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Constructing Reconfigurable and Affordable Robotic Arm Platform to Teach Robotics and Automation

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Constructing Reconfigurable and Affordable Robotic Arm Platform to Teach Automation

Abstract

Since its announcement in 2011, the concepts of Industry 4.0 (I4.0) have moved from theory to real-world applications, and the need for skilled engineers has grown. Therefore, many colleges and universities are strategizing ways to provide students with hands-on experiences to develop the needed practical skills in industry. One of the pillars of I4.0 is human-machine interaction which includes robotics and automation. Undergraduate degrees need to provide applied knowledge of robots that use modern controllers and other integrated hardware rather than the classic robotic design. The curriculum should provide the students with real-world experiences with real hardware. This paper presents the steps of designing and constructing a reconfigurable and affordable industrial robotic arm platform that can be used to teach robotics and automation concepts to many engineering fields. This work presents a step-by-step construction procedure, mechanical and electrical setup, and hardware resources used to build the platform. The cost of the platform was less than $10K, which makes it affordable. Several majors in engineering and engineering technology can use the reconfigurable platform to teach many concepts of the I4.0. For example, Industrial Engineering students can use it to teach manufacturing systems concepts, and Computer Science and Engineering students can use it to teach robotics and automation concepts. We used the platforms in an operating systems and systems programming course in the Fall 2023 semester. The results of the system usability score showed a high usability score (A+) for these platforms.

1. Introduction

Several studies have used educational robots to teach STEM concepts [1]–[3]. Robotics is a multidisciplinary topic that can be integrated into several engineering and engineering technology programs. Constructing a robotics lab provides educational opportunities for undergraduate students to learn programming, mechatronics, and other skills. Hands-on experiential learning is an essential component of any engineering and engineering technology programs. Replication of industrial robotic platforms can help students receive hands-on experiences aligned with industrial practices. However, these platforms are usually costly [4], [5]. Achieving an affordable-reconfigurable-industrial setup can be challenging or expensive, especially for small colleges and/or when many robot arms are required to accommodate a large number of students. In addition, commercial robotic arms are usually hard to modify and customize. To build an affordable industrial robot arm, this paper proposes a setup based on the Dobot M1 Pro, an industrial-level robot arm, and four supplementary systems.

In this paper, we will introduce the proposed platform and provide a detailed description of the mechanical and electrical setups of the platform. The paper also describes the different end effectors that were designed and attached to the platform. Ultimately, we describe how multiple platforms can work and be connected via a network. The developed platform can be used to teach concepts in several engineering and engineering technology concepts in Industry 4.0 (I4.0). We used the platforms in an operating systems and systems programming course. The results of the system usability score showed a high usability score (A+) for these platforms.

To discuss the steps of designing and constructing a reconfigurable and affordable industrial robotic arm platform, this paper is organized as follows: Section 2 describes the system's main components and shows the complete setup. Sections 3 and 4 present the construction procedure, which includes the mechanical and electrical setups, the design of the end effectors, and the approach used to connect different modules via a network. Section 5 describes the implementation, data collection, and result of the experiment performed in a Computer Science course. The last section provides the conclusions and future work.

2. The Overall Robotic Arm Platform

The main component of the robotic arm platform is the Dobot M1 Pro [6]. This robotic arm weighs 15.7kg, can carry a maximum load of 1.5kg, has a maximum reach of 400mm, and has industrial-level repeatability of ±0.02mm. Its power supply uses 00~240 VAC at 50/60Hz, and the arm has a rated voltage of 48 volts DC. Each joint can turn 180°/s, the end effector can turn 1000°/s, and it can move up and down 1000mm/s. The first joint can move ±85°, the second joint can move J2 ±135°, the vertical moves 5mm～245mm, and the end effector can move ±360°. An air pump, suction cup, and gripper are sold in a separate M1 Basic Heads kit.

The overall platform involves four systems: the mechanical setup, electrical setup, end effectors, and multi-robot network setup. First, the mechanical setup uses an adjustable mount and a mobile work area making the Dobot M1 Pro positionable both on the table and in the room with other possible setups. All while staying sturdy, the electrical setup adds a power control cabinet to power the robot arm safely and reliably and to control any additional inputs and outputs that the arm can use, which include switches, pushbuttons, proximity and photo sensors, pilot lights, and control relays. The end effectors are 3D printed pen and camera attachments that cost-effectively add functionality and facilitate future computer vision capabilities. Finally, the developed TCP/IP network allows multiple computers to connect to multiple Dobots M1-Pro robots reliably and quickly simultaneously. Figure 1 shows the Dobot M1 Pro, and Table 1 lists the price of the robot arm and its basic heads at the time of building the robot platform. Figure 2 shows the final assembly of two platforms.

Figure 1. Dobot M1 Pro

Figure 2. Complete Setup of Two Platforms

Table 1. Dobot M1 Pro Pricelist

Component	Price
Dobot M1 Pro [7]	$5,999.00
Dobot M1 Pro Basic Heads [7]	$215.00
Total:	$6,214.00

3. Robotic Arm Platform Construction

3.1 Mechanical Setup

The mechanical system allows the Dobot M1-Pro to be reconfigurable in different placements, can support the weight of the robot arm, and prevents the assembly from shaking when the arm moves to keep precision in performing various tasks. The main components involved are the base of the Dobot M1 Pro, two T-Tracks, and the steel assembly table, as shown in Figure 2. The T-Tracks give complete horizontal placement of the robot arm on the table. Additional components could be mounted on it with the knob kit. The steel assembly table provides a rigid workspace. Its bottom shelf can store any extra components. With the table's lockable swivel casters, the assembly can be wheeled around and locked to make it stationary. This makes it ideal for creating different assembly lines in conjunction with other Dobot M1 Pro setups.

The Dobot M1 Pro mount base has six holes, as shown in Figure 3. These holes are 5/16"-18 (labeled in the figure as 8.00mm) in diameter. Four are placed in a rectangle of 215.00mm by 110.00mm. The two on the front are spaced 160.0mm apart. Since most of the force will be supported by the four in the back, the front holes are not used. Two T-Tracks are mounted on the table via holes drilled on the table surface, dimensioned as 60.24 inches by 36.22 inches, as shown in Figure 4. The holes are #6-32 (labeled in the figure as 0.14 inches) in diameter, drilled in two rows spaced four inches horizontally and 4.33 inches vertically to match the 110.00mm base of the Dobot M1 Pro. The T-Tracks are placed beside the two sides of the table joist to support the weight, as shown in Figures 5 and 6. #6-32 flat-head machine screws with hex nuts are used to mount the tracks to the table. The 5/16"-18 x 1" tee bolts with matching hex nuts are used to mount the Dobot M1 Pro to the two tracks. Loosening the nuts can let the arm slide down the track to adjust/reconfigure the position of the robot arm. Since the table is longer by a foot than the two tracks, the T-Tracks can be unmounted and moved to the other side if needed. There are three extra holes if the robot is needed on the other side, making a total of fifteen drill holes.

Given the design's simplicity, the mechanical setup did not have too many design challenges; However, finding the correct measurements for the products from the Dobot manufacturer's webpage was difficult sometimes. Some measurements from the website were either not entirely defined or provided the wrong dimensions, which made it hard to verify if all components would work together before purchasing the items. Table 2 lists the prices of the mechanical components used to build the platform.

