Virtual Quality Control Robot – Mechanical

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Abstract

A custom SCARA robotic arm was designed and simulated using Solidworks and SimulationX in order to create a Virtual Quality Control Robot. The SCARA robot arm is modeled with 3 ½ DOF in order to grab 3 marshmallows on a stationary conveyor belt one by one and drop them into a garbage chute. The design was first conceived by creating multiple concept sketches, then drawn and simulated in a 2D top view drawing in Solidworks. Once the inverse kinematics for each position were determined, a Solidworks model for the selected design's gripper, arm, and joints was developed. Each relevant part was shown to satisfy stress constraints through stress analysis. Using each part's specifications, the torque, inertia and linear approximations were calculated for each joint before co-simulating the robotic arm design in SimulationX using the PID controller designed in the Controls section of the project.

In this paper, Section 1 describes the workspace setup and chosen dimensions and kinematics for the SCARA robotic arm in 2D. In Section 2, the robotic gripper, arm, and joints are designed and modeled in 3D in Solidworks following the chosen dimensions in Section 1 and demonstrates the stress analysis simulation conducted on each relevant Solidwork part to sustain up to 50% of the maximum motor torque. Section 3 describes the dynamics of the arm joints including torque, inertia, and damping calculations. Lastly, Section 4 combines the control and mechanics sections by simulating the parts in SimulationX using PID controllers for the arm joints.

Nomenclature

AL	Arm Length (mm)
SR	Shaft Radius (mm)
COM	Center of Mass (mm)
DOF	Degrees of Freedom
IK	Inverse Kinematics
SA	Stress Analysis
SCARA	Selective Compliance Assembly Robot Arm
VQCR	Virtual Quality control Robot

1. Workspace, Arm Dimensions, and Inverse Kinematics

Before modeling the robot arm, the workspace dimensions and constraints were first defined. The garbage chute and conveyor belt are both 10cm wide, with the 3cm diameter marshmallows on the belt spaced 10cm apart center-to-center. The shoulder joint of the SCARA arm is located 25cm below the center of the 2nd marshmallow. Using these workspace dimensions as a base, the arm dimensions were defined to maximize movement efficiency and minimize inertia as described in Section 3. Figures 1.1 and 1.2 demonstrate the arm's inverse kinematics when grabbing and dropping the first marshmallow as a 2D Solidworks drawing.

