Term 3 Final Report
CNC Milling Machine

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Executive Summary

This report details designing, developing, and testing a CNC machine that is low-cost, portable, reliable, and capable of moving independently in the X, Y, and Z directions. The motivation behind designing such a CNC machine is due to the increasing demand for printed circuit board (PCB) manufacturing at a small scale. To begin the design process, a problem was defined and thoroughly assessed. That problem is "to create a CNC milling machine that is low-cost, reliable, and portable to allow for cost-effective PCB manufacturing without financial barriers that would come with normal CNC machines." Evaluating the problem led to the team generating concepts that were further assessed. Each of these concepts were assessed using a decision matrix and the best features and design was decided upon. The chosen design used polyoxymethylene (POM) pulley wheels alongside belts to achieve both X and Y movement. With the design decided upon, the manufacturing process was able to commence with a focus on DfMA. Starting with material selection, the materials decided upon were PLA for Fused Deposit Modelling and SAE 304 stainless steel for critical load-bearing parts. All the materials that were used including the NEMA17 motors and spindle motor, meant that the total cost came to $97.22 NZD, and the weight came to 6.2kg. Therefore, looking back upon the manufacturing process and final product, the project successfully met its goals, as it was portable, affordable, and reliable. The final design, along with the CAD files and demonstration videos, can be found in the appendices.

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2 Introduction

In a world where it is becoming necessary to manufacture complex parts at reduced cost, the need for portable, low-cost small component manufacturing is becoming more necessary. One such part is printed circuit boards (PCBs). PCBs were first developed in 1936 and are now widely used across a multitude of sectors with the current PCB market valued at USD75 billion [1].

One such solution to the need for low-cost manufacturing of PCBs is the use of portable, cost-effective CNC milling machines. Firstly, a functional milling machine must be one that can move reliably in the X, Y, and Z-direction. This movement must be independent in every direction to allow for smooth travel for tool paths. This project uses G-Code controllers to initialise and move the milling machine. The choice of materials used in the design is vital to creating a low-cost solution. For the design in this report, the materials used are aluminium and polylactic acid (PLA) filament. The choice of materials is detailed in section 4: Material Selection.

3 Design Process

3.1 Define the Problem

The problem we faced was to create a low-cost, reliable, and portable CNC milling machine that would allow for broad access to cost-effective PCB manufacturing without financial barriers interfering, as would conventional CNC machines.

3.2 Generate Concepts

To arrive at the final concept and solution in this report, we each designed one concept that demonstrated various ways to move the axes and mount the motors. Some Initial concepts included the use of lead screws and linear bearings, whilst others included the use of belts and pulley systems in conjunction with linear bearings. Others incorporated the use of wheels along aluminium tracks for movement. Some designs used fixed motor positions, whilst others had the motors move along the tracks with the milling motor, these are shown in Figures 1-4