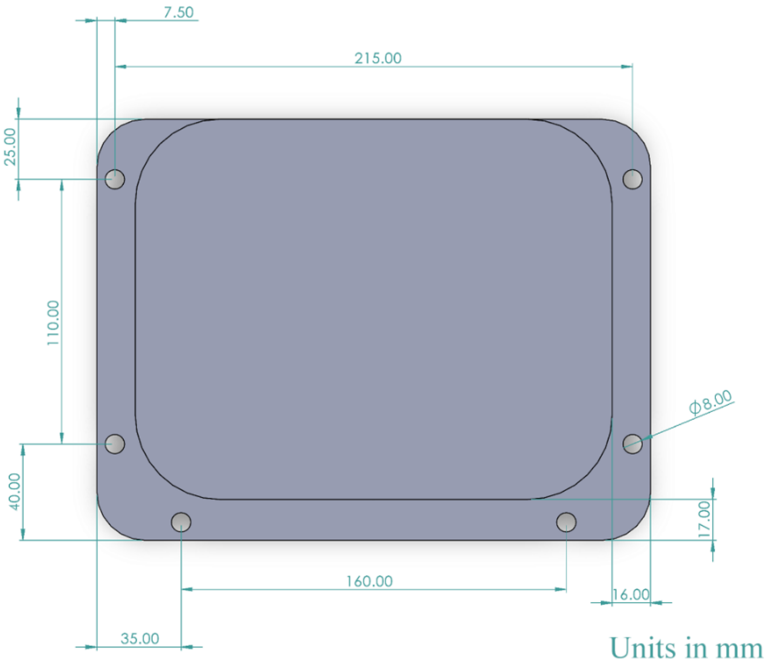


Figure 3. Dobot M1 Pro Base

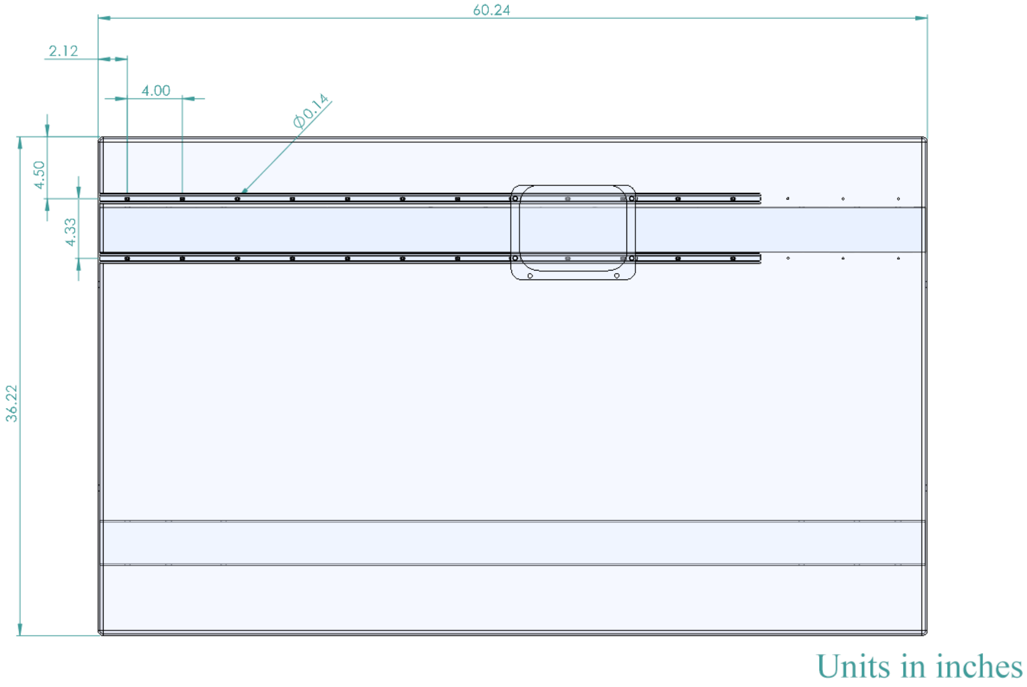


Figure 4. T-Track to Tabletop Mount

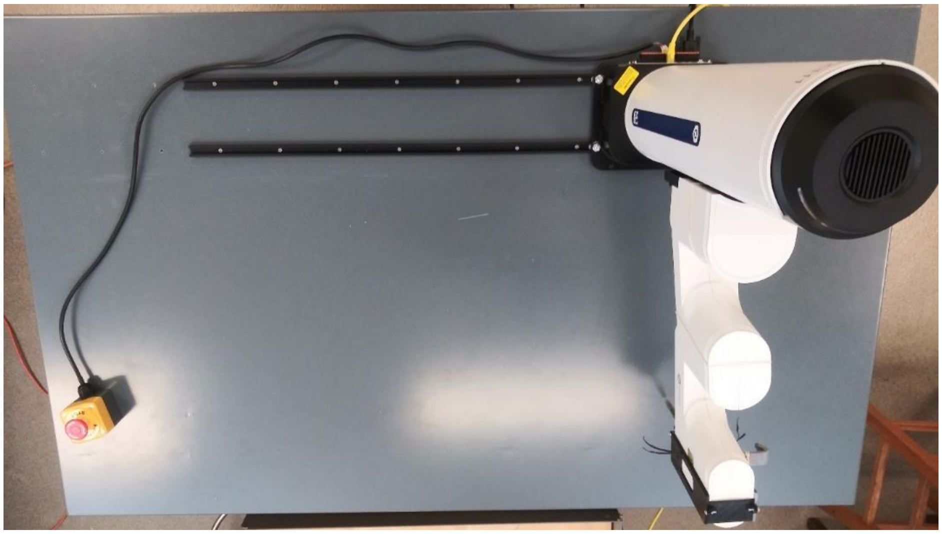


Figure 5. T-Track to Tabletop Mount

Figure 6. Tabletop Mount Underside

Table 2. Mechanical Components Pricelist

Component	Price
Steel Assembly Table w/wheels [8]*	$565
48" T-Track Pack of 2 [9]	$28.99
T-Track Knob Kit [10] [5]	$19.86
#6-32 Flat Head Machine Screws Kit [11]	$13.99
5/16"-18 Inch Nuts Pack of 10	$1.14
5/16"-18 x 1" Tee Bolt Pack of 20 [12]	$12.00

Total: $640.98

*There is a version of the table without wheels that costs $430

The mechanical setup of the platform is mobile via the table wheels and has double shelves for storing the robot accessories. Further, the height of the platform is adjustable, allowing the simulation of different manufacturing settings. The possible configurations of two identical platforms are shown in Figure 7. The two platforms can be adjacent, perpendicular, or inline, where each table can represent a different stage in an industrial manufacturing process.

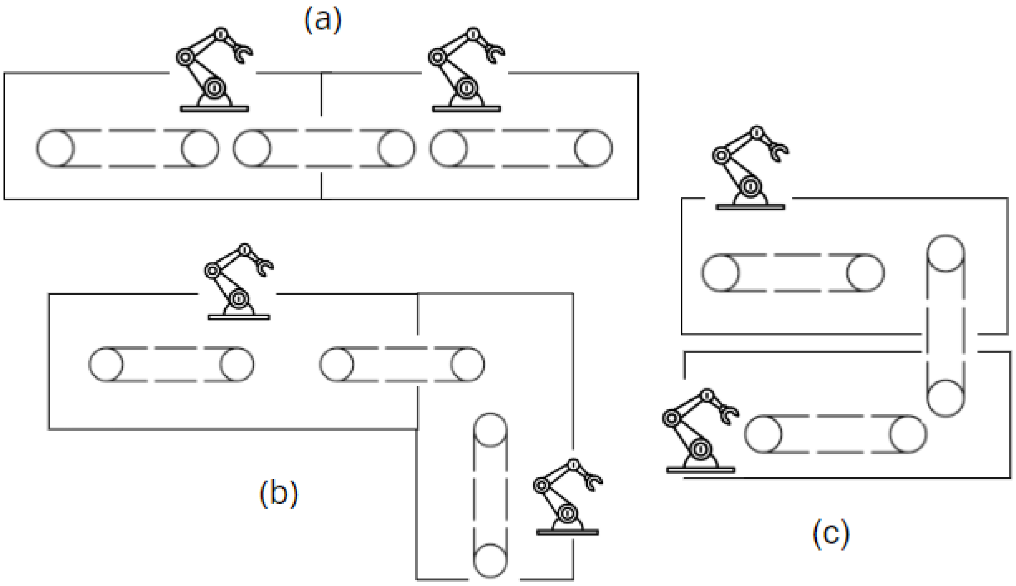


Figure 7. Various Configurations for Two Platforms

3.2 Electrical Setup

The electrical system of the platform consists of three main parts: the mounting system for the enclosure, the power circuit interface, and the control circuit interface. The main objective is to have safe, functional control and power systems. Safe operation is guaranteed by the main power circuit breaker that provides overcurrent and short circuit protection for the 120V circuit. Besides, an emergency switch acts as a kill switch to turn off power instantaneously if needed, located on the tabletop, as shown in Figure 12. A relay module is also added, which provides a control interface for 24V digital outputs from the robot arm to control 120V power circuits of larger motors and other high-power actuators (pumps, valves, etc.).

As seen in Figure 8a, the main enclosure is a steel box (14.06 x 4.15 x 10.6 inches) with a dim rail (12.9 inches long) for attaching electrical components. The enclosure uses two sets of holes, one drilled on top of it and one into the table joist. The four holes on the top of the enclosure have a radius of 0.07 inches to match the #6-32 screws. These holes extend by 0.14 inches towards the back to ensure a better fit with the welded joints between the tabletop and the table joist. The table joist's holes have a diameter of 0.32 inches to match the 5/16"-18 bolts. Because the enclosure could not be attached directly to the center, there are two variants where the enclosure can be mounted slightly left or slightly right from the center, creating four holes total. The enclosure lines up with either the left-most and the middle-right or the right-most and the middle-left hole. Both CAD designs for the holes are shown in Figures 8a and b. The enclosure mounts with four of the same screws that hold the T-Track closest to the edge down and two 5/16"-18 screws and nuts onto the joist.

