Ball Hopper – System Identification

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Jaydon Alexis, Group Portugal, ECE, University of BC, Vancouver, BC, Canada

Abstract

A custom robotic claw was designed and simulated in SolidWorks and Simscape for the purpose of creating a tennis ball hopper. The claw is designed with 1 DOF for grasping and releasing tennis balls and similar objects but is otherwise human driven. The design process involved multiple concept sketches, drawn at reduced scale to characterize the mode of operation and inverse kinematics of each design. A detailed CAD model of the chosen design was created in SolidWorks and FEA was performed on relevant components to ensure that they satisfied stress constraints. Upon completion of the CAD model, it was exported to Simscape for the design of the PID controller in the Controls portion of the project.

The first section of this paper outlines the relevant requirements, constraints and goals for this subsystem of the project that guide the design process. The second section describes dimensions and inverse kinematics of the hopper in two dimensions. A three-dimensional representation of the claw in SolidWorks is explored in the subsequent section as well as the aforementioned stress analyses. The fourth section reviews the various calculations that were conducted to inform selection of the motor and mechanical components such as bearings and the lead screws in addition to parameters for the Simscape model. Finally, the last section details the results obtained from the integration of the mechanical claw assembly with the overall system model.

Nomenclature

AL	Arm Length
CAD	Computer Aided Design
DOF	Degrees of Freedom
FEA	Finite Element Analysis
OTS	Off the Shelf
RCG	Requirement, Constraint, Goal
SR	Shaft Radius

1. RCG Identification

The RCGs that guide the design process for the mechanical subsystem are shown in Table 1.1 below. They will be referenced in discussions throughout the body of the report.

Issue	Requirement	Constraint	Goal
Claw Load	The claw must be able to lift 5 Newtons of load	The lifting force is friction	Maximize the load that can be lifted by the claw
Claw Gape	The distance between the tips of the claw arms which contact the object must be at least 7 cm when in the open position	The moving hub must not exceed 1 inch of linear travel in closing and opening the claw	Maximize the distance between the tips of the claw arms which contact the object when in the open position
Component Stress	None of the claw components must exceed the maximum stress rating for the material they were constructed with at any location	No component should have a thickness greater than 30 mm at any point for the sole purpose of stress reduction	Minimize the stress in each of the claw components
Claw Weight	The claw must have a combined mass less than 750 g	The claw must be large enough to allow the average player to comfortably operate it while attempting to hop balls	Minimize the combined claw mass
Volume Occupancy	The gear assembly and electrical subsystem must fit within a volume of 900 cm^3	The gearbox assembly and the electrical subsystems must exist in isolated sections of the occupied volume	Minimize the volume occupied by the gear assembly and the electrical subsystem

2. Dimensions & Kinematics

Before modeling the hopper, dimensional constraints had to be established in accordance with the previous section. The claw needed to be long enough to allow a player to grasp the tennis ball of approximately 6.8 cm diameter without having to bend down excessively. Furthermore, the claw uses a lead screw mechanism, so the bottom of the lead screw needed to have a certain vertical clearance from the top of the ball when grasped. Given this information, the following dimensions were qualitatively selected to provide a reasonable trade-off between the moment of inertia and efficiency of motion. Figures 2.1 and 2.2 show drawings of the inverse kinematics for the claw in its fully opened and fully closed states, respectively, for a single arm of the claw.

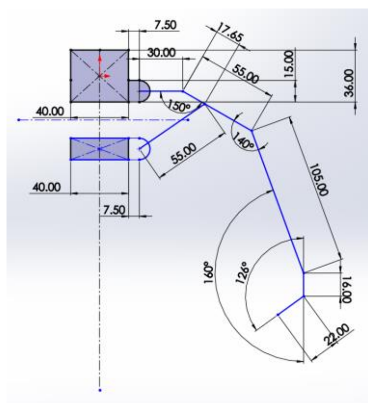


Figure 2.1. Inverse Kinematics in the Open Position

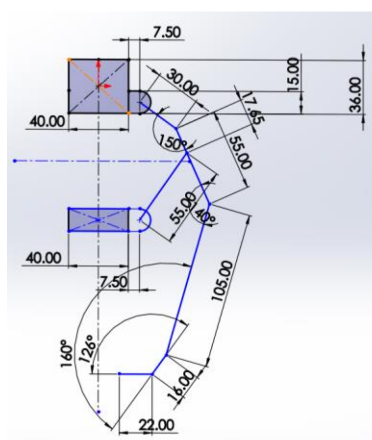


Figure 2.2. Inverse Kinematics in the Closed Position

3. Three-Dimensional SolidWorks Model & Stress Analysis

3.1 Model Features

Using the validated dimensions from the inverse kinematics of the selected claw model design in the previous section, several components were individually modeled before being compounded together in an assembly. These include the claw arms, a fixed and a moving hub, connecting rods to link the moving hub to the arms, a lead screw and its associated nut, the motor and a gearbox. The claw assembly is shown in Figure 3.1 below.

