Design and Development of a Planar Robot Arm

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Project Definition

The purpose of this project is to design and manufacture a planar robot arm. This project is done as a personal project to test and apply knowledge learned during university education. This project will utilize methods of robotics and automation, as well as control systems, actuators and power electronics, rapid prototyping, and mechatronics design.

Requirements

The robot arm must have at least 3 degrees of freedom, but may extend to 6 depending on the capabilities of the system. The arm is to utilize as many on-hand components as possible. The arm must be designed around the use of MG996R servo motors. The links of the arm are to be 3D printed as much as possible. The robot must be controlled using an arduino uno microcontroller or similar. The end effector is to be designed to be replaceable.

Current State of the Art Survey

A search was done into existing designs of 3D printed robot arms. Many designs were found on open source sites like thingiverse, where uploaded designs can be viewed and downloaded. While the purpose of this project was to design the parts from the ground up, a survey was done looking at these existing designs.

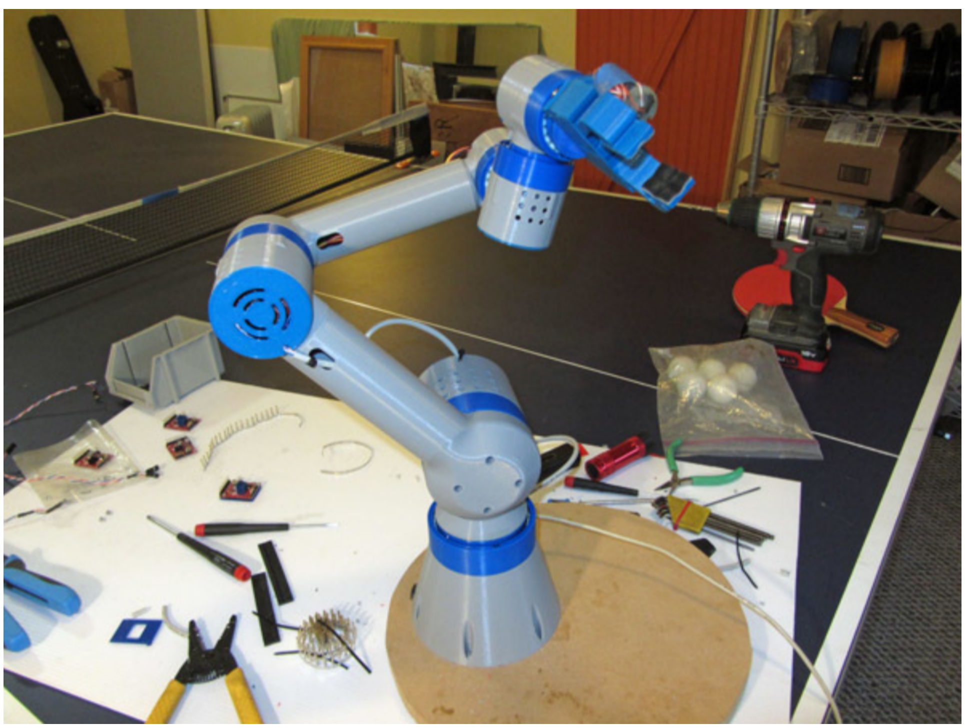


Figure 1

The design shown in Figure 1 shows the 3D printed design from user LoboCNC. It mimics the design of the UR3 industrial robot. This arm uses stepper motors and compound planetary actuators for motion at the joints. It is controlled by Tic T500 stepper controllers using a firmware developed by the user to support coordinated motion. The design of the links for this robot completely encase the actuators housed within the links, significantly reducing the risk of getting hands/fingers caught in the joints, which is a significant part of Canadian robotics safety standards. The robot end effector is an actuated gripper which can be used to grab onto objects.

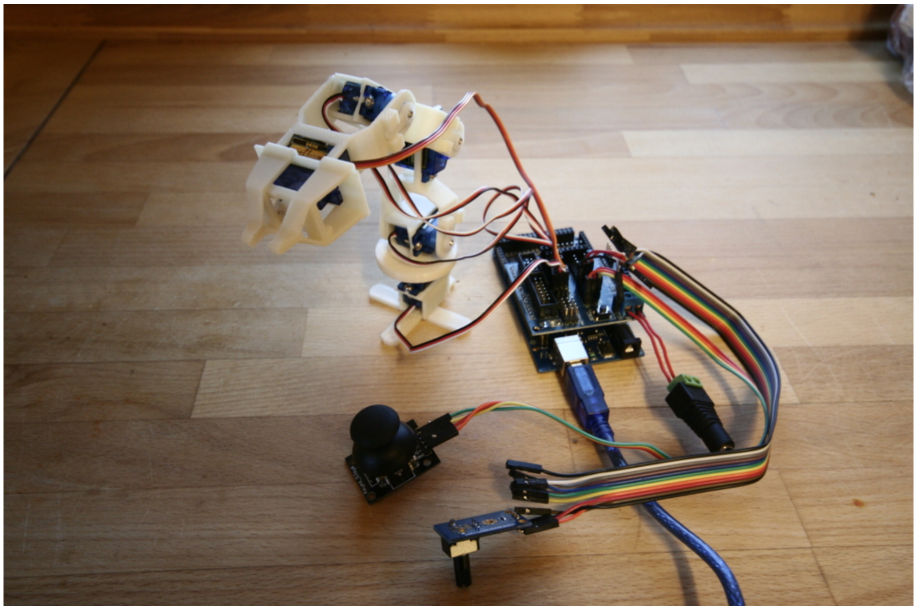


Figure 2

Figure 2 shows another 3D printed design, this one uploaded by user bentommye. It features 3D printed links that house 9g servo motors for movement at the joints. It is controlled with an arduino microcontroller and a joystick module. It uses a servo to actuate the end effector, which acts as a small gripper for grabbing small objects. The servo motors this robot uses are much closer to the requirements of this project than the previous design, taking note of the cages that are used within the links to house the motors. The links also use the small arms that come with most servo motors fit into a track on the joint of the link, so that as the servo rotates, it pulls the entire arm with it.

Figure 3

Figure 3 shows a design from daGHIZmo. It uses servo motors for actuation similar to the previous design from Figure 2, however this uses a much more complicated link structure in terms of its actuation.

A survey was also done into the methods that may be used to control the robot arm remotely. This was done by a search for control modules compatible with arduino controllers. What was found were IR remotes with receivers for wireless control, joystick modules, pushbuttons, membrane switches, and keypads.

Engineering Specifications

The system needs to be able to be controlled by the user. The servo motors max speed should not exceed its maximum operating speed of 60 degrees per second. The arm should be capable of rotation of at or close to 360 degrees perpendicular to the ground plane of the arm. The additional links should have a degree of freedom to rotate at least 90 degrees in either direction from its zero position. The robot arm needs to be able to support the weight of the servo motors, which are 55 grams each. Any end effector designed for grabbing objects should be able to handle a minimum load of 55 grams as well.