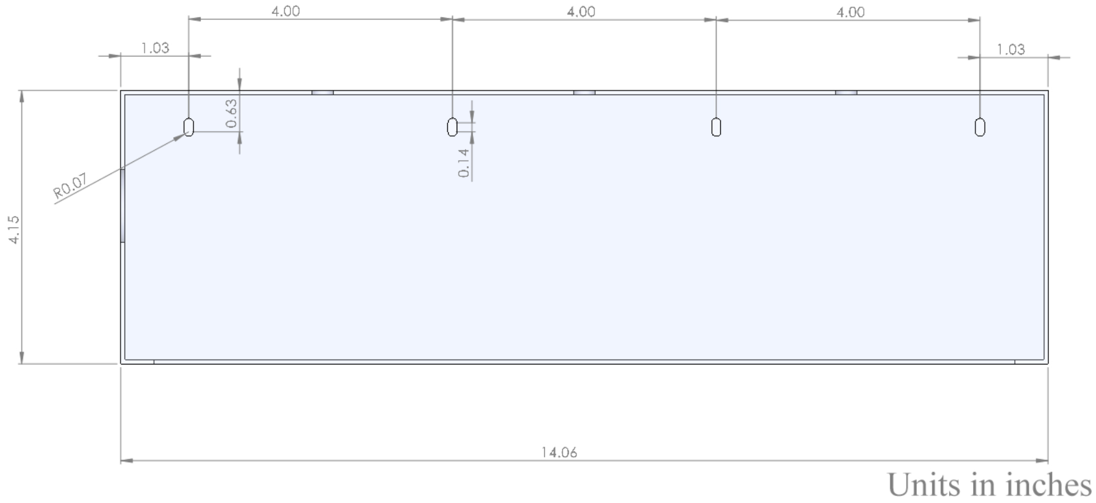


Figure 8a. Main Enclosure to Tabletop Mount

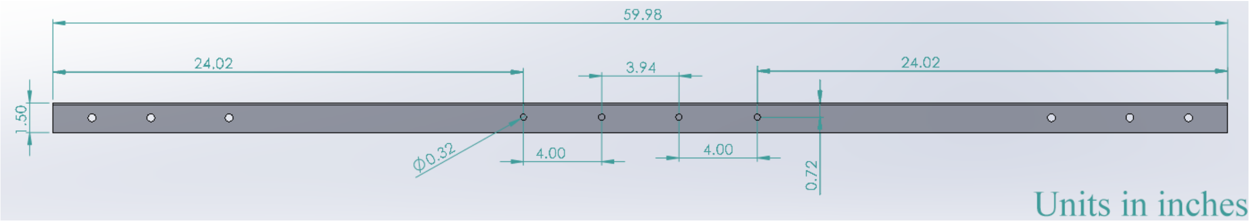


Figure 8b. Enclosure to Table Joist Mount

The electrical circuit uses a circuit breaker, the included power supply, a relay module, terminal blocks, and 20AWG wires. The specs for each component are:

1. **Circuit breaker** - current rating of 10 amps, voltage of 240.0 volts, 1 pole
2. **Power Supply** - input of 100-240VAC 2.6A, output of 48V 5A 240W
3. **Relay Module** - voltage of 12V 24V, rated load current of 10A 250VAC/30VDC, 4 groups, rated current of 21.8mA, coil resistance of 1A 6VDC
4. **Terminal Blocks** - rated voltage of 600V, rated current of 20A

The positive line of the mains voltage goes into the circuit breaker to protect the electrical circuit. It is connected to the power supply to power the robot arm and one terminal of the relay module. Everything connects with screw terminals; thus, no soldering is required. A few terminal blocks are added for future connections to different switches and sensors. Figure 9 shows the diagram for the circuit, and the complete setup is shown in Figure 10.

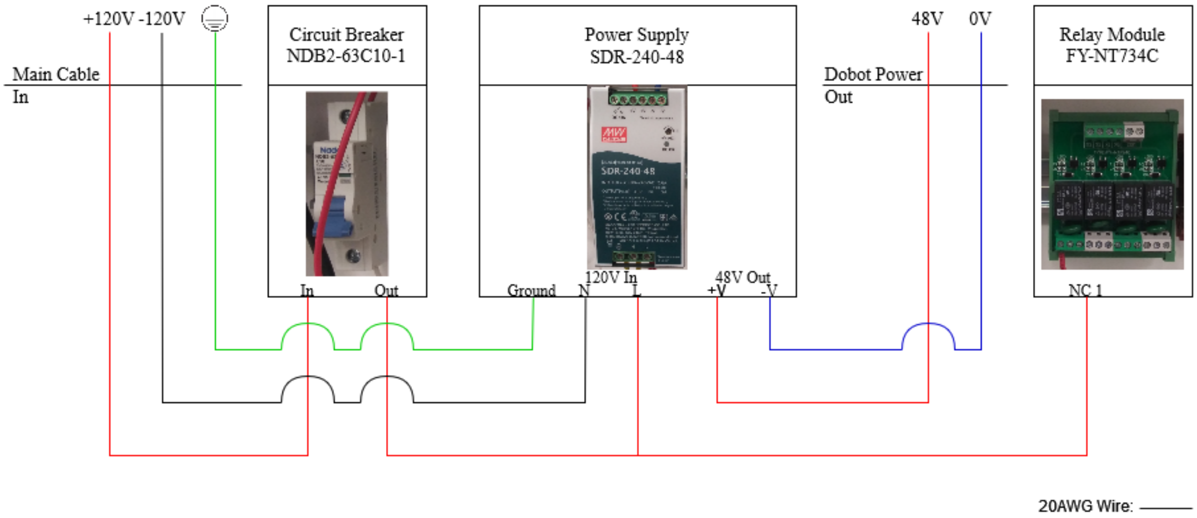


Figure 9. M1-Pro Panel Wiring Diagram

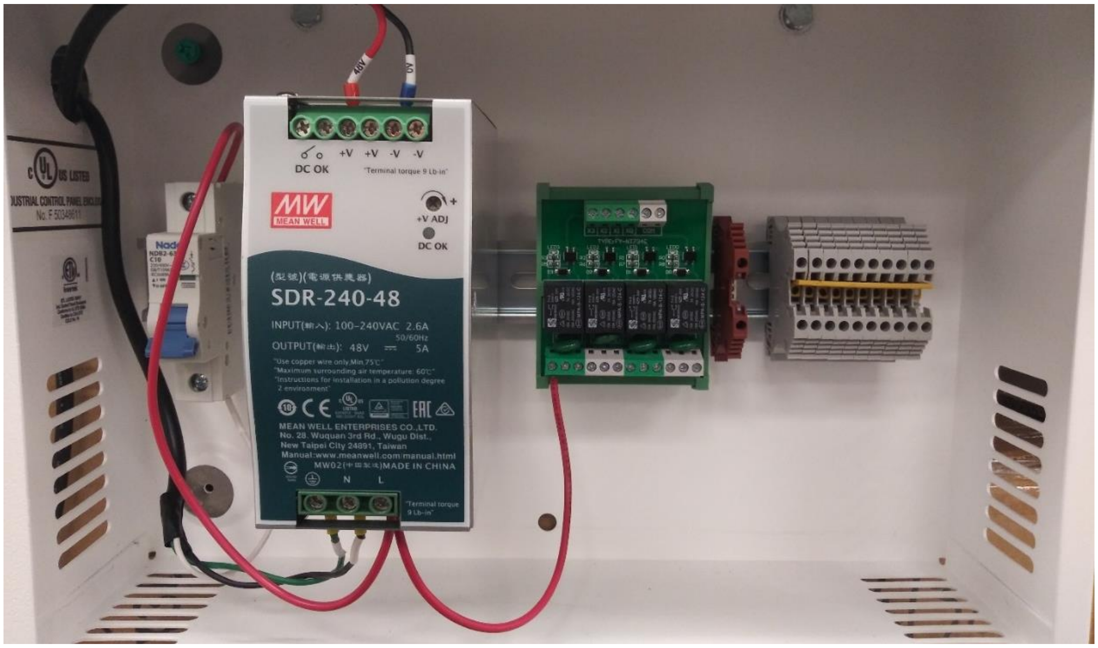


Figure 10. Complete Power Panel Setup

As shown in Figure 11, the Dobot M1-Pro's interface has 32 individual input/output (I/O) ports with 16 digital inputs (DI) located on the bottom and noted with DI xx. At the same time, the other 16 are digital outputs (DO) located on the top and noted with DO xx. Additionally, four 24V channels and four ground channels are on the ends of the I/O channels, noted with 24V and GND, respectively. The output current of every output channel can't exceed 500mA, while the total control circuit current can't exceed 2A. They can be programmed to control outputs, such as the included pneumatic vacuum for the suction cup, or they can be connected to sensors as inputs. They work with ferrule crimped wires since they are inserted and removed multiple times. The ferrule crimping kit can connect future components to the I/O. The emergency stop is shown in Figure 12. The emergency stop should be pressed to arm it. To disarm it, it should be twisted in the direction of the arrows. The emergency stop comes packaged in the stopped state, requiring a twist before it is used. Otherwise, the robot arm will flag an error once it finishes starting up.