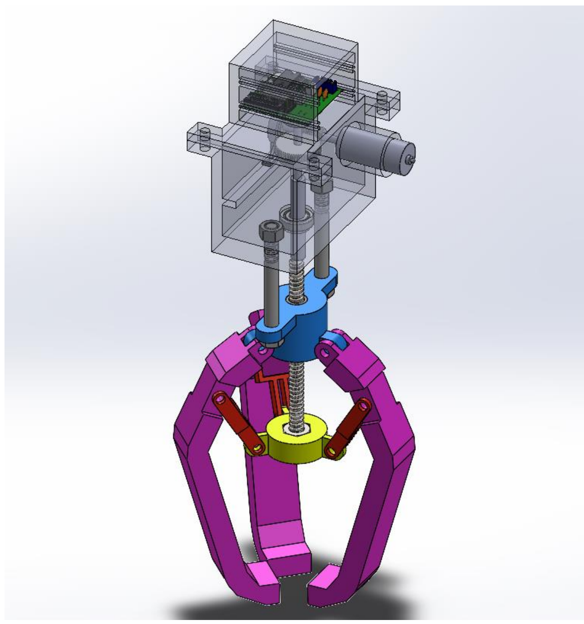
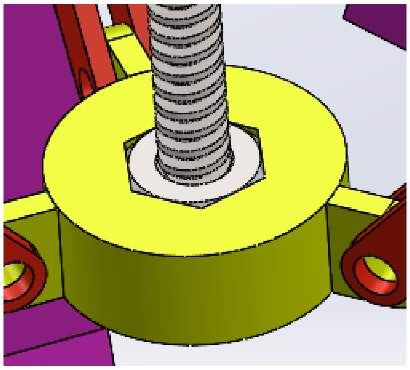


Figure 3.1. Claw Assembly

The lead screw is the component that allows the transformation of the rotational motion of the motor to the linear motion of the moving hub. The lead screw is coupled to the motor shaft via a reduction gear box. As the screw rotates, the threads of the screw and its nut shown in Figure 3.2. interact to exert a vertical thrust force on the nut and the moving hub by extension. Through the vertical motion of the moving hub, opening and closing of the claw can be achieved through the connecting rods shown in Figure 3.3 that are attached to the arms.



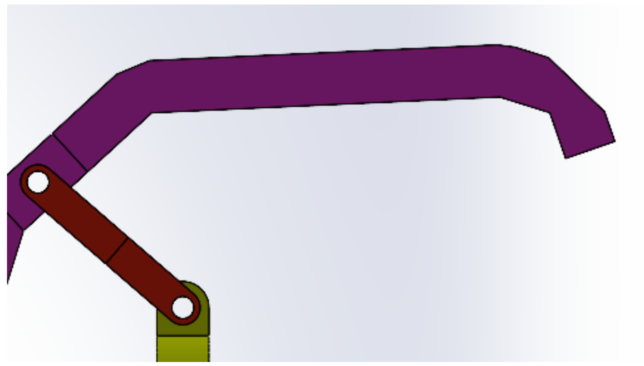
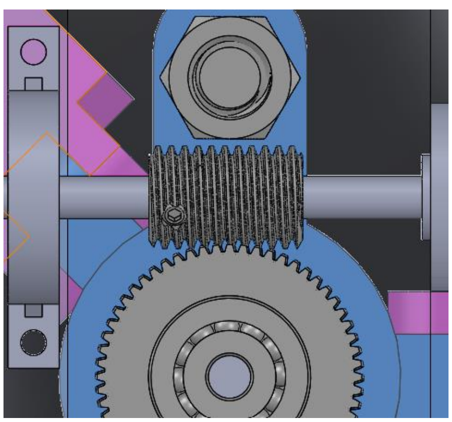


Figure 3.2. Lead Screw & Nut Figure 3.3. Hub-Arm Coupling via Connecting Rod

The gearbox features a 60:1 gear ratio which is accomplished within a confined space using a worm gear mechanism as shown in Figure 3.4. This reduces the torque required by the motor to lift the arms as well as the tennis ball once it has been grasped as described in the third section which allows us to achieve a reasonable speed of linear motion for the moving hub using the Pololu 12V motor the specifications of which can be found in the Pololu motor catalog [1]. The gearbox housing also accommodates the electrical subsystem for the claw, including PCBs and cables as shown in Figure 3.5.