Concept Generation

Body

The body went through a could iterations based on the designs reviewed in the previous section. Figure 4 shows a design for the base and links similar to the first design shown in figure 1. It uses more rounded joints and domes to house the motors to avoid exposed parts. The motors can theoretically be mounted inside the links and base. The base could make use of a planetary gear set to provide the rotation, or a more direct mount to one of the motors.

Figure 5 shows a more blockier design for the links, more closely resembling the design shown in figure 2. The method for mounting the base to the ground is much smaller to reduce the amount of the space that the robot takes up. The motors would be held in the links through cages. This means the parts would be more exposed, however this provides a benefit of being able to provide quick and easy maintenance of the joints and motors.

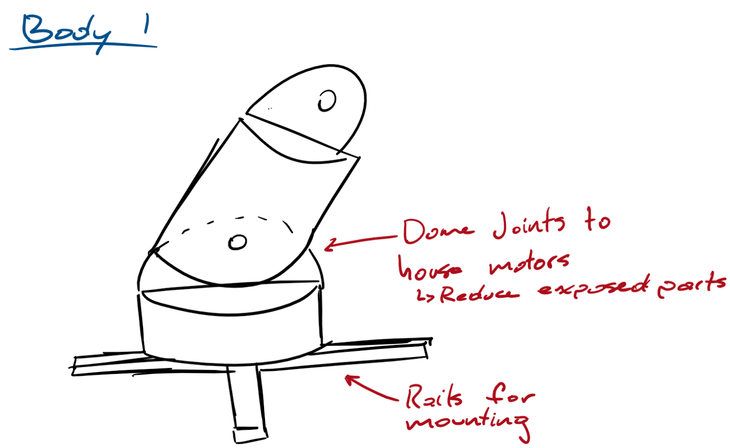


Figure 4

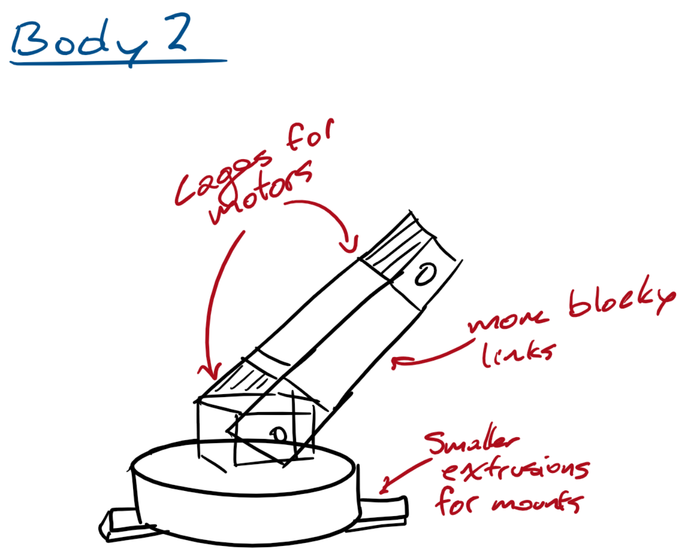


Figure 5

End Effector

Multiple end effectors were conceptualized for the robot arm. Figure 6 shows the design of an end effector meant to hold a marker or pen. This would allow the robot to draw on a piece of paper, and would be good for showing off the robots range of motion, and its ability for the motors to work collaboratively.

Figure 7 shows a gripper design. This is meant to be used for pick and place operations. It would show a more useful application of the arm, as well as the robots accuracy when performing tasks. It would be actuated by a rack and pinion system controlled by another servo motor.

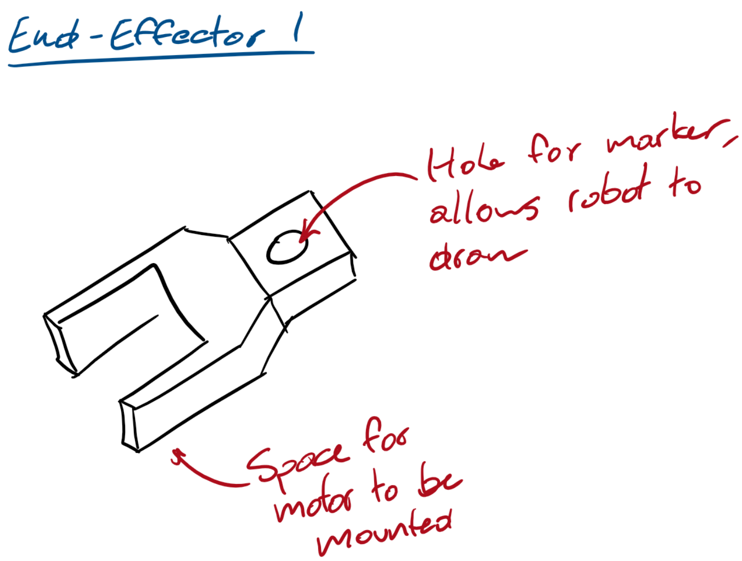


Figure 6

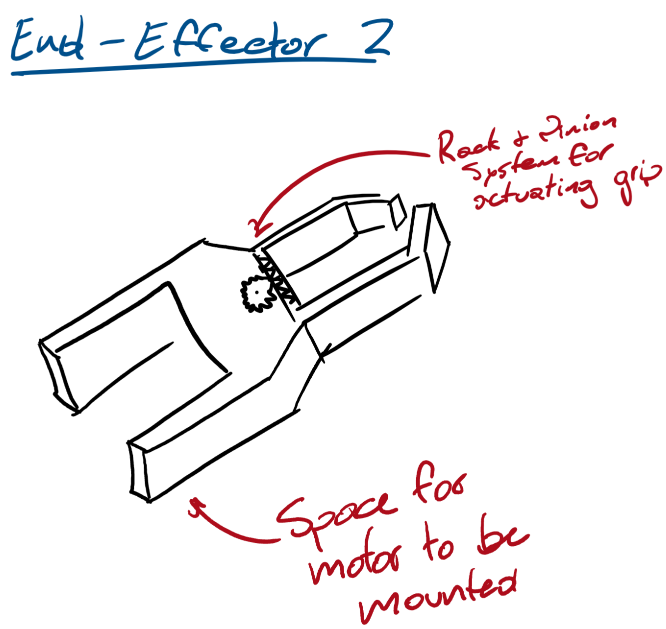


Figure 7

Controller

Control could be implemented using a few different modules. An IR remote with a receiver could be used to control the robot arm without wirelessly. The buttons on the remote could be rigged to control each motor separately. A similar setup could be used with a membrane switch, however this lacks the wireless capability. A joystick could be used similar to the design shown in figure 2, however this creates a problem with usability, and intuitive controls with the motors. The joystick would have limited capabilities with regards to how many motors it could control at a time.

Form Design and Engineering Analysis

Ultimately it was decided that for the first prototype of the robot arm, the second, more blockier concept for the body would be used along with the first concept for the end effector. Modeling and design started with taking the dimensions of the servo motor, and creating a cage that will be present in all of the links for the arm. The 3D model was then loaded onto the printer, and dimensions were tuned until the test print was capable of holding the motor firmly in the cage. The 3D model and final test print of the motor cage can be seen in figure 8 and figure 9. The slot in the motor cage is to allow the wires that come off of the side of the motor to be accessible without interfering with the cages ability to hold the motor.