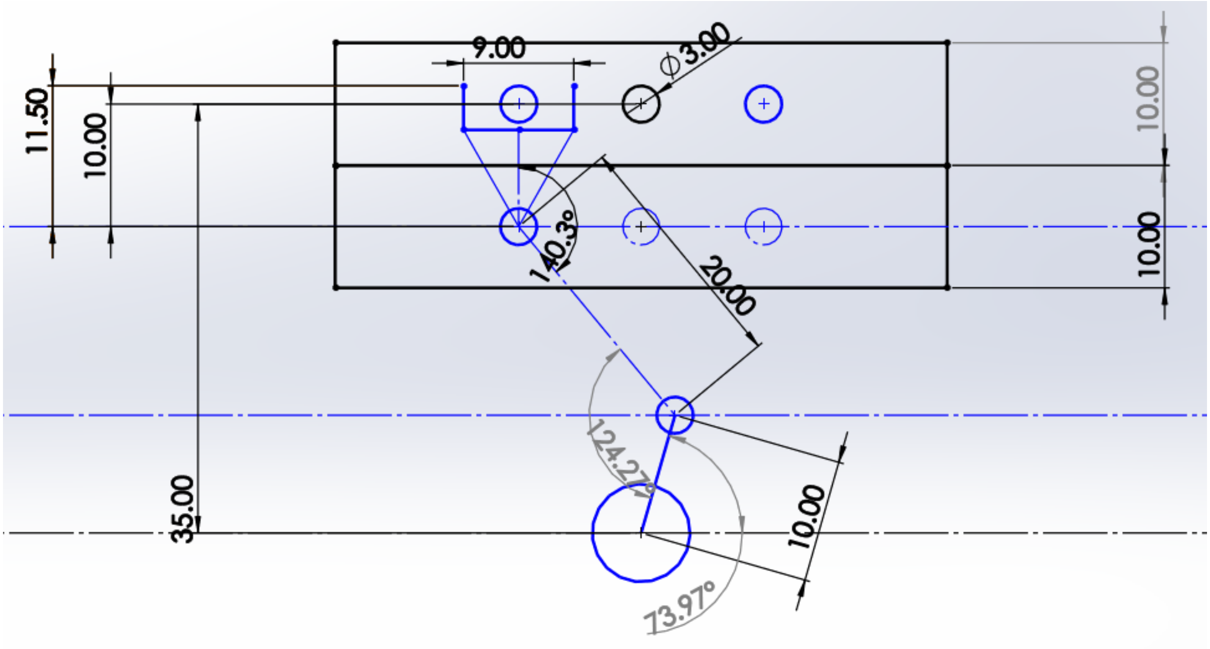

Figure 1.1 Inverse Kinematics and arm dimensions to grab the first marshmallow

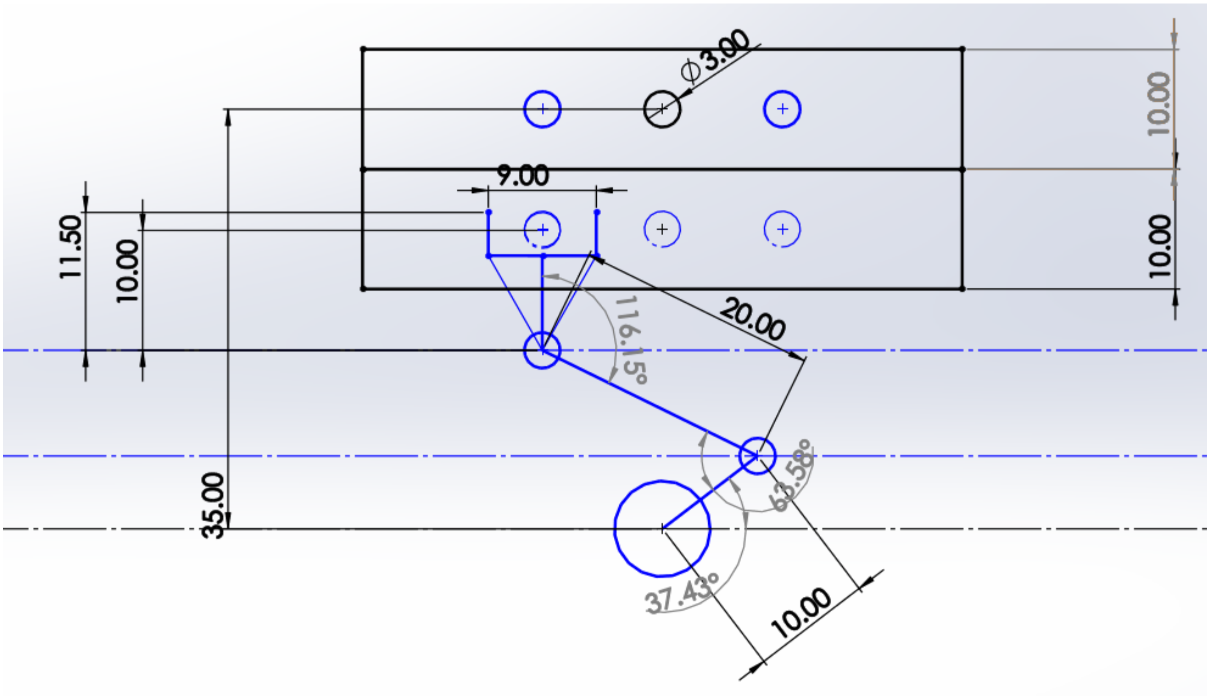

Figure 1.2 Inverse Kinematics and arm dimensions to drop the first marshmallow

Using Solidworks' 2D sketch feature, similar diagrams were created for the grab-and-drop motion of marshmallows 2 and 3 as shown in Figures 1.3a, 1.3b, 1.3c, and 1.3d to determine the remaining kinematics that would later serve as inputs in the controls section of the project.