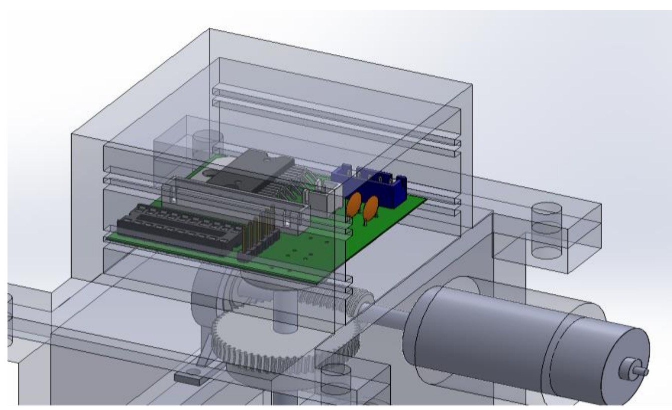


Figure 3.4. Worm Gear Assembly Figure 3.5 Gearbox & Electrical Component Housing

3.2 Stress Analysis

Stress analysis was conducted on the claw arms to ensure that the structural integrity of the PLA material used to fabricate the claw would not be compromised in the case of maximum torque supplied by the motor. A force of 0.79 N was applied to the end of the claw arm in the simulation environment which corresponds to the maximum expected normal force at that location as outlined in section three when it makes contact with the ball. The results of the FEA simulation are shown in Figure 3.6. Given that the tensile strength of the PLA material used to manufacture the claw is about 50 MPa, it is evident that the claw arm design is robust with the maximum stress being 0.22 MPa, corresponding to a safety factor of approximately 220.

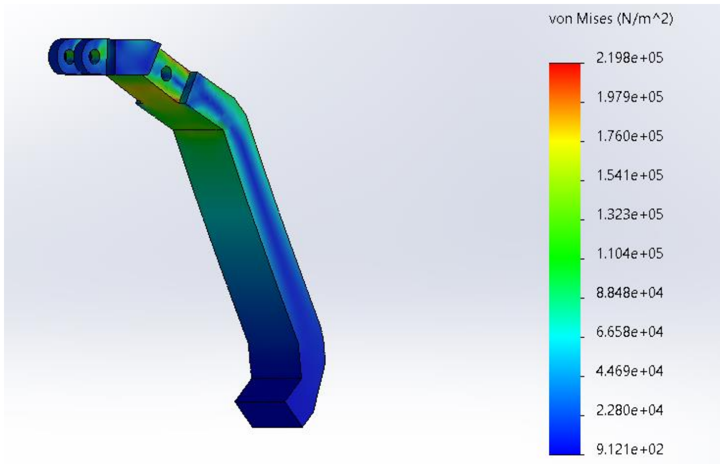


Figure 3.6. Claw Arm FEA Simulation

A similar process was performed for the connecting rods that link the claw arms with the moving hub. The result of the simulation is shown in Figure 3.7 and it shows a safety factor of approximately 29 suggesting that the connecting rod design is also robust.

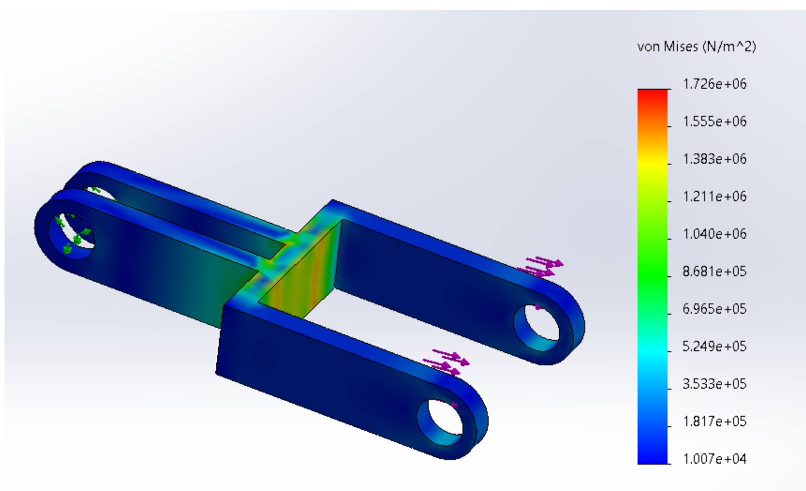


Figure 3.7. Connecting Rod FEA Simulation

3.3 Cost Analysis

An estimate for the cost price of the components of the claw assembly are shown in Table 3.1 below. All prices shown are in USD.