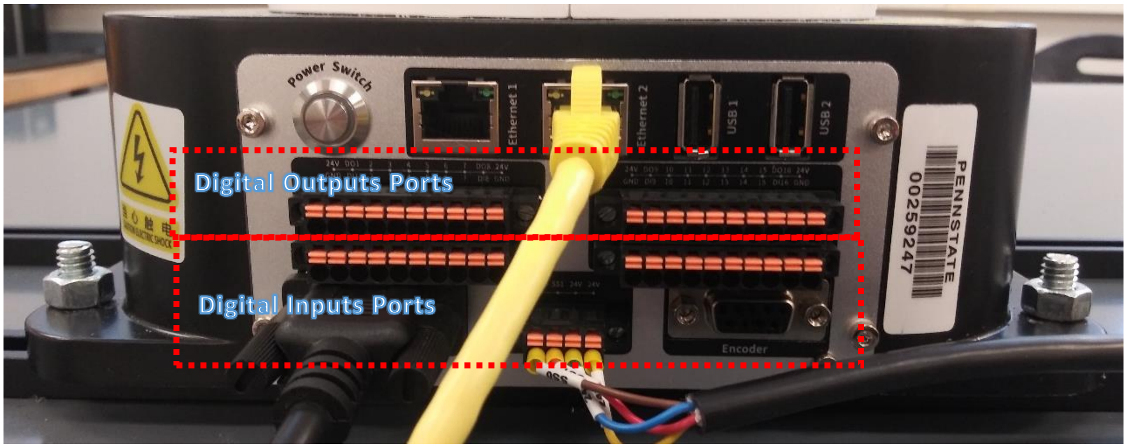


Figure 11. Dobot M1 Pro I/O

Figure 12. Emergency Stop Button

There were very few challenges with this system. The screw clamp terminals made wiring quick. A previous terminal block conflicted with the dim rail. It took up too much space and required to be screwed into the dim rail while it was detached, but it prevented the rail from reattaching. Table 3 lists the prices of the electrical components' setup.

Table 3. Electrical Components Pricelist

Component	Price
Enclosure [7]	$66.85
Circuit Breaker [8]	$9.98
Relay Module [9]	$23.60
Terminal Block Pack of 10 [10]	$4.94
20 AWG Wire [11]	$14.94
Ferrule Crimping Kit [12]	$23.83
5/16"-18 bolts Pack of 25*	$4.25

Total cost: $148.39

*Extra hex nuts were included in the mechanical setup.

3.3 End Effectors

For this platform, two end effectors were designed. The two end effectors include a pen mount and a camera mount. Both are 3D printed and use #6-32 screws and nuts to assemble, which makes them cost-effective. The designs are also adjustable to work with different pens with diameter ranges between 9mm to 7.5mm, and different webcams. The complete setup is shown in Figures 13 - 19.

The pen mount (50.0 x 50.0 x 43.0mm) relies on the included end flange that came with the Dobot M1 Pro kit. It attaches to the robot's fourth joint with a clamp, tightened with an included Allen wrench. Eight holes -located on the bottom - are placed in an octagon pattern, where the opposite side hole is spaced 40mm from each other. The holes alternate between two designs: smaller threaded holes (labeled as 3.45mm diameter) and larger non-threaded holes (labeled as 4.40 diameter). The pen mount uses four 6-32 x 1/2" screws to attach to the threaded holes, as shown in Figure 13. All the holes' designs are carried over to the pen mount, but the larger ones are unused. Therefore, a pen, sized between 9mm - 7.5mm, can be clamped into the chamber. BIC Round Stic pens were used in testing, sized at about 8.10mm in diameter. A screw and a nut of the same size as before close the 3mm gap and secure the pen. One side has a hex-shaped cavity for the hex nut to sit in, and the other allows the screw to go through and thread into the hex nut. In addition, due to 3D printers having a tolerance, any part that needs to contact another 3D print or hardware is spaced with a 0.2mm tolerance. The camera mount does the same.

The camera is required to be above the tool; thus, it is not in the way in case the arm needs to work on a part that extends up and around the tool, requiring an additional camera harness to clamp around the joint. The harness is broken down into four panels to make it easier to 3D print. The left panel (50 x 191.62 x 11.25mm), right panel (50 x 191.62 x 11.25mm), top panel (65.8 x 39.65 x 11.97mm), and bottom panel (65.8 x 50 x 12mm) are shown in Figures 16 & 17, respectively. Each adjacent panel attaches with a #6-32 screw and nut. Features included are multiple points for the camera mount to join. It conforms to the shape of the joint, like the curve on the front and the port on the right side, and a loop for cable ties to secure cables or tubes from the camera. As shown in Figure 18, the camera mount relies on a pair of holes spaced 20mm and slots on the other side for two 6-32 hex nuts. Then two 6-32 x 1/2 screws can attach to the hex nuts without going into the joint. To ensure this, the hole and the space for the hex nut must be at least 3.75mm long. Future designs for tool mounts that can use these mounting points will also need this. The camera's vertical placement can change using the extra mounting points, or additional tools can be attached. The left and right panels have these points, but the right panel has fewer because of the end effector I/O. Any web camera with a hinge or ball socket can be mounted with a rubber band, as shown in Figure 20. The hinge design is for Logitech C270, which has a resolution of 720p/30fps and attaches with an M4 30mm screw and nut. The hinge comes from a design in [13]. Unlike the rubber band technique, the hinge can adjust the camera's angle.

Challenges with the end effectors included designing the camera mount, designing around the 3D printers' tolerance, and general printing problems. The original design for the panels relied on the model that Dobot supplies, but having Solid Works rely on an external model caused multiple errors and made an unclean model. Every 3D printer has different tolerances, from the hardware's accuracy, the filament's shrinkage, or the setting in the slicer profile. One printer could fit well while others have a loose fit or tight fit, and it was ideal to have a mount that was secure regardless. Most printers can support the 0.2mm tolerance, and tolerance tests are available online that can be 3D printed to verify compatibility. The 3D printer used had experienced a minor axis shift and a thermal throttle during some of the prints. There would have been additional problems if the printer could not fit the side panels. It had a print area of 200 x 200 x 200mm.

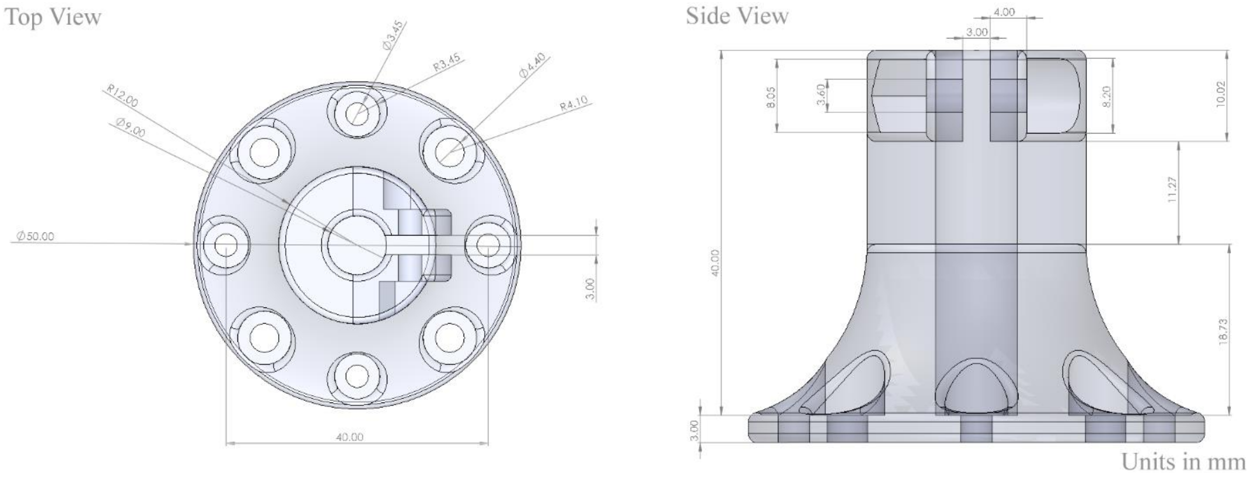
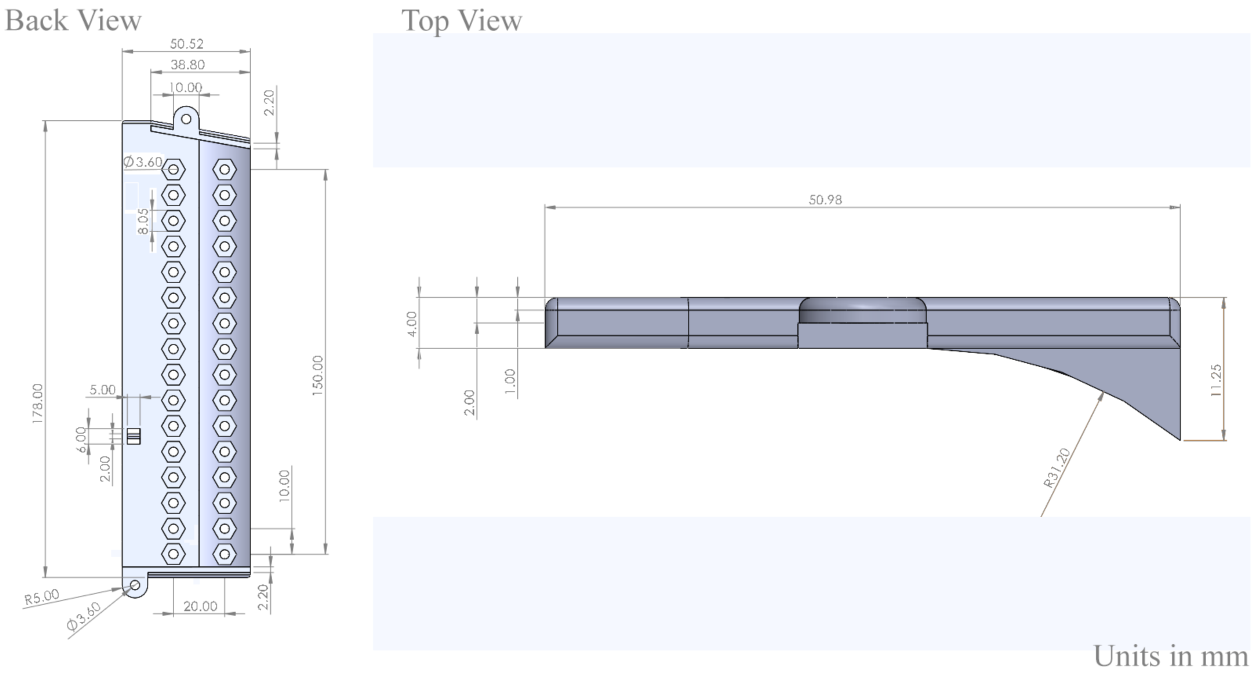