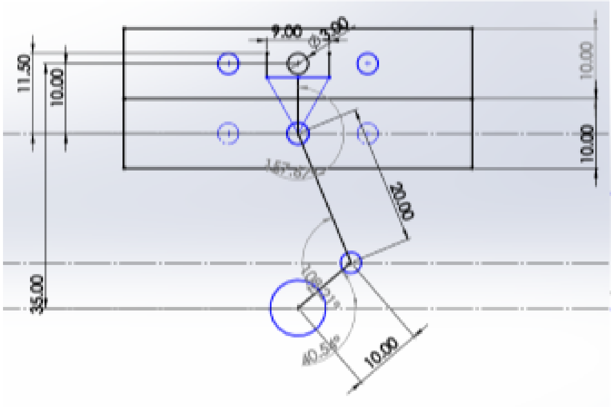

Figure 1.3a Grabbing 2nd marshmallow

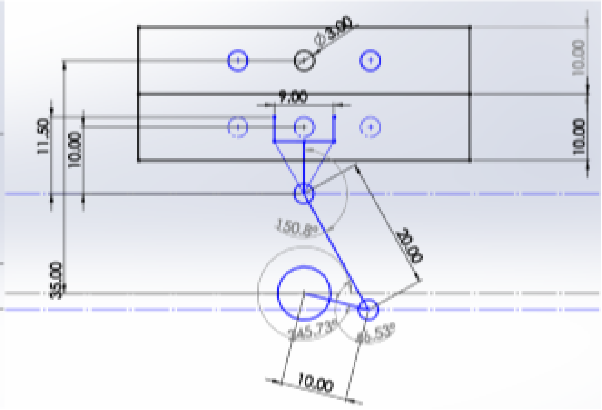

Figure 1.3b Dropping 2nd marshmallow

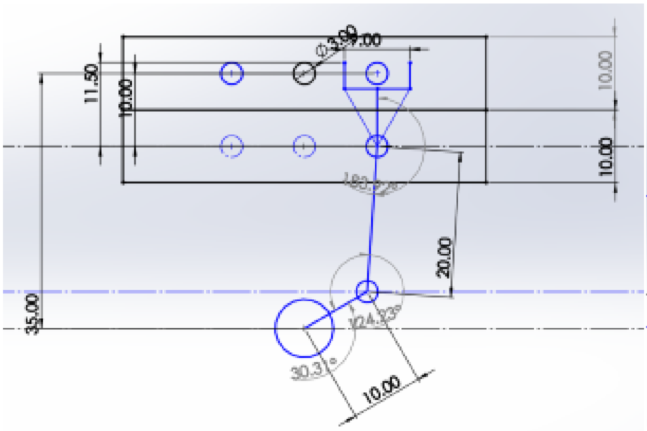

Figure 1.3c Grabbing 3rd marshmallow

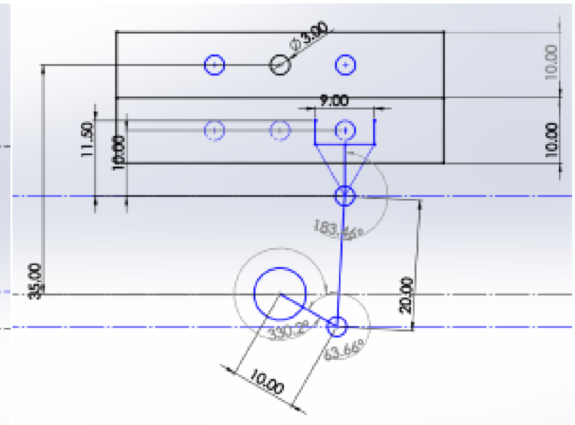

Figure 1.3d Dropping 3rd marshmallow

2. Solidworks and Stress Analysis

2.1 Gripper, joints, and Base Designs

Using the determined arm dimensions in Section 1, gripper, wrist, elbow, and shoulder joint concepts were sketched before modeled in Solidworks. Six individual parts for a standard gripper were created, then duplicated as necessary and assembled to the wrist joint using two Maxon 22S 24V motors as shown in Figure 2.1.

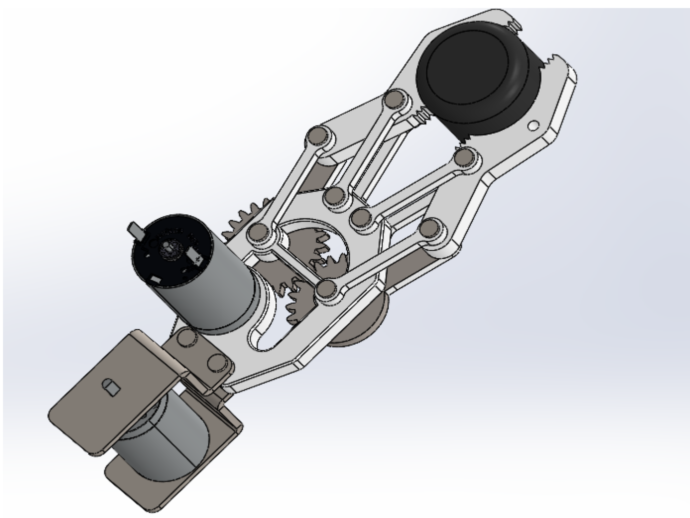

Figure 2.1 Gripper assembly and wrist joint in closed position

Once the gripper and wrist joints assembled, the elbow and shoulder joints shown in Figures 2.3a and 2.3b were created using two more Maxon 22S 24V double shaft motors, with the upper arms screwed onto the elbow motor, and the forearms fixed to the planetary shafts. Reduction gears are used at the shoulder joint in order to reduce the torque required to move the load at the shoulder joint while using a Maxon 22S 24V motor, as later described in Section 3.