Component	Price (USD)
Steel Worm Gear (x1)	$13.56
Plastic Worm Gear (x1)	$17.24
5 mm Ball Bearing (x2)	$34.96
Carbon Steel Acme Hex Nut (x1)	$3.90
Carbon Steel Acme Lead Screw (x1)	$13.80
Needle-Roller Bearing (x1)	$6.50
Zinc Yellow-Chromate Plated Hex Head Screw (x1)	$11.65
Washdown Clamping Shaft Collar (x1)	$10.40
¾ inch Ball Bearing (x2)	$11.78
Medium-Strength Steel Hex Nut (x1)	$15.94
Dowel Pin (x4)	$50.72
18-8 Stainless Steel Hex Head Screw (x1)	$5.76
Steel Hex Nut (x1)	$2.62
Set Screw Shaft Coupling (x1)	$15.95
Pololu 12V Motor	$26.75
3D Printing Material (PLA)	$40.00
TOTAL	**$281.53**

Table 3.1. Cost Report for Claw Assembly

4. Torque & Force Calculations

4.1 Gear Ratio

Due to the relatively large inertia of the claw assembly, a greater torque than that which could be directly supplied by the 12V Pololu motor was required so a gearbox was included to multiply its torque. However, a compromise needed to be made between torque and rotational speed of the lead screw which decreases as the torque increases. To determine the optimum gear ratio, the calculations described below were performed. The variables for the equations used in the calculations are defined in Figure 4.1.

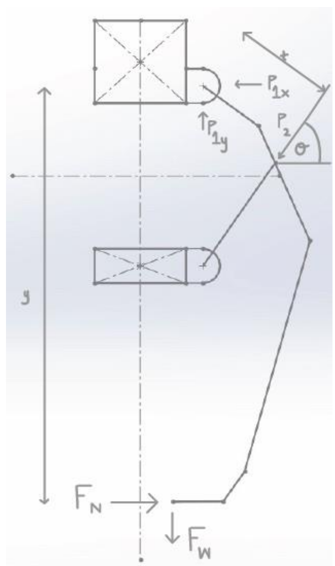


Figure 4.1. Equation Variables

The force and torque balance equations for the system are as follows:

$$P_{1x} + (P_2)(\cos\theta) - F_N = 0 \quad (1)$$

$$P_{1y} - (P_2)(\sin\theta) - (F_N)(\mu) = 0 \quad (2)$$

$$(F_N)(y) = (P_2)(x) \quad (3)$$

$$(3)(\mu)(F_N) - F_W = 0 \quad (4)$$

The quantities x and y were obtained using the measure tool within SolidWorks. μ, the coefficient of friction, was determined using a standard table of coefficients [2].

The thrust required to displace the moving hub was obtained by taking the vertical component of the quantity *P2* and multiplying it by 3 for each of the three fingers. This thrust can be converted to a required torque using the following equations for an acme lead screw:

$$T = \frac{(\mathrm{F})(\mathrm{D_p})}{2}\frac{(\cos \emptyset)(\tan \alpha)+\mathrm{f}}{\cos \emptyset-(\mathrm{f})(\tan \alpha)} \qquad (5)$$

$$\tan \alpha = \frac{\pi}{D_p} \qquad (6)$$

where T is the torque, F is the thrust, D_p is the pitch diameter, Ø is the thread angle which is 14.5° in this case, α is the lead angle and f is the coefficient of friction which was obtained from a standard table for lubricated carbon steel-carbon steel contact [2].

The result for required torque suggested that a gear ratio of 60:1 was sufficient for our purposes.

4.2 Lead Screw

The no load speed of the motor is approximately 10000 revolutions per minute. Therefore, with a speed ratio of 60:1, the rotational speed of the lead screw would be about 166 revolutions per minute. The inverse kinematics of the claw allow a linear range of motion for the moving hub of about 1 inch. Thus, to allow for a reasonable linear speed of travel for the moving hub, a lead screw was selected with a linear distance of 1 inch per turn. This also translates to simpler control system design since only one rotation of the lead screw needs to be considered.

4.3 Material Selection

The torque to actuate the claw assembly is directly proportional to its inertia which is proportional to the mass of its individual components. Therefore, low density materials are preferred but one must make a compromise between material weight and material strength since less dense materials are usually more prone to failure.

The solution pursued in this case was to 3D print the majority of the main claw components including the arms, connecting rods, shafts and hubs with PLA, which has a relatively low density of 1.24 g/cm^3 which was found in a material density chart [3]. but they were made to have a certain minimum level of thickness to avoid the risk of failure. For components that were not 3D printed, specifically the purchased components, Aluminium was the preferred material due to its lightweight (2.7 g/cm^3) and rigid properties.