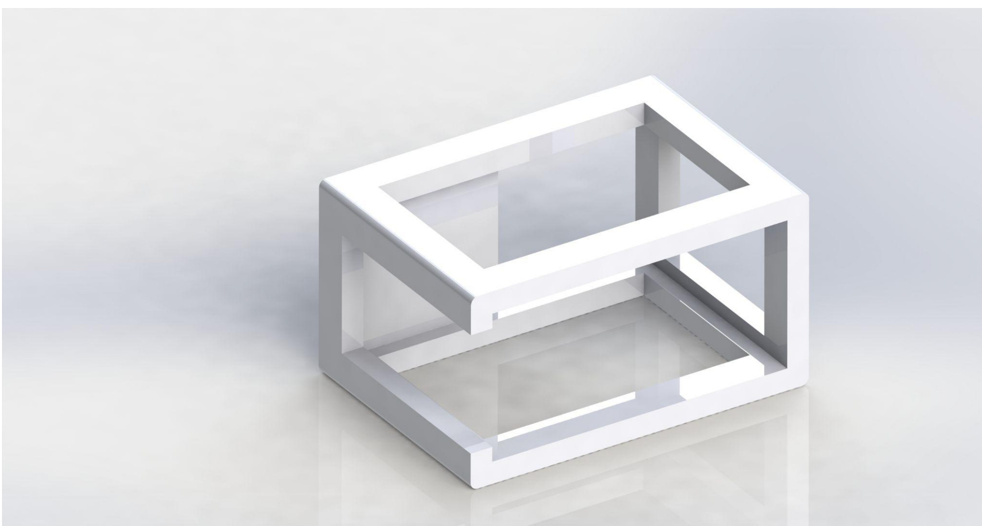


Figure 8

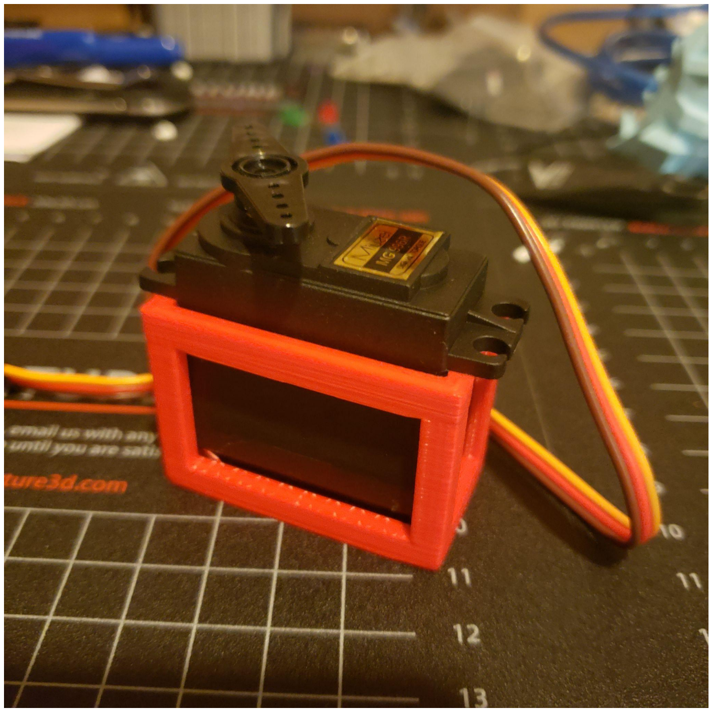


Figure 9

Once the dimensions of the motor cage were finalized, the cage was used as a starting point for the links and base of the robot. The links were designed with a more blocky structure and an exposed motor cage. One end of the link is designed to receive the motor, and has holes cut out and notches extruded to allow the plastic propeller piece that comes with the motor to be attached to the motor to control the link. The opposite end of the link has the motor cage, designed with an additional support pin extruded from the opposite side of the motor cage in line with where the gear of the motor is. The 3D model of the links can be seen in figures 10 and 11. These links were designed with minimal support material in mind for 3D printing, as well as a hollowed out middle section to reduce the amount of material needed to manufacture the parts. The links were also designed so that any number of them could be connected in series without the need to design entirely new parts.

