Team 42: Animal Care Cage Processing

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Dr. Keith Jenné
UCSD Animal Care

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MAE 156B: Fundamental Principles of Mechanical Design II
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Abstract

The Central Research Facility at UC San Diego is home to the Animal Care and Welfare Program, in which animal care cages for rats and mice used in research studies are processed for sanitization in-house for eight hours daily, Monday through Friday. The sponsor, Dr. Keith Jenne, expresses interest in automating the dumping and scraping processes, which are currently done manually, during the sanitization of the cages due to health hazards posed to the workers by the handling of animal waste. The sponsor requested an industrial automation machine capable of grabbing the cages from a predetermined platform, dumping the bedding, and transferring the cages to a tunnel washer machine. At the end of the cycle, the machine must facilitate the transfer of the cages onto the current washer's conveyor system for further high-pressure washing. The goal of the project was to devise such a continuous-duty industrial automation system capable of processing the cages at a rate that is no slower than 66% (8 cages/min) of the current average rate (12 cages/min) of the worker within a 15-week time frame. This automation system has been designed to be compact and movable in case of failure and modular to facilitate further development.

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Chapter 1: Project Description

1.1: Background

The Animal Care Processing Project (ACCP) was sponsored by Dr. Keith Jenné, who has served as the Executive Director of the UCSD Animal Care Program and Campus Veterinarian since April 2023. Dr. Jenné oversees the animal research space at UCSD, which includes participation in and design of new and renovated animal research facilities.

The project specifically focused on UCSD's Central Research Services Facilities Cage Processing Service, which currently relies on manual cage processing methods. The primary purpose of this project was to replace manual cage processing to decrease health hazards for the workers of the facility.

The manual process required the following:

1) The worker picks up two cages face-up from the transport cart shown in figure 1.
2) Over a dump station, the worker flips both cages 180 degrees and knocks the upside-down cages against the edge of the dump to remove bedding.
3) When there is animal refuse stuck to the inside of a cage, the worker uses a scraping tool to remove the refuse from the inside of the cages.
4) The worker places cages face-down on the tunnel washer conveyor belt, at which point the washer automatically cleans the rest of the cages.

Figure 1. Central Research Services cage processing facility. (Photo taken with permission of

sponsor)

The primary motivation behind this initiative stemmed from workplace health and safety concerns. The manual process exposed workers to following health risks:

1) Exacerbation of allergies to mice/rat urine and feces.
2) Carpal tunnel syndrome, tendinitis, and other repetitive strain injuries from repetitive cage flipping and dumping [1].

This project sought to develop an automated cage processing robot to reduce the exposure of workers to these health risks while operating at an efficiency relative to a human worker's efficiency.

1.2 Review of Existing Design Solutions

The animal cage processing field is niche but necessary. Any research lab that deals with animal testing must have their cages cleaned after use. Thousands of cages are shipped every day to facilities across the United States who process and clean animal cages so they can be reused. Automation solutions must be designed for the application; therefore, only two automation solutions are known. Central Research Service (CRS)'s model from BetterBuilt is the only known operational solution of its kind in the United States.

Company	**Getinge**	**BetterBuilt**
Method	 6-DOF robot arm that picks up cages 4 at a time from the designated loading area. Cages are rotated for dumped, scraped on a set of stationary scrapers, then fed into the washer [3].	 Enclosed industrial conveyor belt system with automated rack loading. Cages are flipped and dumped 4 at a time, translated on the conveyor belt, scraped on a set of stationary scrapers, and then fed into the washer

		[2].
Cost	~1,000,000$	~1,000,000$
Advantages	● Fully automated process except for initial loading ● Relatively fast compared to a human worker	● Fully automated process except for initial loading ● Fully sealed; no contaminant dispersion ● Consistent in washing process
Disadvantages	● Prone to not cleaning cages completely and system failure ● Requires specialized technicians for repairs ● Requires an entire dedicated room of space ● Difficult to move in case of failure	● Much slower than a human worker ● Not movable in case of failure

Table 1. Summary of existing design solutions

In summary, current design solutions are both prohibitively expensive and suffer from either being error-prone or slow. This project has proposed a design solution that balances these requirements by developing a cost-effective, consistent solution that operates at a reasonable speed.

1.3 Statement of Requirements and Deliverables

Statement of Requirements:

- Must be easily movable by humans without specialized equipment (in case of failure).
- Must not require human interaction for flipping, dumping, or transferring cages; only require interaction for loading cages into the machine.
- Must operate for typical cage weights of small mice cages (~.68 kg).
- Must fit within a 2m x 2m space.
- Must transfer bedding and animal refuse in cages into a specified dump location on the floor
- Must place the cages' face down on a conveyor belt at the end of the process.
- Must process cages at a reasonable efficiency compared to humans (defined as 70% of human efficiency; 8 cages/minute)

Statement of Deliverables:

Module	High Priority	Medium Priority	WOW Deliverables

Mechanical Assembly	● Design, prototype, and fabricate a mechanical assembly, including a rotary platform, a linear translation assembly, and a cage-grabbing mechanism ● Create mechanical documentation and a bill of materials	● Automate one complete cage processing cycle	● Automate for multiple cycles ● Streamline the loading of cages ● Design a funnel for precise handling of bedding during cage processing
Electrical System	● Create an electrical wiring system for all electronic components ● Create electrical documentation and bill of materials	● Create a semi-permanent electrical wiring system such as a perfboard for implementation	● Create a permanent electrical wiring system with a custom PCB
Automation Software	● Automate processes via motor control in Arduino IDE ● Create software documentation	● Create a human-machine interface and GUI for easy operation	
Design Documentation	● Create technical drawings and documentation for all mechanical and electrical components	N/A	N/A
Bill of materials (BoM)	● Document purchased and manufactured items in BoM	N/A	N/A

Table 2. Statement of Deliverables

Chapter 2: Description of the Final Design Solution

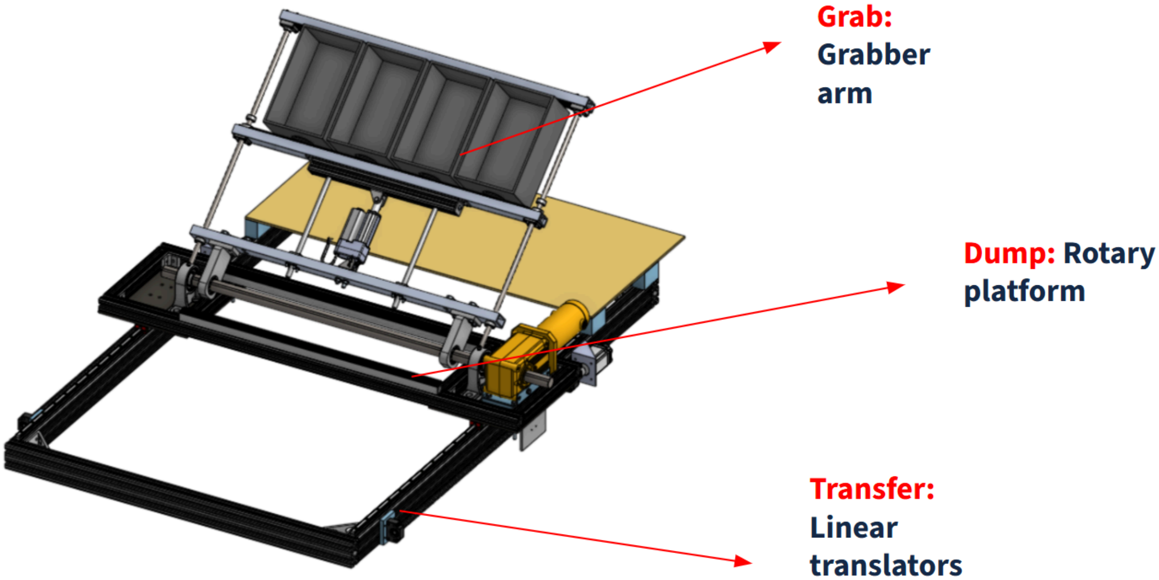


Figure 2. CAD of final design solution

Figure 2 depicts a CAD model of the final design solution, split into three main design modules. The design solution performs the grabbing, flipping/dumping, and transferring actions that a human worker was currently performing. Modules are discussed in detail in their respective sections in Chapter 3.

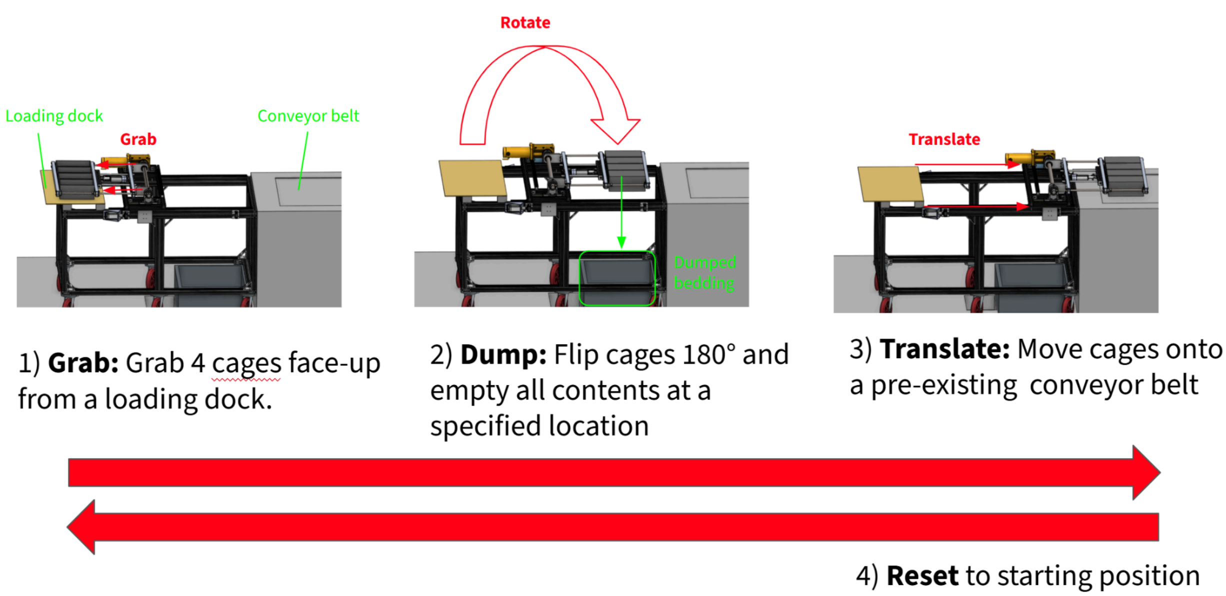


Figure 3. Design solution workflow

Figure 3 shows a design workflow for full implementation in the sponsor's facility. The project centered around the cage processing system, which would be mounted on a cart and routed into the dump in a full implementation. This design allows for the grabbing and dumping motion to occur at designated locations for future implementation, and for the translation step to transfer the cages to the sponsor's current tunnel washer. To perform the tasks of grabbing, dumping and transferring the cages to the washer, a multi-purpose automation system has been designed. This report breaks down the automation process into three main steps, which are discussed in detail in chapter 3.

1) **Grabbing** cages that are loaded into the system, done by the grabber arm.
2) **Flipping** the cages into a position where all bedding and refuse inside the cages can fall into a dump, done by the rotary platform.
3) **Translating** the cages to Central Research Services' in-house washer system, done by the linear translation assembly.

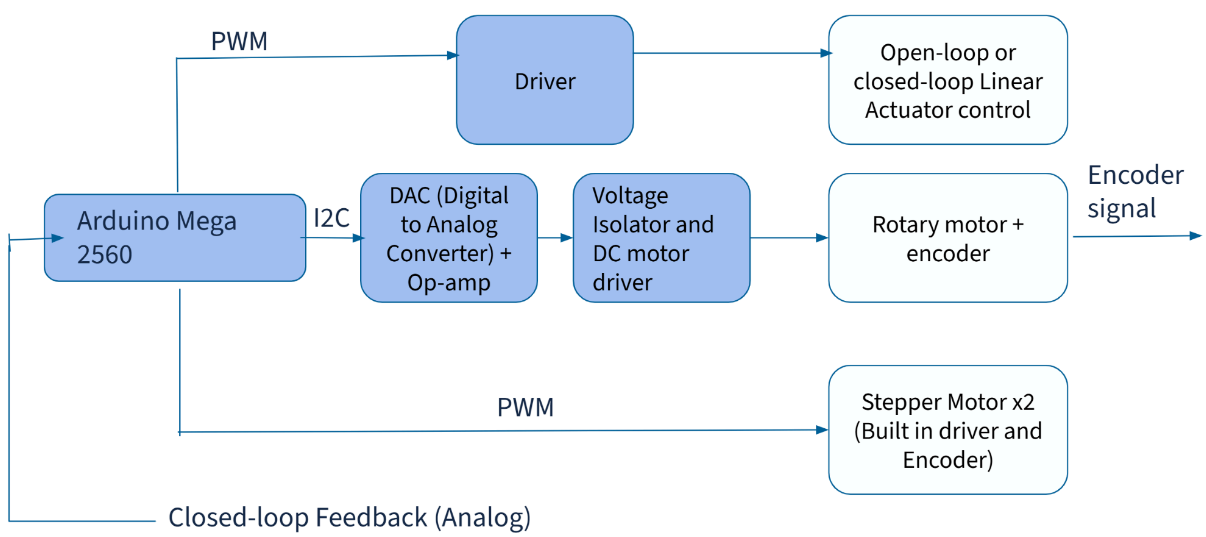


Figure 4. Master controls scheme

The final design is controlled by the master controls scheme shown in Figure 4. An Arduino Mega 2560 is selected as the microcontroller for the design. The three design components in Chapter 3 each receive signal from the Arduino Mega through PWM and I2C connections; the rotary platform (section 3.2) also returns encoder signal for closed-loop feedback.

Chapter 3: Design of Key Components

3.1 Grabber arm

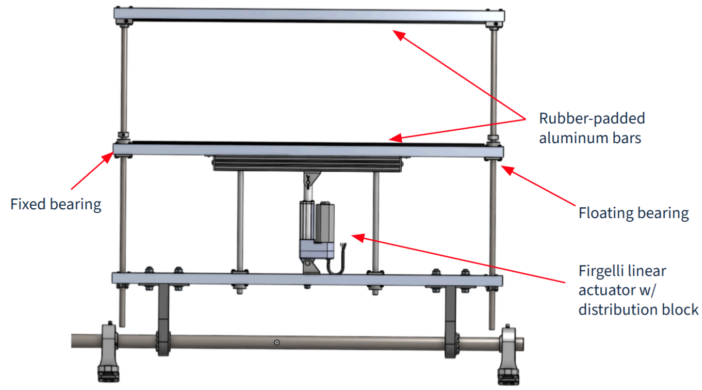


Figure 5. Grabber arm components

Functional requirements:

- Grab 4 cages without applying damage to the cages (the tunnel washer can process a maximum 4 cages at once)
- Hold all 4 cages throughout the entire rotation and translation process
- Perform grabbing process within 4 seconds
- Hold position in event of power loss

Mechanical Parts:

- Rubber-padded aluminum tubes; two bottom and top tubes are fixed while middle tube moves along guide rods to clamp cages
- Fixed and floating (self-aligning) bearings to prevent binding of the moving aluminum tube
- 0.5” diameter stainless steel guide rods
- Linear actuator with force distribution block and smaller guide rods to evenly push and pull the middle aluminum tube without deflection

Electrical Parts:

- Arduino Mega 2560 microcontroller for software control (shared by all three modules)
- DFR0601 Motor Driver to control the linear actuator movement
- 12V DC power supply to power linear actuator

The selection of grabber designs between an enclosed and open version is tabulated below. These two designs were compared due to the key tradeoffs between stability/protection and weight/simplicity.

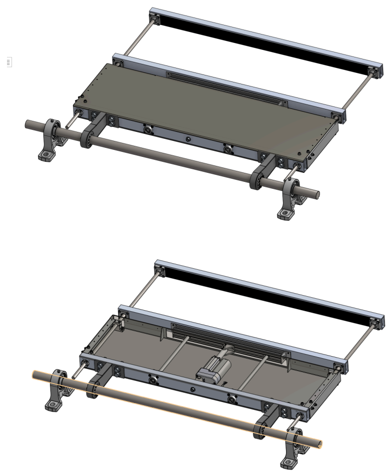
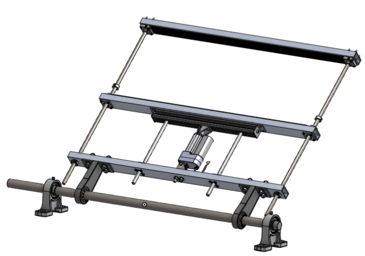
Design	**Description**	**Pros and Cons**
 **Enclosure Design**	● Bent-steel plate enclosure for linear actuator and wires	Pros ● Less stress concentration on the parallel shafts ● Less bending on the parallel shafts ● Prevents dirt built up on the guide rods and linear actuator ● Dedicated torque distribution channel via an extra pair of shaft supports in the enclosure to improve rigidity and strength Cons ● Heavier ● Enclosure needs to be custom ordered or manufactured ● Costly to manufacture
 **No Enclosure Design**	● No additional components between bottom bar and middle bar	Pros ● Lighter weight ● Simpler design ● Less cost to manufacture Cons ● Higher risk of shaft bending ● Higher risk of binding for the parallel shaft mechanism as a result of the previous bullet point ● Less rigid without the extra pair of shaft supports

Table 3. Comparison of gripper designs considered

Final Design Choice and Justification

The greatest design concern of the grabber arm was the possibility of the parallel linear motion shafts bending due to the torque of the arm, leading to misalignment and binding of the mechanism. This concern prompted the team to design a dedicated structural component to redistribute the torque away from the linear motion shaft, leading to the enclosure design. To verify whether the shafts would bend beyond the 2 degree allowable tolerance of the linear sleeve bearings so as to cause binding under the nominal loading condition of the grabber arm, an Ansys static structural simulation (Appendix A.4.3) was performed under the worst-case loading condition, where the free end of the rod is fixed and the joint between the rod and the bottom bar is subjected to half the maximum motor torque at about 509 lbf in. It was found that in the enclosure free configuration, the rod should not deflect more than 0.1 degrees. Based on the simulation results, it was decided that an enclosure as an structural component is not necessary, and the no enclosure design was deemed a sound design choice.

3.1.1 Grabber mechanism controls

To power the Firgelli Super Duty Linear Actuator, a 12VDC power source and a DC motor driver are required. The DFR601 driver, which is rated for 12A current output, 6.5-37 VDC output, and 290W power output, fulfills the power requirement of the linear actuator, which has a 12VDC input and a max current draw of 5.5A. The driver also supports up to two DC Motor, which allows expansion to two linear actuators in case of increase in load requirement. Furthermore, an Arduino with PWM control is required to implement closed-loop position control via hall effect sensor feedback and potentially open-loop force control via an ammeter. The arduino sends PWM signals and two logic signals, INA and INB, to the DFR0601 driver, which has an H-bridge allowing the polarity to be flipped according to the INA and INB inputs. The control schematic is shown in Appendix section A.7.3, and the integration within the full electrical diagram is shown in A.7.1.

3.1.2 Grabber arm torque adapter

The torque adapters of the grabber arm facilitate the rotation of the grabber arm by transferring torque from the rotary motor to the arm. As a critical component of the overall design, the design of different torque adapters was tabulated.

