BMM150.h"

void setup() {
  Serial.begin(9600);
  while (!Serial);
  Serial.println("Started");

  if (!IMU.begin()) {
    Serial.println("Failed to initialize IMU!");
    while (1);
  }

  Serial.print("Accelerometer sample rate = ");
  Serial.print(IMU.accelerationSampleRate());
  Serial.println(" Hz");
  Serial.println();
  Serial.println("Acceleration in G's");
  Serial.println("X\tY\tZ");
}
```

```
void loop() {
  float x, y, z;

  if (IMU.accelerationAvailable()) {
    IMU.readAcceleration(x, y, z);

    Serial.print(x);
    Serial.print('\t');
    Serial.print(y);
    Serial.print('\t');
    Serial.println(z);
  }
}
```