Mechanical Design and Simulation of Inverted SCARA Robot Arm

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***Abstract*—Robotics in the food packaging industry is in growing demand and required to be designed with: (1) performance, (2) safety and (3) capability in mind. This technical paper will cover the mechanical design of a package moving robot including the actuator selection, component design and interfacing, stress analyses, and performance simulation. This belt-less design can be fitted with a vacuum gripper and picker to be applied to packaging of mass up to 3kg.**

I. APPLICATION

A. Requirements, Constraints, and Goals

Our application is to pick and place plastic-wrapped food packaging from one conveyor belt to another. The nominal weight of the package we select to be around 1kg for this design. This is reflective of most cereals, biscuit, and grocery-store level products.

Given this application, we define the following design considerations relevant to the mechanical system design:

1. We require the ability to travel 1 m/s through workspace, approximately 3x the average conveyor belt speed.
2. We constrain the robot to be easy to install and maintain by being lightweight in comparison to competing robot EPSON RS4-550.
3. We require loads of 2x nominal do not affect path planning and speed of robot.

This report will focus on the engineering of the SCARA arm and will only briefly cover the addition of a possible end effector at conclusion of this paper.

II. MOTOR AND DRIVETRAIN SELECTION:

In selecting the motors that drive the robot to match our design requirement, we first apply an estimate to narrow our selection of potential motors from the available Maxon Catalog. It is imperative to design our motors around the application to ensure that the requirement can be met.

A. Estimation of Rotational Inertia:

To get an approximation of the power needed to be supplied by the motor and drivetrain, we simplified our scenario used a mock-up of the arm with possible mass properties as shown in Figure 1.

Using 3003 Aluminum Alloy as a material, we can approximate inertia that the Joint 1 and Joint 2 motor would need to be able to move (inclusive of a 1kg load attached at the end effector) about their respective axis of rotation.

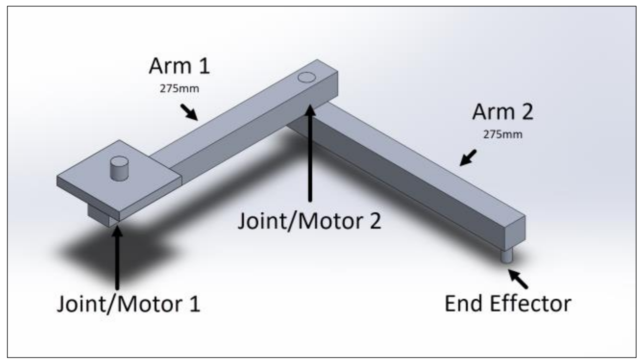

Figure 1: Schematic of Mechanical Model Approximation. With added material properties, this is used to estimate range of possible motor selections.

Estimated Rotational Inertias of Each Joint:		
Joint 1	Carries: Arm 1, Arm 2, & Load	2.60 kg-m^2
Joint 2	Carries: Arm 2 & Load	0.54 kg-m^2

Table 1: Estimated Rotational Masses each motor is required to move. This approximate model is made of solid blocks of 3003 Aluminum, overestimating the inertia we expect to have once completed design.

B. Constant Acceleration Model to Determine Torque:

We take advantage of the following relationship between speed and torque, also known as the mechanical impedance:

$$\frac{\tau(s)}{\omega(s)} = Js + B \tag{1}$$

Where ω(s) represents angular speed in radians/second, τ(s) represents the applied torque in Newton-meters, J represents the rotational inertia in kilograms-meter squared, and B represents the coefficient of rotational damping. For an approximation, we neglect rotational damping and relate the angular speed and torque directly by the rotational inertia.

$$\tau(s) \approx J\,\dot{\omega}(s) \tag{2}$$

Our application demands an ability to move 1m/s through our workspace. This is defined in our robot's Task Space of Cartesian movement, hence we needed to convert to Radial coordinates and approximated the speed. Here is where our Constant Acceleration Model provided by our Controls Lead completed the conversion:

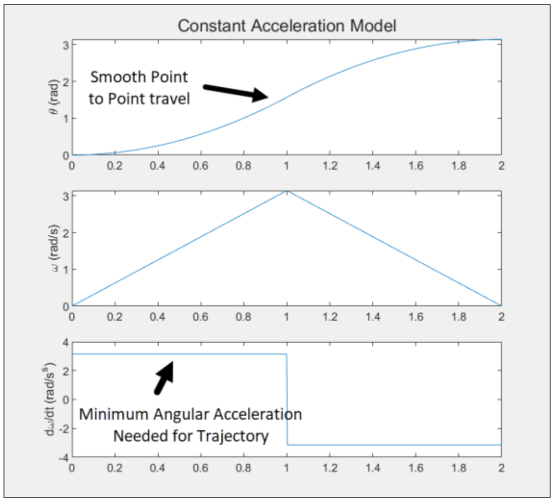

Figure 2: Constant Acceleration Model used to smooth out jerkiness within Path Planning allows us to find the anticipated angular acceleration needed. This shows the acceleration needed to rotate 180° in 2 seconds. This is 0.75m/s with an extended arm length 550 mm

