ENMT221 - Mechatronics Design 1

Department of Mechantronics Engineering

University of Canterbury

Design and Manufacture of Pick and Place Machine for PCB Assembly Using the Engineering Process

Brand, Philip (15776928)

Brown, Michael (48571923)

Donkin, Eva (49252595)

McCord, Liam (45446549)

Reeve, Elizabeth (55869297)

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Abstract

A project was executed to develop and create a working Pick and Place (PNP) machine. The frame construction materials were limited to MDF and 3D printed components. Initial criteria of accuracy, reliability, and modularity were incorporated into the final design. It was also developed at a cost of $264.24, which is below the set ballpark maximum cost of $300.00 (note, all costs are in NZD). This meant the developed solution met all the criteria. An initial design was proposed by each project group member, and these designs were then considered, modified, and developed into a proposed final solution. This solution involved the use of a CoreXY belt scheme and a Z-screw for a 4 degrees-of-freedom system within the machine confines. The final maximum suction head speed was 500 mm/s, with a theoretical maximum placing rate of 1.2 parts per second. Initial versions of components were overly complicated and difficult to modify, but were generalised and simplified to ensure flexibility and reliability. This showed application of DfMA and DfAM, both incredibly important aspects in product design. Future improvements could include allowance for a customisable range of motion, and reduced performance issues such the linear rail carriages sticking. Overall, the PNP was a very successful engineering process application, and an outstanding foray into the mechatronics world of research and development.

Contents

1 Introduction

As PCBs become more complex, manual assembly is becoming increasingly difficult. This project addresses the issue by developing a CNC Pick and Place (PNP) machine targeted towards hobbyists and small businesses to encourage the widespread use of manufacturing technology. The machine's primary purpose will be to place components on PCBs during the prototyping stages of the hobbyist's projects, a task requiring precision and efficiency.

These markets are currently dominated by industrial-grade machin0es which are obtainable only for large organisations at high cost. The current machines also require specialised tools and niche knowledge to repair which is unlikely for a self-taught hobbyist or small business startup to have.

This report details the design and prototyping of a CNC PNP, detailing the design and material selection processes in sections 2 and 3, and the cost analysis in section 4. Section 5 explains the manufacturing process, section 6 the sustainability and environmental considerations, while section 7 evaluates the project. All costs are in NZD.

2 Design Process

2.1 Problem Definition

There is a lack of cheap and reliable PNPs for rapid prototyping at smaller scales, with cheaper PNPs still costing around $3300 [1], [6]. In addition to high cost, the complex components and material choice makes on-site repair difficult, leading to additional long-term costs.

Hobbyists and small businesses want to minimise costs. To reflect this, a ballpark maximum cost of $300 was set, where the machine can be modified and customised. This requires the design to consist of accessible materials so that a hobbyist can maintain the machine without the need for specialist tools. It must be accurate enough to justify the cost for hobbyists.

The solution presented, therefore, must fulfil the following criteria to be considered successful:

- Overall material cost of under $300
- Materials used are easily accessible, such as

  - Medium Density Fibreboard (MDF)
  - Plywood
  - 3D Printed Components
  - Sheet metal
  - Conventional standardised screw and bolt sizes
- Simple to repair and customise without specialist knowledge
- Can be assembled by a customer within an hour using supplied instructions

2.2 Generated Concepts

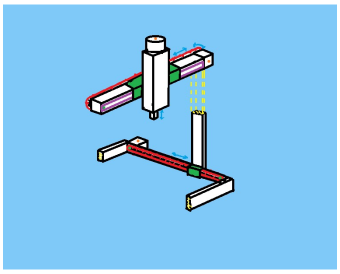
As part of the solution designing process, each group member proposed a different style of solution (Figure 1). The proposed solutions focused on different approaches to gantry systems, and were categorised as follows:

- XY rails move the Z-screw, Z-screw moves the suction tip (Figures 1a, 1b, 1d)
- Z-screw moves the entire rail system, XY rails move the suction tip (Figure 1c)
- The PCB is moved by the platform it sits on, Z-screw moves the suction tip (Figure 1e)

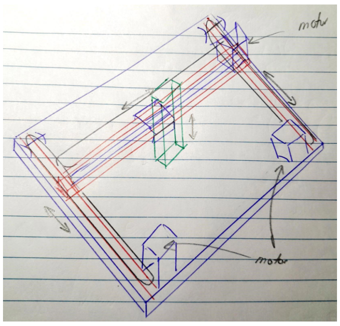
Solutions where the XY rails controlled Z-screw position offered exact control with use of lead screws, and belts also permitted accurate movement at a higher speed. However, there is relatively low maximum acceleration due to the high inertia of the Z-screw.