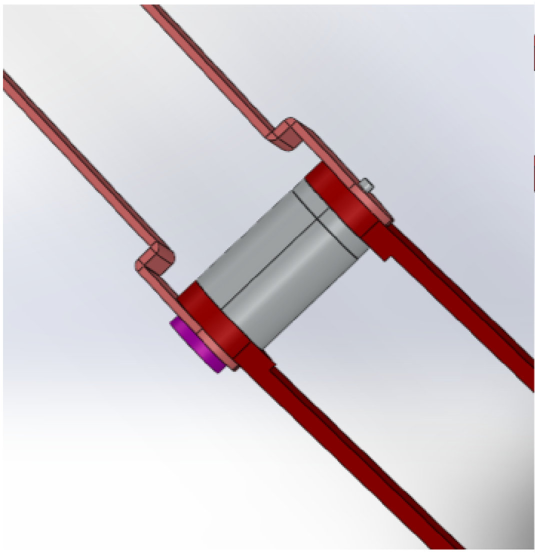

Figure 2.3a Elbow joint and encoder

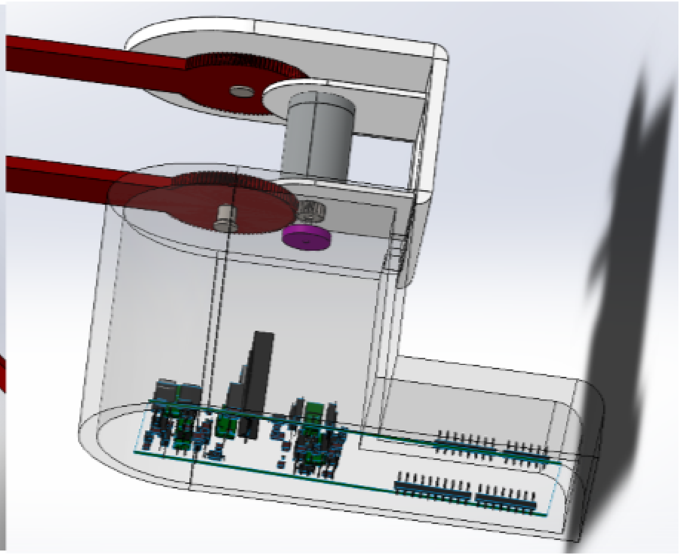

Figure 2.3b Shoulder joint and base enclosure

Furthermore, the hollow shoulder joint's base also acts as an enclosure for the 13.8x5.5x1cm PCB designed in the Electrical section of the project and elevates the robotic arm by 8 cm above ground. The Maxon motors at each joint use wires to connect to the PCB following the insides of the robot arms for clean and simple wire management. Mock encoders (in purple) were created to be fixed to the rear shaft of each of the 4 arm joints. No parts from McMaster Carr were imported in the design.

2.2 Stress Analysis

To simulate the maximum stress constraints on the gripper parts, the motor's nominal torque of 0.0153 Nm was applied to the holes of all gears and hinging pieces, and a force of 0.0153Nm was applied upwards from the pinholes of the gripper tips in order to ensure that the parts were robust with an additional margin of error. The stress simulation proved to below 50% of the maximum torque constraint as shown in Figure 2.2a, 2.2b, 2.2c, and 2.2d.

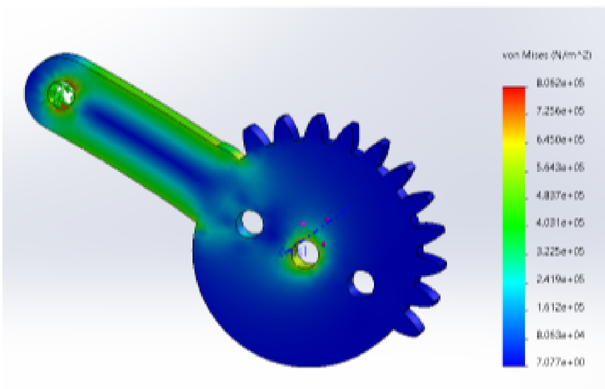

Figure 2.2a Gripper gears simulation

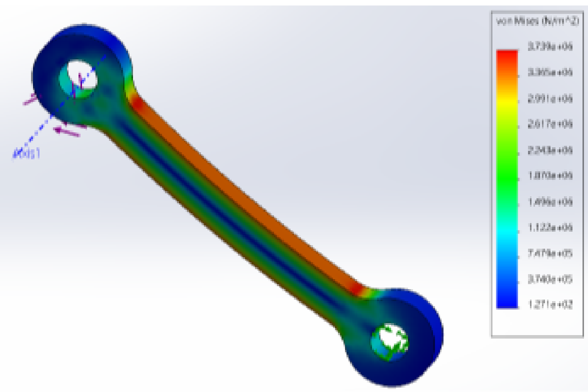

Figure 2.2b Gripper hinge simulation

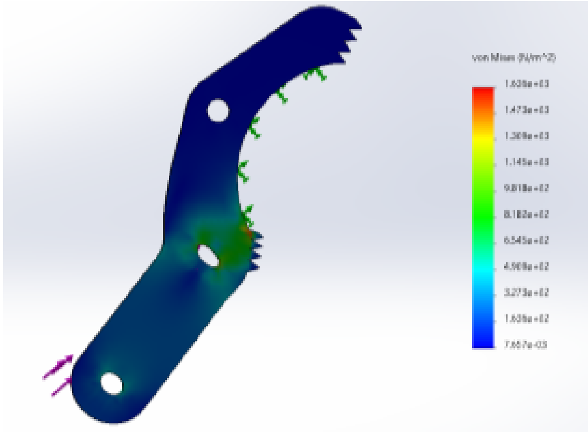

Figure 2.2c Gripper tips simulation

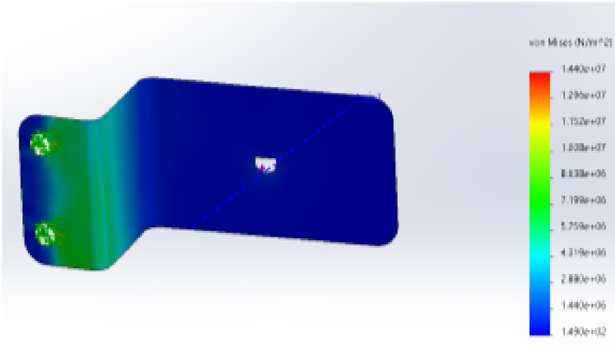

Figure 2.2d Wrist enclosure simulation

The stress simulation of the forearm and upper arm in Figure 2.3a and 2.3b yielded similar results as the gripper simulation above, proving to be much below the stress constraints.