From this we can tell that we need at an angular acceleration of at least 3 radians/second-squared to achieve our desired task space speed. We use this model for both motors to approximate the required torques needed about each joint:

Approximate Required Motor Torques:	
Motor 1	10 N-m
Motor 2	2.5 N-m

Table 2: Required Torques needed by each motor to move our estimated loads at 1m/s in the robot's workspace

With this information, we can estimate applying gear ratios to a motor to determine which motors from the Maxon Catalog can move this load.

When picking the gear ratios, we can select a motor that fits one available. In our case, we ran the simulation of an untuned model to get an approximation on how the gear ratios could impact the performance. We iterated on this to select ratios that best traded-off current consumption and rotational speed.

Motor and Gearbox Selection:			
Motor 1	Maxon RE-40	Gear Ratio	150:1
		Nom. Continuous Torque	94.9mN-m
		Nom. Continuous Current	6A
		Cost*	$1092.22
Motor 2	Maxon RE-30	Gear Ratio	21:1
		Nom. Continuous Torque	51.7mN-m
		Nom. Continuous Current	4A
		Cost*	$720.84

Table 3: Selection Choice of the motors including desired Gear ratio and cost. *Cost includes gearbox and the encoder which is attached at Maxon Gmbh Manufacturing Facility within motor stator.

After combining with our Electrical and Controls subsystem, we discovered the total current draws were well within the motor specifications:

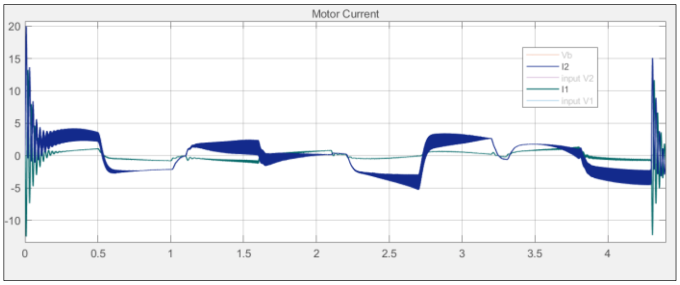

Figure 3: Graph of Current Drawn by Motors 1 and 2 during test Pattern. Current Spikes fall within Stall current ranges, and typical operation current is within the nominal current draws of both motors.

III. Mechanical Design

In our application of moving loads on or between conveyor belts, our robot must be placed hanging above the workspace to maximize its operating area.

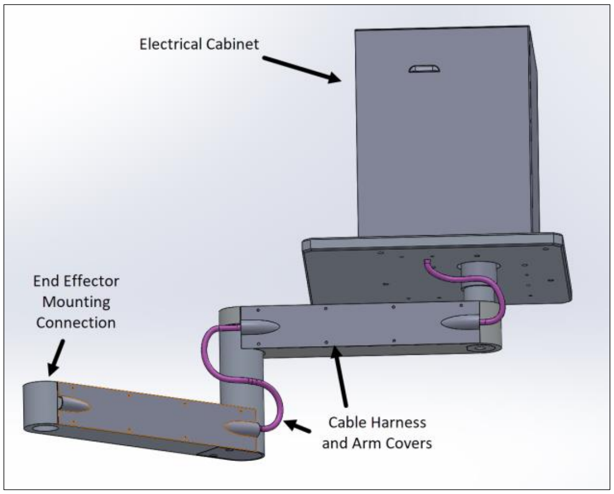

Figure 4: Elevated view of Total Mechanical System. Routed cable harness contains motor power and encoder signals to main circuit boards.

A. *Design Requirements, Constraints, and Goals:*

The application is to carry a nominal load of 1kg. This means that we cannot have any mechanical failure up to a given multiple of that, that multiple being our factor of safety.

We can define our RCGs for the Mechanical design

1. We require a Factor of Safety of at least 3 with no elastic deformation (<500μm) for nominal loads.
2. We require the robot to not mechanically fail under stress up to 10x nominal load, staying within its material yield point.
3. We constrain the robot to weigh less than competitor EPSON RS4-550.
4. We require the base to have the same mounting pattern as the EPSON RS4-550.