Design	Pros	Cons

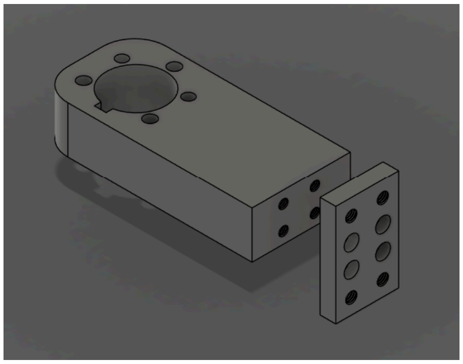
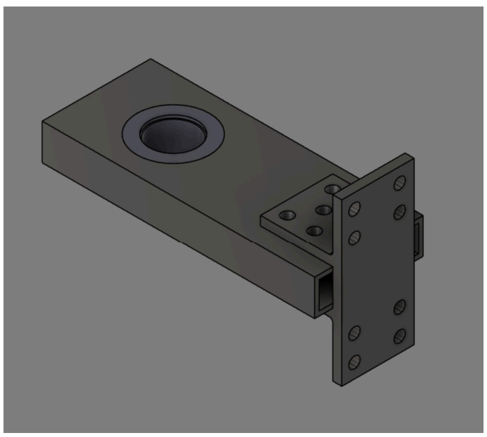
 **Solid-Body and Plate Flange**	● Simple design ● Greater surface area for shaft clamp attachments	● Heavy ● Precision manufacturing introduces difficulties. ● Weaker connection between the flange and the adapter.
 **Tube-Body and T-Flange**	● Simple design ● A stronger connection between the flange and the adapter ● Lightweight	● Sharp corners that can lead to high stress concentrations ● Smaller area for shaft clamp attachment due to tube geometry ● Steel bolts connect the flange to the adapter, which can lead to deformation or loss of material over time as the steel bites into the holes

Table 4. Comparison of torque adaptor designs considered

<u>Final Design Choice and Justification</u>

The tube-body and t-flange design was selected for the torque adapter. This design had comparable strength to the solid body design, and stress under expected load was evaluated in section A.5.1. The multiple bolts connecting the adapter to the flange provide a stronger connection, even if the bolts eat into the adapter over time, the tube design also makes it cheaper to manufacture than a solid body design, which would be made out of an aluminum stock. A tube design also has a better strength to weight ratio than a solid body design. Finally, the lighter weight would reduce additional loads on the shaft.

3.2 Rotary platform

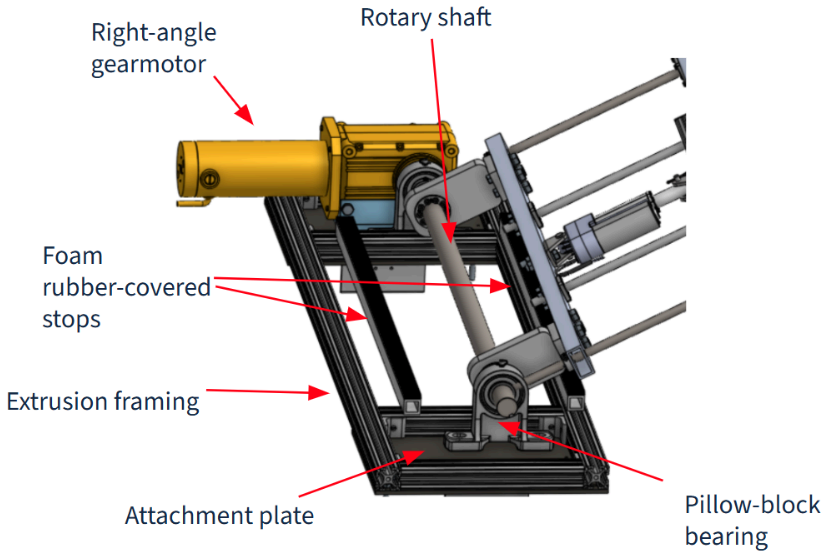


Figure 6. Rotary Platform

Figure 7 shows the rotary platform, which must rotate the grabber arm 180 degrees into the dumping position after it has clamped onto the cages. The rotary platform must also be mounted on the linear rails of the linear translation assembly to facilitate movement of the grabber arm and cages towards the tunnel washer.

Functional requirements:

- Rotate the entire grabber arm 180 degrees in 5 seconds.
- Hold position in event of power loss
- Have sufficient rigidity and sufficiently low weight to be moved smoothly by the linear translators

Mechanical Parts:

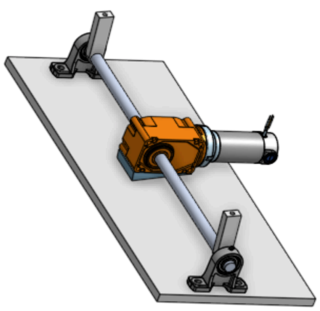
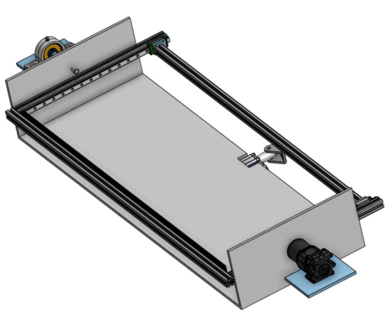
- Keyed 1.25” diameter rotary shaft to rotate grabber arm
- Two pillow-block bearings to support keyed rotary shaft
- Steel assembly plates to hold grabber arm and DC gearmotor above as well as attach to the linear rails and ball screws below
- 8020 extrusion pieces to connect both steel plates together
- Aluminum bars with neoprene foam rubber coating for the grabber arm to rest upon when it completes its 180 degree rotation

Electrical Parts:

- BISON 90VDC Gearmotor to rotate the rotary shaft
- Arduino Mega 2560 microcontroller for software control (shared by all three modules)
- KB8831 Regen Driver to control DC gearmotor and receive 120VAC line input to power DC gearmotor

- KB8832 Signal Isolation board to isolate voltage input into motor driver
- MCP4725 Digital-to-Analog converter to convert Arduino digital signal into analog signal
- TLV2372 Op-Amp to shift (0V to 5V) signal from Arduino into (-5V to +5V) signal for motor driver
- ICL7660S Charge Pump to generate -5V voltage signal
- NC (naturally closed) physical limit switch for homing of rotary arm

Platform designs considered:

Design	Description	Pros and Cons
 Center-mounted motor platform	• 0.5" thick aluminum plate, mounted on both sets of linear rails at the edges • Motor mounted in center with a slant block underneath to allow the grabber to rotate close to parallel • Pillow-block bearings supporting driveshaft load • Driven by BODINE high-torque, continuous duty right-angle DC gearmotor [7]	Pros: • Equal downwards moment force at both edges for smooth linear translation • Equal transmission of force to both adapters through driveshaft, allows a smaller driveshaft to be used Cons: • The grabber arm cannot rotate a full 180 degrees due to the edges of the motor running into the lower bar of the grabber • Platform thickness makes material costly
 Carriage-style integrated grabber platform	• Integrated grabber and rotary platform, grabs cages within platform and rotates in place • C-shape bended steel platform • Small plates holding motor and bearing with shaft, both mounted on linear rails • Motor and bearing both with individual shafts extending into the C-shape platform • Driven by REV NEO light-duty brushless DC motor	Pros: • Requires lower-torque motor to rotate platform • Simpler design due to integrating grabber arm into platform • Simpler controls scheme for motor Cons: • Integration of grabber arm into platform excludes the possibility for cage loading to eventually be an automated conveyor system • Shaft only contacts at one point on the

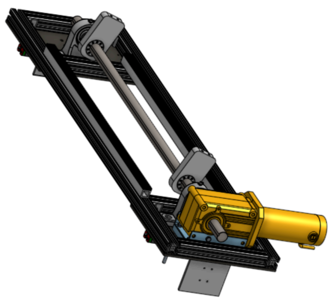
		C-edge nearest to motor
 Braced platform with offset motor	• Two 0.25" thick steel plates connected by 8020 extrusion bracing, mounted on linear rails at the edges • 1.25" diameter keyed rotary shaft • Rubber-coated stops on either side of rotary shaft to hold grabber arm after 180 degree rotation • Driven by BISON motor mounted on the end of rotary shaft [8] • Right-angle brackets connecting the platform to the ball screws for power transmission	Pros: • 8020 extrusion provides rigidity to maintain alignment between both sides of the platform as the linear rails are driven • No material in the center of the platform, reduces overall weight Cons: • Requires more material and cost due to the 8020 extrusion and stops • Requires the 1.25" diameter rotary shaft to prevent torsion due to motor location on the edge

Table 5. Comparison of platform designs considered

Final Design selection:

The Braced Platform design with the BISON Right-angle DC gearmotor was selected for the final design. This platform design offered the advantage of rigidity between both linear rail attachments, while providing a sturdy base for the motor mount and pillow-block bearings. A key aspect of this design was that the rigidity between the two plates is provided by the two long 8020 extrusion pieces, which are bolted into the steel plates with T-nuts. If the stepper motors caused misalignment in the platform for any reason, the T-nuts would shift and the 8020 extrusion pieces would angle. This can be easily reset by removing the 8020 extrusion, straightening the T-nuts, and re-attaching them. This was preferable to the platform being fully rigid and causing potentially permanent deformation to the ball screws or the linear rail blocks. Furthermore, the integration of rubber-coated stops allowed the grabber arm to rest when in the 180-degree position, to avoid a cantilever force on the grabber arm's rod supports as well as stress on the gearmotor's worm drive.

The BISON DC gearmotor was ideal for this selection due to a simpler control system, lower cost, and increased availability while maintaining the continuous-duty and torque/speed requirements. The grabber arm's torque requirement, with a safety factor of 2, was 1022 lbf-in with a speed of 6 RPM (as calculated in Appendix section A.2, with full selection table shown in A.1). The selected motor nominally provides 1662 lbf-in and 10RPM. At the recommendation of the manufacturer, due to internal gear efficiencies, this motor was deemed appropriate for our torque requirement with the safety factor.

3.2.1 Rotary motor control system

The BISON DC gearmotor is controlled via PID control from the Arduino Mega 2560. The BISON DC gearmotor is paired with a single-channel incremental encoder, motor driver and signal isolation unit. In order to electrically control the motor, we convert Arduino 0V to 5V digital signal into -5V to 5V analog signal for the driver and signolation unit. This is accomplished via a digital to analog converter (DAC), inverting op-amp circuit for shifting the signal range, and a charge pump to generate the negative voltage rail. The inverting op-amp design is shown in Appendix section A.7.2, and all components are shown in the master electrical diagram in Appendix section A.7.1.

As shown in the workflow, the arm begins at 180° facing towards the loading dock, where it grips the cages. A limit switch is mounted next to the arm such that the switch is pressed when the arm is lying in this initial position. The switch's signal ensures that the PID controller knows that the starting position is at 0°. Feedback from the single-channel encoder is used to control the DC gearmotor throughout the 180° range of rotation, while adhering to a quintic S-curve motion profile. This motion profile means the grabber arm begins and ends its range of motion slowly, while accelerating in the middle. This prevents the arm from rapidly jerking when it starts or stops, reducing damage to the gearmotor and the rotary stops. The arm stops at 180°, rests there as the rest of the cleaning workflow is completed, and then returns to the initial position to restart the cycle.

3.3 Linear translation assembly

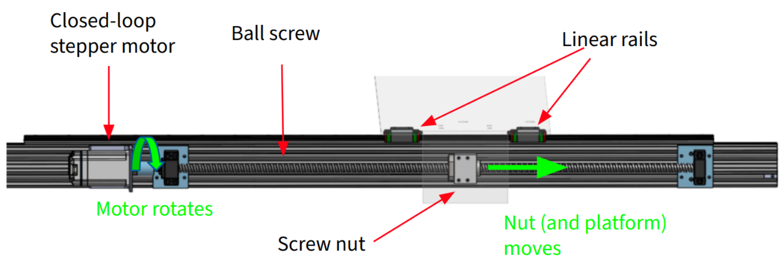


Figure 7. Linear translation assembly components

Figure 8 depicts one linear translation assembly, used to transfer the rotary platform into the position where the grabber sits above the tunnel washer and can release the cages. Note that another linear translation assembly exists on the other side of the rotary platform.

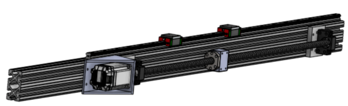
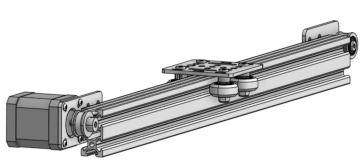
Functional requirements:

- Translate the entire platform and grabber assemblies back and forth into a position in which the grabber can release the cages over the washer
- Complete the translation process (one way) in 6 seconds.
- Hold position in the event of power loss

Mechanical Parts:
- 8020 Extrusion frame to support entire system and provide base for rotary platform
- SFU 1610 Ball Screws to drive linear translation of rotary platform
- BK (fixed) and BF (floating) ball screw supports to align ball screw with 8020 extrusion frame
- HGH15CAZAC Linear rails to physically support rotary platform and allow frictionless translation
- 3D-printed adapters to attach ball screw BK and BF supports to 8020 extrusion frame
- 3D-printed brackets to hold stepper motors in place on 8020 extrusion frame

Electrical Parts:
- Arduino Mega 2560 microcontroller for software control (shared by all three modules)
- ESS24-30 Integrated Stepper Motors to drive ball screws
- NC (naturally closed) physical limit switches to home rotary platform after each workflow cycle
- 48VDC Power supply to power both stepper motors

Linear translation designs considered:

Design	**Description**	**Pros and Cons**
 **Ball screw and linear rail gantry system**	● Linear rail supports rotary platform while ball screw and in-line motor drives linear motion	Pros: ● Relatively high precision (within 2 mm of repeatability) ● Compared to a lead screw, the recirculating ball bearings provide less fraction and longer life Cons: ● Slower than belt drive or motorized rails ●
	● Linear rail supports platform while belt and perpendicular-angled motor drives linear	Pros: ● Lower precision system Cons: ● Faster movement

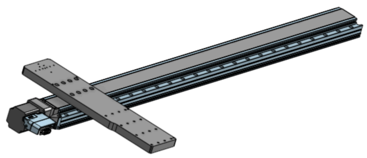
Belt-drive linear translation system	motion	than ball screw system
 **Zaber Motion Control: pre-built motorized rail gantry system [9]**	● Pre-built plug and play linear translation system, offered to be customized by Zaber representative ● Motorized linear rails with integrated control system, speed knob, and emergency stop button ● Customizable motion profile library	Pros: ● Simplified control system ● Faster and more precise than all other options Cons: ● High cost and over-designed for this application

Table 6. Linear translation systems considered

Final Design selection:

A ball screw and linear rail system was selected for the final design. A ball screw was preferred to a belt drive due to better precision and repeatability; our design requires the platform to be translated to only 25mm away from the edge of the 8020 frame to place the cages on the washer. With the danger of running into the edge of the frame, a higher precision option was preferable. Within the family of screw-driven linear actuation, ball screws were also preferable to lead screws due to higher dynamic load capabilities and higher precision due to reduced backlash. Finally, the ball screw and linear rail was preferable compared to the pre-build motorized rail gantry system offered by Zaber Motion Control due to budget constraints and the specific application of our design. It was more optimal for this project to construct a translation system and control scheme specifically for transferring our platform back and forth between the starting and ending position, rather than purchasing a motion control system meant for precise optical staging or CNC machines. The final design of the translation assembly also included bellowed nylon rail covers to protect the linear rails from falling bedding when the grabber arm is in the dumping phase. A visual top-down schematic of this linear translation design with the embedded homing system is shown in appendix A.6.1.

3.3.1 Linear translator control/electrical system

Two stepper motors drive the ball screws of the linear translators synchronously, while two limit switches maintain the alignment and position of the rotary platform within acceptable limits. The rotary platform only needs to move between the starting position x_0 and a defined ending position x_{travel}. However, the location of x_{travel} must be easily adjustable for any potential future design changes. As shown in Appendix section A.6.1, two of the limit switches are located at the start of the rotary platform's movement, which home the rotary platform into proper alignment and position at the start of each cycle. Moving the platform to x_{travel} is accomplished with the ball screw lead and the step count. The stepper motors are wired to standard digital pins, which provide pulse step and direction commands synchronously through Arduino digitalWrite commands. Minor delay errors and misalignment errors are prevented from stacking up through the homing limit switches, which re-aligns the position of both ends of the rotary platform at the end of every cycle. The limit switches are wired to interrupt digital pins for immediate monitoring. These components are all shown in the master electrical diagram in Appendix section A.7.1.

From the initial starting position x_0 to x_{travel} , the distance D is set at 26 inches. The steps formula in Appendix section A.6.2 is used to convert this distance to stepper motor steps. In order to set the speed of the translation, two half-pulse delays were written into each step. One step consists of a digitalWrite(High) and a digitalWrite(Low) to the pulse inputs of each stepper motor. After each digital write command, a half-pulse microsecond delay is added. These half-pulse delays allow control of the translation speed. The half-pulse duration formula in Appendix section A.6.3 is used to calculate the half-pulse duration Δt. Throughout the travel distance, this formula is used to construct a trapezoidal motion profile. The motion profile is constructed by linear interpolation between a user-selected cruise speed and minimum instantaneous speed, as shown in the trapezoidal formula for the half-pulse delay function in Appendix section A.6.4.

Chapter 4: Prototype Performance

4.1 Test Conditions

The goal of the final hardware test was to determine the effectiveness of the automated cage cleaning system in a simulated facility environment. A wooden cart was built to constrain the system at approximately the same height as Central Research Services' tunnel washer, and a moving table was placed on the exit side of the system. A loading dock was added on the entrance side of the system with a taped outline for cage loading.

Figure 8. Automated Cage Cleaning System

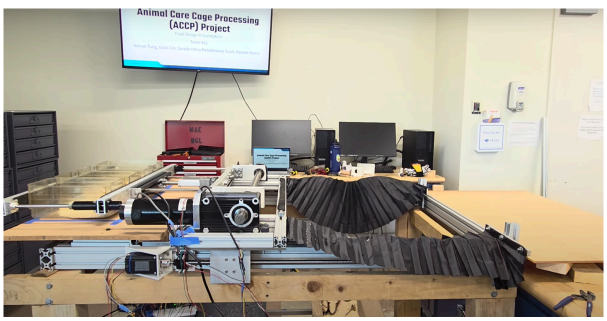
Testing parameters included the following criteria for success:

1) Ability to dump bedding in the correct location during the dumping phase.
2) Cycle speed at or above 8 cages per minute.
3) Complete cycle without dropping or damaging cages.

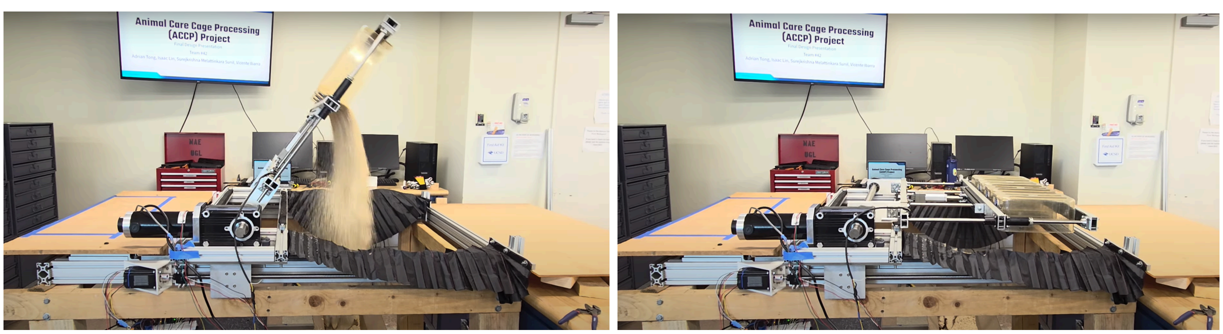
A cycle was defined as follows:
1) System begins in position to grab cages, and performs gripping motion (**Grab**).
2) System completes the dumping phase (**Dump**).
3) System moves to place cages on the platform (**Translate**).
4) System releases cages on platform and returns to start (**Reset**).

In order to evaluate the speed, a video of the cycle workflow was taken and each step was timed, in addition to the overall cycle time.

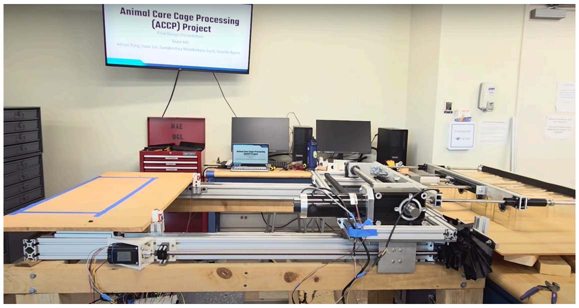
4.2 Test Performance



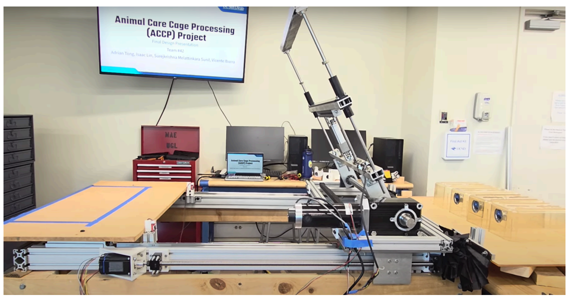
1. **Grab**: System was able to grab all four cages without damage or deformation. This action took 4 seconds.