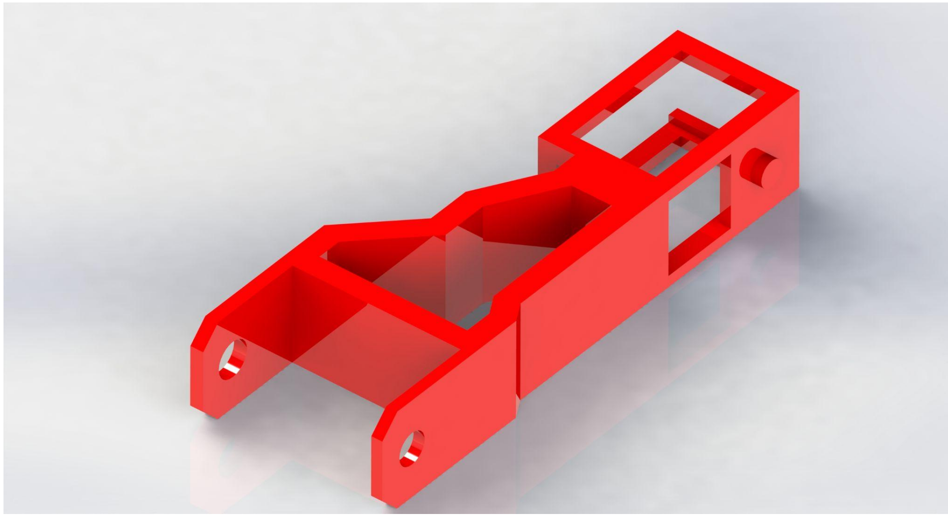


Figure 10

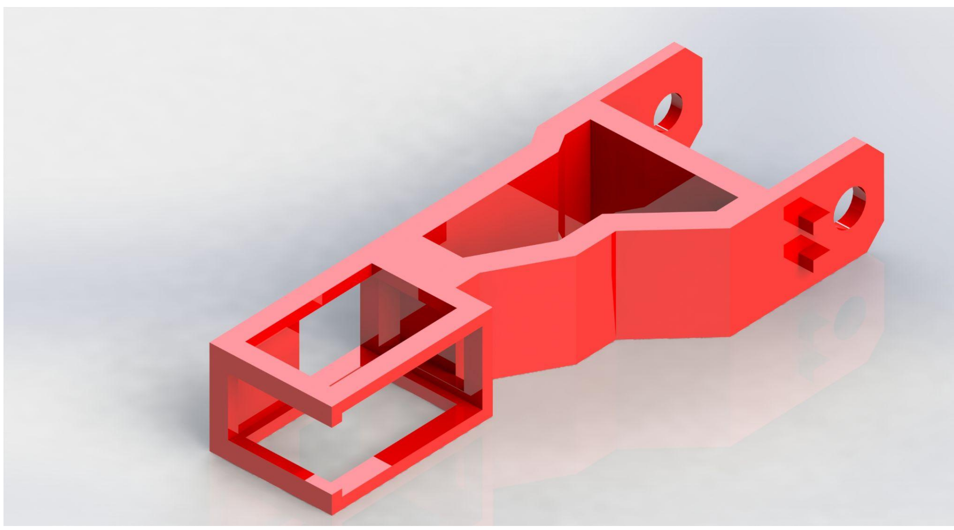


Figure 11

The platform and base of the robot arm were designed together. The base is a large cylindrical container with a motor cage in the center. The top of the cylinder contains a counterbore to allow the platform to sit on top, making it flush with the top of the base. The platform also contains a small ring around the bottom that will allow it to be screwed into a table to fix it to a surface. The bottom of the base contains a through hole directly underneath the motor cage, to allow the entire motor and platform to be removed safely from the base without pulling on the top of the robot. Just punching the motor through the hole should lift the assembly out of the base. Another through hole is cut out from the side of the base to allow the wires for the motor inside the base to be accessible. The platform contains a motor cage in a horizontal position to act as a shoulder joint. The platform also has 4 holes in a circular pattern that line up with one of the propeller pieces from the servo motors. The propeller can be screwed into the platform, and then the platform attached to the motor to allow it to rotate perpendicular to the ground. The platform and base can be seen in figures 12 and 13.

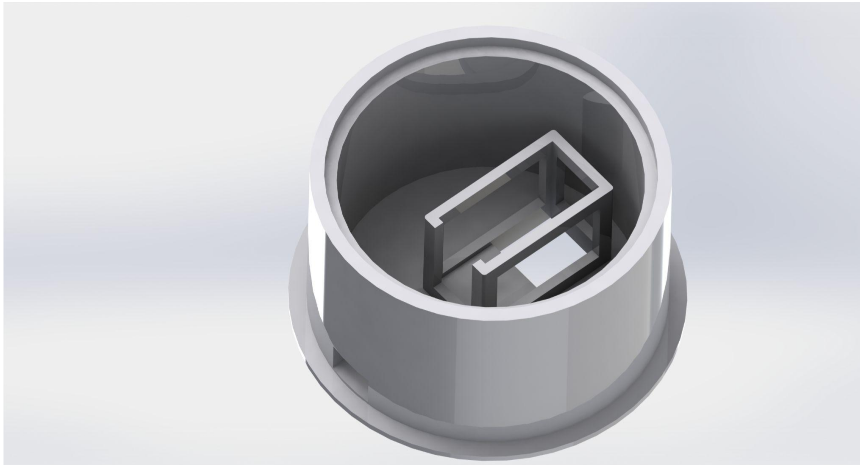


Figure 12

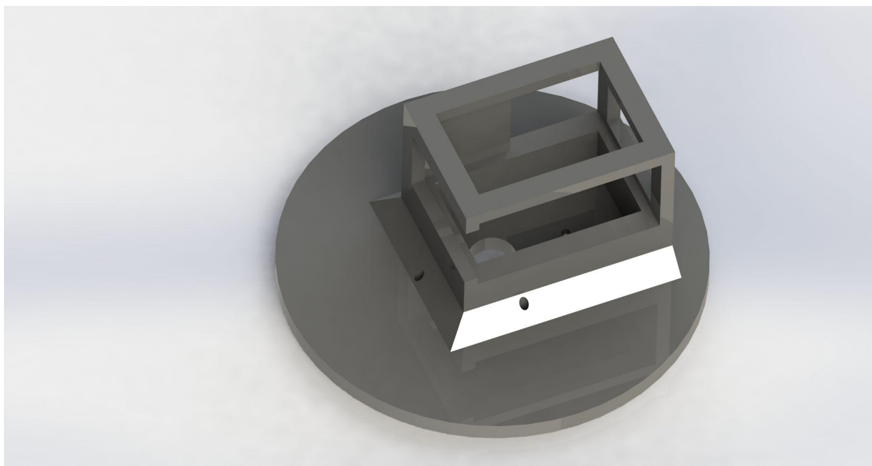


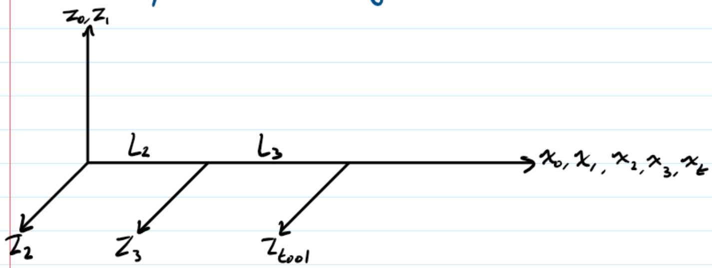
Figure 13

The end effector of the robot was designed to hold a sharpie, and connects to the motor cage of the end link. The full assembly of the robot can be seen in figure 14

Figure 14

In addition to the mechanical design, an inverse displacement solution was derived for the first 3 joints of the robot. The reason that the end effector joint was not included in the inverse displacement was that the end effector can be swapped out depending on the current application for the robot. The solution can easily be continued once the design of specific end effectors has been finalized, and the different equations can be implemented depending on the design and application. The full inverse kinematics derivation can be seen below:

Zero-Displacement Diagram



D-H Table

F_{i-1}	a_{i-1}	α_{i-1}	d_i	θ_i	F_i
0	0	0	0	θ_1	1
1	0	$\pi/2$	0	θ_2	2
2	L_2	0	0	θ_3	3
3	L_3	0	0	0	tool

Transformation Matrix

$$ {}^0_1T = \begin{bmatrix} C_1 & -S_1 & 0 & 0 \\ S_1 & C_1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} $$

$$ {}^1_2T = \begin{bmatrix} C_2 & -S_2 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ S_2 & C_2 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} $$

$$ {}^2_3T = \begin{bmatrix} C_3 & -S_3 & 0 & L_2 \\ S_3 & C_3 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} $$

$$ {}^3_{tool}T = \begin{bmatrix} 1 & 0 & 0 & L_3 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} $$

Forward Displacement

$$
{}^{0}_{2}T = {}^{0}_{1}T\,{}^{1}_{2}T = \begin{bmatrix} C_1 & -S_1 & 0 & 0 \\ S_1 & C_1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} C_2 & -S_2 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ S_2 & C_2 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}
$$

$$
{}^{0}_{2}T = \begin{bmatrix} C_1C_2 & -C_1S_2 & S_1 & 0 \\ S_1C_2 & -S_1S_2 & -C_1 & 0 \\ S_2 & C_2 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}
$$

$$
{}^{0}_{3}T = {}^{0}_{2}T\,{}^{2}_{3}T = \begin{bmatrix} C_1C_2 & -C_1S_2 & S_1 & 0 \\ S_1C_2 & -S_1S_2 & -C_1 & 0 \\ S_2 & C_2 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} C_3 & -S_3 & 0 & L_2 \\ S_3 & C_3 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}
$$

$$
{}^{0}_{3}T = \begin{bmatrix} C_1C_2C_3 - C_1S_2S_3 & -C_1C_2S_3 - C_1S_2C_3 & S_1 & C_1C_2L_2 \\ S_1C_2C_3 - S_1S_2S_3 & -S_1C_2S_3 - S_1S_2C_3 & -C_1 & S_1C_2L_2 \\ S_2C_3 + C_2S_3 & -S_2S_3 + C_2C_3 & 0 & S_2L_2 \\ 0 & 0 & 0 & 1 \end{bmatrix}
$$