B. *Arm Design:*

Both arms are based on hollowed blocks inspired by the traditional I-Beam design. The main design goals requirements 1, 2, and 3 are of focus, where the I-Beam structure aims to achieve lightweight strength.

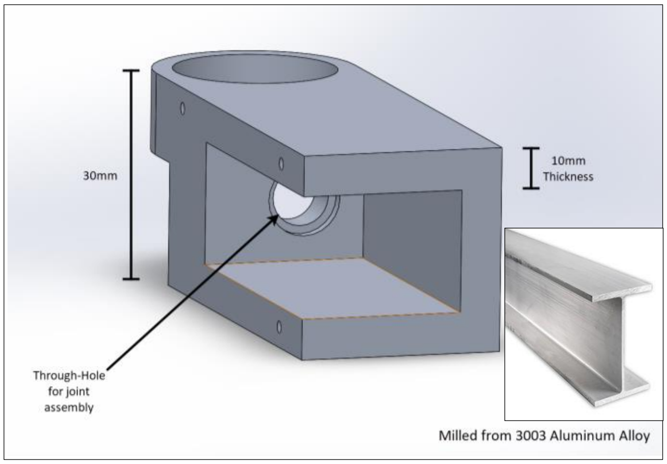

Figure 5: Cross Section of Arm 1 and 2 Design with inset of typical I-Beam (right)

The hollow space inside the arms is reserved for any end effector components and where extra slack in cable management can be stored elastically to prevent excessive dangling leading to cables being twisted around the joints. Although it removes a large amount of mass, it creates a structural twist when the end is loaded.

We combat this by keeping to a 10mm thickness for the arm I-Beam structure to keep our deflection to within 500um, which keeps the arms lightweight and strong enough to support loads when the entire Assembly is considered.

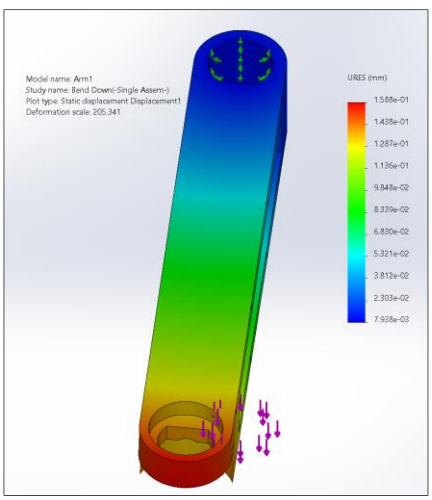

Figure 6: Exaggerated deformation when Arm 1 end is loaded with a downward force of 30N. The offset I-Beam Structure deflects outwards to the left rather than downward. This is well within our constrain of 500um deflection limit via the addition of thickness to the I-Beam structure.

C. *Coverings, Cable Routing, and Casing:*

To keep the insides of the robot inside, we use plastic coverings on the arms to prevent wires from dangling, silicon wire-harnesses to keep bunches of wires aligned parallel, and steel sheet metal for the electrical cabinet. As seen in Figure 4 the side covers are made of plastic and screw on using M3 screws. The Silicon Tubing extends into the arm and can be pulled and retracted when needed via an elastic connection.

D. *Base Design:*

The only RCG required for the base is to have the same mounting pattern as the EPSON RS4-550. This allows us to compete with their product by offering customers the ability to directly swap out their EPSON RS4-550 with our robot without need for refurbishment of existing mounting structures. See Appendix for detailed schematic and Stress Analyses.

E. *Interfaces and Components:*

To connect the arms via the joints, we use tapered roller bearings to support both axial and radial loads. The axial load is placed downwards on the inner ring for Joint 1 and is placed downwards on the outer ring for Joint 2 to allow for the hanging arm configuration. The Joint 2 configuration allows for no hanging force to be exerted on the motor via the rotor shaft. All hanging force is exerted on the Arm 2 ledge as shown in Figure 8. Figure 9 shows the Joint 1 interface of actuator and Arm1 in a simpler application.

Figure 7: Example of Tapered Roller Bearing capable of bearing both radial and axial forces supplied from McMaster-Carr

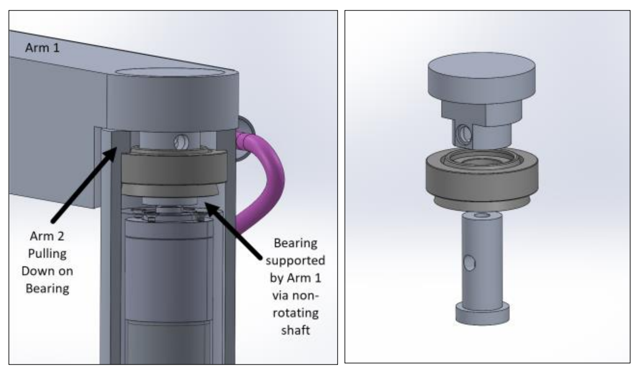

Figure 8: Joint 2 Construction. Left: Cut-away view of how Arm 2 is suspended from the Tapered Roller Bearing which is held in place by the locked assembly on the (Right) that hangs from the end of Arm 1. Right: The flat side on the supporting shaft prevents axial rotation and is connected to the rotor of Motor 2 which allows Arm 2 to spin relative to the locked shaft atop of the Tapered Roller Bearing.