2. **Dump**: System dumped the bedding in the proper location. This action took 7 seconds. Some bedding fell on the rail covers and forward rotary stop, as expected. However, the accumulation of bedding over the course of full workdays in an actual implementation might require additional human interaction to clean the system.



3. **Translate**: The system successfully transferred the cages over the simulated washer. This action took 5.5 seconds.



4. **Reset**: The system released the cages and moved to return to start position. This action took 15.5 seconds.

Overall, a full cycle was conducted in 32 seconds. This would correspond to a speed of 7.50 cages per minute and 64% of worker efficiency, which falls short of our goal of 8 cages per minute by 6%. The consistency of this system also fell short of expectations. While the ability of the system to operate continuously is a medium-priority goal, the system encountered issues with consistent direction change of the grabber arm within the PID control. However, the system was able to dump the bedding in the designated location during the dumping phase, and the cages were picked up and placed in the proper location and orientation without any damage.

4.3 Conclusions

Two of our three testing goals were met– the system was able to dump in the proper area and perform full cycle workflows placing cages in the proper position without any damage. The system fell short of speed requirements by 6%, which can be adjusted by further PID tuning for the grabber arm rotation; the grabber arm rotation was the main culprit for added time. Additionally, the consistency of the system is undesirable for full implementation at this time. These tests indicated that the design has promise for implementation in a real work environment, but needs further refinement and improvement to fulfill production standards.

Chapter 5: Design Recommendations and Conclusions

5.1 Safety:

This system has a high amount of moving parts and can potentially cause physical harm; thus, it has been designed with user safety in mind. There were two main areas of risk– the rotation of the grabber arm, and the movement of the platform along the linear rails. Both systems have rigid mechanical endstops to prevent movement past their intended range, and digital safety measures to allow emergency stop or account for user error. Operating procedures have been developed to ensure user safety in section F.8.

5.1.1 Mechanical Safety Measures:

For the rotation of the grabber arm, there are two rubber-coated aluminum bars on both sides of rotation. These normally support the arm when it has fully completed a 180 degree rotation; however, they also serve as mechanical stops in case the arm malfunctions and attempts to rotate past 180 degrees. For the linear translation of the rotary platform, two pieces of aluminum extrusion are fixed to the rails at a point beyond the forward travel distance. These serve to physically stop the platform if it does not stop at the intended 26-inch travel distance. The homing limit switches at the starting location are also mounted on pieces of aluminum extrusion, which can physically stop the platform if it fails to home properly.

5.1.2 Software-based Safety Measures:

The automation code that ran both of these systems includes several safety measures. All relevant parameters and variables were listed for the user to confirm with a serial command before running the cycle workflow. While the system was running, the user was informed that a serial command of ‘1’ will completely and immediately stop the entire system at any point. When this digital emergency stop was activated, all motors would stop; both stepper motors, linear actuator, and DC gearmotor would all immediately stop movement and lock in their current position. Additionally, the following safety checks were automatically run during every code execution:

- Maximum RPM check (Stepper motors): The user can select the RPM of the stepper motors to determine the speed of the rotary platform. If the user accidentally entered a value past the maximum speed of the stepper motors at the rated torque, the stepper motors will miss steps and the platform will not move as expected. This check automatically confirms the input RPM is within rated values and returns an emergency stop otherwise.

- Trapezoidal interpolation denominator check (Stepper motors): When the trapezoidal motion profile is set as explained in section 3.3, if the user accidentally inputs an extremely small value for the travel distance, the denominator of the linear interpolation might round to zero. If this occurs, the computed pulse delay might fall to zero, causing theoretically infinite speed and crashing the code or damaging the stepper motor drivers. This check ensured that the denominator will not be zero and returns an emergency stop otherwise.
- Homing over-misalignment check (Stepper motors): If one switch trips and the other switch does not trip within 0.5 seconds, an emergency stop occurs. This check was to guard against a scenario where only one switch is damaged and does not return signal even when the platform physically triggers both switches, which would cause one stepper motor to forcibly rack the platform indefinitely.
- Homing trip check (Stepper motors): If neither switch trips during the homing routine, an emergency stop occurs. This was to guard against a scenario in which neither switch trips and the platform rams into the physical endstops.

5.2 Lessons Learned and Future Improvements:

The design satisfied most functional requirements and was a success in terms of producing an effective prototype. However, aspects that the design fell short in were consistency and speed. Specifically, the rotation of the grabber arm did not always behave properly due to issues with direction changing in the PID controller, which lowered the consistency of the system. Additionally, the design was 6% slower than the desired speed. As a result, these aspects would need to be resolved before the design is fully implemented in Central Research Services' facility. These future improvements are further explained in the following sections, as well as other potential improvements and lessons learned.

Further developments may be done to automate loading of cages in the loading dock or to route the bedding from the dump location into one of Central Research Services' drag chain dumps. For the former, a potential option would be to explore the carriage-style integrated grabber platform in section 3.2, table 4. This design would allow sleds of cages to be mounted above the system to slowly load into the platform. Automatic loading could also be done by extending the current loading dock into a conveyor belt system.

5.2.1 Mechanical:

Several parts in the final design were 3D printed due to time and budget constraints. The stepper motor mounting brackets, adapters for attaching ball screw supports to 8020 extrusion rails, limit switch holders, and the DC gearmotor mounting block were all 3D printed. In particular, everything except for the DC gearmotor mounting block were printed with 80% rectilinear infill ABS plastic. The DC gearmotor mounting block was printed with 20% honeycomb infill ABS plastic. While sufficient for this project's initial testing, these parts should be replaced with equivalent aluminum or stainless steel versions in production or further project stages.

5.2.2 Electrical:

In the final design, circuits were set up on two breadboards and a single Arduino Mega 2560 due to time constraints. One breadboard contained the circuit for the DC gearmotor, and the other contained the circuits for the linear actuator and stepper motors. Loose wire connections on the breadboards occasionally led to issues; for example, one DAC unit was fried and one stepper motor was nearly damaged due to wires falling out of the breadboards. Additionally, this design ran into unforeseen issues after attempting to move the system, again due to loose connections on the breadboard. For a future project or production, these parts should be replaced with a soldered perfboard or a custom PCB to avoid similar issues. Another potential improvement would be to wire a physical emergency stop button and start button into the circuit, rather than relying on a digital emergency stop and start command.

5.2.3 Software:

The rotation of the grabber arm, powered by the DC gearmotor, is controlled via PID control with feedback from a single-channel encoder. Because the encoder is single-channel, it does not know which direction the arm is rotating in. After the arm rotates 180 degrees into the dumping position, it must switch directions. This direction change was hardcoded to flip only if the PID controller's desired direction is opposite to the current direction (i.e. it is trying to slow down the speed of the arm), the motor is effectively stopped (current encoder count - previous encoder count = 0), and the positional error is outside of a predetermined deadband around 180 degrees. However, this occasionally triggered a direction change when the arm was not stopped at 180 degrees. This was the main culprit of the design's inconsistencies in operation. It can be fixed fairly easily by replacing the encoder with a double-channel encoder. If this is not possible, it is also possible to resolve by adding a second limit switch on the other side of the rotary shaft and coding a S-curve motion profile without PID.

Additionally, the linear actuator for the gripping mechanism within the grabber arm contains a Hall effect sensor to provide relative position feedback. The final design did not incorporate this sensor and relied on shaft collars to constrain the gripping motion to the appropriate position for the cage size. This was due to difficulty in operating the sensor; the sensor often continued signaling step counts after the actuator had fully extended and stopped moving. Further investigation into the Hall effect sensor can make future developments more robust and effective.

When initializing the DAC for control of the DC gearmotor, the Wire.begin()

command was used in the Arduino code. This command sends a signal to every pin on the Arduino to prepare it for I2C communication. In the specific case where the Arduino is plugged in for the first time in a test cycle and the Wire.begin() command is sent at the beginning of an Arduino script, the Wire.begin() command would cause the linear actuator to extend all the way; this was hypothesized to be a fault of the signal that the command sent to the pins for the linear actuator. This error was not an issue during actual tests of the full workflow, but is worth noting for future troubleshooting. A potential solution would be to use a different initialization command that specifically initializes the pins needed for the DC gearmotor voltage control.

A future potential software improvement would be to create a user-friendly graphical user interface (GUI) to aid in ease of operation. Currently, operation is limited to the Arduino.ide software, which is less accessible to the general public due to requirements of coding knowledge.

5.3 Impact on Society:

Automated animal cage processing sets the standard for using automation instead of humans when the health risks to the operators are very high.This reflects an engineer's professional responsibility to design and implement systems that protect human well being and promote ethical labor practices. Though human labor might seem to be more cost effective, automation is the more sustainable and responsible solution.

5.4 Economic Profit:

Animal cage processing is necessary for any facility that performs animal testing experiments. Central Research Services provides processing services for multiple animal testing laboratories. Several other similar facilities exist throughout the United States. While cage cleaning is not a widespread field, it is a highly necessary one to support animal testing. Current competitors in this field are limited to the current proprietary design and the Getinge 6-DOF arm. According to the sponsor, these existing design solutions are also expensive and unwieldy. Thus, there is a demand for a commercial solution that overcomes these limitations. This project's design sought to improve on current designs in mobility, speed, and cost.

5.5 Public Health:

The sponsor currently operates two cage-washing stations. One station is processed automatically by the proprietary design solution, and the other is manually operated by a worker. The worker was required to repeatedly dump the cages in a dumping station, which requires them to flip the cages and knock them over the dump. This task would continue over the course of an entire 8-hour work day, processing approximately 12 cages per minute. This corresponds to approximately 5,760 cages processed per day. According to Cleveland Clinic, individuals who perform repetitive motions with their hands and wrists at work are at risk for carpal tunnel syndrome [1]. Thus, the workers in this facility are significantly exposed to the risk of carpal tunnel syndrome. Additionally, the sponsor has stated, from his own expertise in veterinary science, that allergies to mice/rat feces can cause significant allergy problems. The allergy issues are exacerbated by the duration of exposure that the workers must face. This project's design seeks to alleviate these health risks by removing workers from the cage flipping and dumping part of the process.

5.6 Automation:

Process automation may impact the availability of manual career opportunities. There is a concern about the potential loss of job availability with the implementation of this project. Though the majority of the process has been automated, this project strives to relieve workers from potential health risks without removing them from the process entirely. Additionally, worker health is a fundamental priority of this design. Removing elements of the cage-cleaning workflow through automation is deemed to be a positive benefit to society.

5.7 Professional Responsibility

This project upheld professional responsibility by maintaining transparency, ethics, and financial accountability in the interactions with the sponsor. Updates were provided regularly to ensure that the sponsor was informed of progress and limitations.

Financial responsibility was prioritized by designing around the predefined budget and by balancing affordability with functionality. All design changes were clearly communicated and all decisions were made with the longevity of the parts in mind.

The primary concern associated with this project was worker safety due to the presence of moving mechanical components. All machinery and automated components were designed with appropriate safety measures. Moving parts were designed such that loss of power will result in immediate cessation of movement. Operational protocols have been established in section F.8 to ensure personnel are informed and prepared to operate the system safely.

There are negligible environmental effects anticipated from this project. Nonetheless, environmental responsibility was maintained through responsible material sourcing and waste handling.

5.8 Applicable Standards

The robot contains aluminum tubing in the grabber mechanism, which must withstand constant force applied by a linear actuator. All aluminum tubing used in the robot conforms to ASTM B210/B210M-19a [4].

The robot contains multiple moving parts, which could cause danger to nearby humans. Moving machinery has been guarded for human protection (hard-limit endstops) in a manner that conforms to ANSI B11.19:2019 [5].

As the robot processes animal bedding and refuse, there is potential for dust to interfere with the operation of electronic equipment. Motors and electronics enclosures have been protected from dust in a manner that conforms to IEC 60529:2013 [6].

Acknowledgements

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Fabrication, Assembly and Operation Guide

This guide provides step-by-step fabrication, assembly, operation, and quality-assurance procedures for the Automated Cage Processing System, which consists of three primary subsystems: the Grabber Arm, Rotary Platform, and Linear Translation Base.

All critical dimensions and tolerances are defined in the CAD models and detailed drawings. Always cross-reference the CAD before machining.

Safety Note: Wear appropriate personal protective equipment (ANSI-approved eye protection, ear protection, gloves) and follow UCSD machine shop protocols at all times.

F.1 Tools & Equipment

The following tools are required for successful completion of the design. Substitute equivalents only if they meet the same accuracy class.

- Vertical milling machine with DRO (±0.001")
- Bandsaw or cold-saw (ferrous & non-ferrous blades)
- Drill press or manual mill for hole patterns
- Tap & die set (UNC/UNF ¼-20 to ½-13; metric M3-M8)
- Torque wrench (2-20 N·m) and Allen key set
- Digital calipers & micrometer (0-150 mm, 0-25 mm)
- 3-D printer (FDM, ABS or PETG, 0.4 mm nozzle)
- Soldering iron & heat-shrink station

F.2 Materials

These following materials are required for successful completion of the design. Individual fasteners are not listed, appropriate sizing can be determined from the drawings in Appendix section A.8,

- 6061-T6 Aluminum rectangular tubing & plate stock
- 8020-series T-slot aluminum extrusion (15-series)
- 304 Stainless-steel guide rods Ø12 mm (h6)
- Firgelli™ Super-Duty linear actuator (12 V, 150 mm stroke)
- BISON® right-angle DC gearmotor (35 N·m, 60 rpm)
- ESS24-30 NEMA 24 Closed-loop Stepper motors (24-48V)
- SFU1610 ball-screws + BK/BF supports, C7 grade
- HIWIN HGW15 linear rails & blocks (precision class H)
- Pillow-block bearings (Ø32 mm, self-aligning)
- Clamping PowerLock™ shaft collars
- Fasteners: socket-head cap screws (SS), T-nuts, washers

F.3 Manufacture Grabber Arm

This section describes the procedures for fabricating the grabber arm from the required materials. All machining tolerances ±0.1 mm unless otherwise noted.

F.3.1 Torque Adapter (Quantity 2)

- Cut 3" × 1" 6061‑T6 rectangular tubing to length on the bandsaw, leaving ≥2 mm excess for facing.
- Face both ends on the mill to achieve length tolerance ±0.05 mm and squareness ≤0.05 mm. This precision prevents binding when the adapters clamp onto the rotary shaft.
- Center‑drill and bore a through‑hole. Counterbore one to seat the PowerLock™ collar flush; a flush seat ensures even clamping force. Follow drawing A.8.6.
- Machine two L-brackets for adapter attachment per drawing A.8.6.
- Deburr all edges with a countersink; sharp burrs can score the shaft during assemblies.

F.3.2 Structural Tubes (Top, Middle, Bottom)

- Machine three 6061‑T6 tubes to identical length (±0.05 mm). Length mismatch greater than 0.1 mm causes the guide rods to rack under load.
- Spot, drill, and tap the hole patterns shown in drawings A.8.1, A.8.2, and A.8.3. Verify tap depth with a depth gauge—bottom‑out taps improve thread engagement without breaking through the rear wall.
- Top bar: install self‑aligning shaft supports
- Middle bar: Press-fit two bearings into the bearing seats
- Bottom bar: Mount the linear actuator clevis and linear bearings.

F.3.3 Guide Rods Installation

- Insert guide rods into the top‑bar shaft supports
- Slide the middle bar onto rods; the bearings should glide freely without perceptible play. If resistance is felt, re‑inspect the rod straightness.
- Attach the force‑distribution block to the middle bar.
- Slide the bottom bar onto the lower set of rods; secure linear bearings with retaining rings.

F.3.4 Subsystem Verification

- Operate the linear actuator. The grabber must complete a full duty cycle without audible binding.

F.4 Manufacture Rotary Platform

This section describes the procedures for manufacturing the rotary platform from the required materials. All machining tolerances ±0.1 mm unless otherwise noted.

F.4.1 Base Plates (Quantity 2, 6 mm steel)

- Water‑jet cut the plates per drawing A.8.4

F.4.2 Stiffening Braces

- Cut 8020‑1515 extrusions to length (+0/‑1 mm).
- Bolt braces between plates using corner brackets and T‑nuts, maintaining squareness ≤0.2 mm. The braces raise torsional rigidity.

F.4.3 Platform Brackets

- Drill holes in 6061-T6 aluminum brackets per drawing A.8.5.
- Attach platform brackets on underside of both base plates.

F.4.4 Pillow-Block Bearings & Shaft

- Secure pillow-blocks to plates with fasteners and washers; this avoids loosening due to vibration

F.4.5 3D Printed Base Plate and Switch Mount

- 3D Print motor base plate to raise the height of the motor to the appropriate height.
- 3D print mount for limit switch that will be connected to the rotary platform's base plate.

F.4.6 Gear Motor Assembly

- Mount the BISON gear motor via the motor base plate; shim as required so the output shaft is concentric with the rotary shaft coupling.
- Install the optical encoder on the gearmotor shaft, following the manufacturer's instructions.
- Mount limit switch in position such that the bottom bar depresses the switch when the grabber arm is rotated fully 180° towards the loading dock

F.5 Manufacture Linear Translation Base

This section describes the procedures for manufacturing the linear translation base from the required materials. All machining tolerances ±0.1 mm unless otherwise noted. All 3D printed parts to be made out of ABS plastic with 80% rectilinear infill.

F.5.1 Frame Assembly

- Assemble three sides of the 8020 frame on a granite surface. Shim as necessary to keep the opposite rails coplanar within 0.1 mm.
- Install HIWIN rails using the factory-drilled holes in the rails and t-nuts to connect to the extrusion frame.

F.5.2 3D Print Housing and Mounts

- Print mounting brackets for stepper motors.
- Print mounts for limit switches.
- Print extrusion adapters for ball screw supports.

F.5.3 Ball-Screw and Stepper Motors Installation

- Mount BK (fixed) and BF (floating) supports to extrusion adapters; ensure axial misalignment ≤0.05 mm. Attach extrusion adapters to 8020 frames.
- Slide the SFU1610 screw into supports; preload angular-contact bearings to eliminate axial lash (<0.02 mm).
- Attach stepper motors to mounting brackets and attach mounting brackets to 8020 frames.

- Attach and tighten the shaft couplers to couple the stepper motor shafts and the ball screw shafts. The ball screw shafts should stick out of the BK support end.

F.5.4 Limit Switches & Wiring

- Mount inductive naturally-closed limit sensors 3 mm from the carriage hard-stop; verify triggering repeatability ±0.02 mm.
- Route wiring to electrical cabinet, ensuring that wires are not caught by the ball screw supports or any rough edges when the platform or grabber arm moves.

F.7 Quality Assurance Checklist

- All threaded holes are cleaned with a tapping tool; no cross-threads.
- Guide rods are free from scratches or corrosion.
- Subsystem dimensions verified against 2-D drawings within specified tolerances.
- Operator safety interlock functional; emergency stop cuts power in <50 ms.

F.8 System Integration and Operating Procedure

The following system integration steps must be completed before operating the system. Ensure all of these steps have been completed.

- Mount the rotary platform onto the translation carriage, following these steps in order:
    - Mount both base plates on the linear rail blocks. Refer to drawing A.8.4 for proper holes.
    - The platform should now be able to slide freely back and forth along the 8020 frame. Align the holes in the platform brackets with both ball screw nuts and attach the nuts to the brackets.
- Insert rotary shaft through grabber torque adapters; engage PowerLock™ collars according to manufacturer specifications
- Ensure that all nuts and screws are thoroughly tightened before operation.