$$
{}^{0}_{3}T = \begin{bmatrix} C_1C_{23} & -C_1S_{23} & S_1 & C_1C_2L_2 \\ S_1C_{23} & -S_1S_{23} & -C_1 & S_1C_2L_2 \\ S_{23} & C_{23} & 0 & S_2L_2 \\ 0 & 0 & 0 & 1 \end{bmatrix}
$$

$$
{}^{0}_{4}T = {}^{0}_{3}T\,{}^{3}_{4}T = \begin{bmatrix} C_1C_{23} & -C_1S_{23} & S_1 & C_1C_2L_2 \\ S_1C_{23} & -S_1S_{23} & -C_1 & S_1C_2L_2 \\ S_{23} & C_{23} & 0 & S_2L_2 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 & L_3 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}
$$

$$
{}^{0}_{4}T = \left[\begin{array}{ccc|c} C_1C_{23} & -C_1S_{23} & S_1 & C_1C_{23}L_3 + C_1C_2L_2 \\ S_1C_{23} & -S_1S_{23} & -C_1 & S_1C_{23}L_3 + S_1C_2L_2 \\ S_{23} & C_{23} & 0 & S_{23}L_3 + S_2L_2 \\ 0 & 0 & 0 & 1 \end{array}\right]
$$

Inverse Displacement

$$\begin{Bmatrix} P_x \\ P_y \\ P_z \\ 1 \end{Bmatrix} = \begin{Bmatrix} C_1 C_{23} L_3 + C_1 C_2 L_2 \\ S_1 C_{23} L_3 + S_1 C_2 L_2 \\ S_{23} L_3 + S_2 L_2 \\ 1 \end{Bmatrix}$$

$$\begin{Bmatrix} C_1 P_x + S_1 P_y \\ -S_1 P_x + C_1 P_y \\ P_z \\ 1 \end{Bmatrix} = \begin{Bmatrix} C_{23} L_3 + C_2 L_2 \\ 0 \\ S_{23} L_3 \; S_2 L_2 \\ 1 \end{Bmatrix}$$

From $(1,4)^2 + (2,4)^2 + (3,4)^2$

$$P_x^2 + P_y^2 + P_z^2 = C_{23}^2 L_3^2 + 2 C_{23} C_2 L_3 L_2 + C_2^2 L_2^2 + S_{23}^2 L_3^2 + 2 S_{23} S_2 L_2 L_3 + S_2^2 L_2^2$$

$$P_x^2 + P_y^2 + P_z^2 = L_3^2 + L_2^2 + 2 C_3 L_2 L_3$$

$$C_3 = \frac{P_x^2 + P_y^2 + P_z^2 - L_2^2 - L_3^2}{2 L_2 L_3}$$

$$\theta_3 = \pm \operatorname{Atan2}\left(\sqrt{1 - C_3^2},\ C_3\right)$$

From $(2,4)$

$$-S_1 P_x + C_1 P_y = 0$$

$$\Rightarrow \theta_1 = \operatorname{Atan2}(P_y, P_x) \;\&\; \operatorname{Atan2}(-P_y, -P_x)$$

From $(1,4)$ & $(3,4)$

$$C_1 P_x + S_1 P_y = C_{23} L_3 + C_2 L_2$$
$$P_z = S_{23} L_3 + S_2 L_2$$

$$\Rightarrow C_1 P_x + S_1 P_y = C_2 C_3 L_3 - S_2 S_3 L_3 + C_2 L_2$$
$$P_z = S_2 C_3 L_3 + C_2 S_3 L_3 + S_2 L_2$$

$$\Rightarrow C_1 P_x + S_1 P_y = C_2 (C_3 L_3 + L_2) - S_2 S_3 L_3$$
$$P_z = S_2 (C_3 L_3 + L_2) + C_2 S_3 L_3$$

Let $a = C_3 L_3 + L_2$
$b = S_3 L_3$
$c = C_1 P_x + S_1 P_y$
$d = P_z$

$\Rightarrow \theta_2 = \operatorname{Atan2}(ad - bc,\ ac + bd)$

Design For Manufacturing

The robot arm was designed with 3D printing in mind as the method of manufacturing parts. Because of this, all parts were designed with minimal overhang to reduce the amount of support material needed during printing. The parts were printed with a 0.2mm layer height and an infill density of 15%. This ensures that the parts are decently strong, but still reducing the amount of time the parts will take to actually print. The expected load on the parts is not high, so the structural integrity of the parts is not the largest concern.

Any holes where a screw would need to be threaded into were made slightly smaller than the diameter of the screw to ensure that the threads had a solid wall to grip onto when they were put in place.

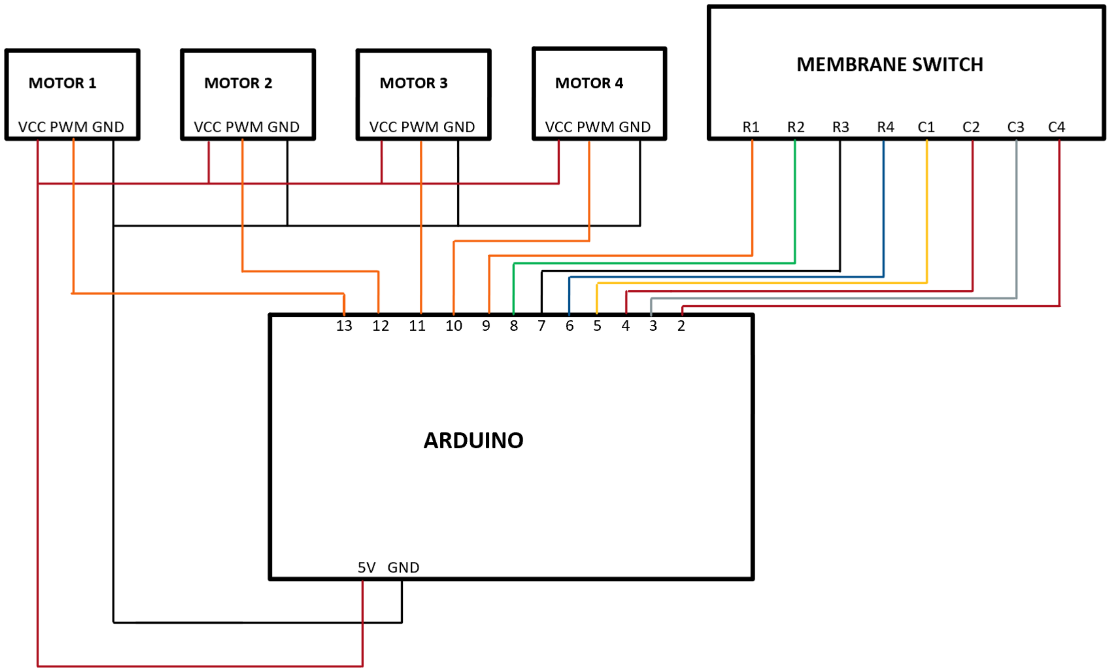
Design For Safety

Because the links were designed with the motors exposed, they were also designed to minimize the area where fingers could get caught in during operation. The controller also prevents the motors from moving more than 15 degrees at a time during controlled operation.