Concept 1 – Aditya

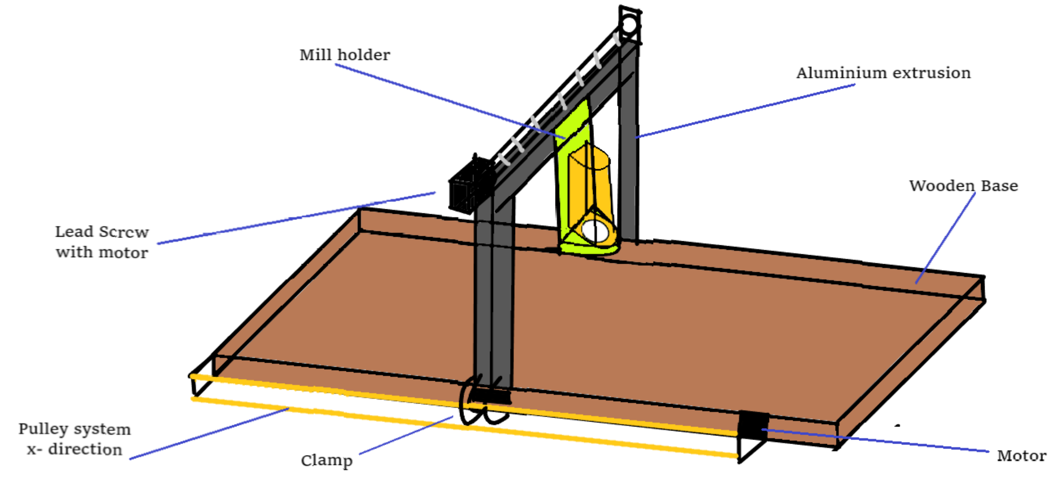

Figure 1 – Aditya's Concept

Concept 2 – Cade

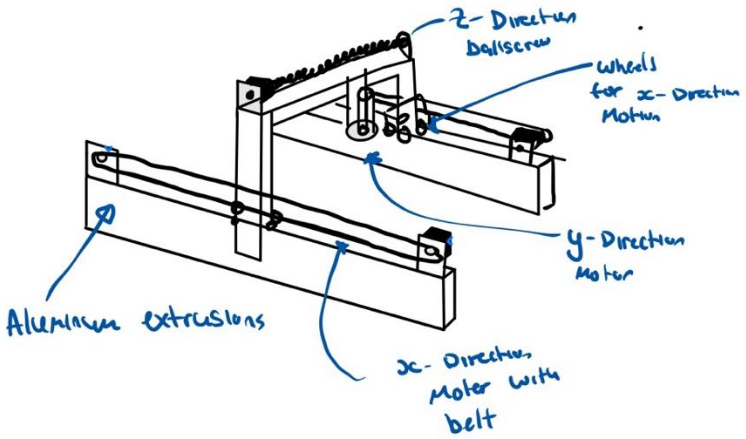

Figure 2 – Cade's Concept

Concept 3 – Conner

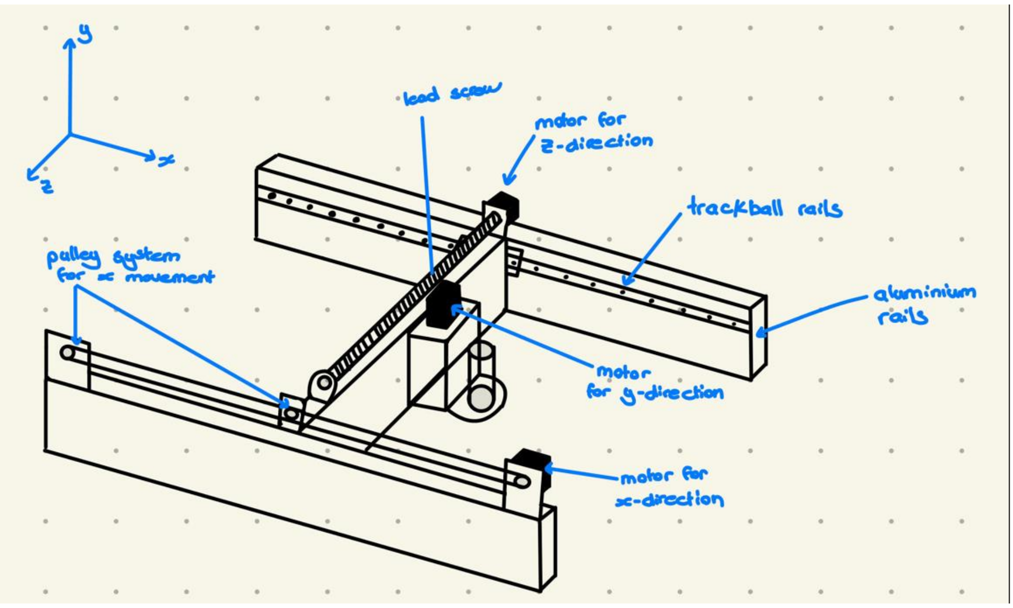

Figure 3 – Conner's Concept

Concept 4 – Tim

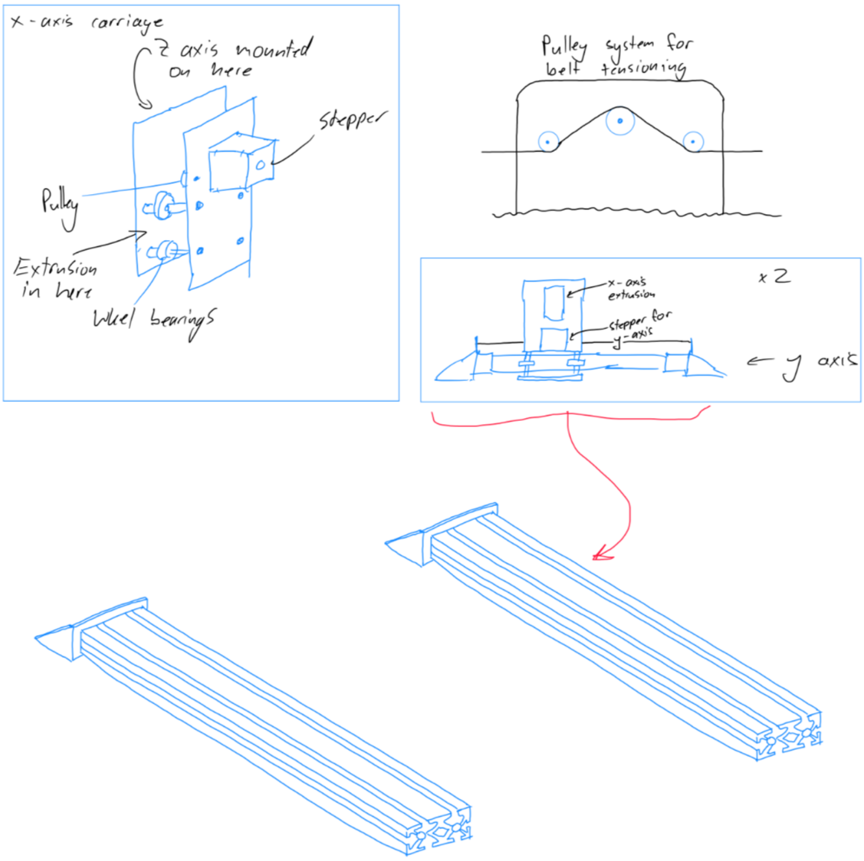

Figure 4 – Tim's Concept

3.3 Develop a Solution

We used a weighted decision matrix, as seen in table 1 below, to compare our initial designs based on the criteria set by the team, such as the movement of the mill in each direction, materials to be used in each part, and the overall aesthetics of the design. After the scores were calculated between the concepts, we integrated the highest scoring elements from each criterion into the final design. Such as the aesthetic pulley system for belt tensioning from Tim, aluminium extrusions to give it some solid structure by Cade, adding a lead ball screw in the z-direction for the mill's movement by Connor, and using a wooden base material for all the parts to be assembled on by Aditya.

Table 1: *Decision Matrix for Concepts*

Criteria	Weight	Tim's Concept		Conner's Concept		Cade's Concept		Aditya's Concept	
	/5	Rating	Weighted Score	Rating	Weighted Score	Rating	Weighted Score	Rating	Weighted Score
Movement	5	5	25	4	20	4	20	3	15
Materials	3	3	9	3	9	3	9	4	12
Aesthetic	2	4	8	3	10	4	8	2	4
Total Score			**42**		**39**		**37**		**31**

3.4 Construct and Test Prototype

For the motor bracket, we 3D printed three iterations of this part. This was due to inaccuracies in our measurements. The first iteration had inaccuracies in all the holes and thus 0% of the holes lined up. The second iteration had inaccuracies only in the holes for the motor itself; thus, 50% of the holes did not line up. The third iteration had no errors and 100% of the holes lined up, allowing for the motor to be effectively secured in place.