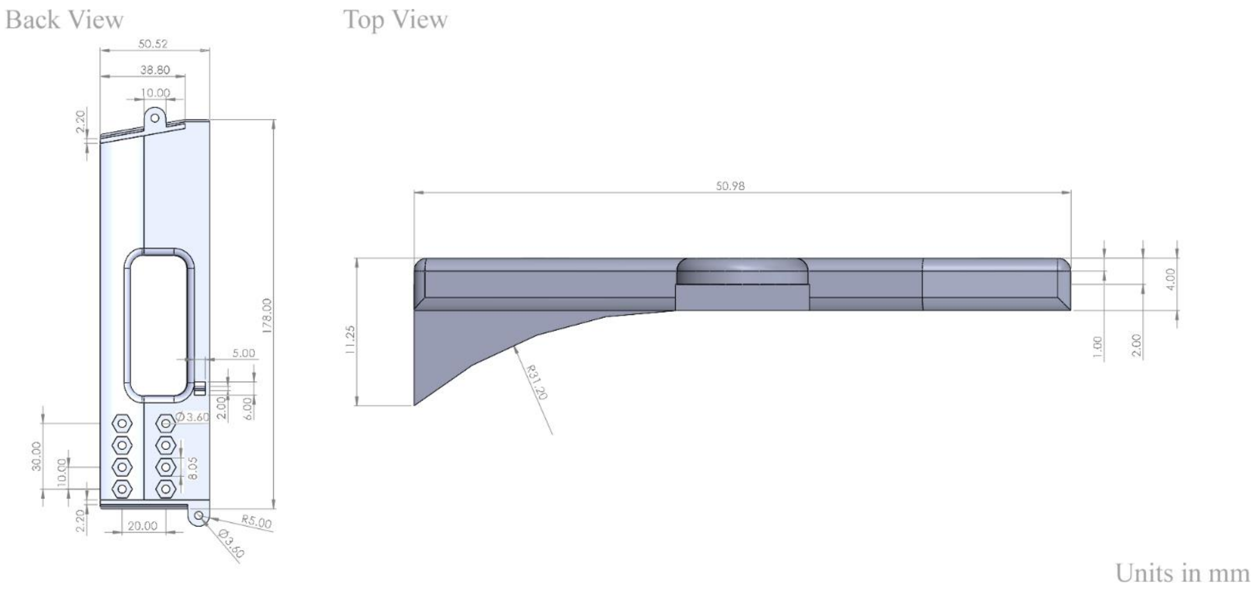
Figure 13. Pen Mount


Back View

Top View

Units in mm

Figure 14. The left Panel for the Camera Mount Holder


Back View

Top View

Units in mm

Figure 15. Right Panel for the Camera Mount Holder

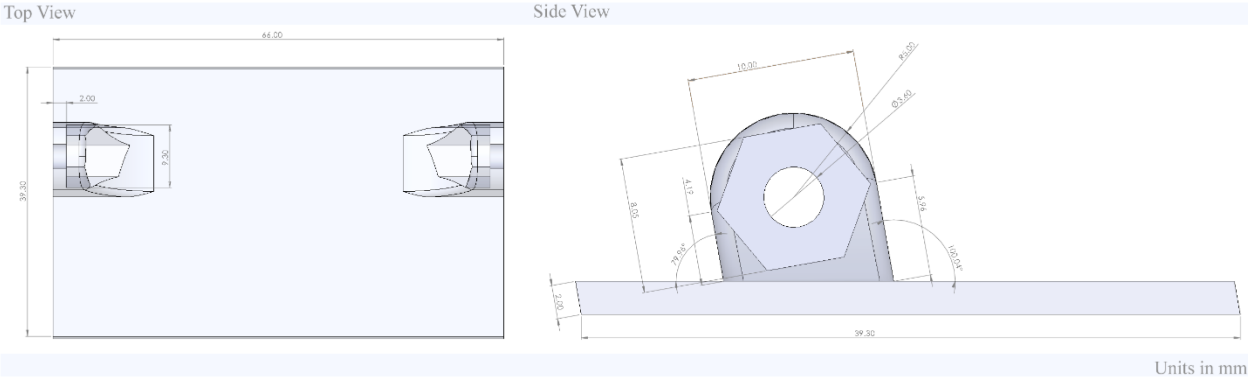


Figure 16. Top Panel for the Camera Mount Holder

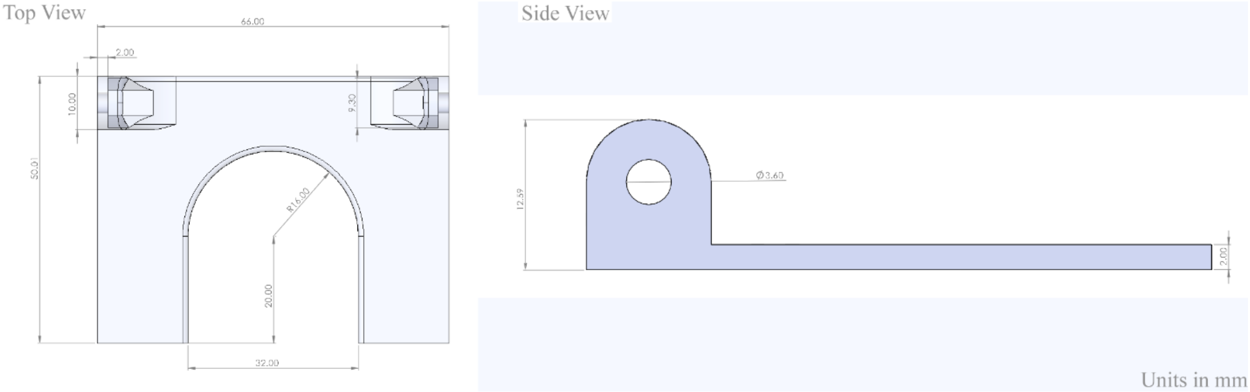


Figure 17. Bottom Panel for the Camera Mount Holder

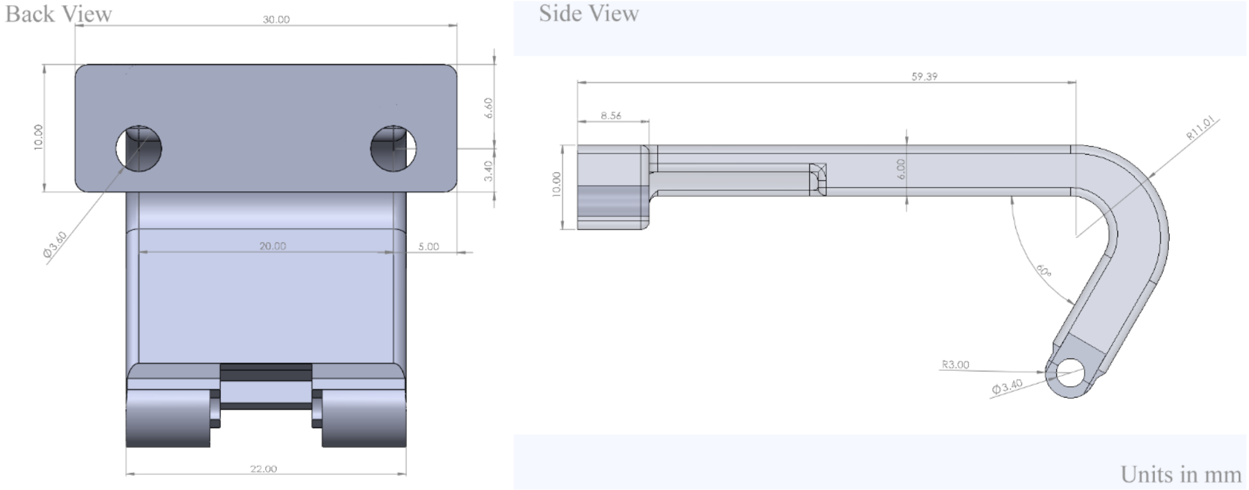
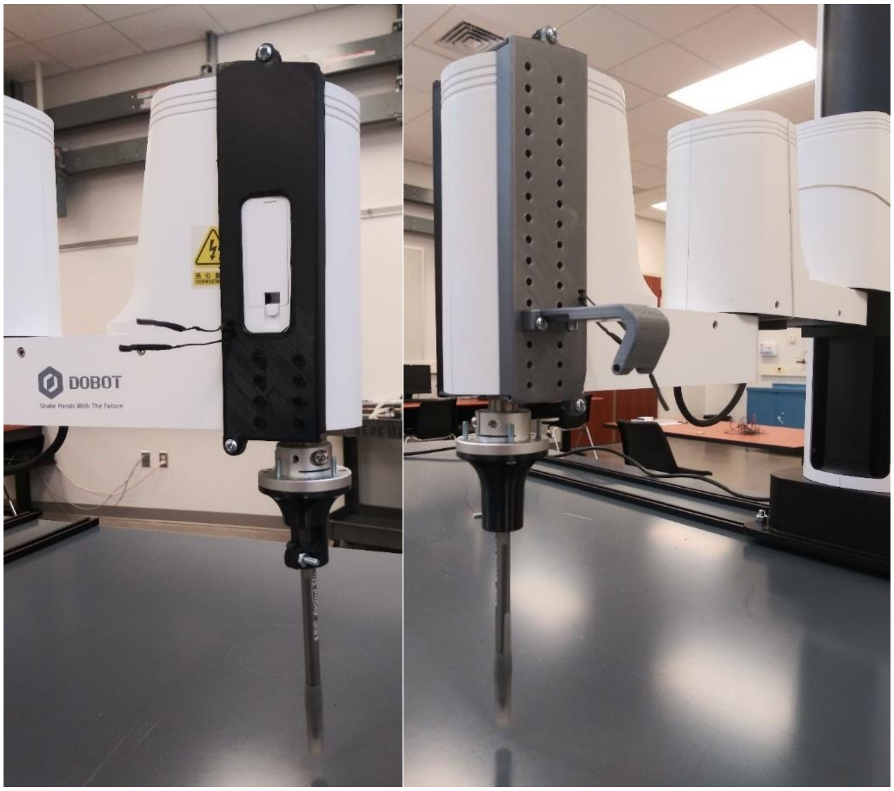
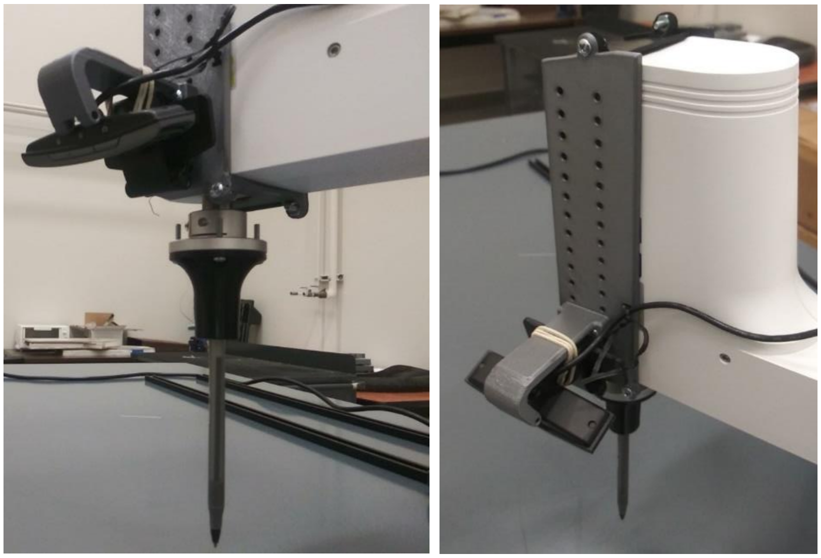


Figure 18. Camera Mount Side View



a) b)

Figure 19. Complete End Effectors a) Right Side, and b) Left Side



a) b)

Figure 20. Different Camera Setups

Table 4 lists the prices of the end effectors components. In addition, it shows the estimated printing time and material weight.

Table 4. End Effectors Pricelist

Component	**Filament** (grams)	**Estimated print time** (HH:MM)	**Price**
Pen Mount	13	2:02	\$0.30
Left Panel	29	4:48	\$0.67
Right Panel	26	4:08	\$0.60
Top Panel	7	1:15	\$0.16
Bottom Panel	7	1:07	\$0.16
Camera Mount	9	1:23	\$0.21
6-32 x ½” screws (x11) and nuts (x7)	NA	NA	\$0.97
Pens	NA	NA	\$6.49
Webcam (C270) [14]	NA	NA	\$24.99
M4-0.7 x 30 mm Machine Screw (x1)	NA	NA	\$1.03
M4-0.7 Hex Nut (x1)	NA	NA	\$1.25

Total cost: \$36.83

The 3D printing cost including filament and time is estimated by default Ultimaker Cura setting. As a rough estimate. The following shows a sample calculation of how the cost was estimated.

Calculation 1: Material Price

$$\frac{(grams\ of\ part)}{(grams\ per\ spool)}(cost\ per\ spool) \approx cost\ of\ part$$