Carefully read the following warnings before operating:

- Keep all body parts at least one foot away from all moving parts during operation. If it is required to touch parts during operation for testing purposes, be careful of potential pinch points between the grabber arm and the rotary platform, and the rotary platform and each ball screw support.
- The system includes a 110-120VAC to 12VDC converter power supply unit, a 110-120VAC to 48VDC converter power supply unit, and a gearmotor driver that accepts 110-120VAC line input. These voltage levels can be dangerous if the following procedures are not followed:

    - All three plugs should ideally be plugged into the same extension cord. Ensure a consistent supply of AC power to the extension cord, or to each power supply unit. Do not attempt to operate the system without consistent 110-120VAC power.
    - The two AC-DC converter power supply units (12V and 48V) have ground and voltage connections attached to button screws with spade connectors. Ensure that the plastic shield is lowered over the connections at all times and do not touch the power supplies when the power is on. Also ensure that both power supply units are set to 110VAC and not 220VAC; both units are capable of switching between settings via a switch on the side.
    - The gear motor driver accepts direct 110-120VAC line input. Do not touch the driver when the power is on. Take care not to adjust the trim pots on top of the driver; these have been carefully tuned to the system specifications. If these are accidentally adjusted, instructions for tuning are in the manufacturer specifications.
    - Check the fuses on the gear motor driver and power wires before operation. Do not operate the system if any fuses are blown.
- After the power has been turned on, check that all limit switches are operational before beginning operation. Physically press each limit switch and verify that a red LED turns on when the switch is pressed.
- When operating, be prepared to stop the system at any time using the serial emergency stop command in the serial monitor (‘1’ or ‘i’). Do not close the serial monitor while running the cycle workflow. It is recommended that a second person stands near the extension cord and prepares to unplug it if any issue occurs with Arduino software, although not necessary.

The following procedure outlines the operating procedure.

1) Connect all wires and Arduino Mega 2560 according to master electrical diagram A.7.1.
2) Compile and upload full_workflow.ide sketch in Arduino.ide software (full sketch on website).
3) Open serial monitor at 115200 baud.
4) Immediately, this prompt will appear:

```
Integrated workflow ready. Press '1' or 'i' at any time for emergency stop.
=== Setup complete. Enter 's' to start workflow. ===
```

5) When you type ‘s’, these messages will appear in sequence as the system executes the workflow. Note that ‘extending’ and ‘retracting’ refer to the linear actuator gripping and releasing the cages. Steps 1, 2 and 3 are the grab, dump and translate stages of the cycle; steps 4, 5 and 6 are resetting back to the start for the next cycle.

```
Starting workflow...
```

```
[Step 1] Platform homing
extending
[Step 2] Grabber arm → 178°
[Step 3] Platform → full forward
retracting
[Step 4] Grabber arm → 60° (back)
[Step 5] Platform homing (again)
[Step 6] Grabber arm homing (end)
```

6) The system has finished a cycle.

F.9 Troubleshooting

A list of common issues and solutions has been compiled to aid in troubleshooting.

Error: Platform misaligned due to one stepper motor not firing or faulty setup.
Solution: Stop the system using the digital emergency stop (‘1’ or ‘i’). Turn off all power. If the misalignment is not severe (less than approximately 5 degrees from one side) comment out the section of the code that forces an emergency stop if both platform-homing limit switches are not triggered within 0.5 seconds. Plug in power and run the code. This will self-align the platform when the code is run; one stepper motor will stop first when its limit switch is tripped and the other stepper motor will force the platform back into alignment until its limit switch is tripped. If the misalignment is severe (more than approximately 5 degrees from one side), unscrew the T-nuts attaching the 8020 bracing to the base plates of the rotary platform. Unscrew the ball screw nut from the platform bracket to allow the base plates to freely move along the linear rails, and detach the shaft couplers that attach the stepper motor output shafts to the ball screws. Slide both base plates clear of the ball screw nuts, and re-attach the 8020 framing. Take care to ensure it is aligned when re-attached. Re-attach both ball screw nuts and re-check the full circuit to ensure both stepper motors receive signals and voltage.

Error: Grabber arm rotates too far, or attempts to rotate in the wrong direction.
Solution: Stop the system using the digital emergency stop (‘1’ or ‘i’). Turn off all power. If the grabber arm has over-shot 180 degrees and is pressing into one of the rotary stops, immediately loosen the screws on the Tsubaki power-lock mounting hubs in the torque adapters to disengage the mounting hubs. This stops the arm from putting stress on the worm drive and the rotary stop that it is pressing against. Re-check PID tuning to identify the cause of the issue.

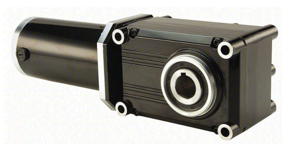
Error: Grabber arm does not rotate.
Solution: Stop the system using the digital emergency stop (‘1’ or ‘i’). Turn off all power. it is likely that a circuit component has been fried. Ensure that power is OFF and probe the circuit with a multimeter to identify the source of the issue. Ensure that the op-amp, DAC, and charge-pump are connected to the ground rail, and that the ground rail is properly grounded.

Check all fuses on the gear motor driver to ensure that something within the driver is not fried. If the issue persists, test each component of the circuit in isolation, including the Arduino. Identify the damaged component and replace it.

Error: Platform rams into a physical endstop.
Solution: Regardless of which side of the system this occurs on (loading dock side or tunnel washer side), immediately stop the system using the digital emergency stop (‘1’ or ‘i’). The force of the ball screws and stepper motors will drive the platform into the aluminum 8020 extrusion endstops, which are connected to the 8020 base frame by angle brackets and T-nuts. The force of the platform will forcibly loosen the T-nuts and angle the 8020 endstops. Thus, if the platform is stopped in time, it should not cause damage to any components. Immediately detach the platform brackets from the ball screw nuts and move the platform away from the endstops. Check limit switches for damage if the incident occurred on the loading dock side, and replace if necessary. Check the code for errors in control of the stepper motors. In particular, ensure that the equations for step control are intact (shown in Appendix sections A.5 and A.6). Check the full circuit for any loose connections.

Appendices

A.1 Rotary Motor selection

Motor	Specifications	Pros and Cons
 BISON Right-Angle DC Gearmotor	● 1662 lb-in of max torque ● 8RPM max speed	Pros: ● Meets torque and speed requirements with safety factor of 2 ● Continuous duty Cons: ● Moderately heavy (25 lbs) ● Requires a moderately complex control system ● Lower max speed
 BODINE Right-Angle DC Gearmotor	● 1535 lb-in of maximum torque ● 10 RPM max speed	Pros: ● Meets torque and speed requirements with safety factor of 2 ● Continuous duty ● Higher max speed Cons: ● Moderately heavy (25 lbs) ● Requires a complex and expensive control system ● High turnaround time and limited availability
 Bodine Parallel Shaft DC gearmotor	● 702 lb-in of maximum torque ● 23 RPM max speed	Pros: ● Meets torque and speed requirement without safety factor ● Small size and low weight Cons: ● No safety factor, could lead to system failure
 REV NEO V1.1 Brushless motor	● Up to 1000 lb-in of maximum torque ● Up to 10 RPM of max speed	Pros: ● Very small size and weight ● Meets torque and speed requirement with safety factor Cons: ● Light duty, prone to overheating and not rated for continuous use ● Hex shaft attachment results in

		less sturdy power transmission

A.2 Rotary motor selection calculations

Necessary rotation torque:

We determine the maximum torque needed to rotate the grabber arm, while holding the cages, for an entire 180 degree rotation within 5 seconds. Computations are performed with a safety factor of 2.

Variables:

Moment of inertia of grabber arm: $I_{grabber} = 10621.8\, lb * in^2$

Angular acceleration of rotation to satisfy speed req: $\alpha_{desired} = \frac{\pi}{4} \frac{rad}{s^2}$ (see section 4.2.2)

Mass of grabber arm: $m_{arm} = 29.67\, lb$

Distance from axis of rotation to grabber arm COM: $d_{arm} = 16.59\, in$

Safety factor: $SF = 2$

Calculation

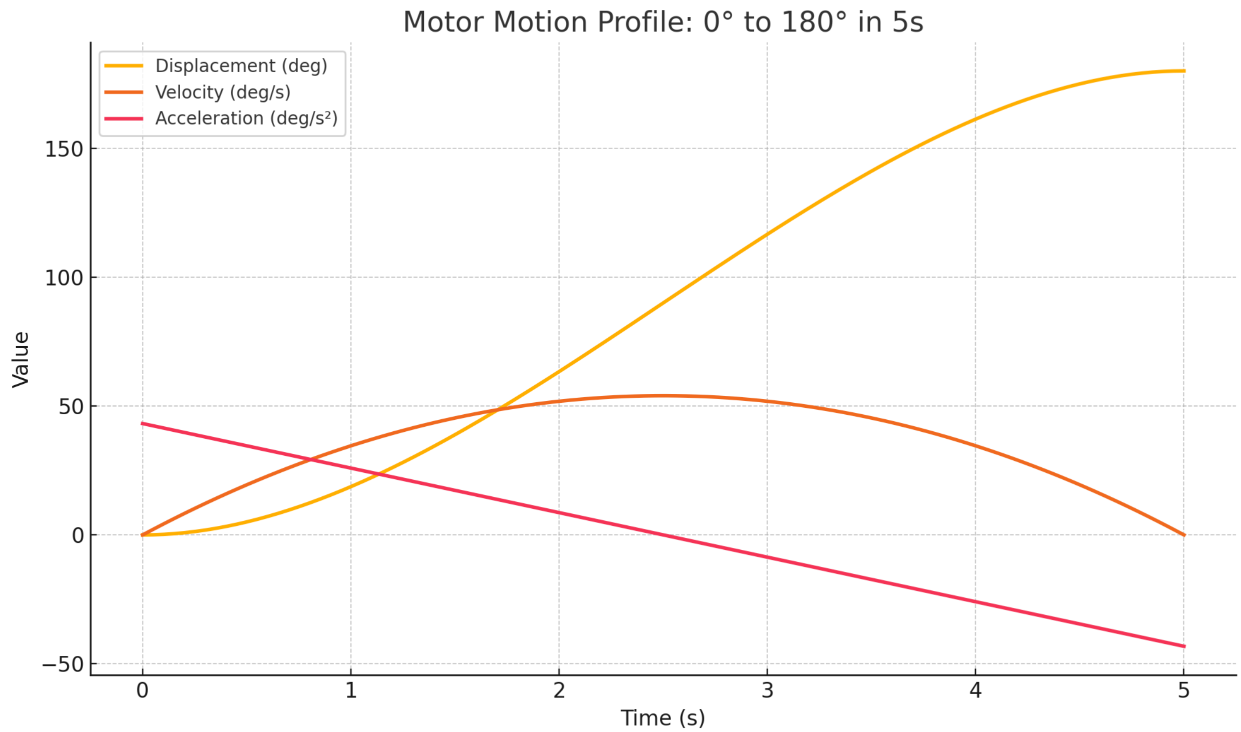
$$T_{required} = SF(T_{inertial} + T_{gravitational}) \quad (1)$$

$$T_{inertial} = \frac{I_{grabber} * \alpha_{desired}}{g} = \frac{10621.8\, lb*in^2 * \frac{\pi}{4} \frac{rad}{s^2}}{386\, \frac{in}{s^2}} = 21.6\, lb * in \quad (2)$$

$$T_{gravitational} = m_{arm} * d_{arm} = 29.67\, lb * 16.59\, in = 492.225\, lb * in \quad (3)$$

$$T_{required} = 2 * (492.225\, lb * in + 21.6\, lb * in) = 1027.66\, lb * in \quad (4)$$

A.2.1 Motion Study



From the displacement profile above, which was required to satisfy 180 degrees of motion in 5 seconds to meet the speed requirement of the workflow, the angular velocity and acceleration profile are derived. As such, the motor must be able to achieve the performance dictated by the velocity and acceleration profile. Besides, the motion profile must not have any discontinuity, which could result in jerky motion or even catastrophic failure.

From the curves, the maximum acceleration and speed is derived, which will decide the motor requirement. The motion profile is inputted into a Solidworks motion study simulation, which determines the torque requirements to observe the motion profile given the material properties of the grabber arm.

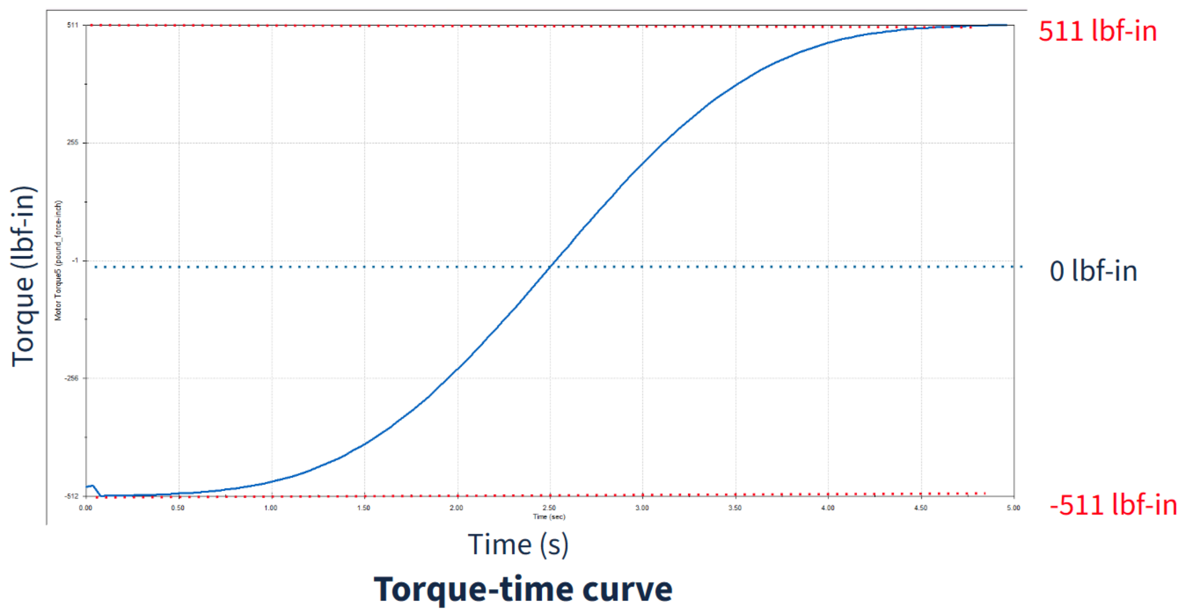


Figure 15. Torque-time curve generated from motion profile.

From the motion study, we determine that our motor needs a nominal torque of 1022 lbf-in when a safety factor of 2 is applied. Additionally, the rotation requirement of 180 degrees in 5 seconds corresponds to a speed of 6 RPM. These primary factors are used to select the motor.

A.3 Linear Actuator Selection

	Pros	Cons	Selected
Electric actuator	-Can hold position in event of power loss -Easier to implement controls	-Heavier -Slower actuation	
Pneumatic actuator	-Faster actuation -Lighter	-Considerably more difficult controls	

A.3.1 Calculations

Necessary grabbing force:

We determine the maximum force needed to hold the cages in the worst-case position (grabber arm is parallel to the floor). Computations are performed with a safety factor of 2.

$m_{cages} = 1.50 \frac{lb}{cage} * 4\, cages = 6\, lb = 0.1865\, slugs$

$\mu_{rubber} \sim 0.6$

$CL\ (cycle\ load\ percentage\ of\ lin.\ actuator) = 0.25$

$SF\ (safety\ factor) = 2$

$Motor\ Max\ Static\ \&\ Dynamic\ Load = 220lb$

$Motor\ Max\ Load\ at\ 50\%\ duty\ Cycle = 55lb$

$$Required\ gripping\ force = F_g = \frac{m_{cages} g}{\mu} * SF = \frac{0.1865\, slugs * 32.174 \frac{ft}{s^2}}{0.6} * 2 = \mathbf{20\ lbf} \quad (1)$$

$$Actuator\ gripping\ force = F_g = 220\, lbf * 0.25 = \mathbf{55\ lbf} \quad (2)$$

Final Design Choice and Justification

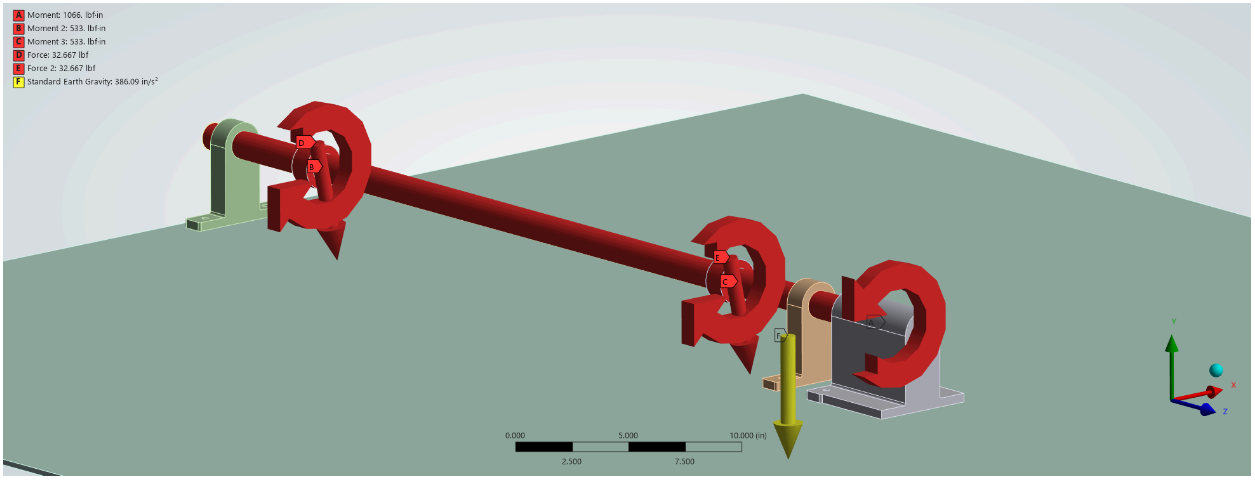
The Firgelli Super Duty Linear Actuator is an DC motor electric linear actuator with a Hall Effect sensor. The model selected for the project, F-SD-H-220-12v-2, is capable of 220 lbf of dynamic and static load and can travel at 0.6in/s at no load. Furthermore, it is rated for 50% duty cycle at 100% load and 25% duty cycle at 25% of the load. In order to satisfy the duty requirement of the grabber mechanism (section 4.2.1), a motor that satisfies the force requirements needs to be chosen and operated within its continuous duty performance range, which will typically correspond to loading it at a force way below its max load rating. In this case, the model F-SD-H-220-12v-2 can provide 55 lbf of load at 50 percent duty cycle, which is satisfactory for the application.

The linear actuator also comes with an integrated hall effect sensor, which enables closed-loop position control of the linear actuator through Arduino. The precise position control will be crucial for accommodating different sizes of cages, for which the length of the linear actuator travel will have to be adjusted accordingly. It also adds flexibility to any future modification to the grabber arm design, which may impact the installation position of the linear actuator and require readjustment to the travel length.

A.4 Deformation analyses

A.4.1 Rotary shaft deformation analysis

Boundary Condition of the Quasi-Static Analysis of the drive shaft



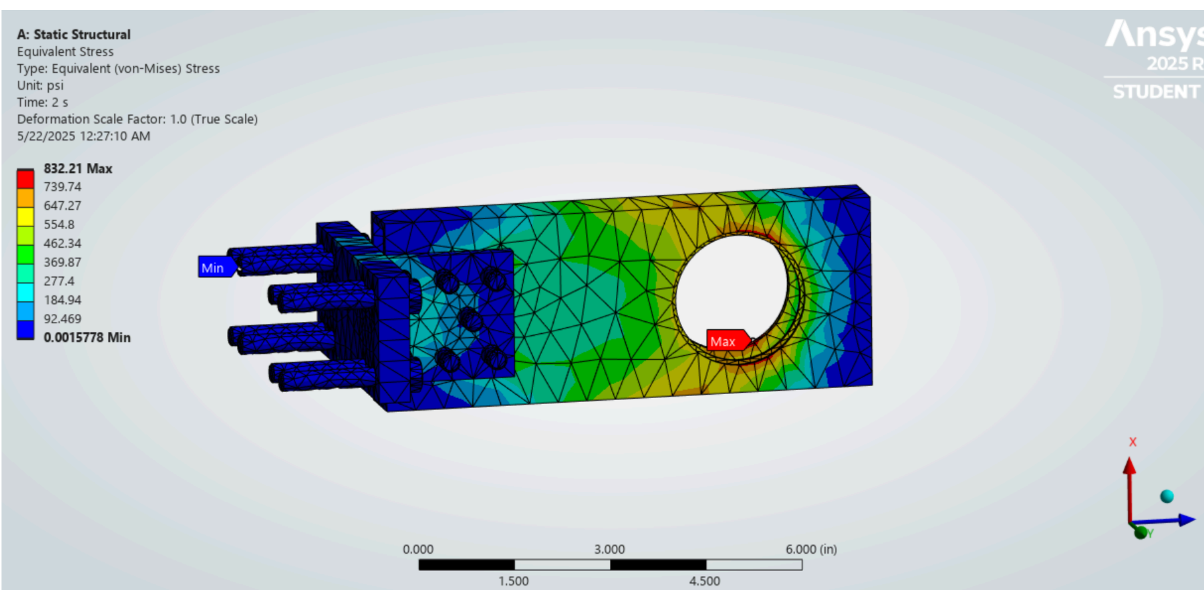
Results of the Ansys simulation of the driveshaft

Results	Minimum	Maximum	Units	Time (s)
Equivalent Stress	5.0886e-003	0.15273	psi	0.85756
Equivalent Elastic Strain	5.5161e-010	5.0339e-009	in/in	1.
Strain Energy	1.7564e-021	4.2501e-009	BTU	1.
Total Deformation	2.5965e-014	2.222e-004	in	1.
Safety Factor	15.	15.	Units Unavailable	1.