Other solutions have the Z-screw moving the XY axis rail system vertically, where the suction tip attaches directly to the XY rails. This comes with the advantage of a higher maximum XY speed due to the lower inertia of the suction tip. However, the Z-screw would be have to support a considerable moment, reducing stability and increasing the wear rates on that component.

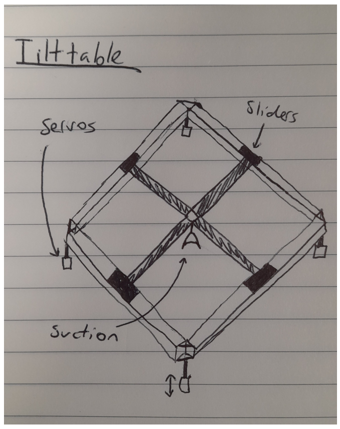
Another solution entirely forgoes the use of the rail system to move the suction head, instead moving the platform on which the PCB rests. Depending on the platform movement, such as with wheels, this could theoretically extend the range of movement significantly without adding extra components. The Z-screw would also only have to move the suction tip, thus will have no moment disadvantages. However, there were concerns over the wheel system accuracy.



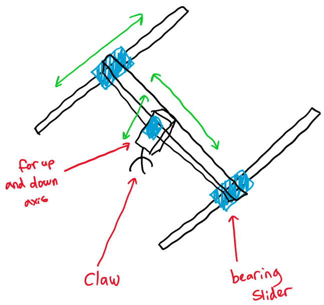
(a) Raised Z-Screw



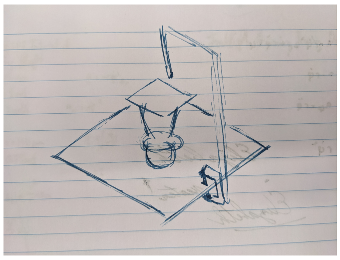
(b) Same-Height Gantry System



(c) Tilt Table Design



(d) Claw Machine Design



(e) Moving Platform Ball Support

Figure 1: Design proposals submitted by each project team member.

2.3 Developed Solution

The final solution was a belt-driven CoreXY configuration. The belt configuration used two vertically offset belts driven by corresponding stepper motors to move the vacuum tube mount. Both stepper motors were fixed to the main frame and not carried on the sliders, significantly lightening the vacuum mount weight. This reduced slider loading, allowing for considerably increased motion acceleration. The dual belt combination in the CoreXY setup allowed fast movement in the X-Y plane, while using only two motors. CoreXY was also chosen due to inherent force balancing in belt tensions, avoiding the need for fine calibration for smooth movement. For Z-axis motion, the baseplate was raised and lowered by the provided Z-Screw. This was fixed directly to the PNP frame to avoid increasing the moving mount inertia. Through a combination of CoreXY and the vertically moving baseplate, a full range of motion was achieved.

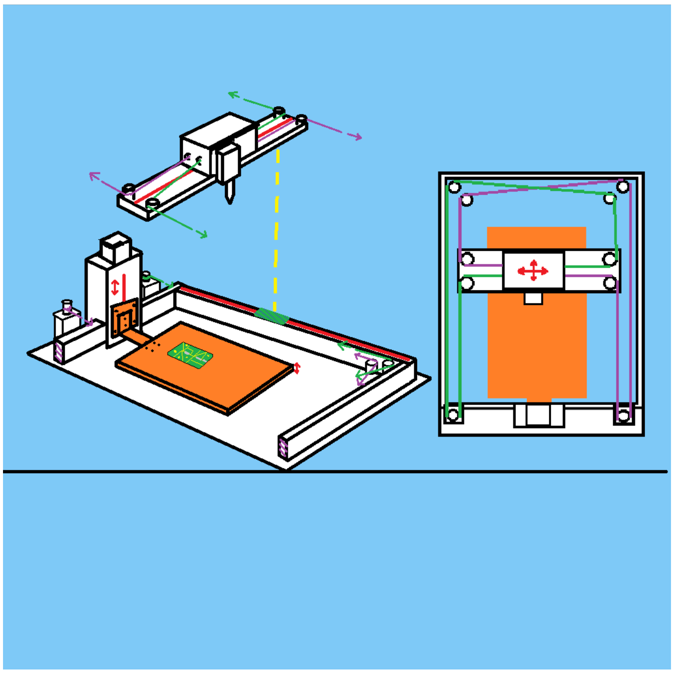


Figure 2: CoreXY Design Solution

2.4 Prototype Construction and Testing

Changes were made to both the overall design and specific parts of the design during machine construction. There are multiple ways of positioning the belts opposite the motors in a CoreXY system. Designs have a combination of belts crossing over, and belts positioned at different distances from the motor, which have a significant impact on the relevant brackets supporting the belts in that location.