F. *Stress Analysis:*

We can conduct a holistic stress analysis of the entire arm and find that we begin to see the 3003 Aluminum Alloy reach it's Yield Strength, or Plastic Deformation point under a 25kg load. This is far beyond our typical loads, but under this force the arm deflection is much larger than our requirement of 100um. This gives us an estimate of the absolute maximum mass our arm can support.

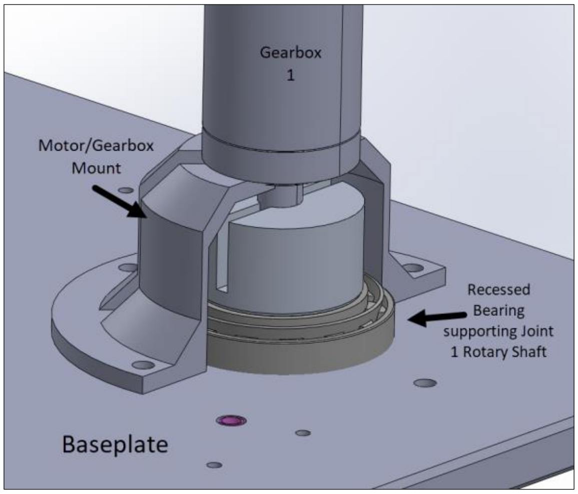

Figure 9: Joint 1 Construction with Cut-Away view through the Motor Mount. Tapered Roller Bearing bears the downwards weight of the Joint 1 Shaft connected to Arm 1.

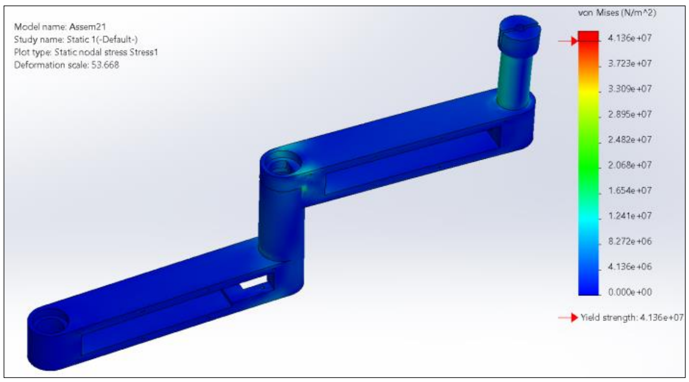

Figure 10: von Mises Stress analysis under 250N (25kg) load beginning to show small plastic deformation points near the inside of joints in red (not visible). Though the rest of the arm manages the force, these points are plastic deformation and result in permanent structural damage.

Using a nominal 1kg load we find in simulation that we achieve our requirement to have less than 100um of deflection with this design. We aim to verify the factor of safety using a 3kg load to get a maximum displacement of 350um within the Yield Strength.

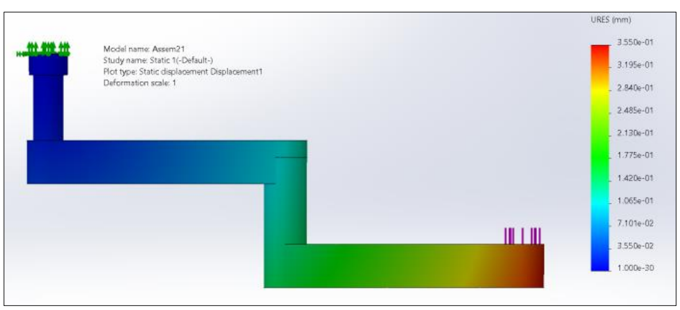

Figure 11: Deflection of Arm with 30N force on End Effector Mount. Maximum deflection occurs at the tip of the arm of value 0.355mm, within requirement of 0.5mm. Red indicates areas that deflect more than blue areas under this force.

IV. SIMULATIONX

There is an incredible amount of modelling needed to be done to fully characterize an integrated, multi-component mechanical system made of power transmissions, rigid bodies, and interfacing components. To take advantage of the latest developments in Computer Aided Design (CAD), we will use SimulationX by ESI Group.