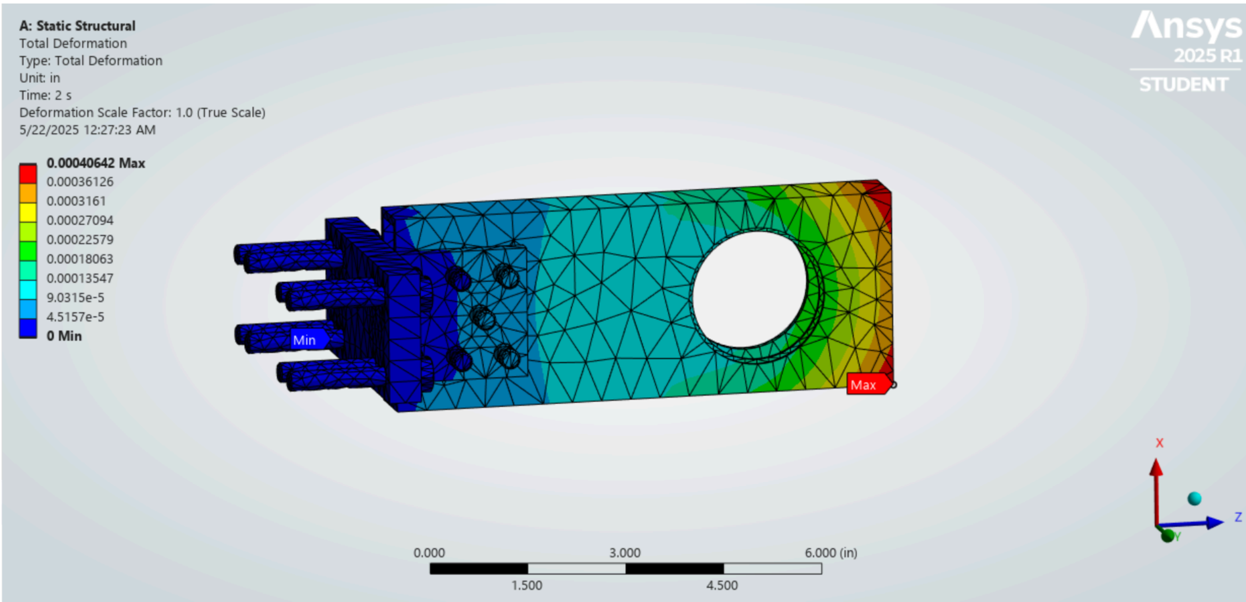
Probe: Reactions	X Magnitude	Y Magnitude	Z Magnitude	Total	Units	Time (s)
Force Reaction	-4.6188e-002	-42.799	-1.4733e-002	42.799	lbf	1.
Moment Reaction	-4.4476e-002	-7.5009	-8.4484e-002	7.5015	lbf·in	1.
Force Reaction 2	20.199	-9.7392	-3.3364e-003	22.424	lbf	1.
Moment Reaction 2	-5.5899e-002	-7.5162	-6.2017e-009	7.5164	lbf·in	1.
Force Reaction 3	-6.5424	-28.69	1.807e-002	29.426	lbf	1.
Moment Reaction 3	-9.078	-219.47	-1.9709e-007	219.65	lbf·in	1.
Force Reaction 4	6.8152e-010	16.242	2.5681e-009	16.242	lbf	1.
Moment Reaction 4	-0.17323	1.4017e-008	-3.7064e-004	0.17323	lbf·in	0.52857

A.4.2 Static stress analysis of torque adapters

Equivalent Von-Mises stress analysis of the aluminum-tube adaptor design from Ansys Static Structural.

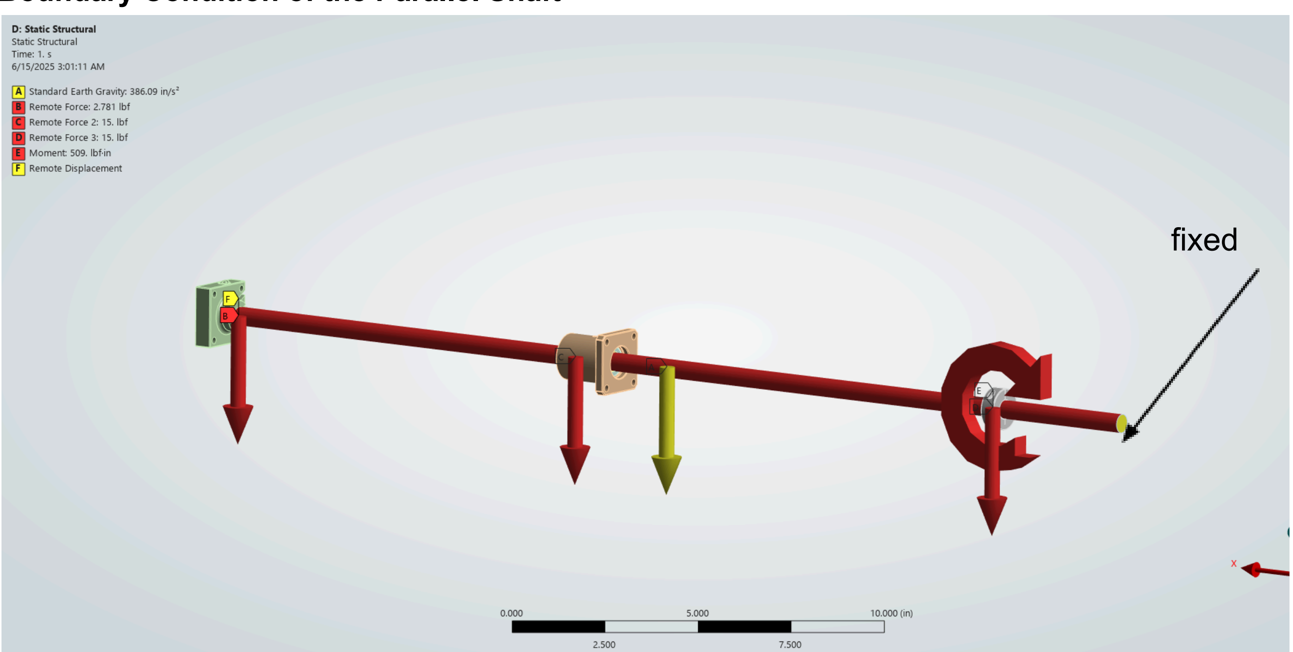


Total deformation analysis of the aluminum-tube adaptor design from Ansys Static Structural.

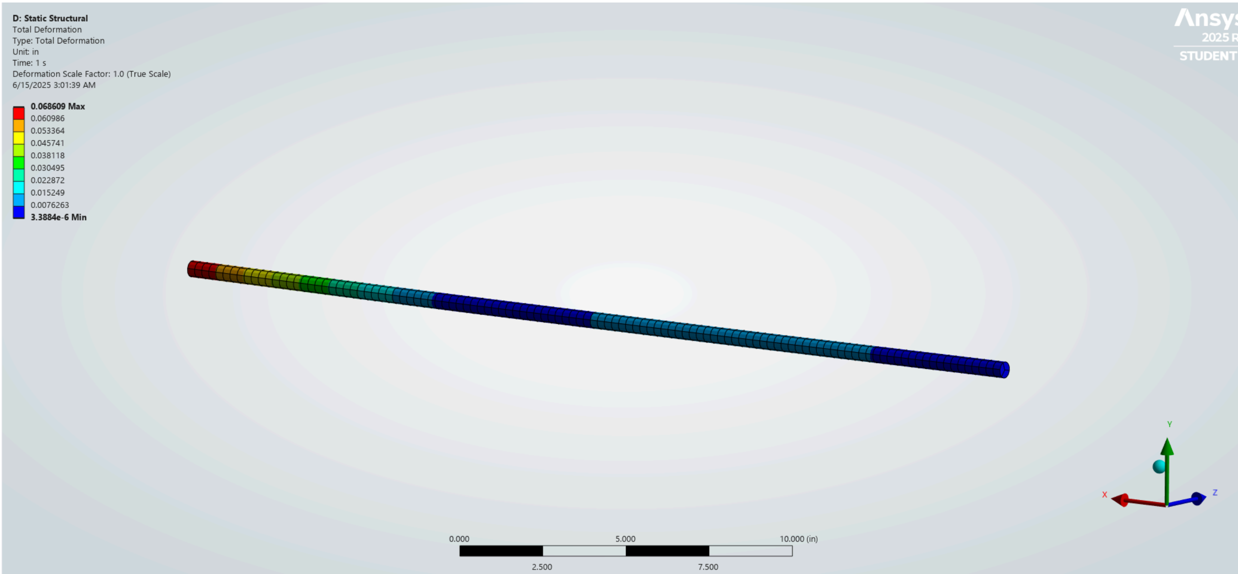


A.4.3 Static Stress Analysis of Parallel Linear Motion Shafts

Boundary Condition of the Parallel Shaft



Total Deformation Plot of the Parallel Shaft



Total deflection of the rod =
$tan^{-1}(deflection\ at\ the\ mounted\ end/length\ of\ the\ rod)\ =\ tan^{-1}(0.0686in/38in)\ =\ 0.10^{\circ}$

A.5 Linear translation assembly calculations

A.5.1 Calculations

Axial Load Calculation

$\mu\ =\ 0.003$

$m_1\ =\ 20\ kg\ (Rotary\ platform\ mass\ divided\ by\ two)$

$\alpha\ =\ \frac{Desired\ max\ speed}{acceleration\ time} = \frac{V_{max}}{t_{acc}} = 0.1446\ \frac{m}{s}$

$g\ =\ 9.81\ m/s^2$

$f\ \ =\ Guide\ Surface\ Resistance\ =\ 1.768N$

Forward movement

$F_{a1}\ =\ \mu(m_1)\ g\ +\ f\ +\ (m_1)\alpha\ =\ 5.2N$ (5)

$F_{a2}\ =\ \mu\ (m_1)\ g\ +\ f\ =\ 2.36N$ (6)

$F_{a3}\ =\ \mu(m_1)\ g\ +\ f\ -\ (m_1)\ \alpha\ =-.53N$ (7)

Backward movement

$$F_{a4} = -\mu(m_1)g - f - (m_1)\alpha = -5.2N \quad (8)$$

$$F_{a5} = -\mu(m_1)g - f = -2.36N \quad (9)$$

$$F_{a6} = -\mu(m_1)g - f + (m_1)\alpha = .53N \quad (10)$$

$$Average\ axial\ load\ F_{am} = \sqrt[3]{\frac{F_{a1}^{3}l1 + F_{a2}^{3}l2 + F_{a6}^{3}l6}{l_1 + l_2 + l_3 + l_4 + l_5 + l_6}} = 2.28N \quad (11)$$

Required RPM

$V = desired\ speed = 0.1446\ m/s$

$Ph = lead = 10\ mm$

$$Required\ RPM\ N_{required} = \frac{(V)(60)(10^3)}{Ph} = 868\ RPM \quad (12)$$

Service life

$f_w = 1.5\ (Load\ Factor)$

$C_a = 6600N\ (Load\ rating)$

$$L_{nom} = \left(\frac{1}{f_w} * \frac{C_a}{F_{am}}\right)^3 * 10^6 = 7.15 * 10^{15} revs \quad (13)$$

$$L_{service} = \frac{L_{nom}}{60 * N_{max} * 24 * 360} = 1.56 * 10^7 years \quad (14)$$

Motor selection

$\eta = .8\ (ball\ \ screw\ efficiency)$

$SF = 2$

$Angular\ acceleration:\ w' = 91\ \frac{rad}{s^2}$

$Motor\ moment\ of\ inertia:\ J_m = 1 * 10^{-3} kgm^2$

$Screw\ moment\ of\ inertia:\ J = .0049\ kgm^2$

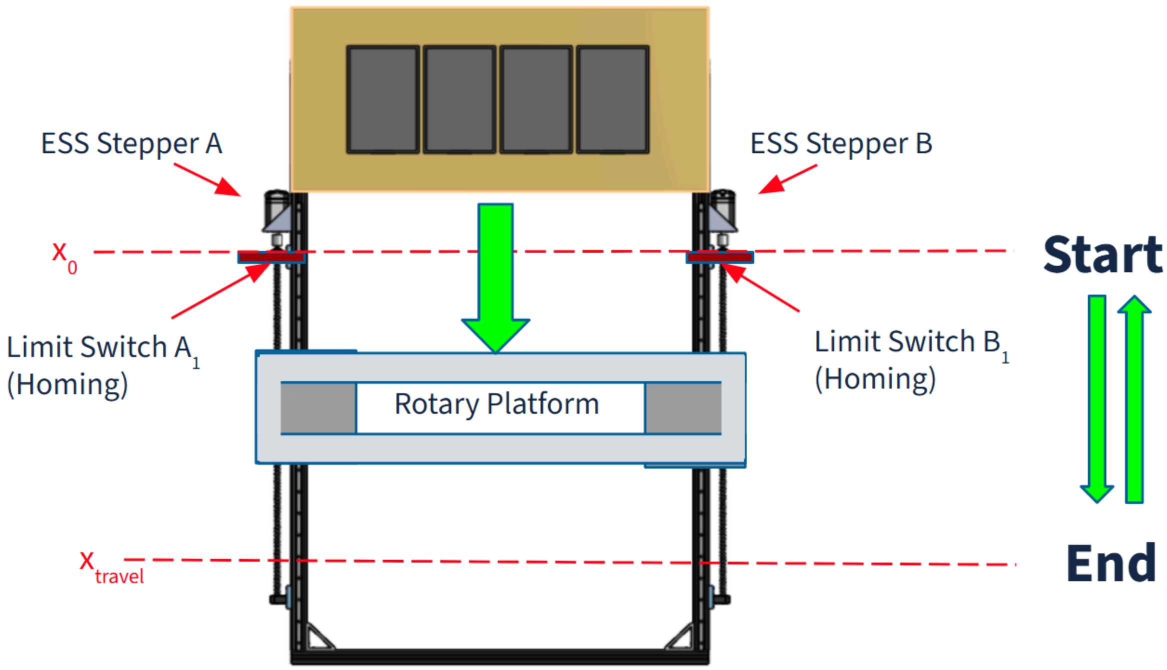
$$Frictional\ torque: T_{friction} = \frac{Fam * Ph}{2\pi * \eta} = .0045Nm \quad (15)$$

$$Inertial\ torque:\ T_{inertial} = (J + J_m) * w' = .539\ Nm \quad (16)$$

$$T_{total} = SF * (T_{friction} + T_{inertial}) = 1\ NM \quad (17)$$

A.6 Linear Translation Assembly Integration

A.6.1 Depiction of integration of the limit switch and stepper motor system.



A.6.2 Step count equation

The following formula was used to calculate the required step count, where PPR corresponds to the Pulses Per Revolution of the stepper motors and $Lead$ corresponds to the ball screw's lead length.

$$Steps\ N \ = \ D\ x\ \frac{Pulses/revolution}{Lead}$$

A.6.3 Half-pulse duration equation

The following formula was used to calculate the half-pulse duration.

$$Half\ pulse\ duration\ \Delta t \ = \ \frac{minutes}{revolution} * \frac{revolution}{pulse} * \frac{60s}{1\ min} * \frac{10^6 \mu s}{1s} * \frac{1\ pulse}{2\ half-pulses}$$

A.6.4 Trapezoidal half-pulse delay function

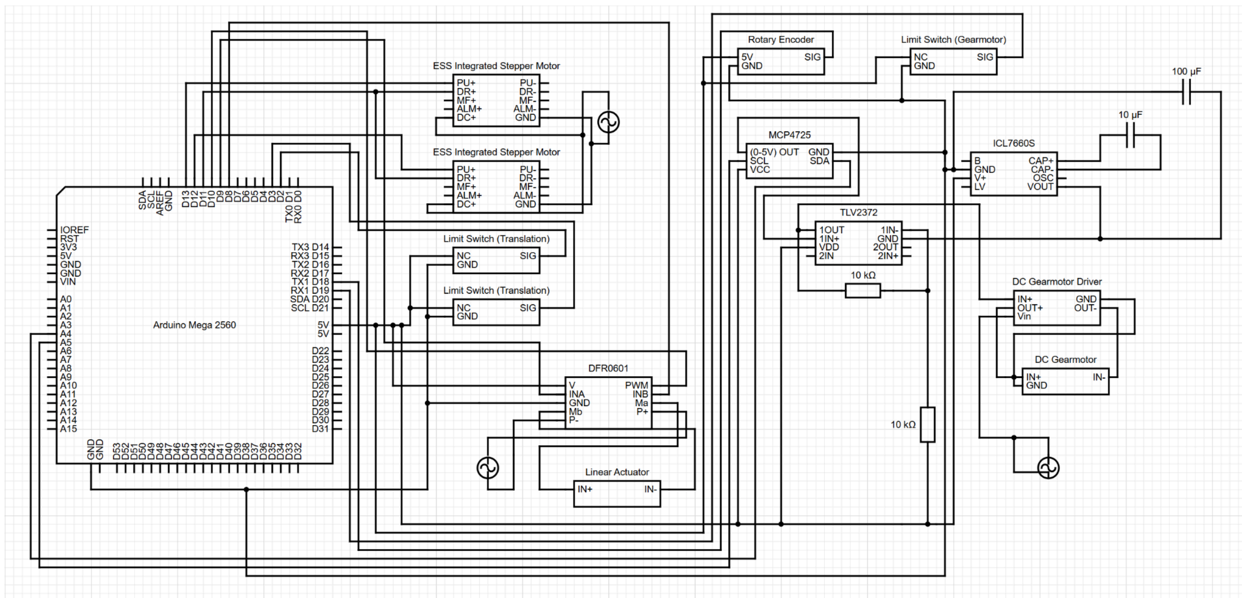
The following half-pulse delay function was used to construct the motion profile given user input for travel distance (converted to number of steps N by the formula in A.6.2), and desired RPM in the cruise section and ramp regions (converted to number of steps N_a and N_c in the ramp-up and ramp-down based on user-defined rise and settling time percentages within the code. The final design test was performed with 10% ramp-up, 80% cruise, and 10% ramp-down. These values were automatically converted to N_a,N_b,and N_c based on the defined travel distance D.

