TACTILE GRIPPER END EFFECTOR DESIGN

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ABSTRACT

In the field of manufacturing, there is often a problem of tasks being too dangerous, difficult, or monotonous for human workers to perform. In order to solve this issue, manufacturing robots are implemented, and must be able to grasp a similar array of objects as a human hand so as to perform the same tasks. A tactile sensing gripper end effector has been designed and prototyped for the Baxter and Sawyer robots to aid in these efforts. At the time of this report, the gripper has successfully been able to grasp all 10 of a varied set of objects. The results indicate that replication of human grasping is possible with a non-hand-shaped end effector and that a truly efficient end effector is able to grasp different objects with the same design.

PROBLEM DEFINITION

Robots such as the Baxter or Sawyer robots are used to perform repetitive manufacturing tasks in place of human workers, thus sparing the need for humans to perform difficult tasks. This problem is important to factory workers who perform dangerous tasks, and manufacturing companies who require a high product output volume or high precision. Alternatively, the Baxter robot is used for research projects in many fields to study how to replicate human motion and better perform complex tasks.

The current parallel jaw end effector on the Baxter robot is insufficient for manipulating various objects and lacks the necessary sensing to detect force closure. Designing an end effector that is capable of grasping differently shaped objects will increase the versatility of the Baxter robot and allow robots to better replicate human motion. This can decrease human risk and increase safety and efficiency in the field of manufacturing.

REQUIREMENTS, SPECIFICATIONS, DELIVERABLES

The team has agreed to the following deliverables:

- Gripper Prototype
- Theory of Operation Manual (Including Assembly Guide and Instructions)
- Final Design Report
- Digital Database (CAD Files and Drawings)
- Test Mounts

The Work Breakdown Structure (WBS) and Critical Path Method (CPM) contain the details for all the deliverables that make up the project solution and represent the most extended sequence of tasks that must be accomplished to ensure the completion of the entire project (Annex A).

Under the scope of the problem definition, the following requirements are defined:

- Proficient at picking up and holding a selected set of YCB test objects.
- Delivered end-effector includes the documentation required to manufacture, assemble, and run.
- End-effector and test object mass must not exceed the weight limitations of the robot.
- The design of the gripper includes mounting points for the necessary sensors to implement tactile.
- A mounting point for vision sensor-aided grasping must be provided.

Additionally, this requirement was later added but not originally agreed to at the beginning:

- End-effector must have a compliance mechanism.

The following specifications will be verified during the testing phase of the project:

- Weight of the gripper plus end effector adapter must be smaller than 3 kg using a weight balance to verify.
- No YCB benchmark objects will fall, drop or move after the gripper grasps it for 3 seconds, using video assessment to verify.
- The connection between the gripper and the Baxter & Sawyer robot is fastened, preventing detachment when the arm is oriented downward under a 2 kg load, using video assessment to verify.
- The team must stay under the budget of 1000 dollars, using the money spreadsheet tab to verify.
- End-effector closes and opens within 1 second, using video assessment and motor signal feedback to verify.
- Materials and boundary condition uncertainties must be under a factor of 2.

Concepts

The process of selecting a final design concept was separated into 2 phases: Preliminary Concept Selection and Final Concept Selection. A Pugh Matrix was used to identify promising concepts to be further developed and evaluated during Final Concept Selection. Concepts C, E, and F were compared and deliberated on until a consensus was found on whether they were favorable, similar, or worse (1,0, and -1 respectively) in 6 weighted categories. Category weights ranging between 1 (least important) and 5 (most important) were informed by their perceived importance toward project success as defined by the Requirements, Specifications, and Deliverables. (Table 1 annex B)

To evaluate each design and to verify the feasibility of picking up each selected YCB object, estimates for the required clamping force for each object were calculated. Given masses of selected YCB objects were used to derive the clamping force required to counteract the force of gravity on each object. A standard coefficient of friction value of 0.3 was used for this calculation. (Table 2 annex B) The team is currently looking into finding the maximum acceleration of the Baxter's hand in order to calculate worst-case clamping force requirements. Additionally, the team will refine the estimated coefficient of friction once materials for end effector tips have been selected.

The design concept E was created as a CAD model. It consists of two long parallel curved jaws that only move linearly such as on a rack and pinion mechanism or worm gear. (fig. 9)

The design concept F CAD model shows a hinged mechanism rotated by gears that close two bent claws around a part. This design only rotates about one axis. (fig. 10)

The design concept C model consists of an asymmetrical finger design where one moves perpendicular relative to a fixed bottom plate and another one displaces at a 45-degree angle. (fig. 11)

Ultimately the team found Design C to be slightly more favorable than Design E and F because it offered more reliable contact. Design F's rigid "fingers", while simpler than Design C's spring-tensioned hinged end tip design, did not provide as reliable of contact when grasping objects with variable cross sections such as the Spatula and Hammer. Additionally, the existence of object-specific features such as the cutout for the Large_Marker (fig 11) in Design C was deemed advantageous. Similar features are likely to be implemented in the delivered design.