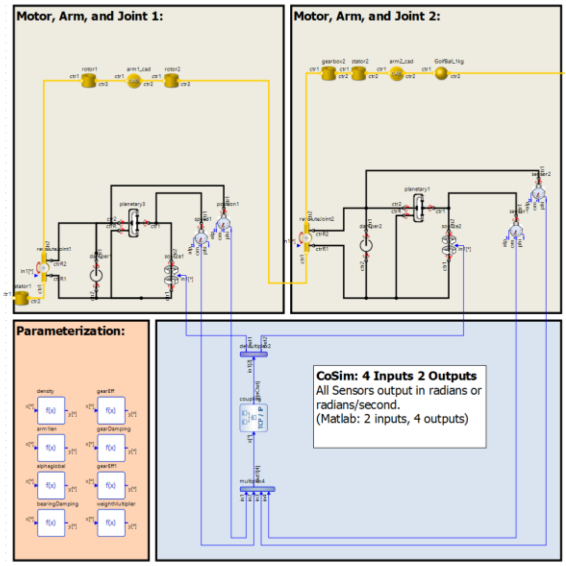

Figure 12: SimulationX Block Diagram Model. CoSimulation Block (bottom right) feeds to MATLAB via TCP connection where our controller is modelled. Chosen End Effector connects to the right of Joint 2 Block.

A key feature of SimulationX is allowing us to parameterize our designs. Every device has a lifetime for their parts, one to especially note are bearings. We can save simulation data from SimulationX into CSV files to then process multiple iterations with different parameters, such as the bearing friction changing over time.

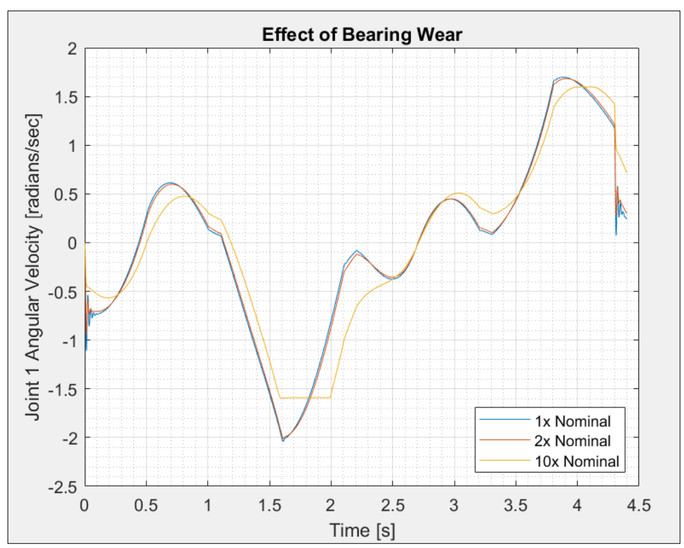

Figure 13: Joint 1 Angular Velocity simulated over multiple iterations with varying effects of wear on all connected bearings in SimulationX. We can see that at a 10x nominal bearing wear Joint 1 cannot spin faster than slightly over 1.5 radians/second severely impacting performance.

We note that changing the gear efficiency as a parameter does not affect our mechanical performance, as the electrical controller makes up for this. Graph can be found in Appendix as Figure 19.

Another key sensitivity analysis is to validate if our controller keeps accurate when faced with changes of mass. This situation can arise when picking and placing products of various masses, or if arm upgrades and redesigns are implemented without the upgrade of the controller. We simply adjust the mass of the placed load and rerun simulations.

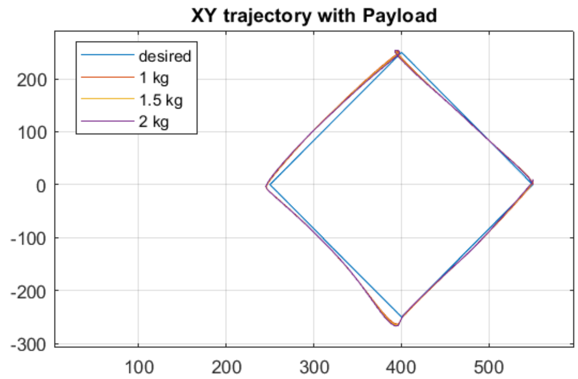

Figure 14: Variances in Trajectories with changes in load mass with all other parameters constant. Despite increases in Mass, the robot keeps the same path regardless of weight. Our 2kg path is the same as our 1kg path. This graph is provided by our Controls Lead N.C.