$N \; = \; total\ number\ of\ steps$
$N_a \; = \; steps\ in\ ramp\ up\ region$
$N_b \; = \; steps\ in\ cruise\ region$
$N_c \; = \; steps\ in\ ramp\ down\ region$
$\Delta t_{slow} = \; half\ pulse\ delay\ at\ the\ start\ and\ end\ instants\ of\ the\ total\ movement$
$\Delta t_{fast} = \; half\ pulse\ delay\ during\ the\ cruise\ region\ (constant)$
$i \; = \; step\ index$
$\Delta(i) \; = half\ pulse\ delay\ function$

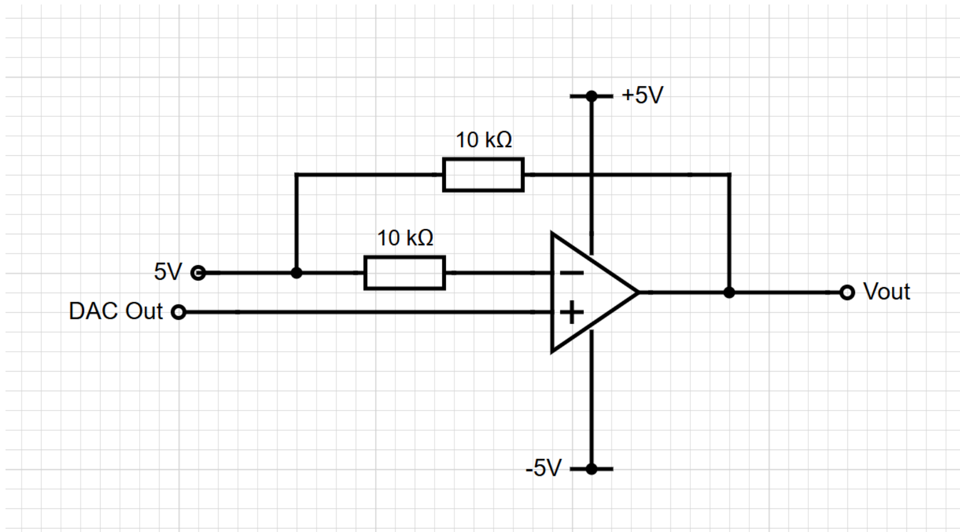
$$\Delta(i) = \begin{cases} \Delta t_{slow} + (\Delta t_{fast} - \Delta t_{slow})\frac{i}{N_a - 1} & , 0 \leq i < N_a \\ \Delta t_{fast} & , N_a \leq i < N_a + N_c \\ \Delta t_{fast} + (\Delta t_{slow} - \Delta t_{fast})\frac{i-(N_a+N_c)}{N_a - 1} & , N_a + N_c \leq i < N \end{cases}$$