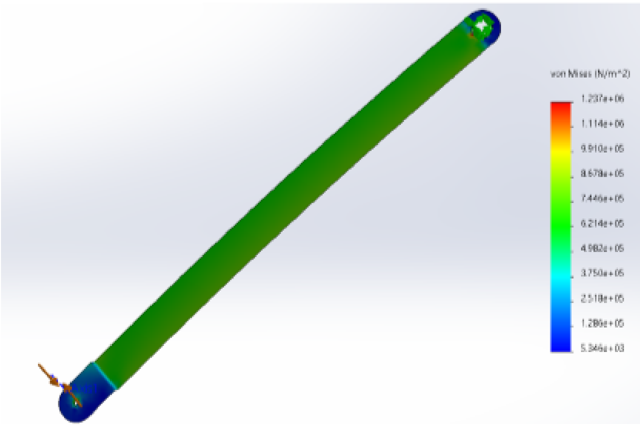

Figure 2.3a Forearm simulation

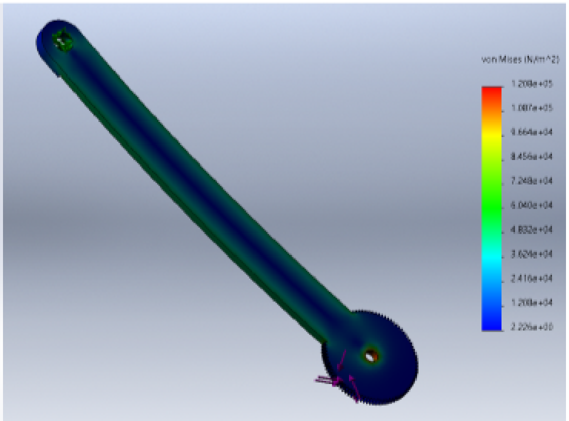

Figure 2.3b Upper arm gear simulation

2.3 Full Solidworks Assembly

The final Solidworks assembly model for the SCARA robotic arm with functional joints and mated gears is shown below in Figure 2.4, with a 20cm forearm length and 10cm upper arm length as shown in the arm and workspace dimensions in Section 1.

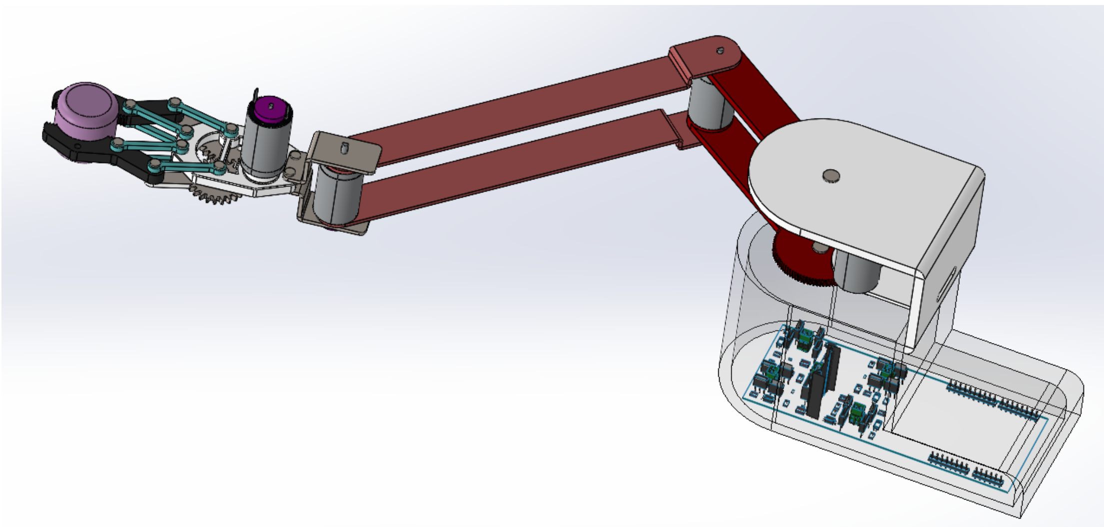

Figure 2.4 Full Solidworks SCARA robotic arm assembly

2.4 Total Cost Estimate

With the Solidworks arm assembly and Electrical design completed, an estimate of the total manufacturing cost can be made based on the motors, encoders, power supply, PCB, and materials. All prices are in Canadian Dollars (CAD).

Components	**Price**
Maxon Motors 22S 24V (Configured) + Encoder ENX 10 EASY, 1 - 1024 CPT	$372.79 * 4 joints = $1491.16
Alumina Material Parts [3]	$0.0028/g * 142.21g = $0.40
PET Material Parts [4]	$0.0172/g * 527.40g = $9.08
Power Supply [5]	$76.49
PCB Parts and Arduino Leonardo	$75.22 (refer to Electrical Report for BOM)
PCB Manufacturing	$7.10 for 5 pcs at JLCPCB
Material Parts Printing (3D Printing)	100$
SUM	$1759.45

Table 2.4.1 Total Cost of Manufacturing

3. Inertia, Torque and Calculations

3.1 Mass Properties and Torque

Three factors can be used to calculate motor requirements and specifications; Moment of Inertia, Torque, and Speed. Using the completed Solidworks robotic arm assembly, the individual mass that each joint motor would be required to move was determined by observing the parts' mass properties. The force on a part can be defined as $F = m * a$ with the Acceleration Torque as $T = F * R = J * \alpha$, where J = moment of inertia of a rotating object and α = angular acceleration.