An important aspect of SimulationX modelling is keeping the model representative of the system. We can place our CAD assembly models as STEP files into the system and carry the masses of our created parts into SimulationX but were not able to associate the weights of the motor and gearbox within that model. We must include them explicitly in our Block Diagram for the SimulationX model to take their masses into account.

V. Application and Conclusion:

A typical application includes a vacuum gripper and z-axis linear actuator that can be connected as an End Effector.

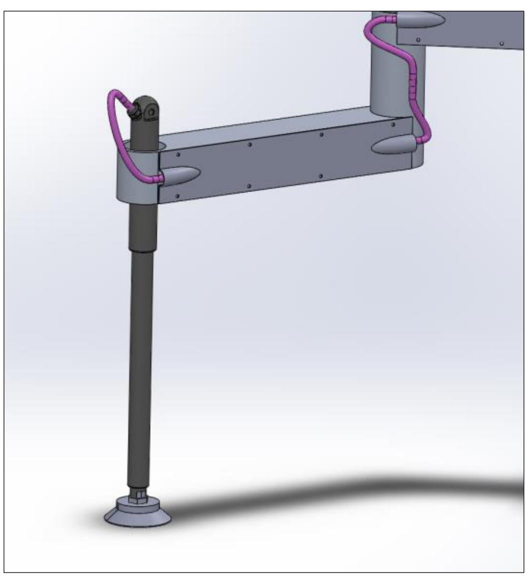

Figure 15: A typical End Effector screwed into the End Effector Mount, using vacuum suction to gently lift and place packages without damage in conveyor belt applications.

The weight of our implemented end effector is under 500g, leaving extra capability to carry packages of up to 2.5kg. The intended application is still for loads under 1kg; hence we still operate with a considerable factor of safety. Returning to our initially stated RCGs:

1. We can achieve our 1m/s speed via the careful selection of the RE-40 and RE-35 Maxon Motors with appropriate gearboxes.
2. Our total mass of the system inclusive of the base and casing comes to 8.4kg (shown in Appendix: Figure 23) significantly less than the EPSON RS4-550.
3. Our robot maintains its path with no path variations when carrying a load of 2x nominal as shown in Figure 14.

The cost to manufacture this system is within reason as well. Without considering material and machining costs for the aluminum, all fasteners and bearings from McMaster-Carr combine for a total of less than $200. Our motors are of high precision from Maxon Gmbh, which is something we can potentially trade off in future designs given the accuracy of our controller to reduce the cost of the most expensive component.

VI. Acknowledgments:

This project was completed alongside Nicole Campbell, and Nusair Islam who respectively completed the Controls and Electrical Systems. The project would only be the bones of a robot without their collaboration in defining and completing a working system with real world use.

VII. Appendix:

A. Motor Details:

RE 40 Ø40 mm, 150 Watt	
Part number 148866	
Weight	480g
Rotor Inertia	139 gcm²
Nominal speed	6380 rpm
Nominal torque (max. continuous torque)	94.9 mNm
Nominal current (max. continuous current)	6 A
Diameter	40mm

RE 30 Ø30 mm, Graphite Brushes, 60 Watt	
Part number 268193	
Weight	280 g
Rotor inertia	33.7 gcm²
Nominal speed	7600 rpm
Nominal torque (max. continuous torque)	51.7 mNm
Nominal current (max. continuous current)	4 A
Diameter	30mm

B. Base Schematic and Stress Analysis:

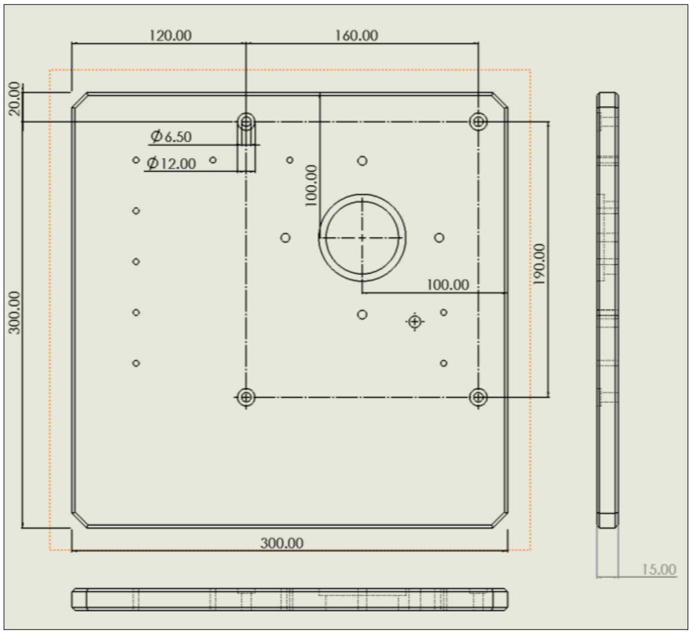

Figure 16: Dimensioned Schematic of Robot Base Plate for Manufacturing. Includes mounting holes for casing, Motor 1 Mount, and Installation.