5. Simscape Model

The completed SolidWorks model was exported to Simscape so that the gains of the PID controller could be tuned appropriately taking the entire system model into account. The gearbox was not included in order to increase the simplicity and accuracy of the model, but scaling was introduced where necessary to account for such an optimization. The model within the Simscape environment is shown in Figure 5.1 in its open position.

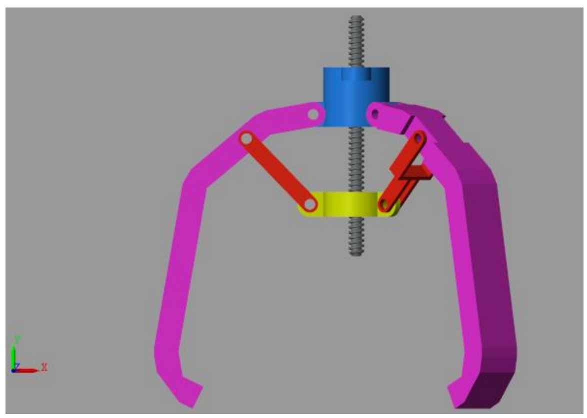


Figure 5.1. Simscape Model View

To close the claw, the moving hub moves to the free end of the lead screw which corresponds to a linear distance of about 1 inch. Torque is applied to the other end of the lead screw and is scaled by the gear ratio to account for the torque amplification of the gearbox while the angular speed of the lead screw is sensed by the controller. The speed is scaled by the gear ratio as well since the lead screw rotates at a slower rate than the motor shaft. The exported Simscape model is shown in Figure 5.2 while the complete system model is shown in Figure 5.3.

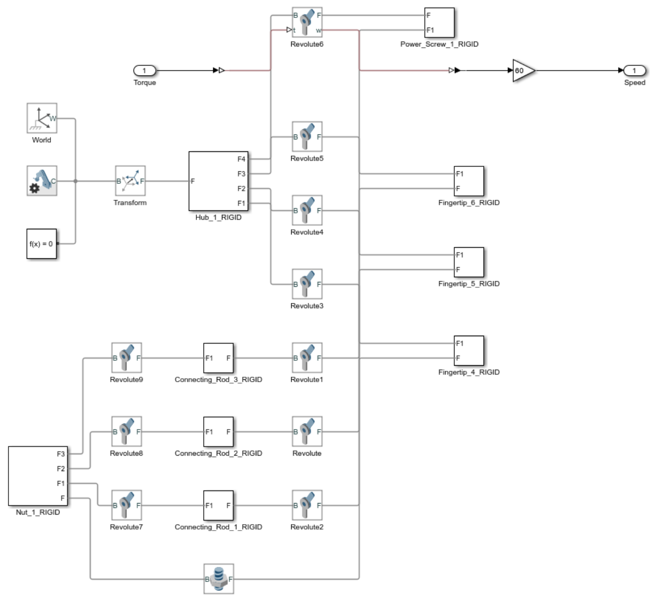


Figure 5.2. Exported Simscape Model

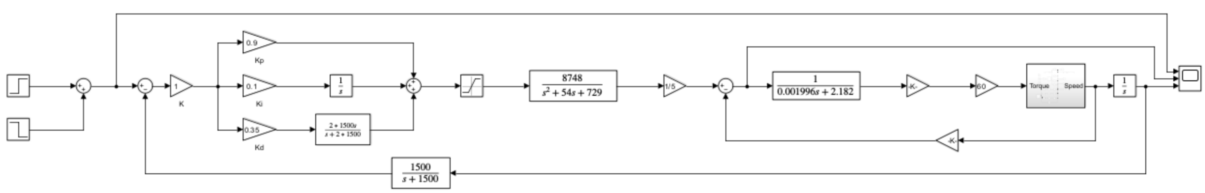


Figure 5.3. Complete System Model

Most of the joints are revolute joints since the model contains mainly hinge joints which rotate about each other. A damping coefficient was applied to all revolute joints corresponding to the PLA-PLA coefficient of friction. A lead screw joint was created between the lead screw and its associated nut to allow for the torque applied to the screw to translate to the linear motion of the nut. Damping associated with carbon steel-carbon steel contact was applied at this joint.

References

[1] Pololu motor catalog, (2023), https://www.pololu.com/product/2821

[2] Friction Coefficients and Calculator, (2023), https://www.engineeringtoolbox.com/friction-coefficients-d_778.html

[3] Density of Elements Chart, (2023), https://www.angstromsciences.com/density-elements-chart