There were two iterations of the motor mount responsible for x-direction movement. Although the first iteration (3mm thick) geometrically met the requirements, it was not strong enough. This was discovered during testing and a mock assembly where the weight of the milling and x-direction motors was too much, causing an unsafe amount of flex in the mount. This would lead to both failure of the CNC machine itself due to gradual wear and inaccuracies in products milled. The second iteration had the same infill but was twice as thick (6mm) as the first. This change in thickness created superior rigidity in the part and thus allowed for the CNC machine to function as desired.

In addition, the original design used separate spacers for the mount mentioned above. However, to reduce the number of parts for assembly, it was decided that it would be best to integrate these spacers into the motor mount and have one part rather than the original design, which consisted of a motor mount and four spacers.

The first iteration of the overall design was to use trackball rails in conjunction with a lead screw for the X and Y movement. However, after creating a mock build, although the movement was as desired, issues arose with how the motors would be mounted. Due to this, it was decided it would be best to find and develop a new solution for the movement. This led to the current and final design that used POM pulley wheels in conjunction with pulleys to achieve the desired movement.

3.5 Evaluate Solution

The final design features independent movement in the X, Y, and Z directions using 4 NEMA17 stepper motors, as shown in Appendix B. In addition, only one person is required for assembly; however, two are preferred for quick assembly, as shown in Appendix B. The final solution is cost-effective and portable, weighing 6.2kg and costing $97.22.

3.6 Present Solution

Our final design utilises a dual v-slot linear rail design for our Y and X axis motion. This type of design is used throughout industrial machinery, providing stable and effective movement. The project uses PLA and SAE 304 (Stainless Steel 304) materials for a cost-effective, sustainable, and portable product. A full video demonstrating and assembling our design using principles of DfMA and DfAM has been included in Appendix B.

4. Materials Selection

Throughout the project, we have chosen to use PLA (Polylactic Acid) as our main material due to the properties that the material has to offer. PLA has a tensile strength of 50 MPa and a Young's modulus of 3.5GPa, which exceeds the expectations for our project. These properties are as such: high strength and resistance to failure by permanent deformation, as well as high stiffness to resist any shape deformation when a force is applied. These two properties go hand in hand with each other. They are key as force is constantly applied and the possibility of warping and deformation during movement is possible, so maintaining structural rigidity is an important factor. PLA allows lower extrusion temperatures compared to other plastic materials used in the same application. As this is a project, a lot of prototyping had to be done for test fitting and PLA is a really good choice for rapid prototyping as it is easily accessible and can provide with 3D printing. 3D printing with PLA can offer components with good levels of detail. Cost of PLA was a benefitting factor, PLA is quite cheap in comparison to other plastics and is low budget friendly for multiple prototypes without compromising on quality. As environmental impact and sustainability is an important factor, PLA being biodegradable allows us to minimize the environmental impact.

The second choice of material was Stainless Steel 304 or SAE 304. SAE 304 is an austenitic stainless steel and isn’t magnetic, and so Is a good choice when working with magnetic motors. Another choice to use this over PLA was its superiority in material properties. Stainless Steel has much higher tensile strength of 515 MPa in comparison to PLA and has very long-term durability. This makes it more suitable to be used in harsh conditions withstanding stress without fear of fracture or deformation failure. Heat from belt friction can be present within our project, so the choice of stainless steel further redeems itself as it has good heat resistance. SAE 304 has a higher upfront cost in comparison to PLA, however the material's improved mechanical properties justify this choice and ensures longevity of the components. Stainless steel is 100% recyclable so this allows us to reduce the environmental impact when the material reaches the end of life, it can be reused.

5. Manufacturing Process

The CNC milling machine design was considered for both DfMA and DfAM, and these principles can be seen throughout the project. We applied Design for Manufacturing and Assembly principles by minimizing the number of parts used. In one of our earlier designs, there was a problem with over complexity and the number of parts. The final design showcases the large reduction in parts, such as our bearing spacers; these have been integrated onto both sides of the Y-Axis motor mounts. Standardizing parts is prominent in our project, there are 13 individual 3D printed parts, with only 3 are single use parts. This has made manufacturing a lot easier, ensured symmetry and reduced geometric error when assembly. Ease of handling has been considered throughout our design, as this is a portable machine. Each part has been considered for the way it can be orientated during assembly to reduce awkwardness, error and improve efficiency during assembly.