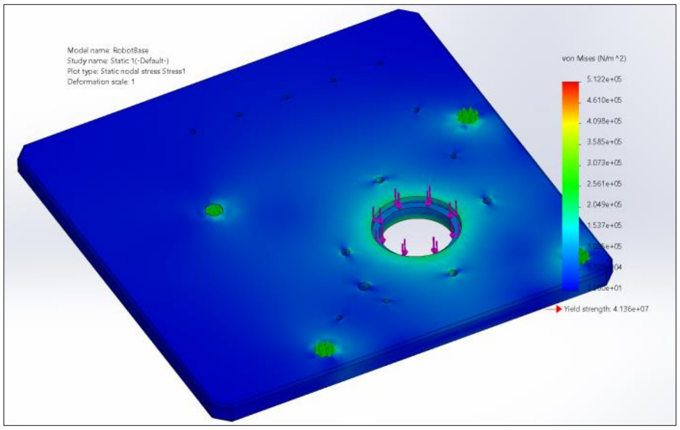

Figure 17: Stress Analysis of Base with 100N Force exerted on bearing seat. Total stress is two orders of magnitude less than the Yield Strength.

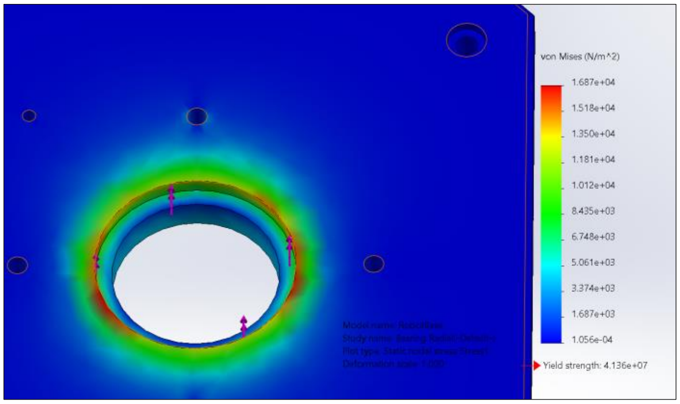

Figure 18: Von Mises Stress Analysis on Joint 1 Bearing Seat with 30N downwards force, what would be a 3x nominal load. At our arm's maximal load of 100N, this does not deform or come near to the Yield Strength, indicating the arm will fail before the base will give way.

C. Additional SimulationX Sensitivities:

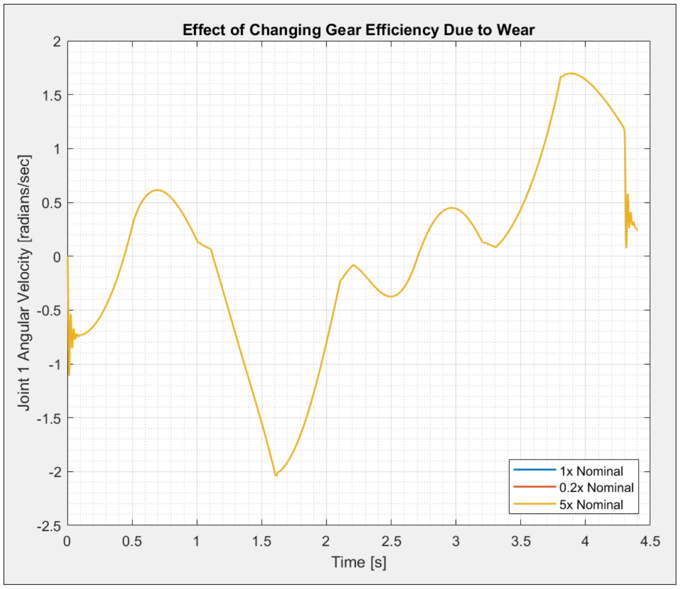

Figure 19: Applying different multipliers to the Gearbox Efficiencies. We note that there is no change in mechanical performance but do see changes in electrical performance due to this.