Therefore $\alpha = \frac{T}{J} = \frac{F}{m * R}$rad/s^2 and $J = m * R^2$g*mm^2.

The values for the moment of inertia in grams * square millimeters taken at the output coordinate system are given in the Solidworks mass properties of each joint assembly.

Assembly Joint	Mass (g)	Center of Mass (mm)	Moment of Inertia (g*m^2)
Gripper	21.59	(25.34, 101.77, 50.45)	0.04821246
Wrist	68.44	(26.10, 57.43, 46.94)	0.25398155
Elbow	149.79	(35.50, -19.06, 48.60)	5.49140013
Shoulder	281.24	(76.88, -99.33, 50.34)	12.48545071

Table 3.1.1 Joint Mass, COM, and Moment of Inertia (taken at the output coordinate system)

Table 3.1.1 displays the mass, COM, and moment of inertia taken at the output coordinate system, however does not take into account the use of reduction gears for the gripper and shoulder joints.

The Torque-Radius relationship is defined as follows: $T1 = T2 * \frac{R1}{R2}$[1] where R1/R2 is the ratio of the radius of the first gear to the second. Therefore for Inertia: $J1 = J2 * \frac{R1}{R2}$

Using a 5:1 gear ratio at the shoulder joint, the reflected moment of inertia at the shoulder motor is $J2 = J1 * \frac{1}{5} = 2.497090142$ g*m^2.

Similarly, using a 2:1 gear ratio at the gripper joint, the reflected moment of inertia at the gripper motor is $J2 = J1 * \frac{1}{2} = 0.02410623$ g*m^2.

Section 3.3 further covers the use of reduction gears and their role in minimizing load inertia. From the Maxon Motor 22S 24V datasheet, the rotor inertia is 0.000555g*m^2.

The Acceleration Torque is defined as the product of inertia and the acceleration rate of the mass $Ta = (Jr + Jl) * \alpha$ where Jr is the rotor inertia, Jl is the load inertia, and α is the acceleration rate. As the desired acceleration rate of the motor is not a known constraint, an adequate minimum acceleration rate to move the arm joints will be defined as α = 2 rad/s^2. The resulting minimum required torque for the chosen angular acceleration is shown for each joint in Table 3.1.2.

	Gripper	Wrist	Elbow	Shoulder
Torque (mNm)	0.04932246	0.5090731	10.98391026	4.995290284

Table 3.1.2 Joint Mass, COM, and Moment of Inertia (taken at the output coordinate system)

As all of the model's parts were tested and proven to withstand the Maxon 22S 24V motor's as the nominal torque of 15mNm during the stress analysis, did not exceed 50% of the yield strength, and the required torque of each joints using reduction gears were each below the nominal torque value, it was determined to be safe to use a Maxon Motor 22S with 24V nominal for increased arm movement efficiency.

Despite the gripper motor torque being plenty to grasp a marshmallow, reduction gears were added to the design for further possible applications to larger or heavier objects than marshmallows requiring a greater grip strength. The shoulder joint bears the most mass and has the greatest inertia, therefore reduction gears were added to ensure more robustness and versatility in the case of a heavier item being picked up or any other factors that may affect the arm's stability.

3.2 Operating Point

Using the above calculations and the PCB design from the Electrical section of the project, Table 3.2.1 displays a reasonable common operation point for each joint motor, compared to the required electrical data for the operating point from the datasheet.

	Required Electrical Data	Actual Electrical Data
Speed	8640 min^-1	11120 min^-1 (at given load)
Torque	12.24 mNm	15.3 mNm

Voltage	19.21 V	24 V
Current	0.70 A	0.87 A

Table 3.2.1 Required Operating Point vs Actual Operating Point

3.3 Minimizing Inertia

The moment of inertia is the measure of an object's resistance to changes in its rotation rate. When the arm is sitting without motion, the moment of inertia is zero [2]. The load inertia can be reduced directly by reducing the mass of the load or by changing its dimensions; in this case, the arm length.

3.3.1 Gear Ratio

The reflected inertia felt by the motor can also be reduced indirectly by increasing the gear ratio, as accomplished in the gripper and shoulder joint. The gear ratio indicates the speed reduction from motor to load.

The inertia N1 reflected from the load is reduced by N^2 where N is the gear ratio (N > 1 indicates speed reduction from motor to lead). Assuming a gear ratio is N1:N2, the reduction gear has N1 times the radius size of N2. Small increases in gear ratio can significantly reduce the load inertia, however such changes will also decrease the rotational speed of the mass.

A gear ratio of 5:1 was used at the shoulder joint, and a gear ratio of 2:1 was used at the gripper. The reflected moment of inertia and torque calculations can be seen in Section 3.1.