A.7 Electrical Diagrams

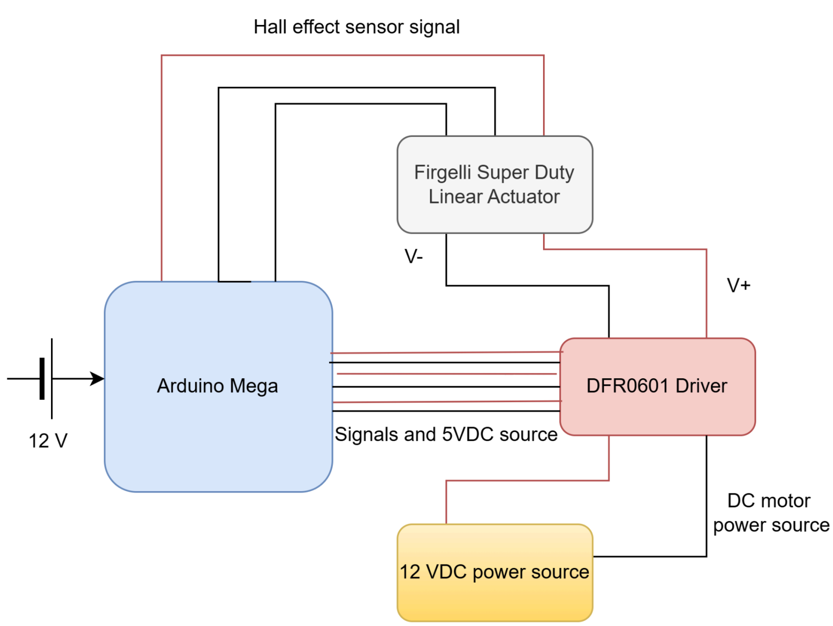
A.7.1 Master electrical schematic



A.7.2 Inverting Op-Amp configuration for control of DC gearmotor

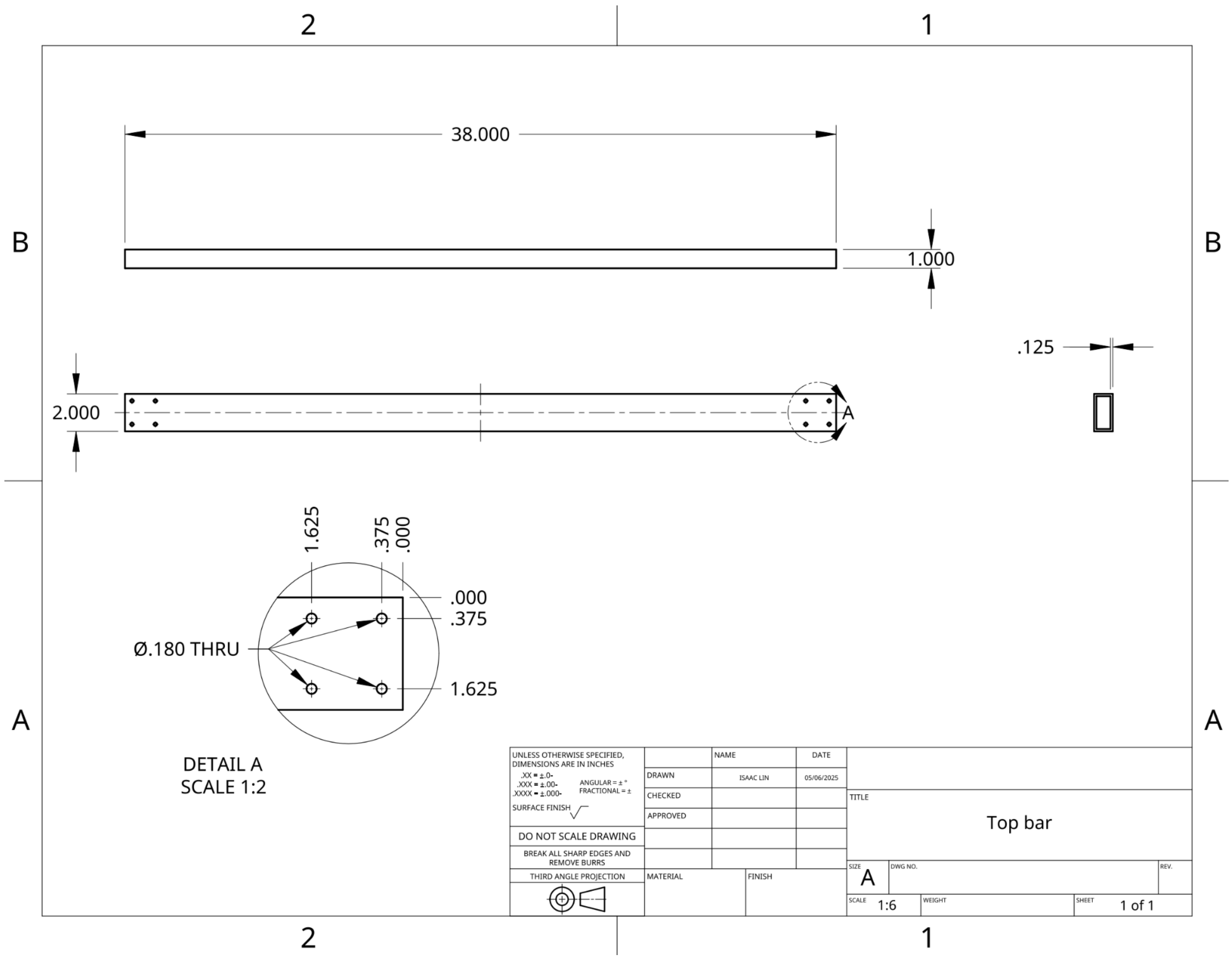


A.7.3 Circuit diagram of the grabber arm

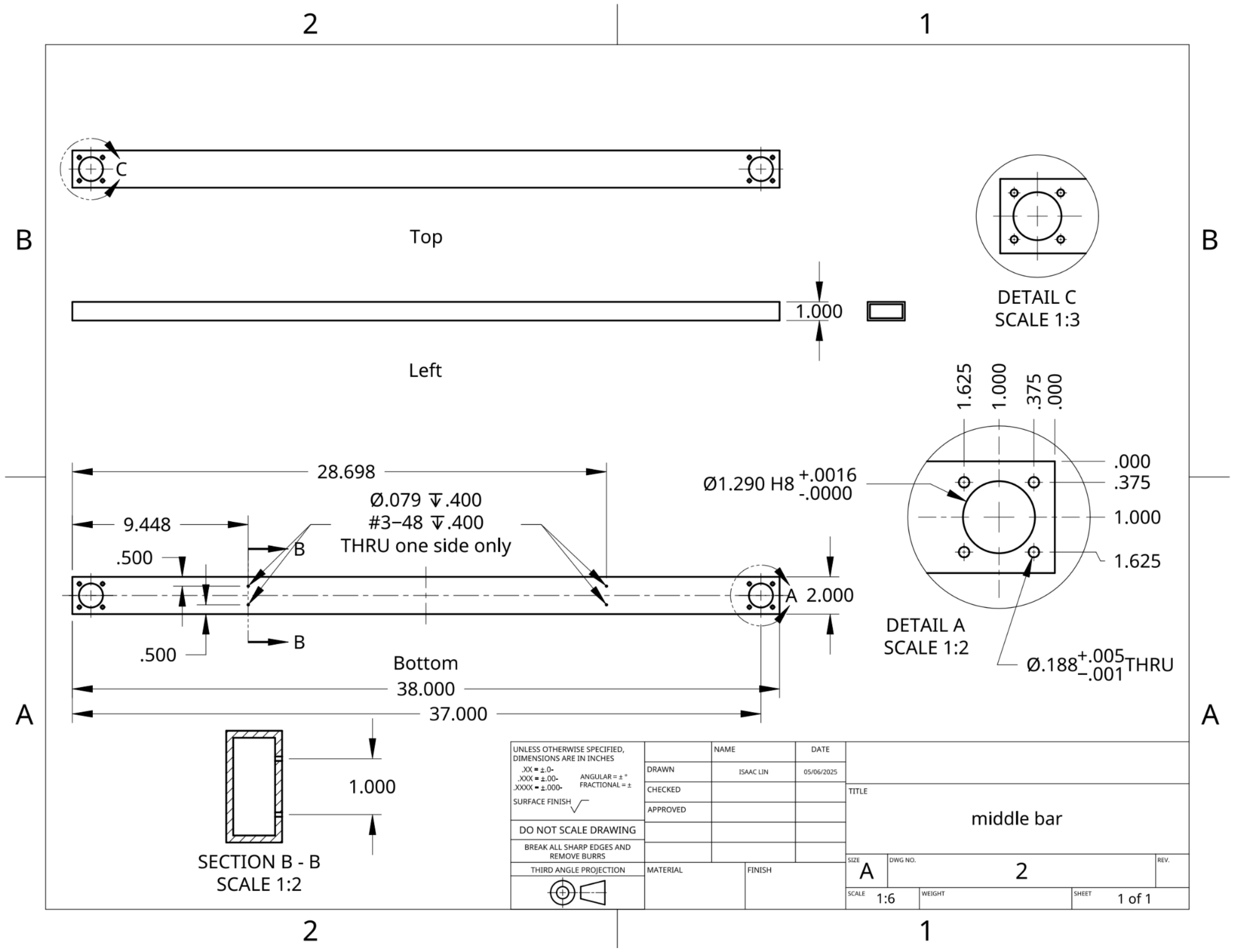


A.8 Drawings

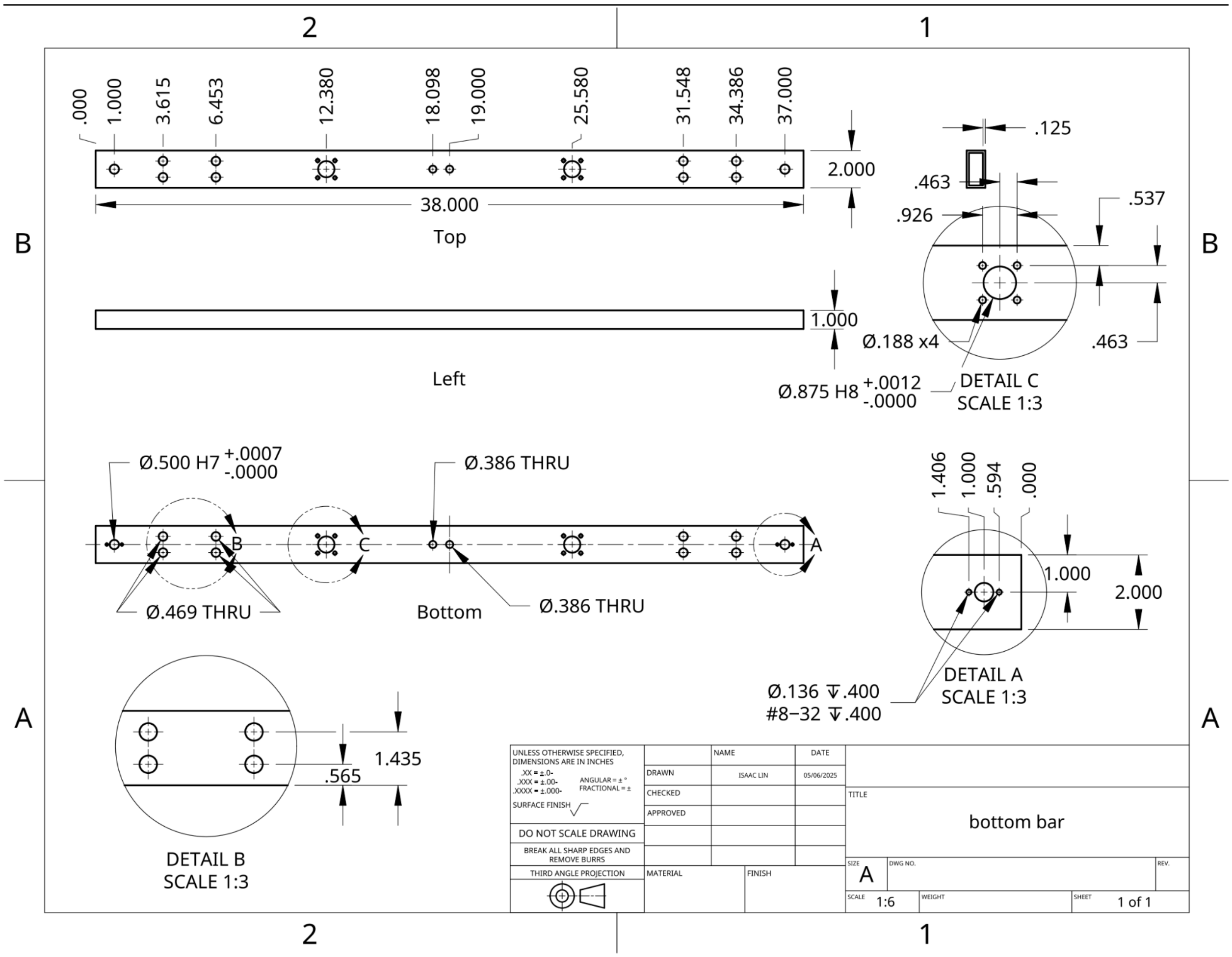
A.8.1 Grabber arm top bar



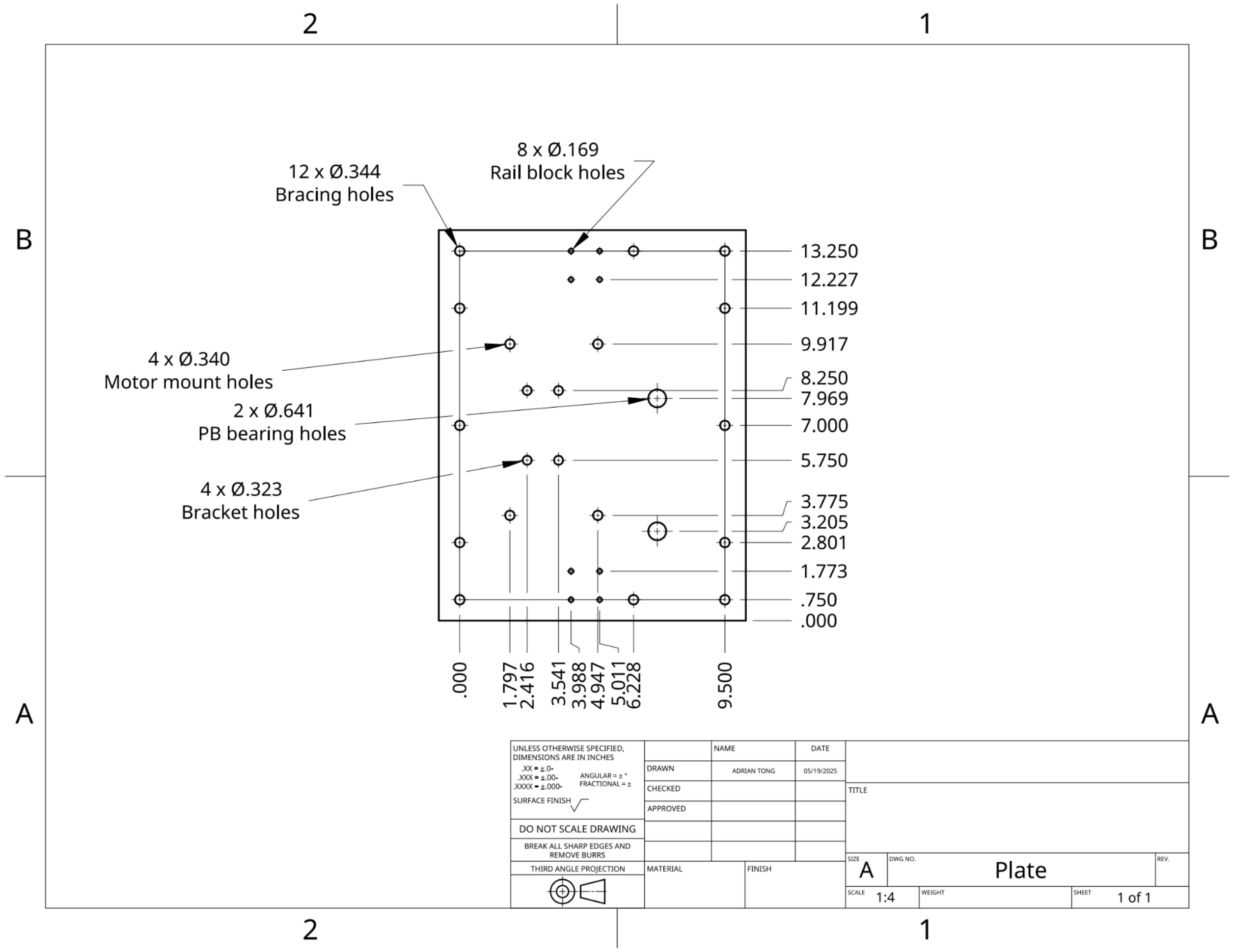
A.8.2 Grabber arm middle bar



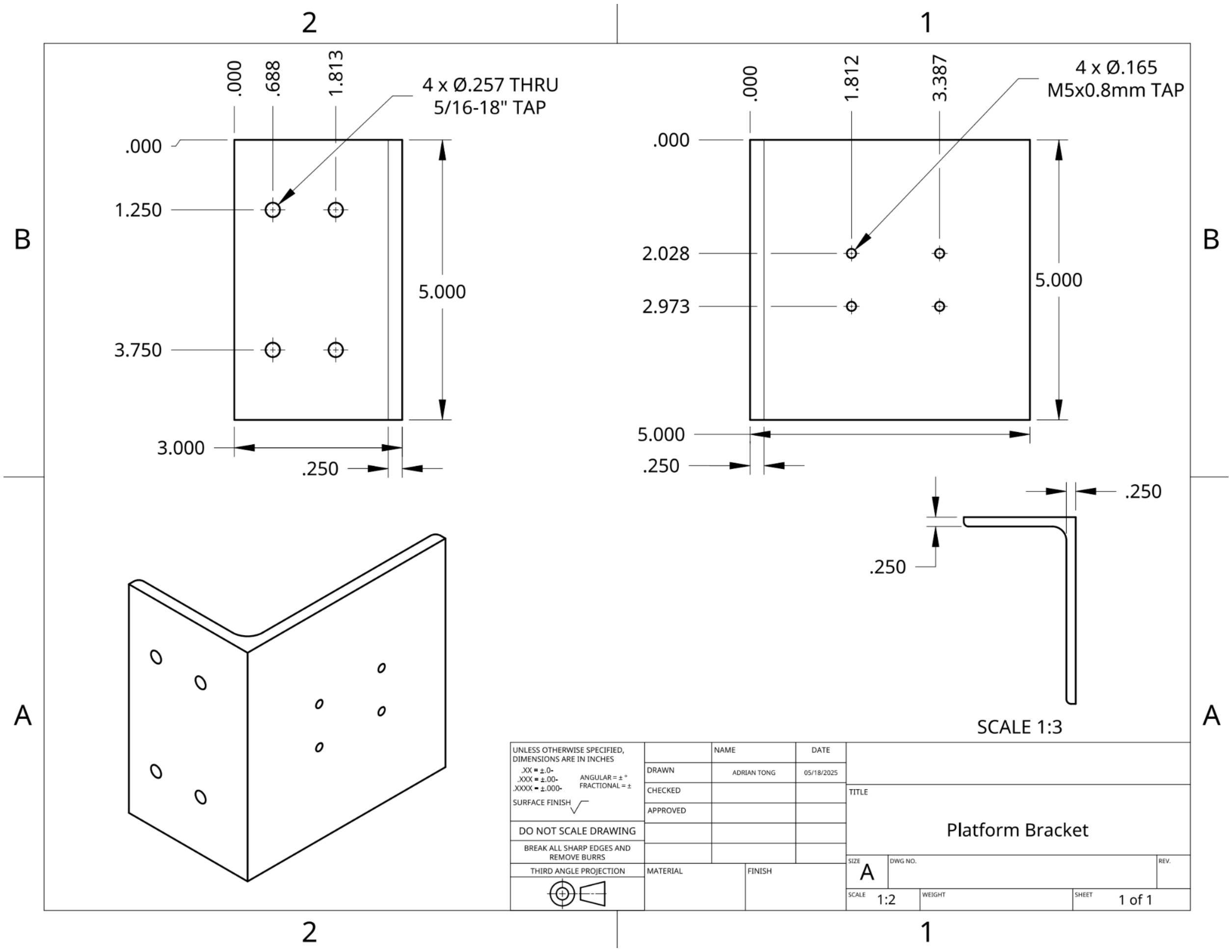
A.8.3 Grabber arm bottom bar



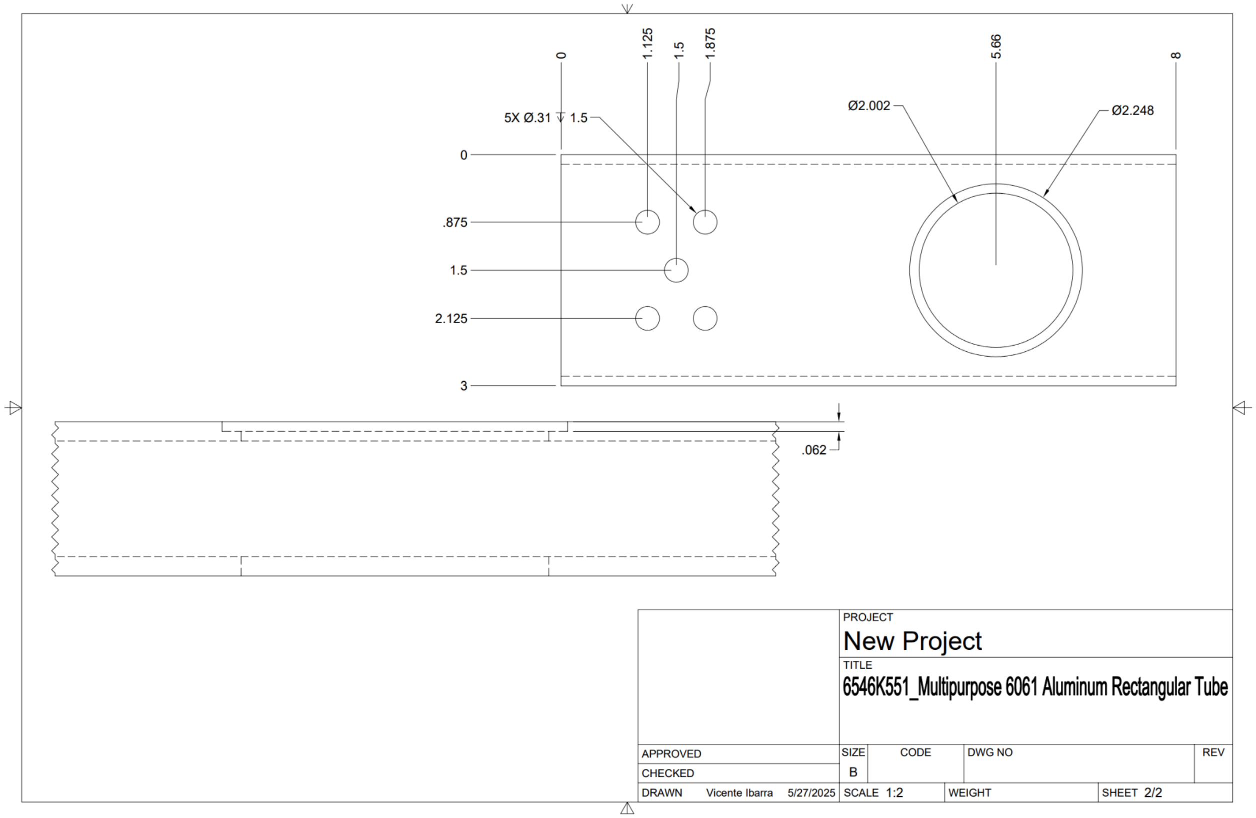
A.8.4 Rotary platform base plates



A.8.5 Rotary platform brackets (connecting steel plates to ball screw nuts)



A.8.6 Torque adapters



A.9 Project Management

A.9.1: Task Distribution

Isaac Lin	- Grabber arm design and manufacturing - Linear actuator control system - DC Gearmotor control system
Adrian Tong	- Rotary platform design and manufacturing - Stepper motor control system - DC Gearmotor controls
Surejkrishna Melattinkara Sunil	- Linear translators design - General Manufacturing
Vicente Ibarra	- Torque adapters design - General Manufacturing

A.9.2: Budget

The Bill of Materials for this project is linked below. Out of the total project budget of $6,500, this project used $6,416.27.

Bill of Material

A.10 Individual Component Analyses

A.10.1 Material for Scraper and Grabber arm

NOTE: The scraper was initially a part of this project at the beginning. However, it was removed from the scope due to budget and time constraints.

Individual Component Analysis- Material for Scraper and Grabbing Arm

Surejkrishna Melattinkara Sunil
2/27/25

Project Description

Our sponsor is Dr. Keith Jenne and the Central Research Services Facility. The Central Research Services Facility at UCSD is in charge of the vital role of cleaning and sanitizing animal cages from multiple research labs. The cages contain bedding and droppings from rats or mice. Though the facility has an automated washing system in place, workers are still required to manually remove the bedding and droppings before the cages can be processed. This often involves scraping off stuck debris. This process is very time-consuming and repetitive and puts strain on the body. Prolonged exposure to feces also increases the risk of health conditions and injuries.

To address this challenge, our project focuses on creating an automated system that will improve the cage-cleaning process. The system is designed to flip cages of various sizes, dump bedding, scrape refuse, and place the cages onto conveyor belts for automated cleaning. The grabber arm serves as the primary component in charge of safely flipping cages, dumping bedding, and accurately placing cages on the conveyor belt. The scraper arm is the secondary core component that is tasked with effectively scraping stuck debris. Material research is a fundamental aspect of
the design and creation process. Improper selection of materials will cause the entire project to fail. This importance led us to select material research for the grabber arm and the scraper as a core focus for the ICA.

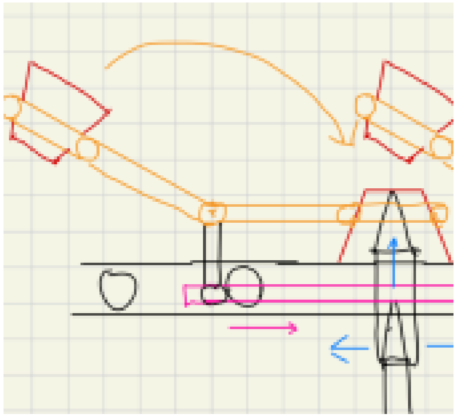


Figure 1. Drawing of scraping mechanism Figure 2. CAD of Grabber

Functional Requirements

The functional requirements for the material used in both the gripper and the scraper are designed to ensure that both components are reliable and will allow for efficient operation of the robot.

The material selected should have enough strength to be able to withstand gripping a 10lb cage without bending or deforming in any way while it flips, dumps, and scrapes. It should have enough durability to allow the robot to safely process 4000 cages a day without any issues. It also needs to be highly resistant to constantly being around fecal matter and moisture, potentially offering nonstick and corrosion resistance. The material also needs to be cost-effective and easy to machine, as the project group would most likely be machining the parts themselves in the machine shop.

Description of 3 Different Materials

1. Aluminum 6061-T6
    - Heat-treated alloy composed of aluminum, magnesium, and silicon,
    - The T6 variation of it is heat-treated and artificially aged in order to become stronger and more durable. It also improves the machinability of the material to good.
    - Commonly used material in robotics due to its high strength-to-weight ratio and durability
    - Highly resistant to corrosion and surface can be treated to improve its resistance to corrosion and stickiness
    - Density: 2.7 g/cc Youngs modulus: 68.9 GPa
2. Stainless steel 304
    - 304 Stainless Steel is an austenitic steel alloy made by combining iron with around 18% chromium and 8% nickel
    - Used in Robotics, Wastewater treatment, and Automotive parts
    - High corrosion resistance and durability and easy-to-machine
    - Not naturally nonstick

- Density: 8.00 g/cc Youngs modulus: 193 GPa

3. Steel 4142
    - Medium-carbon alloy steel
    - Used in gears, hydraulic rods, and axles
    - High strength and wear resistance
    - Not naturally corrosion-resistant or nonstick
    - Density: 7.85 g/cc Youngs modulus: 205 GPa

Summary Table

Material Name	Pros	Cons
Aluminum 6061-T6 **Cost:$22.29** **Shipping: 12 days**	Cheapest Lightest Easy to machine Corrosion-resistant	High deflection High Wearability
Stainless Steel 304 **Cost:$79.78** **Shipping: 15 days**	Minimal deflection Corrosion resistance Easy to machine	High weight Costly
Steel 4142 **Cost:$71.32** **Shipping: 15 days**	Minimal deflection Strongest High weight	Costly Harder to machine No corrosion resistance

*Price is for a 0.625" x 1.5" x 36" Rectangular Flat Bar

After evaluating the materials, I recommend Stainless Steel 304 for the project. Aluminum 6061-T6 has the critical failure of being high wear and high deflection. Our parts need very low deflection and must be used repetitively for numerous cycles. Stainless steel 304 was picked over Steel 4142 because they are relatively around the same price, and we need to machine these parts ourselves, being hard to machine will end up costing more money and time. Also, having natural corrosion resistance means less maintenance in the long run.

Impact of ICA

The material selection had a significant impact on the overall project. One effect was the change to steel caused the needed motor torque to be much higher than what was needed for aluminum. It eventually led us to pick more expensive motors for the components in the grabber arm. The ICA also affected the types of coatings we needed. The aluminum required a coating that helped improve the corrosion resistance and also allowed it to become nonstick. Now that Stainless steel has been selected, we only need to focus on nonstick coatings. It also drastically changed how much of the budget we needed to allocate for construction due to the price difference between stainless steel and aluminum. Another result from the ICA is that we will more likely spend more time with prototyping to ensure that we get the design worked out before building because each error with stainless steel will cause major dents in the budget.

Summary of Information Gathering

Summary of Calls/Meeting in person

Stephen Mercsak-This meeting was held to get advice on material selection and general advice. It was concluded that Aluminum is a bad choice for the final robot as aluminum will flex a lot, and because it is not good for parts like rails because of its high friction coefficient. I was advised to switch to a better material like stainless steel or change my aluminum to hollow tubing, as it significantly reduces the deflection.

References

General info

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Keyword Aluminum 6061

https://asm.matweb.com/search/specificmaterial.asp?bassnum=ma6061t6

Keyword Stainless Steel 304
https://www.matweb.com/search/DataSheet.aspx?MatGUID=abc4415b0f8b4903 87e3c92 2237098da
Keyword AISI 4142 Steel
https://www.matweb.com/search/DataSheet.aspx?MatGUID=c36e280cfc5241a6 b0672ee 40b9f974b

Material prices research

granger steel
buymetal al 6061
onlinemetals stainless steel

A.10.2 Microcontroller

Isaac Lin

Animal Cage Processing ICA for microcontroller

Project Description:

The goal of this project is to automate the cleaning process of the animal cages that are used for in-vivo research in UCSD Medical School. The current process involves the dumping of the beddings out of and the scraping of the cages prior to loading the washer. The aim is to automate the process up until the loading by devising a robotic grabber and scraper system. The motivation for such automation is to eliminate the occupation hazard involved with the handling of animal refuse and the physical fatigue caused by repetitive dumping motion. The facility is located in the Centralized Research Facility on the UC San Diego campus.

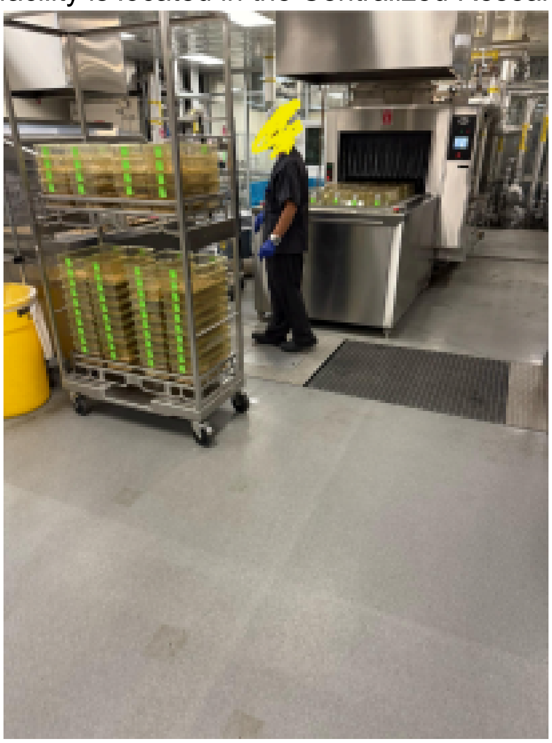


Figure 1. pre-processing operated by a human

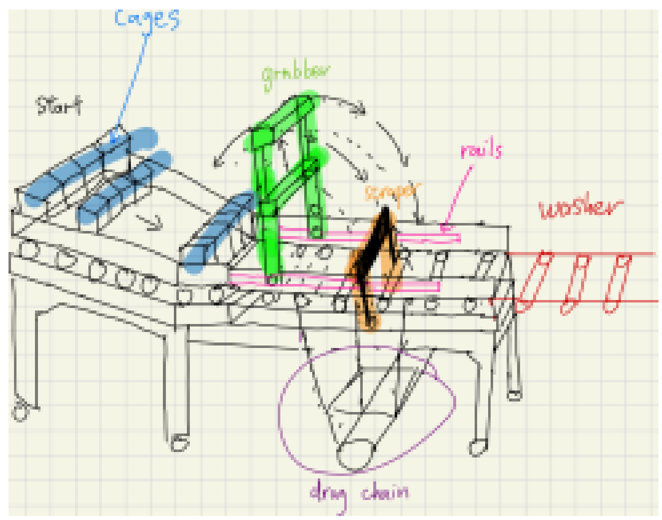


Figure 2. Preliminary schematic of the design

Functional Requirements

The grabber and the scraper components will require a controller/s in order to control the precise rotation of the arm, the clamping of the grabber with feedback control, the linear motion along the rails as well as the extension and retraction of the scraper, and receive data from the sensors (figure 2). Depending on the results of our risk reduction experiment, The design could incorporate a single controller or 2 controllers for a top down control scheme as shown in the diagram

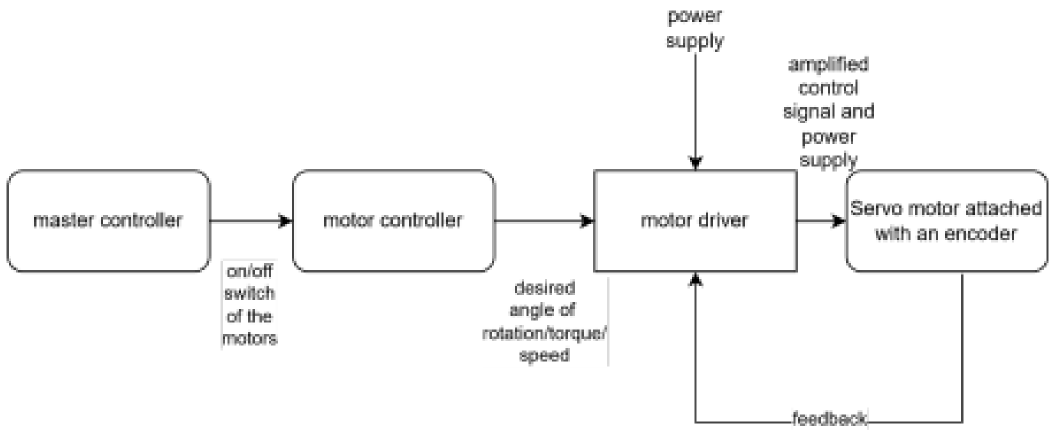


Figure 3. Control diagram for a top-down control scheme

For clarity, the controller a level immediately above the motor driver will be referred to as microcontroller thereon.

For the functional requirements, the microcontroller must be capable of sending pulse width modulation (PWM) signal, which is a relatively simple control method, to control the servo motors that does not require a separate motor driver. Alternatively, if the servo motor requires an external motor driver, then the microcontroller must be capable of communicating with a motor driver as well. To allow for the maximum flexibility, our ideal microcontroller must be able to satisfy both control methods (Usually the former can be satisfied if the latter is achieved). Therefore, we are seeking a microcontroller capable of accomplishing the latter method [5].

Additionally, the microcontroller should support the driver libraries if connecting to the motor driver. Given that the grabber requires one motor for clamping, the grabber arm requires two motors for rotation, the scraper requires one motor for translation along the platform and another motor for extension and retraction (15 for a conservative estimate), it is more suitable to route all the motors to a single motor driver to which the microcontroller sends top level commands, which contains a substantially greater amount of PWM and I/O pins [4]. Since our motors will be powered by an external power source, the microcontroller is not constrained by the voltage requirement of the motors.

There are different options when it comes to choosing a microcontroller. The most commonly used in the industry are the programmable logic controllers (PLCs). They require a motor driver to actuate and control the servo motors. They could be more costly, but are more reliable and more suitable for industrial applications. Other options include microcontrollers used by hobbyists, such as Arduino, Raspberry Pi, or ESP 32. They could be less robust for industrial applications and harder to integrate with the existing automation system that runs on Modbus architecture.
The following are 3 possible options for the microcontroller:

PLC:

Arduino Opta Wifi:
https://store.arduino.cc/collections/turnkey-solutions/products/opta-wifi [1]

The Arduino Opta Wifi is a PLC that combines the functionality of a standard PLC with the capabilities of the Arduino architecture. It supports up to four output relay devices at 250V AC - 10A and contains 8 digital/analog input pins for feedback control. It can easily integrate with industrial automation systems, being IEC-61131-3 certified.

Hobbyist microcontroller:

Arduino Mega 2560 Rev3

https://store.arduino.cc/products/arduino-mega-2560-rev3?srsltid=AfmBOoo9GmExwDOSNMaJ6l27VVgFIuTol_wLEKQjYXuDCbai9EKG5PfE [2]

The Arduino Mega 2560 is a standard arduino microcontroller but comes with additional digital and analog pins for projects requiring a high amount of I/O controls. It has 54 digital output pins, 16 analog input pins, and 15 PWM pins. It has more memory and processing speed than the Arduino Uno, which makes the Arduino Mega 2560 more suitable for bigger projects requiring more I/O controls and sensors.

Raspberry Pi 5

https://www.raspberrypi.com/products/raspberry-pi-5/ [3]

The Raspberry Pi 5 is a single board computer that runs on Linux operating systems. It has an onboard gpu, and 2 ,4, 8, and 16 GB of RAM depending on the model. It provides an HDMI output, allowing the user to access its UI, making it very user friendly. It is capable of advanced algorithm computing thanks to its high processing speed, making it suitable for AI/Image processing, high level automation, and ROS2 applications .