D. Mechanical Top-Level Assembly:

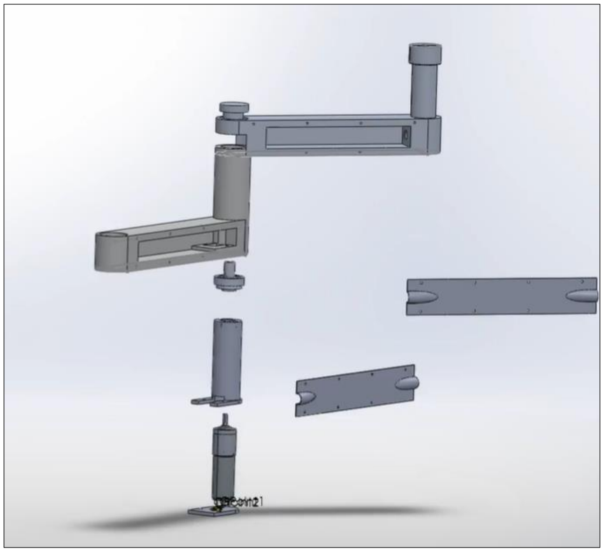

Figure 20: Exploded View of Arm Assembly

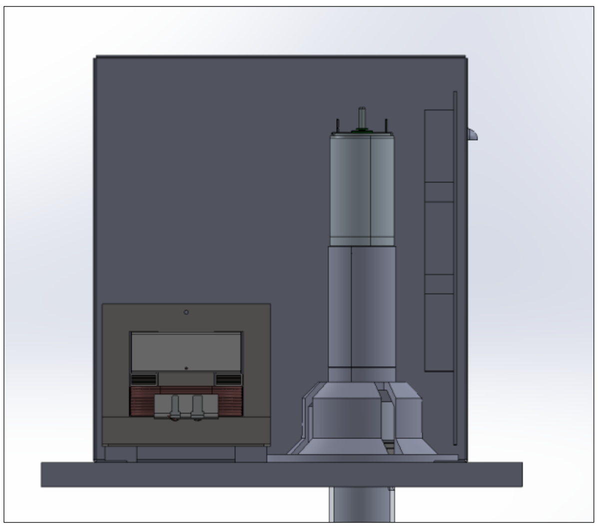

Figure 21: Electrical Cabinet Layout. Transformer on Left and PCB motherboard mounted on Right Sidewall. PCB was approximated with model to increase load times of Top-Level Assembly.

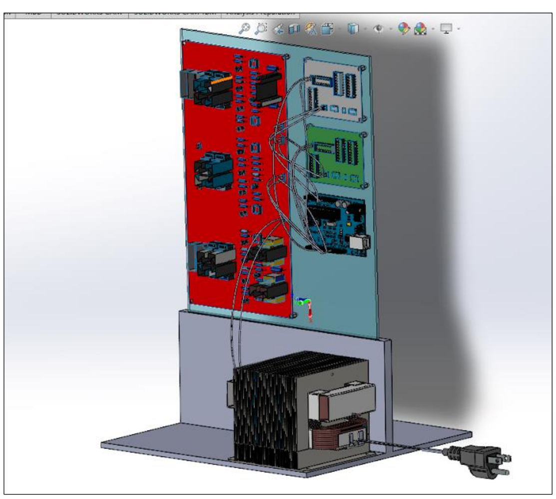

Figure 22: Electrical PCB design with dimensions integrated into Electrical Cabinet designed by Electrical Lead N.I.

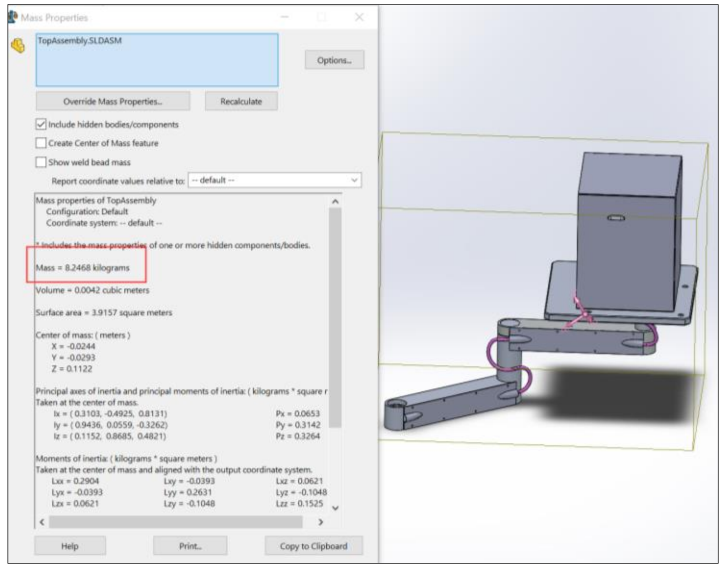

Figure 23: Total Mass of entirety of System. Mass of competitor EPSON RS4-550 is 23kg.