Design for Additive Manufacturing principles have also been included within our design, as Majority of our parts were 3D printed. Additive Manufacturing has allowed us to create complex parts, whilst retaining important details and features and keeping cost minimal. To minimize material use, we used 20% infill using a rectilinear pattern throughout all our parts, this allowed a reduction in cost, and an improvement in performance and weight associated with each part. Further reducing material wastage and improving efficiency, the use of supports has been minimized. This has been done by considering orientation and geometry in the way the parts have been printed. Part Consolidation was included with the spacers on the Y-axis motor mounts, integrating the spacers, rather than keeping separate, this not only reduced assembly steps, but also minimized the possibly of losing parts. Design for Functionality was included, we have included specific mounting points and holes for bolts within each part.

6. Cost Analysis

The total cost for our entire project was $97.22, this was just for the materials used, there were no Labor or overhead costs due to the nature of the project. The cost of materials can be broken down as follows; the 500g of PLA cost $15.00, the 90cm of 20x40mm aluminium T-Slot beam cost $26.18, four NEMA17 stepper motors cost $5.82 each, the four SAE304 Belt clamps cost $1.5 each, a 200W DC spindle motor at $31.62, three pulley and belt kits at $3.70 each, and twelve POM pulley wheels at $1.11 each. Our BOM in Appendix A lists all our 26 components, with details such as each respective, component, quantity, prices and supplier links.

7. Sustainability and Environmental Considerations

The 3D parts for our supports were printed using PLA, a thermoplastic material that is already biodegradable. Since PLA is thermoplastic, it can be melted down and reused as filament for the 3D printer, and it can also be recycled after disassembly for other designs.
For the base plate, we used a large, solid wooden piece, which is also biodegradable. We also repurposed a metal plate for one of our parts. Other materials, such as stepper motors, pulley wheels, and components made of rubber and aluminium, can be recycled for future projects and designs.

8. Conclusion

We successfully created a low-cost, reliable, durable, and portable CNC milling machine. Our CNC machine is fully capable of moving independently in the x, y, and z-axes, all whilst being lightweight, quick to disassemble (roughly 5 minutes) and an assembly time of 37 minutes. Through the process of design and manufacturing, there were many changes made and many things that could be improved. Some changes made were to the movement and materials. From the beginning to end of the engineering design process, our whole team became far more competent at designing and printing parts, this was seen in our first part needing three iterations, whilst the parts printed in the latter part of the project only needed one iteration. Some things that could be learnt and improved upon are the delegation of tasks and better documentation during the manufacturing process. Although our team was able to successfully create a CNC machine, task delegation was at random which made it hard to know what to do between group meetings. As for better documentation during manufacturing, this is solely for the aid of authoring a final report, as making small progress throughout would be superior to writing everything at the end and having to recall decisions and thought processes from 5 weeks ago.

9. References

[1] https://www.power-and-beyond.com/pcb-manufacturing-these-are-the-biggest-players-a-c38499760ae9053b34d796adf3d0746f/#:~:text=An%20Austrian%20inventor%20Paul%20Eisler,market%20stands%20at%20USD75%20billion - PCB Manufacturing: These are the biggest players by Venus Kohli - 2023-08-17.

Appendices

Appendix A

Bill Of Materials

Component	Quantity	Unit Price	Total Price	Supplier Link
PLA (500g)	1	$15.00	$15.00	Link
Aluminium T-slot (90cm)	1	$26.18	$26.18	Link
NEMA 17 Motors	4	$5.82	$23.28	Link
200W DC Spindle Motor	1	$31.62	$31.62	Link
Pulley and Belt Kits	3	$3.70	$11.10	Link
POM Pulley Wheels	12	$1.11	$13.32	Link
Belt Brackets	4	$1.5	$6	Link

Appendix B

Movement Video
Full Assembly Video