Control Algorithm Design

The controller for the robot uses a membrane switch connected to an arduino microcontroller. The program makes use of the default servo library, as well as a keypad library developed by Mark Stanely and Alexander Brevig. The keypad library allows you to define an array and label the buttons in the array according to the rows and columns on the membrane switch. If statements are then set up to allow the buttons on the keypad to control motors individually. Each motor is set to change the angle a specific amount each time one of the buttons on the membrane switch is pressed. The full source code for the initial prototype of the robot arm can be seen in the appendix.

Wiring Diagram



Testing and Test Results

Initial tests of the robot arm included varying the angle that the motors changed on each button press until a good average change was found. This was done by starting at 5 degrees and increasing the angle change until a number was found that moved the robot enough to see a decent change in the angle, but not so high that the risk of injury for getting a finger caught in the joints was severe. This angle change was found to be 15 degrees. Further testing of the system included adding the end effector to the system, and seeing the range of motion the end effector was capable of. The end effector used for testing was designed to hold a sharpie to allow the robot to draw. Under controlled operating conditions, the robot was able to draw back and forth on a page at varying distances. An image of the lines the robot was able to draw can be seen in figure 15

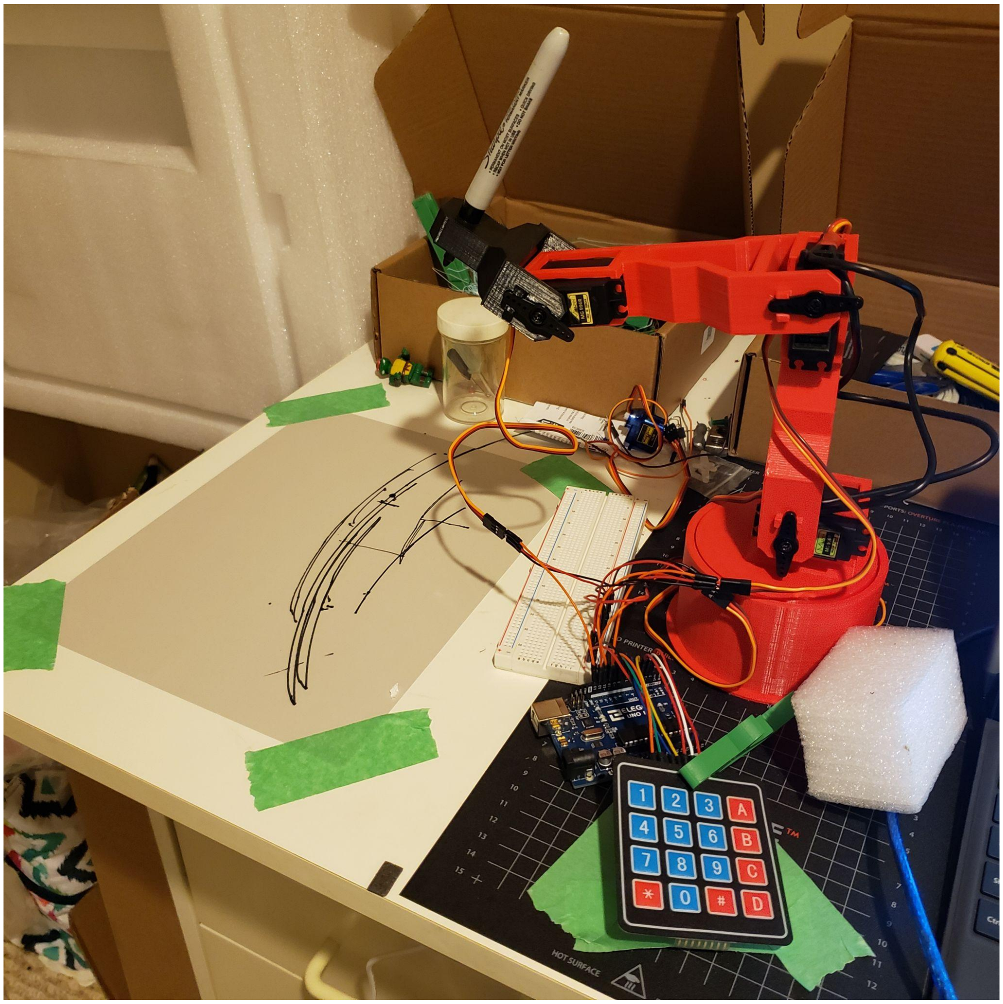


Figure 15

Plans for future tests include development of a program that will allow the robot to draw shapes automatically, and design of manufacturing of new and different end effectors for the robot. Other changes that are to be made as a result of testing are adjustments to the dimensions of the hole in the end effector to better fit the marker that is attached to it. Modifications may also be made to the end effector to ensure that the cap can be placed back on the marker when it is attached to the robot arm.

Improvements for Future Prototypes

For future iterations of the design, the first issue to address is the weight of the base. The arm was not tested while fixed to something, so either the base needs to be fixed to a desk, or the cylinder that acts as the base needs to be filled with some dead weight to allow it to better hold the weight of all of the servo motors on the rest of the arm. The structural integrity was not determined to be an issue during the testing, the issue mainly lies with the center of gravity.

Other considerations may be made to the method of controlling the robot. The membrane switch uses a lot of the digital pins on the arduino, and does not leave much room for additional components to be added to the arm. Currently, the most desired controller for the system would be a game controller, similar to what is used for Xbox, however any control module that uses less pins on the microcontroller would be ideal.

References

[1] https://www.thingiverse.com/thing:3327968, source for robot arm shown in figure 1