Summary of the Options

	Type	Cost	Shipping Time	Vendor
Arduino Mega 2560 R	Microcontroller	53.50 USD w/tax and shipping	Overnight with prime (0.00 USD)	Amazon
Raspberry Pi 5	Computer	120.0 USD w/tax + shipping	3 days with FedEx saver (16.99 USD) from	Digikey
Arduino Opta Wifi	PLC	193.2 USD w/tax + shipping	1-5 Business days with express delivery (7.83 USD)	Arduino

	Arduino Mega 2560 R	Raspberry Pi 5	Arduino Opta Wifi
Pros	real-time control Direct control via PWM Numerous I/O and PWM outputs Easy to use/ simple to set up	High processing power Multi-processing Wifi, bluetooth, HDMI ready Ideal for AI, ROS2, high level automation	Low-latency Durable for 24/7 operations Supports industrial communication protocols such as Modbus Easy to integrate with existing industrial infrastructure/ scalable
Cons	Does not support parallel processing Does not support industrial communication Not heavy-duty Smaller RAM	High latency Poor support for PWM I/Os Not robust for industrial environments	Requires industrial knowledge More expensive More complicated setup process Limited support for PWM I/Os

Choosing the controller in consideration of the overall design

Depending on the motor choices, each option may or may not be suitable for the project For example, the Arduino Mega 2560 is capable of real-time, low-level control of motors that accept PWM or step inputs [7] and offers decent connectivity with motor drivers through UART if needed, whereas the Raspberry Pi 5 or the Arduino Opta Wifi may not be able to send signals directly to the motor and may require an external controller or motor drive to send PWM or stepper inputs to such motors, increasing the cost.

The PLC supports industrial communication, which is compatible with many industry-grade servo drivers [6]. Therefore, if an external servo driver were to be used, the PLC is a favorable
option. Although more pricey, the PLC offers unique advantages with its scalability and

durability, enabling better integration of the machine with the facility and more flexibility with future modifications or upgrades. It can also handle high level automation of the machine and partition controls of each component, reducing the chances of conflict. However, it has less processing power than the Arduino Mega 2560 and may fail at tasks requiring demanding real-time computations. As far as non-deterministic computations are concerned, PLCs generally fare worse than Arduinos.

Therefore, the recommendation is to adopt a hybrid approach, in which an Arduino Mega 2560 is chained below the PLC, in a similar fashion as shown in figure 3. For this approach, the PLC, serving as the master controller, handles the high-level automation of the grabber-scraper assembly, global sensor data, and safety protocols, whereas the Arduino Mega 2560 sends precise, real time control to the grabber, scraper, and any additional motors through PWM or step signals to the driver. This setup takes advantage of the low-level motion control of the Arduino while ensuring the scalability and automative capabilities of the PLC.

Reference

"Arduino Opta Wifi." *Arduino*. https://store.arduino.cc/collections/turnkey-solutions/products/opta-wifi. Accessed 13 March 2025. [1]

"Arduino Mega 2560 Rev3." *Arduino*. https://store.arduino.cc/products/arduino-mega-2560-rev3?srsltid=AfmBOoo9GmExwDOSNMaJ6l27VVgFIuTol_wLEKQjYXuDCbai9EKG5PfE. Accessed 13 March 2025. [2]

"Raspberry Pi 5." *Raspberry Pi*. https://www.raspberrypi.com/products/raspberry-pi-5/. Accessed 13 March 2025. [3]

"How to Control Servo Motors with Arduino – Complete Guide." *HowToMechatronics*. https://howtomechatronics.com/how-it-works/how-servo-motors-work-how-to-control-servos-using-arduino/#h-arduino-and-pca9685-pwm-servo-driver. Accessed 13 March 2025. [4]

Databases Searched

McMaster. McMaster-Carr, https://www.mcmaster.com/products/temperature-controls/. Accessed 13 March 2025. [5]

- I looked into the motors on the website in order to gain a better understanding of servo motor and stepper motor control requirements and specifications.

"Programmable Logic Controller Basics Explained - automation engineering." *YouTube*, uploaded by The Engineering Mindset, 14 Dec. 2020, https://www.youtube.com/watch?v=uOtdWHMKhnw. [6]

- I watched the video to understand how to interface PLCs with microcontrollers and motor drivers

"How to Wire an Arduino to a ClearPath Servo Motor." YouTube, uploaded by Teknic Inc, 3 Aug

2017, https://www.youtube.com/watch?v=QZLwDnGSaeI [7]

- I watched this video to learn more about the direct control of motors through Arduino.

Search Engine / AI Tool.

ChatGPT https://chatgpt.com/ - I used ChatGPT for fact checking and to gain a general understanding of PLC, Arduinos, and Raspberry Pi by prompting it to explain the functionalities of each.

A.10.3 Force sensor for grabber arm gripping mechanism

Individual Component Analysis- Gripper Sensor

Project Description

Our sponsor, Dr. Keith Jenne, runs the Central Research Services Facility on UCSD. Animal research labs in other locations have large amounts of rat and mice cages, which they send to Central Research Services for cleaning. The cages contain bedding and rat or mice droppings (no animals). In the facility, an automated system is in place for washing the cages. However, before the cages can be placed into the automated system, the bedding and droppings must be removed. Our goal is to automate the process of picking up the cages from loading carts, dumping the bedding and droppings, and placing them on the automated washer system.

In order to perform this automation, our robot's grabber arm must be able to grip the cages with enough force to hold them steadily throughout the entire process. However, it must not apply more force than the cage can withstand. Additionally, because our grabber arm must be able to process cages of different sizes, our system must be able to robustly determine when to stop clamping on the cages without pre-programmed clamp distances. To relay this information live, a sensor in our gripper is necessary to provide feedback to our control system.

Functional Requirements

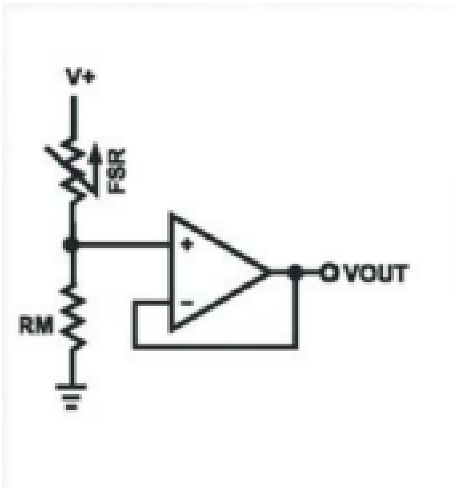
The sensor must be small enough to fit on our gripper arm. Since our gripper arm is meant to pick up four cages at once, it must be cheap enough for us to purchase four, or long enough to encompass the entire arm. The sensor must also be able to relay information without significant time lag to prevent excessive delays in the gripping process, which would hold up the assembly line. As the automation process will involve processing hundreds of cages a day, the sensor must be resistant to wear and tear and also resistant to mild chemicals from the droppings. As we design our gripper material, our sensor must be able to account for the necessary range of force needed to grip the cages without slipping or falling. Finally, the sensor must be able to be mounted on the gripper arm with minimal disruption to the assembly line process.

Description of 3 Component Options

Interlink Technology FSR Model 408
https://cdn.robotshop.com/media/i/int/rb-int-04/pdf/datasheet-30-61710.pdf?_gl=1*10sgu8b*_gcl_au*NTkzOTIxMjc2LjE3NDA2ODE3ODM.*_ga*MjEyNjA5Nzg4MS4xNzQwNjgxNzY1*_ga_FXHVC4EYRV*MTc0MDY4MTc2NC4xLjEuMTc0MDY4MjM0NC41MC4wLjA.

The Interlink Model 408 is a force sensing resistor in the form of a 10mm x 622 mm flat strip. It can measure from 0.2N to 20N. It has a rise time of <3 microseconds. It is a two-wire device with a resistance depending on the applied force. The strip consists of adhesive, a substrate, spacer adhesive, and a bottom substrate. The entire strip area mentioned above is an active area and can be used for force sensing. A model with female contacts and solder tabs is available.

The following graph is provided to show Force vs Voltage for a force sensor placed in a voltage divider with a resistor.



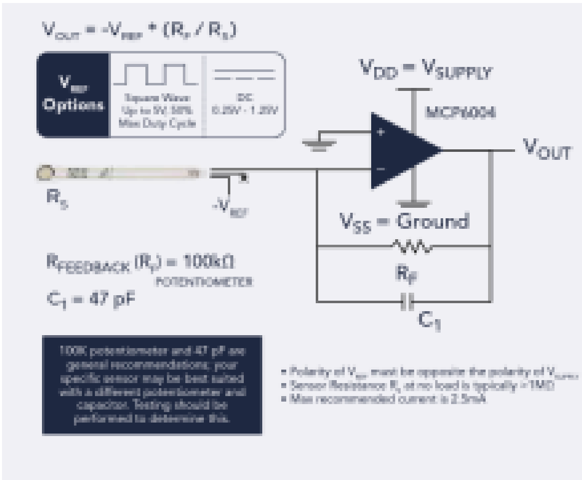
Voltage Divider Circuit Sensor Drawing **FlexiForce Standard Model A201**

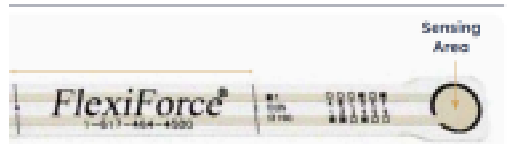
https://www.mouser.com/datasheet/2/1460/Tekscan_FlexiForceA201_Datasheet2_0_RevJ-3568354.pdf

https://www.digikey.com/en/products/detail/tekscan/A201-1/14565598

The FlexiForce Model A201 is a piezoresistive force sensor with a 9.35mm diameter sensing area in a flat strip. It can measure up to 4,448N of force and has a response time of <5 microseconds. However, measuring higher voltages requires applying a lower drive voltage and reducing the resistance of the feedback resistor, and measuring up to 445N is a realistic maximum. The connector is a 3-pin male square pin.

The following circuit is recommended by the manufacturer for integration. Note that this implementation is more complex than the Interlink sensor, which only recommends a voltage divider:



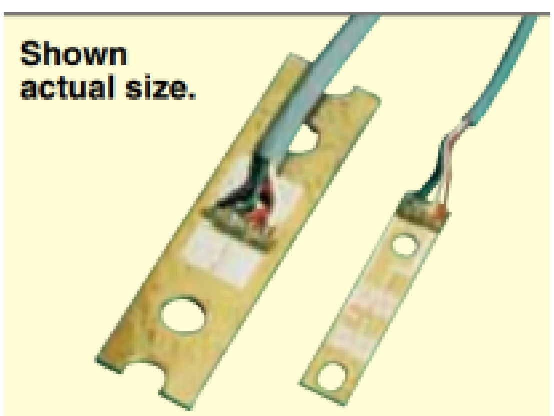


Voltage Divider Circuit Sensor Image` **DywerOmega Full-Bridge**

Thin-Beam Load Cell LCL-010

[https://www.dwyeromega.com/en-us/full-bridge-thin-beam-load-cell-for-low-capacities/p/ LCL?srsltid=AfmBOoojlxkdhFUSnOxukRYeBv5iA5rk9uQC5-ooLcDQ5VumzZfhse-e](https://www.dwyeromega.com/en-us/full-bridge-thin-beam-load-cell-for-low-capacities/p/LCL?srsltid=AfmBOoojlxkdhFUSnOxukRYeBv5iA5rk9uQC5-ooLcDQ5VumzZfhse-e)

This load cell has an integrated strain gauge and can measure up to 10lb of weight. The load cell has a resistance of 1200+/-300 ohms for both input and output, and is urethane coated. The cell is made out of 301 stainless steel and beryllium copper. The cell has a thickness of 1.12mm. This cell can also measure displacement in addition to force. When implemented, the manufacturer recommends that mounting clamps are used to create a double bend during loading, as shown in the following image (exaggerated).



Sensor Image

Force sensor	**Pros**	**Cons**	**Price**

Interlink FSR Model 408	- 24 inch long sensing area, long enough to encompass entire gripper - Shorter rise time than flexiforce - Can be glued on to gripper - Cheap - 0.2N-20N, might be too low depending on material	- Can report an increase in force due to bending along the gripper - One long strip can provide data from all four cages	1 for $20.00 (Interlink) Line Price: $20.00 Shipping Time: ~2-5 Business Days
Flexiforce Standard Model A201	- 0.375in. Diameter sensing area - Can be glued on to gripper - 0N-4448N, will be enough regardless of material	- Can report an increase in force due to bending, but less likely due to smaller surface area - Requires 4 of these, one for each cage - Moderately expensive	1 for $18.23, 5 for $83.10 (Digikey) Line Price: $83.10 Shipping time: ~1 Week
DywerOmega Full-Bridge Thin-Beam Load Cell LCL-010	- Resistant to flexing and environmental conditions - 0-44N (Moderately good range, most likely will be good enough depending on material)	- Must be specially calibrated by user - Larger and will require specially built holding plates - Expensive	1 for $182 (DywerOmega) Line Price: $648 Shipping Time: ~1 Business Day

Out of our three options, the Interlink FSR Model 408 seems the best option for testing due to low price and ease of installation. In the final model, the Flexiforce Standard Model A201 might be a better choice for long-term installation due to its higher force sensing range and less potential for bending to bias the force measurement.

Team Impact

The range of the sensor may affect the material chosen to be placed on the inside of the gripper arm. If the sensor range is too low, we may choose a material with more friction in order to require less normal force to hold the cages without slipping. The voltage divider circuit for the FSR's may have a small impact on the final board selection, which will likely be a perfboard or a PCB. If we select the flexiforce sensor and require higher force ranges, we will have to alter the circuit. The complexity of the voltage divider might impact our selection for a larger board. I do not expect the sensor choice to impact our control system choice as the rise times are sufficiently fast.

Expert Contact

Jonathan Klingspon, Embedded Systems Engineer, Looq AI
jklingspon@looq.ai

Discussed the impact of potential bending on force resistive sensors (FSRs) and explained how the voltage divider circuit allows increasing voltage to be read by the microprocessor as varying force.

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Industries, A. (2025, February 16). Extra-long force-sensitive resistor (FSR). https://www.adafruit.com/product/1071

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Electronics, I. (2025, February 16). 34-00152. Digi-Key. https://www.digikey.com/en/products/detail/interlink-electronics/34-00152/16803572

Tekscan. (March 14, 2025). A201-1. Digi-Key. https://www.digikey.com/en/products/detail/tekscan/A201-1/14565598

Tekscan. (March 14, 2025). How does a force sensing resistor (FSR) work?. https://www.tekscan.com/blog/flexiforce/how-does-force-sensing-resistor-fsr-wor
k

Keywords

"Force sensing resistor", "Load cell", "Strain gauge", "Force sensor", "piezoresistive sensor", "Strain cell".

A.10.4: Motors.

Individual Component Analysis - Rotary Motor
Vicente Ibarra
2/28/2025

Team 42 is committed to manufacturing a machine that processes dirty animal cages. A crucial component of the rotating arm is a motor that is capable of providing enough torque to flip the cages and dump refuse, in addition to holding the cage still while the scrapper makes contact with the cages. As such, the system needs to have an appropriate motor that will rotate the arm smoothly and provide sufficient torque.

Functional Requirements of the Rotary Motor

The primary functional requirements for the robotic arm's rotary motor are:

● Must provide at least 276 lb-in of torque to lift and rotate up to 4 fully loaded cages, each weighing approximately 2 pounds to perform a cycle with a safety factor of 20%.

● Requires precise position control for accurate cage positioning.

● Must operate within a speed range of 10-60 RPM for safe and controlled cage manipulation. Another aspect to consider is energy efficiency, as reducing power consumption will extend operational time and decrease heat generation, which is important for laboratory environments. The motor selection will also determine requirements for the driver circuitry and power supply system.

With these functional requirements in mind, the following products should be considered:

● NEMA 23 DC Servomotor with Integrated Drive: Model 5151N141

● NEMA 34 DC Servomotor with Integrated Drive: Model 5151N161

● NEMA 34 DC Servomotor with Brake: Model 5082N21

Description of 3 Different Component Options

1. NEMA 23 DC Servomotor with Integrated Drive: Model 5151N141 ($527.14, delivers in 2-4 weeks) [1] This system includes a motor, encoder, and drive for accurate positioning and fine control over speed and position. This motor is a compact 6.4” ⨉ 2.3” ⨉ 3.2”, overall. It has a shaft diameter of ⅜ inches and a shaft length of ¾ inches and weighs 3.2 lbs. It can provide a continuous torque of 10.4 in*lbf and a maximum torque of 52.8 in*lbf. This motor can operate at speeds up to 1,860 rpm. It can ensure precise controls with 6400 counts per revolution, however, it lacks a brake mechanism. This motor has a power consumption of 213 W.
2. NEMA 34 DC Servomotor with Integrated Drive: Model 5151N161 ($511.43) This motor is slightly thicker and heavier than the NEMA 23 model in return for higher torque capabilities. The NEMA 34 motor has overall dimensions of 5.1’’ ⨉ 3.4” ⨉ 4.3” and a weight of 4.4 lbs. It has a shaft diameter of ½” and a shaft length of 1.17”. It can provide 18.1 in-lbf of continuous torque and 68.4 in-lbf maximum torque and can operate up to 1410 RPM. It can ensure precise controls with 6400 counts per revolution, however, it lacks a brake mechanism. This motor has a power consumption of 227 W.
3. NEMA 34 DC Servomotor with Brake: Model 5082N21 ($2,502.86) The NEMA 34 motor has overall dimensions of 7.2’’ ⨉ 3.4” ⨉ 4.7” and a weight of 7 lbs. It has a shaft diameter of ½” and a shaft length of 1.1”. It can provide 12.8 in-lbf of continuous torque and 45 in-lbf maximum torque and can operate up to 4960 RPM. It can ensure precise controls with 20000 counts per revolution and has a brake mechanism. This motor has a power consumption of 750 W.

	Pros	Cons
NEMA 23 DC Servomotor with Integrated Drive: Model 5151N141	- Most compact lightweight option - Integrated drive simplifies installation - Moderate Power Consumption (213W) - Reasonable price ($527.14)	- The lowest torque of the selections - No brake mechanism - Lower resolution than the premium option

NEMA 34 DC Servomotor with Integrated Drive: Model 5151N161	- Best value - Highest torque capabilities (18.1/68.4 in-lbf) - Integrated drive simplifies installation - Reasonable size and Weight - Moderate power consumption (227 W)	- No brake mechanism - Lower resolution than the premium option
NEMA 34 DC Servomotor with Brake: Model 5082N21	- Includes brake mechanism - Highest precision (20,000 counts/revolution)	-Significantly more expensive - Heaviest - Largest option - Highest power consumption (750 W) - Does not have an integrated drive

Figure 1: Pros and Cons of different motor selections

Of the three, the NEMA 34 DC Servomotor with Integrated Drive: Model 5151N161 seems to be the best fit for our design. The selection in the motor will influence our selection in the controller. The controller design must adapt to the specific motor type chosen, with the integrated drive options simplifying installation but still requiring compatible communication protocols. If selecting non-brake models, the controller needs to implement active position holding, increasing computational demands. These considerations directly impact the complexity and cost of the control system.

Brake functionality represents a critical safety and operational consideration. Without the integrated brake of the premium model, alternative solutions must be implemented, to ensure safety but potentially add complexity, cost, and points of failure. These could include external brake mechanisms, self-locking gears, or counterweight systems, each introducing its own design and maintenance challenges.

Mechanical integration varies significantly based on motor dimensions and mounting patterns. The smaller NEMA 23 enables more compact arm designs but sacrifices torque capacity, while the larger NEMA 34 options require more substantial mounting structures but offer greater power. Different shaft diameters between models necessitate different coupling mechanisms, potentially affecting parts inventory and maintenance procedures.

If cage weights approach maximum capacity, the NEMA 23 might require a gearbox for adequate torque margin, introducing backlash concerns that could compromise the desired speed.

References

[1] DC Servomotor with Integrated Drive, NEMA 23, 51.8 in.-lbs. Maximum Torque | McMaster-Carr

[2]DC Servomotor with Integrated Drive, NEMA 34, 68.4 in.-lbs. Maximum Torque | McMaster-Carr

[3] DC Servomotor, with Brake, NEMA 34 Frame Size, 45 in.-lbs. Maximum Torque | McMaster-Carr