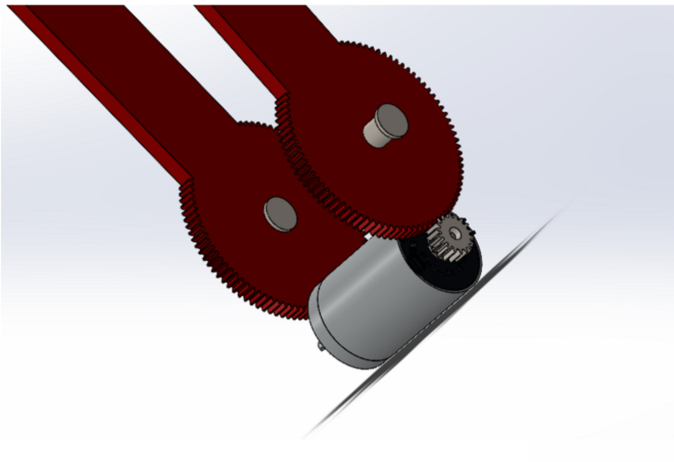

Figure 3.2a Shoulder Joint 5:1 Reduction Gear

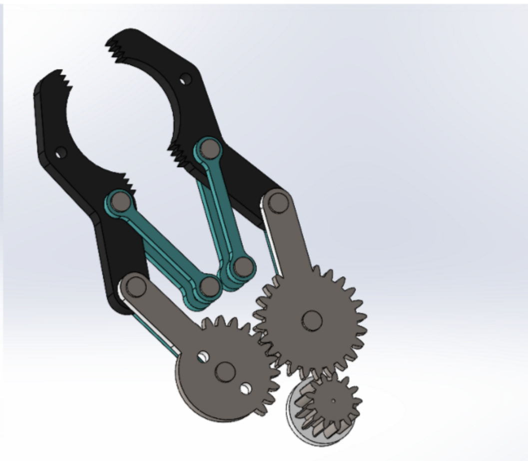

Figure 3.2b Gripper 2:1 Reduction Gear

3.2.2 Dimensions and Materials

As both torque and moment of inertia is directly dependent on mass, shown by the equations $T = F * R$ and $J = m * R^2$, the forearm and upper arm of the robot were optimized by trial and error with the dimensions as shown in Section 1 using the 2D Solidworks workspace simulation, with adequate inverse kinematics and dimensions, such that the arm length would be minimized while keeping low path angles of rotation. As the distance of the mass being rotated around the joint is minimized, the required torque and moment of inertia are also decreased.

Mass is another factor on which inertia is dependent, as shown from the equations above, and $F = m * a$. The type of material used in the manufacturing of the arm holds a large influence on the moment of inertia a joint will possess. Lighter plastic such as 3D printable PET with a mass density of 1.38 g/cm^3 was used for the forearms and gripper, while a light metal such as Alumina with a mass density of 3.95 g/cm^3 was used for gears and pins.

4. Simulation X Model

Once the Solidworks parts and simulations completed, a SimulationX model of the arm was created, with linear approximations of the Solidworks assembly as appropriate to avoid importing too many parts and hindering the simulation performance. The SimulationX robotic arm model retained its exact dimensions, with two long 20cm and 10cm cuboids as its forearm and upper arm respectively. The joint motors were modeled as 22mm diameter cylinders similarly to the Maxon motors used, and were stationed exactly on top of the revolute joints to simulate turning around their own axis, however using a single shaft design rather than a double shaft for ease of simulation. Each extension (arms and the panel for the gripper gears) of the joints were connected to the cylinders and also rotated with the joints.

Only the three gripper spur gears were imported into the SimulationX design to retain more accurate simulation of the gripper closing and opening motions. Contact between the gears was established by tooth contact blocks. The gripper tips were replaced by straight cuboids as opposed to the Solidworks curved claw tips, however the length and intended closing position were approximated to be similar to the original part, with a 6.5cm length, and 9cm mouth wide open position. Finally, three marshmallows were simulated as well as a garbage chute to use as a benchmark for the robot arm's positions, as seen in Figure 4.1.

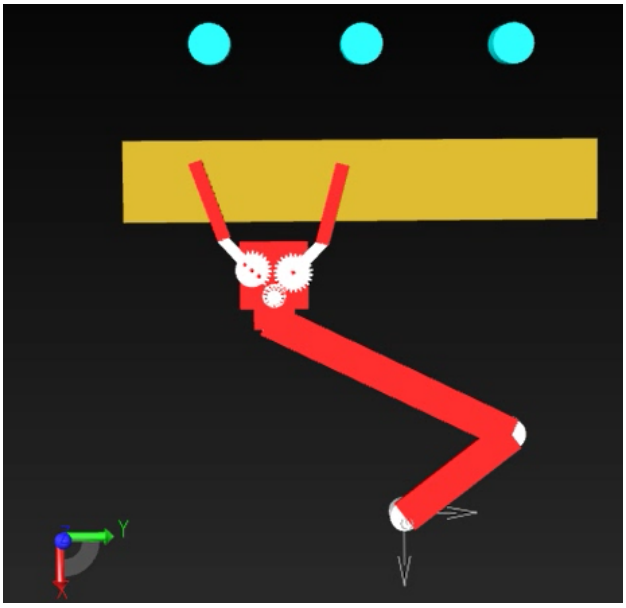

Figure 4.1 SimulationX 3D Model View

The starting position of each joint was set to what was considered to be 0 degrees. These positions were determined by the Solidworks simulation used to calculate the angles (Section 1, Figure 1.1, Figure 1.2). The Motor torque was applied directly to the revolute joints and the blob sensors used to read the angle and speed were connected to these joints as well. The sensor readings were transmitted to Simulink by the use of the TCP-IP Cosimulation block and similarly the torque applied was taken from Simulink.