[2] https://www.thingiverse.com/thing:34829, source for arm shown in figure 2

[3] https://www.thingiverse.com/thing:1454048, source form figure 3

[4] https://playground.arduino.cc/Code/Keypad/, keypad library

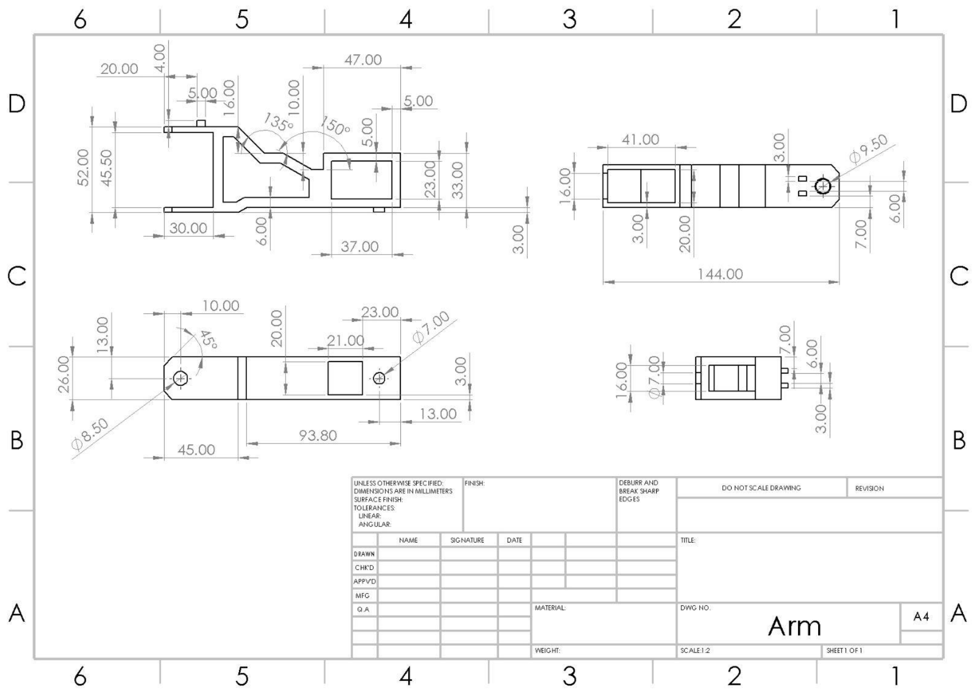
Appendix

Source Code

```
#include <Keypad.h>
#include <Servo.h>

//define servo motors and angle variables for each motor
Servo sev1;
Servo sev2;
Servo sev3;
Servo sev4;
int angle1 = 90;
int angle2 = 50;
int angle3 = 90;
int angle4 = 90;
int change = 15; //Variable determines how large the angle change is on each button
press

//Create the parameters of the membrane switch, and define its labels
const byte ROWS = 4; // number of rows
const byte COLS = 4; // number of columns
char keys[ROWS][COLS] = {
{'1','2','3','A'},
{'4','5','6','B'},
{'7','8','9','C'},
{'#','0','*','D'}
};

byte rowPins[ROWS] = {9, 8, 7, 6}; // row pinouts of the keypad R1 = D8, R2 = D7,
R3 = D6, R4 = D5
byte colPins[COLS] = {5, 4, 3, 2};    // column pinouts of the keypad C1 = D4, C2 =
D3, C3 = D2
Keypad keypad = Keypad(makeKeymap(keys), rowPins, colPins, ROWS, COLS);

void setup()
{
//define the pins that the motors are attached to
  Serial.begin(9600);
  sev1.attach(10);
  sev2.attach(11);
  sev3.attach(12);
  sev4.attach(13);
}

void loop()
{
//control each motor direction depending on which button has been pressed.
```

```
  char key = keypad.getKey();
  if (key != NO_KEY)
    Serial.println(key);
    if (key == '1')
      angle1 += change;
      sev1.write(angle1);
     if (key == '4')
      angle1 -= change;
      sev1.write(angle1);
     if (key == '2')
      angle2 += change;
      sev2.write(angle2);
     if (key == '5')
      angle2 -= change;
      sev2.write(angle2);
     if (key == '3')
      angle3 += change;
      sev3.write(angle3);
     if (key == '6')
      angle3 -= change;
      sev3.write(angle3);
      if (key == '7')
      angle4 += change;
      sev4.write(angle4);
     if (key == '8')
      angle4 -= change;
      sev4.write(angle4);

}
```