Example: Let the spool of filament be a net weight of 1kg for \$22.99 and the part is 13 grams. $\frac{(13)}{(1000)}(\$22.99) \approx \$0.30$

Material Price does not include additional costs like time or electricity, which may be added if requested by a print farm.

To test the precision of the pencil's end effector, simple software is developed as shown in Code-1. The code manipulates the arm to initial coordinate as the initial drawing point, next, the code starts moving the pencil in square tracks of length = 5mm to draw the mesh shown in Figure 21.

The operator can control the number of columns/rows drawn in the code as well. Meanwhile, the camera holder provided a clear photo of the pencil location as depicted in Figure 22.

Code 1: Drawing Sample

```
-- Version: Lua 5.3.5
-- This thread is the main thread and can call any commands.

MovL({coordinate = {260,-60,139,0}})-- move to point above page

for i = 1,Y,1 do
  for i = 1,X,1 do
    RelMovL({0, 0, -5, 0}) -- move down onto page
    RelMovL({0, L, 0, 0}) -- move right
    RelMovL({L, 0, 0, 0}) -- move down
    RelMovL({0, -L, 0, 0}) -- move left
    RelMovL({-L, 0, 0, 0}) -- move up
    RelMovL({0, 0, 5, 0}) - move out of page
    RelMovL({0, L, 0, 0}) -- move right
  end
  MovL({coordinate = {260+(i*L),-60,139,0}}) -- move to down for the next row
end

MovL({coordinate = {260,-60,139,0}})-- move back to point above page to show where it starts
```

```
- This file is only used to define variables and sub functions.
-- variables are used to set the size of the chart
X = 8 -- Number of rows
Y = 4 -- Number of columns
L = 5 -- Length of each square's side
```