The original PNP design had both belts crossing over, and located at different distances from the motors. The first version of brackets modelled were complicated, requiring multiple supports when printed and no ability for adjustments when installed. They were printed successfully, but during installation the bracket on one side had been mirrored incorrectly and was incompatible with the bracket on the opposite side. Due to its complex design, modification of the bracket to fix this issue was required.

The problem was solved by redesigning the bracket entirely with positioning adjustments, enabling flexible bracket location during installation (Figure 3). This new design had added benefits in that the bracket on one side mirrored the other. Conversely the first version required significant modification to produce the corresponding 'mirrored' part. Once the XY axes had been assembled and the belts were installed, a minor issue arose - the belt would rub on the rear side of the slider pulley mount. Another advantage of the second version of the bracket was that it was easy to fix this issue — extend the outermost pulley 40mm away from the machine centre.

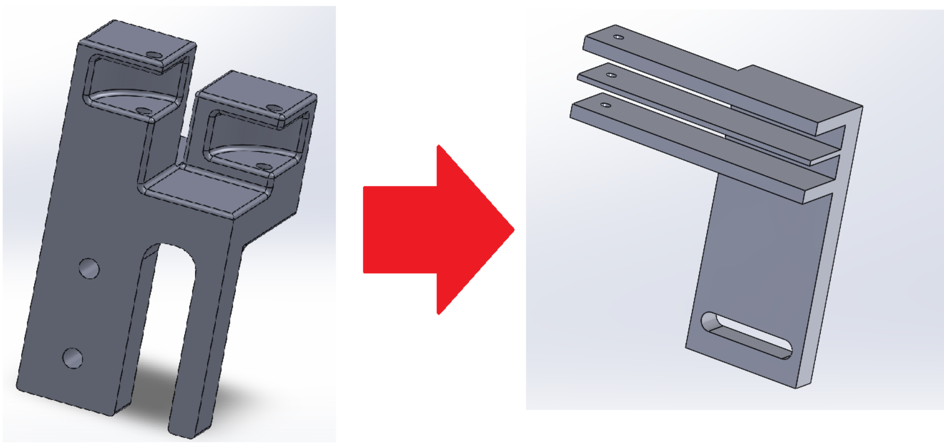


Figure 3: Comparison of bracket design versions

Another part of the PNP requiring multiple iterations was the bracket mounting the motor to the MDF supports. The original motor mount had no room for horizontal positional adjustment, so when the bracket was mounted and the belts attached, alignment issues were identified. This was solved by reshaping the vertical edge on the bracket and adding slots to allow horizontal movement. In a similar fashion to the brackets, when the bolt fixing the bracket to the wooden side was tightened a washer would clamp up against the bracket and prevent any movement.

2.5 Presented Solution

The PNP design, as seen in Figure 4, is suitable for hobbyist applications. The CoreXY control enables quick and accurate suction head movement to any position on the plate, and the variable plate height enables use of PCBs with a wide range of depths. The belt tension is easily adjustable, allowing users to ensure tension is consistent across all conditions, as belt tension will decrease as the belts warm from continuous use, and wear out over time. The device demonstrated good behaviour, with a maximum suction head speed of $500\,mm/s$. By measuring the movement of the head around the available workspace, the theoretical pick and place rate was determined to be 1.2 parts per second.

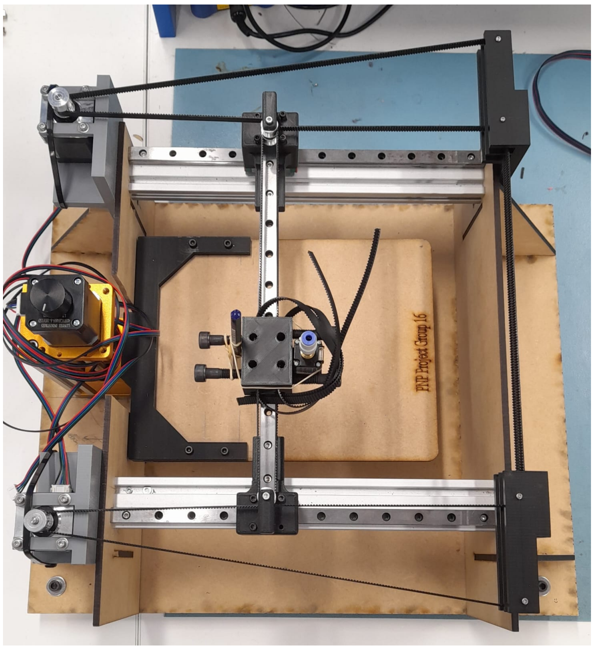


Figure 4: PNP machine.