Part Drawings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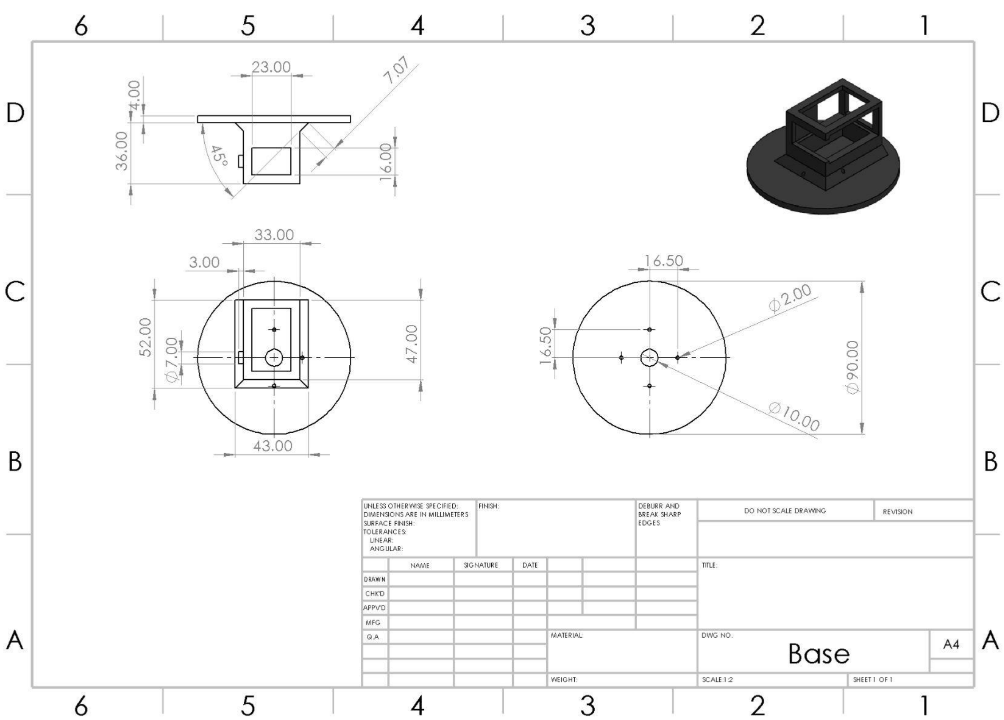
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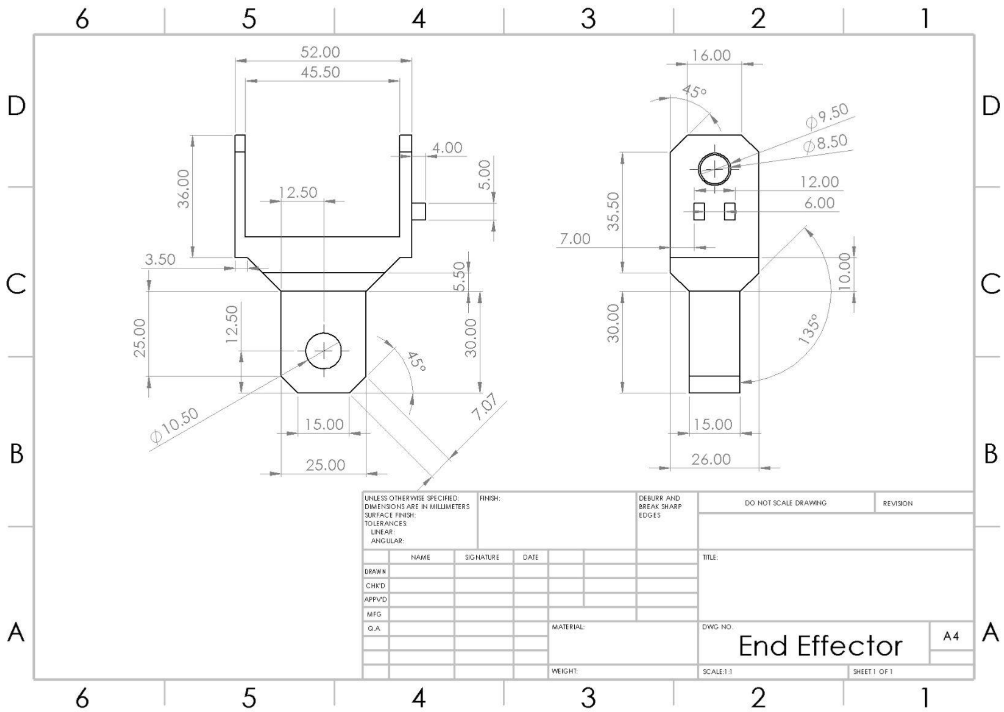
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
SURFACE FINISH:
TOLERANCES:
LINEAR:
ANGULAR:
FINISH:
DEBURR AND BREAK SHARP EDGES
DO NOT SCALE DRAWING
REVISION
NAME
SIGNATURE
DATE
DRAWN
CHK'D
APPV'D
MFG
Q.A
MATERIAL:
WEIGHT:
TITLE:
DWG NO.
Base
A4
SCALE:1:2
SHEET 1 OF 1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135°
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UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
SURFACE FINISH:
TOLERANCES:
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DEBURR AND BREAK SHARP EDGES
DO NOT SCALE DRAWING
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NAME
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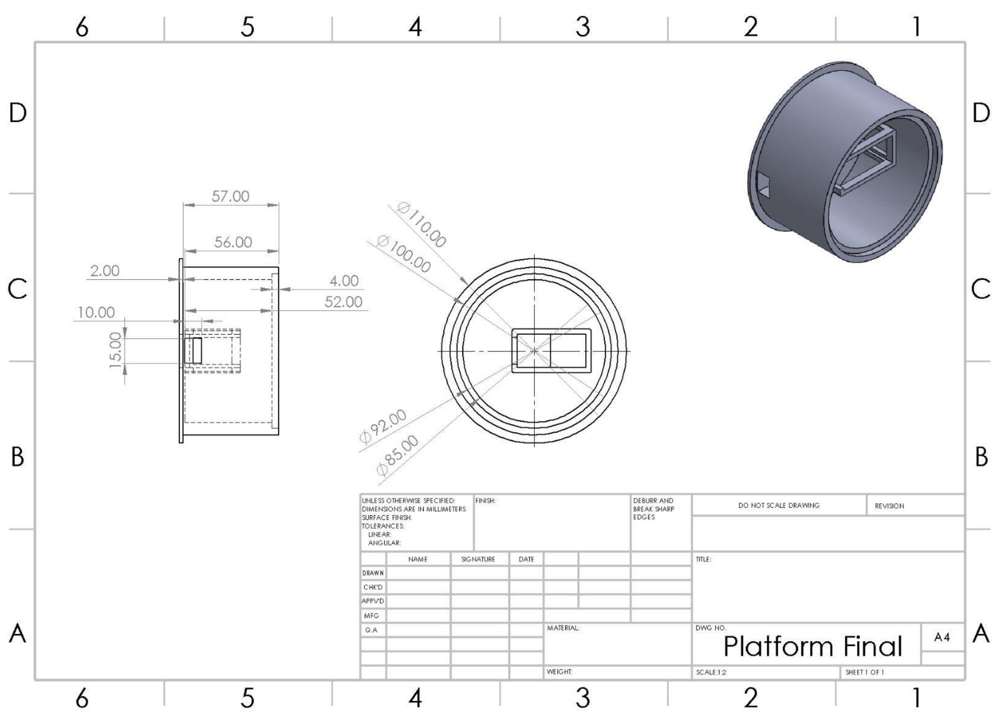
TITLE:
DWG NO.
End Effector
A4
SCALE:1:1
SHEET 1 OF 1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UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
SURFACE FINISH:
TOLERANCES:
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FINISH:
DEBURR AND BREAK SHARP EDGES
DO NOT SCALE DRAWING
REVISION
NAME
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DATE
DRAWN
CHK'D
APPV'D
MFG
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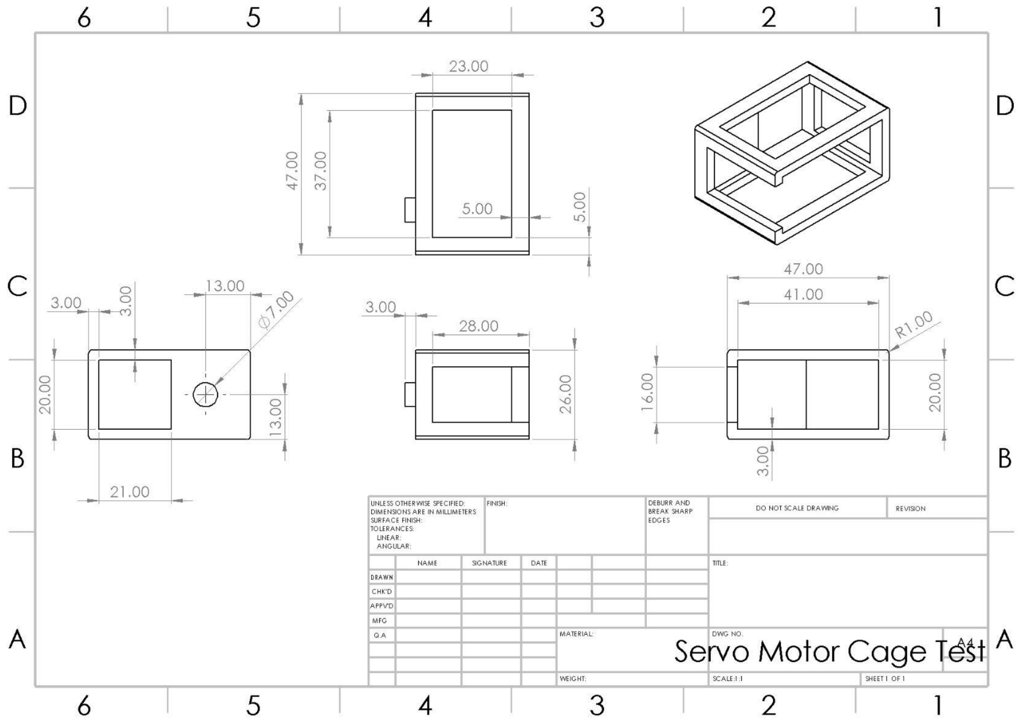
MATERIAL:
WEIGHT:
TITLE:
DWG NO.
Platform Final
A4
SCALE:1:2
SHEET 1 OF 1



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UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
SURFACE FINISH:
TOLERANCES:
LINEAR:
ANGULAR:
FINISH:
DEBURR AND BREAK SHARP EDGES
DO NOT SCALE DRAWING
REVISION
NAME
SIGNATURE
DATE
DRAWN
CHK'D
APPV'D
MFG
Q.A
TITLE:
MATERIAL:
DWG NO.
Servo Motor Cage Test
A4
WEIGHT:
SCALE:1:1
SHEET 1 OF 1