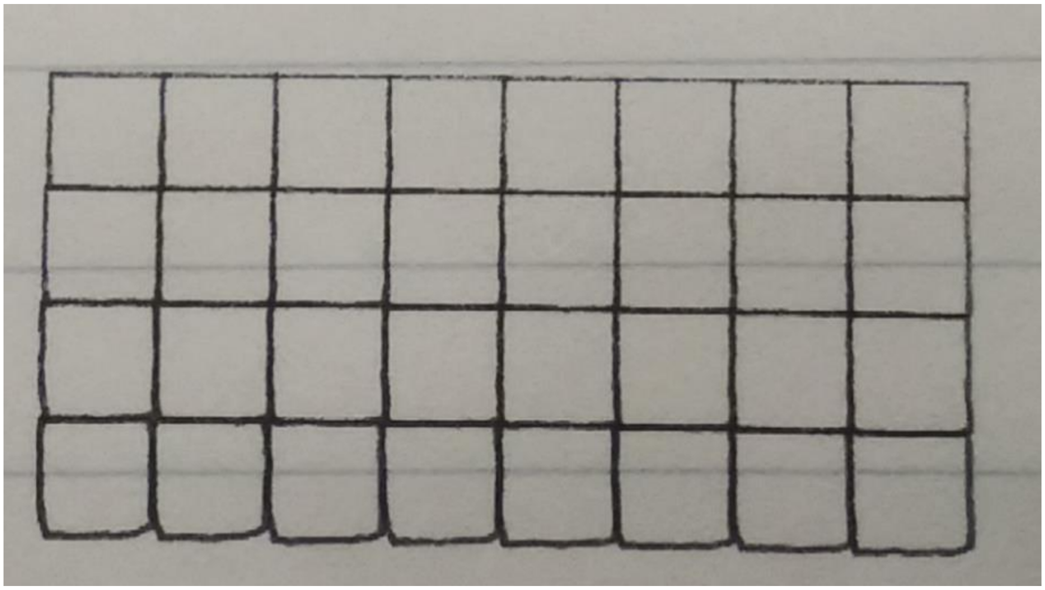


Figure 21. Drawing a 5x5mm Mesh using the Pencil End-Effector

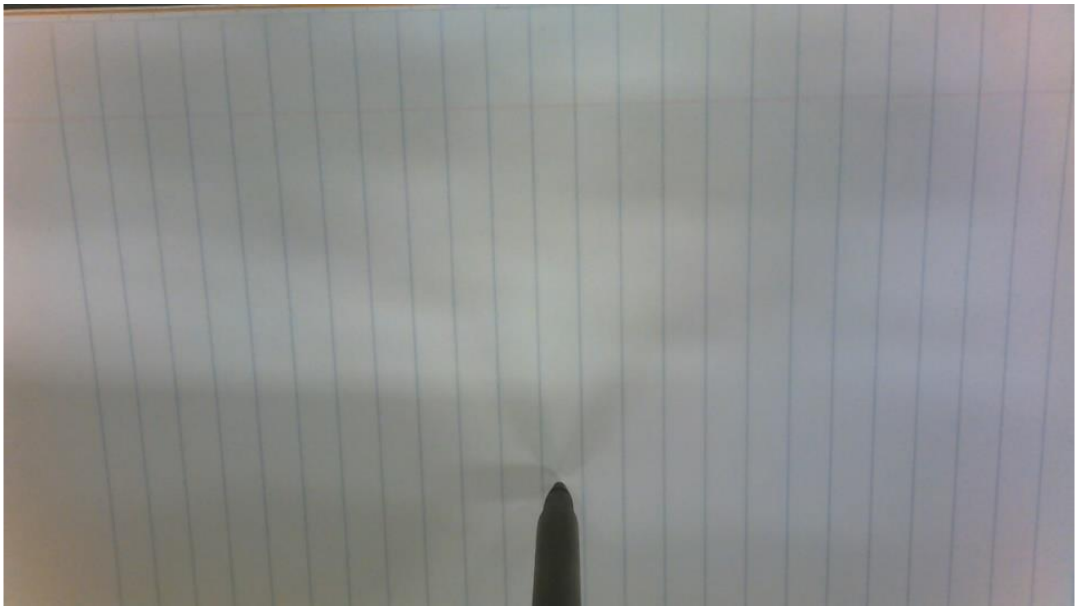


Figure 22. Camera View During Drawing

4. Multi-Robot Network

Establishing a reliable and fast TCP-IP network for multiple PCs to connect to multiple robots simultaneously involves setting up the software, configuring each arm's IP address individually, and creating a LOCAL LAN network with an ethernet switch.

Dobot provides a software package called DobotStudioPro. The software package can be downloaded from the Dobot website under their download center. Additionally, Dobot provides a Python demo program on GitHub. While it does not come with all the required features, it provides a starting point for code features. It requires IDE with Python and the NumPy library installed to run. Directly connecting to the Dobot M1 Pro with an Ethernet cable requires the Ethernet port's Internet Protocol Version 4 (TCP/IPv4) IP address to be modified. Dobot has two ethernet ports for two separate networks; LAN 1 and 2 networks as shown in Figure 11. While the LAN 1 port on the Dobot M1 Pro is set up to have a static IP and will always be 192.168.1.6, have the IP address match the subnet, for example, 192.168.1.10, to connect to it. The LAN 2 port is non-static and will be 192.168.2.6 on initial setup. After this setup, DobotStudioPro should be able to detect and connect to each Dobot M1 Pro individually.

Creating a network with multiple Dobot robots and PCs requires each robot to have a unique IP and MAC address with each PC having a different TCP/IPv4 IP address. Figure 21 shows an example of what IP to use for a network. In DobotStudioPro there is an option to change the IP of the robot by connecting through the LAN 2 port. Again, LAN 1 stays with a static IP for individual programming purposes, so the Dobot can be connected again if LAN 2's IP is changed. If the IP is changed in the network with the MAC addresses kept, all Dobot robots connected in the network will change to the same IP; thus, It is ideal to set them up independently from each other, wired directly to a computer, first. The MAC address burning program can set new MAC addresses. Start it by running the .bat file. It will ask for the IP and what MAC address you would like to give it.

Restart the robot after the operation. If left as is, only one computer can control multiple Dobot robots.

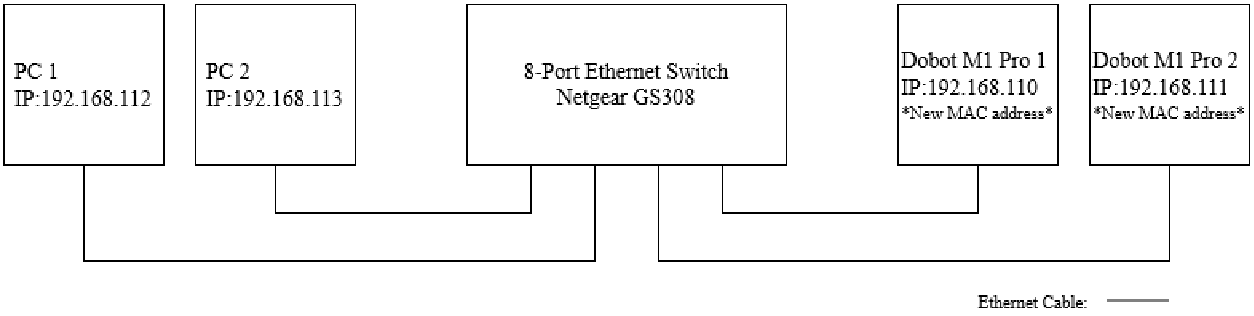


Figure 23. Network Example

Wiring the networks is simple. As shown in Figure 21, everything connects to the network switch with an Ethernet cable. The switch is a Netgear GS308, an unmanaged switch with eight-Gigabit Ethernet ports. PCs will either have a port to connect with from their built-in I/O or a USB to Ethernet adapter can be used. As stated before, LAN 2 will be used for the multi-robot network, leaving the first port if the Dobot robot needs to be interfaced individually. The cost of the wires depends on the positioning of the PC, the Dobot robots, and the switch. The pricelist (see Table 5) assumes that both connections will use two 25ft cables. The Dobot package includes an Ethernet cable that can connect the PC to the switch if it is close enough to reduce cost.

Some challenges have developed during network configuration. First, the documentation does not mention that all Dobot M1 Pros robots come with the same MAC address, Regardless of whether you use a router or a splitter while the MAC address is set as the default, only one PC can connect to a Dobot robot. If another PC attempts to connect to the other Dobot, the first one loses connection, and the other does not connect due to MAC address conflict on the network. Thus, the MAC address program had to be acquired from Dobot support to configure the robots with different MAC addresses. With this information and software, setting up a network with multiple connections is made more accessible. Another challenge that has developed during the network configuration is that M1-pro requires certain Samba installation, which is a software package that gives network administrators flexibility and freedom in terms of setup, configuration, and choice of systems and equipment. There was a problem where Samba failed to install it onto a PC, preventing the software from connecting. Reinstalling the software solved this issue.

Table 5. Network Pricelist

Component	**Price**
8-Port Ethernet Switch (Netgear GS308) [15]	$19.99
Two Ethernet Cable (25ft) (x2)	$19.52

Total cost: $39.51

5. Implementation

5.1 Class and Exercise Description

The robotic platforms were used in an operating systems and systems programming course at Penn State Behrend as a part of a lab exercise to demonstrate concepts related to task design, timing, synchronization, and mutual exclusion mechanisms. The exercise was divided into sections: Introduction to the robotic platform operation, task design using timing and synchronization mechanisms, and feedback and reflection on the lesson learned.

The tudentts were first introduced to the basic operation of the robotic arm using manual control and Application Programming Interfaces (API) control through a Python control program. The challenges of moving the arm in space using different coordinates and keeping track of the arm's position were explored using the manual and programming mechanisms.