3 Materials Selection

The design focus was to give hobbyists reliable access to PNPs, so the materials had to allow such people to easily repair and/or replace device components. The design also focused on minimising cost, so this was also a driving factor in material selection. Both wood and metal were considered for the main body supporting the X-Y axis plane and related motor and pulley brackets. Metal had advantage of being more durable than wood, and would provide better rigidity to the machine. However, the design would be more complicated if metal had been used for these parts. MDF was chosen instead, as it would provide sufficient stability for the machine, and is very accessible as virtually every local hardware store in New Zealand and in other first-world countries supply it. MDF is also very easy to machine. Some limitations of MDF are increased flexibility and lack of stability in damp environments, but these limitations were outweighed by its benefits.

For the brackets designed for specific tasks such as motor and pulley mounting, and connecting X and Y axes, 3D printing was chosen. If the aim for the project was mass production, custom injection moulded parts would have been used due to their superior strength and low manufacturing cost. However, these parts would not be easily repairable or replaceable by hobbyists. Hobbyists looking to invest in a PNP would be highly likely to already have a 3D printer, so 3D printing was chosen as it maximised accessibility while minimising cost. The filament used in the printing was PLA filament. One limitation of using this material is the long print times in the manufacturing, and the increased material cost.

4 Cost Analysis

Aside from the standardised parts supplied, the main costs associated with the PNP were 3D printing and the MDF base. PLA 1.75mm filament was used for the 3D printing, with an assumed cost of $\$0.25/cm^3$ [4]. The MDF base was $\$17.70/m^2$ [3]; however, cheaper materials may be sourced if this product were to be produced in mass. Cost estimates were made for each major component, and can be seen in Table 1.

Component	*Cost*
3D printing	$82.80
MDF	$14.75
Supports	$20.13
Motors	$45.82
Belts	$7.90
Miscellaneous	$32.84
Labour	$60
Total	**$264.24**

Table 1: Estimated costs of materials and components [5]

The cheapest commercial PNPs cost between $2000 and $4000 which is high above many customers' price range, so this PNP model opens up a market for those who require a less costly alternative that still produces high quality results.

5 Manufacturing Process

The PNP primarily uses a combination of 3D printed and laser-cut MDF components. Both of these manufacturing processes are relatively simple and widely available, reducing the overall manufacturing complexity. To applying DfAM principles, 3D printing support use was minimised. In the case of the belt mount block, supports are used in the circular mount holes and are easy to remove with the correct drill.

An aspect of DfM is minimising the number of custom brackets in the design, and the final design uses only six different bracket designs. This was achieved by utilising symmetry, as four of the parts were mirrored for the opposite side.

Another DfMA application maximised off-the-shelf component usage. All non-3D printed and non-laser-cut components were purchased off-shelf. These include the aluminium extrusions, readily available bolts, slider beams, etc. The usage of standard parts eliminated the manufacturing need for those components. This standardised the sizes of points of attachment, further reducing the number of custom fittings.

DfMA was taken into account during the design process by reducing the overall number of bolts required. The laser-cut MDF components slot together without need for additional fasteners. The aluminium extrusion bolt holes lined up with the motor and pulley mounts, eliminating a double up of bolts. To account for potential manufacturing tolerances and how they affect assembly, slots instead of holes were manufactured in the pulley and motor mounts to allow for horizontal adjustment without reprinting the components. The belt mount block was designed to be multi-functional by both clamping the belt ends and mounting the vacuum head; reducing the required number of printed parts improves the manufacturability.

DfMA was considered for the pulley bracket and perpendicular axis mounting bracket. If the parts were 3D printed separately, as seen in Figure 5, there would be potential alignment difficulties when bolting the blocks to the carriage, increasing assembly time and complexity. The alternative was printing the brackets as a single piece, which simplified assembly but complicated manufacturing as generous support was required during printing. The increased assembly complexity had less impact than the complications with printing the brackets as a single unit, so the parts were printed separately.