A sliding friction torque of 655.2 uNm was added to each joint of the SimulationX model similarly to the mini project to simulate joint friction. A diagram view of the SimulationX model can be observed in Figure 4.2, simulating the mechanical components of the simulation.

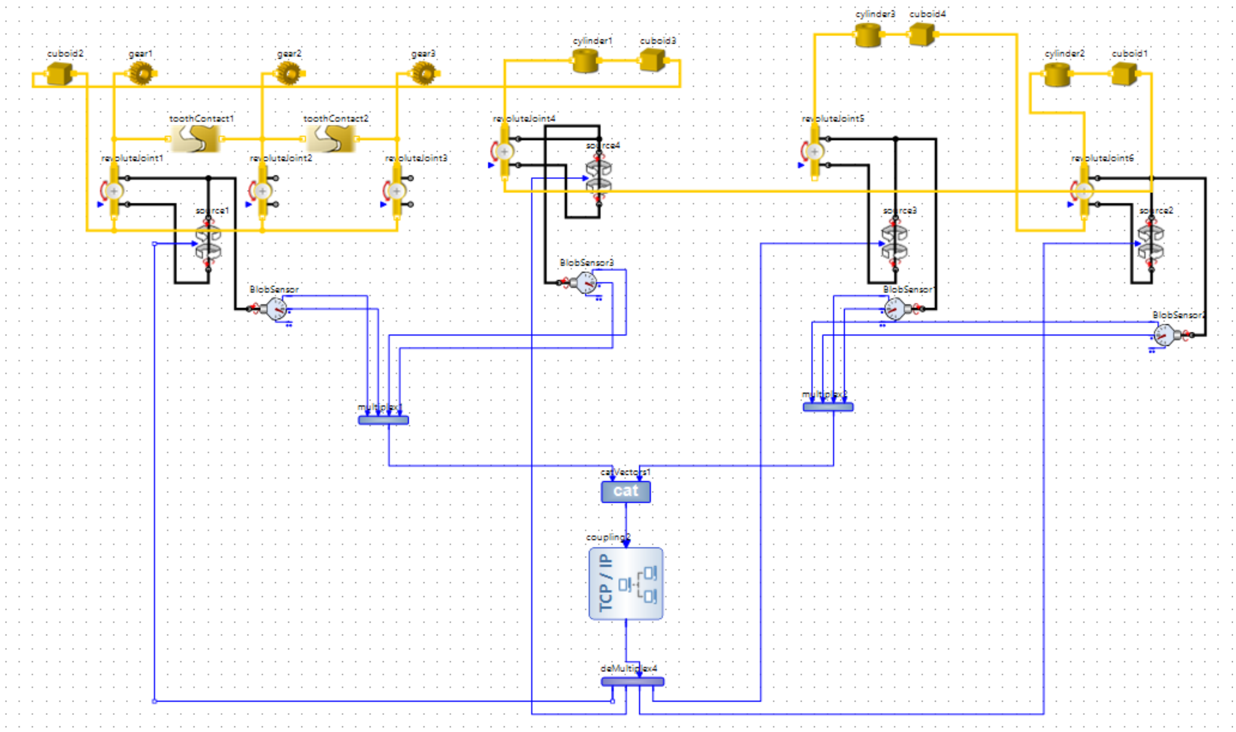

Figure 4.2 SimulationX Diagram View

References

[1] Oriental Motor. (2020). *Motor Sizing.* Oriental Motor. https://www.orientalmotor.com/technology/motor-sizing-calculations.html

[2] Ellis, G. (2012). *Compliance and Resonance.* Science Direct. https://www.sciencedirect.com/topics/engineering/motor-inertia

[3] Daily Metal Spot Price. (2021). *Aluminum Prices.* Daily Metal Spot Price. https://www.dailymetalprice.com/metalprices.php?c=al&u=oz&d=1

[4] Resource Recycling. (2021). *Mixed Trends for Plastic Pricing.* Resource Recycling. https://resource-recycling.com/plastics/2020/05/13/mixed-trends-for-plastic-pricing/

[5] Amazon. (2021). Power Supply. https://www.amazon.ca/Flycow-Adjustable-Switching-Temperature-Protection/dp/B081JQV816/ref=pd_d_dss_r_1?pd_rd_w=htjvA&pf_rd_p=012c05e2-d24f-4e6e-9e50-aa15c92556a2&pf_rd_r=NCRKZCSM7F9RNQQ3ZJM4&pd_rd_r=c30f2c9b-9146-4679-99be-c0099d5db74a&pd_rd_wg=lBqoa&pd_rd_i=B081JQV816&th=1