The Python API interface could be used to develop a program to move the arm to specific coordinates or call a predefined stored procedure at the robot's internal storage—the benefits and drawbacks of each method were explored and demonstrated.

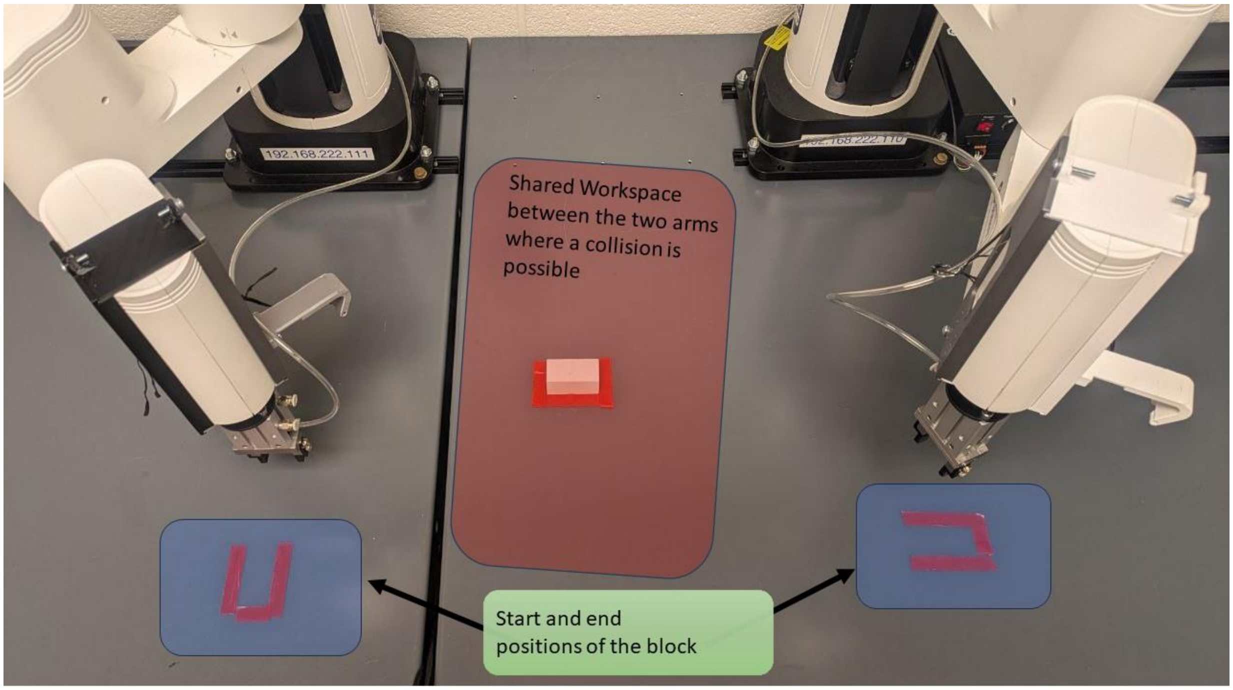


Figure 24. Two robotic arms with shared workspace.

An exercise was designed to develop a task for each robot where the two robotic platforms collaborate to exchange blocks. The first robot arm moves a block to a predefined location accessible to both robots. The first robot must retract its arm before the second robot can move to get that block. The challenge is to build an independent task for each robot while maintaining synchronization between the two arms to avoid collisions in the shared/common workspace area. The students had to test and implement the proper sequence of events in space and time while enforcing mutual exclusion in the shared workspace to prevent arm collisions. The Python control program is connected to both robots using an Ethernet network, which queries the robots' status and coordinates the execution of tasks for each robot. Each robotic task execution was performed independently as separate threads. The Python control program coordinated the two task threads' access to the shared workspace to avoid collision between the arms. The block start and end locations were predetermined during programming time.

The block location was assumed throughout the experiment since the students placed the block in predefined coordinates on the workspace. The coordinates had to be statically programmed in each handover sequence. This limitation might be an issue if the block shifted outside the predefined coordinates; the arms could not complete the handover sequence. This drawback could be solved by adding a camera system to the robotic arm utilizing the 3D printed mount. The Python control program could be used to perform image recognition to detect the object's location and move the arm accordingly instead of using pre-programmed coordinates. The block coordinates would be inferred from the image using either image processing or a machine learning model; students are currently investigating both mechanisms, and the results will be incorporated in future exercises.

The students were asked for feedback at the end of the lab exercise. Most students' feedback was positive, with a high level of excitement. The real-world example of how design choices affected the operation of the robotic arm made the students more interested in learning better ways to design tasks and control sequences. Multiple students have shown interest in pursuing research activities in robotics and computer-based control of such systems. More details on students' feedback can be found in the following section.

5.2 Data Collection and Results

After the lab session, a survey was conducted. The survey included questions to collect student demographics, their level of interest in programming and networking, and the System Usability Score (SUS).

The majority of the participants are male students (17 out of 20). The racial composition is predominantly White (15 out of 20), followed by Hispanic (2), with students identifying as Black/African American, Other, and Asian. Students come from a mix of software and computer engineering majors, primarily in their third or fourth semester. Academically, the participants have a good standing, with an average GPA of around 2.98.

Interest in robotics and networking is high, with an average interest level of 7.25 out of 10, despite varied self-assessed knowledge levels. The results of the SUS survey showed high scores, averaging 86.63 (A+ grade), indicating that the module is engaging and accessible to students. In other words, the platforms and the developed module meet the needs of a broad section of students.

In addition to this survey, the students were asked to reflect on this experience. Here are some of the comments received from the students:

"I had never seen a robot and played with it, so this was very exciting for me; I knew before that the robot knew what to do using a code. I hope to do something like it in the future."

"I thought the robot demo was super interesting as it's a real-world application that is extremely useful. Assembly lines and other types of manufacturing systems utilize robotics in this way and have similar synchronization requirements to what we saw in the demo today. Adding a camera to cover for the inaccuracies of absolute position was also quite interesting to me.

I really enjoyed this course quite a lot. The coding exercises were engaging and genuinely fun to me, and were also applying important concepts that we learned in class. I will absolutely apply the concepts I learned from this course in my future endeavors."

"This lab was very interesting and introduced me to a field that I do not have extensive experience in. I enjoyed the correlation between what we learned in this course and the techniques used to implement the robot software. Examples of such techniques were synchronization, threading, mutual exclusion, and inter-process communication. To handle the I/O ports, they could be treated as interrupts that determine how the user interacts with them. Some efficiency improvements could be made by implementing asynchronous threads or using data structures in ways that promote synchronization. The type of operating system that would be ideal for this robot would be a real-time operating system because it relies on time-critical events. A software design pattern that is relevant to this situation is the client-server pattern, where the arm is continuously waiting for commands that the user is sending to it."

"I thought the lab was fun, interesting, and educational."

"I think this lab was great. It has great potential to be implemented into what we are learning."

"I thought the robotics lab was a nice change from the typical lab in this class, especially since very few classes I have taken have included hardware and software at the same time, even though they are both important together. Robotics have always been interesting to me, I have a very small amount of experience with robots from a battle bot club in high school, but I didn't do anything related to programming in that, so it was cool to get a glimpse at how it works. One of the hardest about learning software and programming for me has been understanding how to actually apply it in useful scenarios since it usually gets taught in an isolated context. I enjoy learning about things, but I feel like most classes do not attempt to cover things outside of a basic curriculum, even if I am willing to do more work to learn more."

"I think introducing students to robotics is brilliant. As someone who was once a CS and is currently a software major, I wasn't too sure on which field I wanted to go into, I just knew I wanted to see that what I learned yielded applicable results. With the first 2 years I've spent here, I feel like without doing research or external projects, I would've easily lost sight of why I was here at all. I believe that introducing robotics to students more would help to remind students why they chose to come to college in the first place."

6. Conclusions and Future Work

This paper presents the steps of designing and constructing a reconfigurable and affordable industrial robotic arm platform that can be used to teach robotics and automation concepts to many engineering fields. This work presents a step-by-step construction procedure, mechanical and electrical setup, and hardware resources used to build the platform. The reconfigurable platform can be used by several majors in engineering and engineering technology to teach many concepts of Industry 4.0. For example, Industrial Engineering students can use it to teach manufacturing systems concepts, and Computer and Electrical Engineering Technology students can use it to teach programming concepts, robotics, and automation.

The total cost for a single setup is $7,079.71, excluding the labor cost. The project was completed over three months in the summer. The design has managed to deliver an affordable-industrial level, reconfigurable robot arm, having a reliable interface for power and control circuits, adding a pen and camera as end effectors, and working with multiple other setups in a network. The initial implementation showed a high usability score, which means that the robotic platforms and the teaching modules were engaging to the students. The qualitative data confirmed these results. Future work includes attaching more end effectors and hardware like a conveyor belt, utilizing the camera to add image recognition functions, and creating learning modules for different concepts.

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