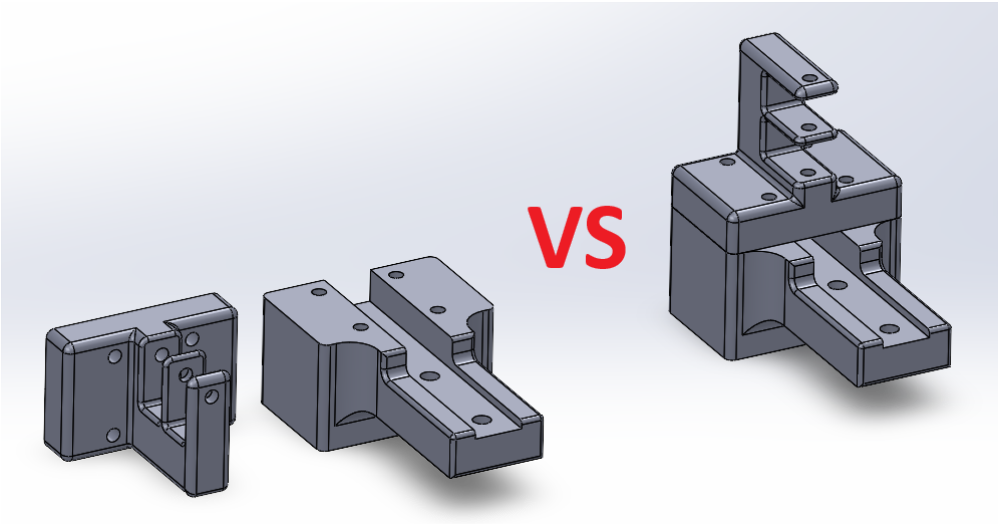


Figure 5: Comparison of manufacturing approaches

6 Sustainability and Environmental Considerations

Sustainability and end of life are huge factors in product design, and were taken into account when selecting materials and production methods. One consideration was to limit materials and the number of parts, minimising filament usage. MDF is recyclable [7] and PLA is biodegradable [2], therefore most of the machine can be either recycled or reused, in case of the smaller parts such as nuts and bolts. To ensure it is properly processed at the end of its lifetime, comprehensive disposal instructions would be included in the instruction manual, and a take-back program for end-of-life procedures may be implemented to encourage sustainable usage. By applying DfAM principles, a 20% reduction in 3D printed material used from the initial concept to final design was achieved, alleviating the carbon footprint and any associated costs.

7 Evaluation

The PNP met all initial design criteria. The total material cost was $264.24, $35.76 under target. The materials used were all readily accessible, and material variety was minimised to lower costs. The overall design was reasonably simple, enabling maintenance, repairs, or upgrades by a competent hobbyist. The device can be assembled in approximately 40 minutes, 20 minutes under the initial design criterion.

One challenge with CoreXY control is G-code generation for motor control. Although there are X and Y axes, there are not individual motors to control these axes. To move the suction head parallel to the long edge of the base plate, both motors rotate in the same direction. To move perpendicular to the long edge, both motors rotate in opposite directions. G-code designed for a conventional motion control results in movement in a plane rotated 45 degrees. Consideration during usage ensures the suction head moves in the desired direction; this added complexity is minimal but must be accounted for.

There were several future developments for the PNP that can be implemented. One repeated issue noticed during testing was the occasional jamming of the carriages on the the linear rails. Another design aspect that could have been improved was dimensioning the laser-cut slots in the MDF such that no additional machining MDF machining would be necessary to assemble the wooden frame. The current dimensions meant slot filing was required to properly assemble the frame. Other future developments focus more on overall system design, such as enabling modular sizing of components, allowing expansion of the machine depending on customer requirements.

8 Conclusion

A project was undertaken to develop and create a working PNP for rapid prototyping by hobbyists. A cost constraint of $300.00 was set to ensure the machine was affordable for hobbyists, while the development cost was only $264.24. Usable material was constrained to MDF, 3D-printed plastic, and conventional standardised screw and bolt sizes. Five designs were proposed, and a solution was further developed. The initial development was prototyped with complicated parts that were hard to modify, and which were eventually replaced with generalised parts that worked better in the system and were easier to replace.

The final maximum suction head speed was $500\,mm/s$, with a theoretical maximum placing rate of 1.2 parts per second. These measurements demonstrated the system usefulness and showed that a hobbyist-oriented PNP is viable and cost-effective. Several future improvements were removing the slight jamming of the carriage on the linear rails, more detailed dimensioning of the laser cut MDF to ensure a fit without any sanding, and introducing more modularity to fit customer requirements. Overall, the final system was an excellent example of an affordable PNP for hobbyists, and demonstrated many important engineering design and assembly concepts.

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