Mechanical Analysis

To construct a compliant backplate that is able to automatically reset, spring plungers, extension springs, and compression springs were used. Spring plungers were used for positioning the initial position, and setting the threshold load for activating the compliant mechanism in the XZ plane. Additionally, two compression springs facilitated rotation along the X-axis and were employed to control the friction between plates by adjusting the normal force. For rotation along the Y-axis, two extension springs were deployed. These springs not only provided the necessary threshold load but also pulled the movable backplate back to its original position.

A static analysis is necessary to determine the appropriate spring constants and the initial lengths of all springs.

Initially, Hooke's Law was employed to calculate the spring constants for the compression and extension springs.

$$F = -\, kx \quad (1)$$

In Eqn(1), F is the spring force, k is the spring constant, and x is the displacement.

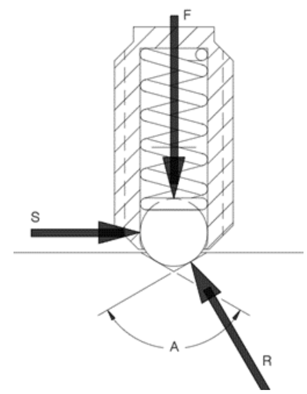

Figure 1. Free body diagram of the spring plunger [2]

As shown in Figure 1, the relationship of forces in the spring plunger is illustrated, where S is the side force, F is the end force(spring force), A is the countersink angle, and R is the reaction force(perpendicular to the contact surface). An M3 heat-set insert was selected as the holder for the spring plunger; it features an inner diameter of 3mm. Given that the nose size is also 3mm, the countersink angle A required manual calculation.

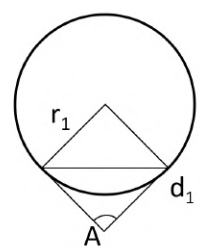

Figure 2. Geometry of the spring plunger with M3 heat-set insert as holder

In Figure 2, r_1 is the radius of the nose which is 2mm, d_1 is the diameter of the heat-set insert part which is 3mm, and A is the countersink angle consistent with the previous figure.

Therefore, by solving the triangle, it was found that A equals 97.181°.

$$F = S * tan(A/2) \quad (2)$$

Using Equation 2 [2], the spring force can now be expressed as a function of the side force, which represents the threshold force required to activate the compliance mechanism.

Also, based on the equation of friction,

$$f = Fn * \mu \, (3)$$

F_n is the normal force.

Assuming the coefficient of friction μ between the PLA plates is 0.3, the friction between plates can be calculated.

In this system, there are two spring plungers, two compression springs, and two extension springs creating a backplate with three degrees of freedom(translation along z, rotation along x and y). These components form a backplate endowed with three degrees of freedom: translation along the z-axis, and rotation about the x and y axes. Detailed analyses of these movements, based on Equations (1-3), are documented separately in Annex C (Figures 12-14). These analyses informed the determination of the appropriate sizes for the springs, as shown in Annex C Figure 16.

To calculate the threshold loads required to activate the compliant mechanism under various conditions, the compliant backplates were examined in their initial static equilibrium state. In this state, all spring plungers are engaged within their respective holders, and the plates maintain maximum static friction while remaining parallel (refer to Annex C Figures 12-14).

The forces at the maximum extension of the extension springs are detailed in Annex C Figures 12 and 13. Furthermore, considering the acceleration of the gripper when grasping objects, along with the requisite friction forces to hold different objects against gravity, clamp forces for various objects were computed and are displayed in the table in Annex C Figure 15.

From the expression of all forces, the expected loads, and the design criteria, all requirements were confirmed (shown in Annex C Figure 15).

The design ensures that the movable backplate does not rotate along the x-axis under maximum clamp force but allows rotation when the force slightly exceeds this threshold. In the z-axis translation, the threshold load is set to be higher than the self-weight of the gripper to ensure stability. If the load exceeds this weight limit, the compliant mechanism is triggered to protect the structural integrity of the gripper. After reviewing available parts online, suitable springs were selected and underwent testing. The final design met all specified requirements as detailed in Annex C Figure 16.

Fatigue Analysis isn't necessary to perform in this project, with all components 3d printed, the modification factors for plastic parts are not available. Besides, there aren't any component movements that are repetitive or cyclic loading. To attest to the structural stiffness of the gripper, a Finite Element Analysis (FEA) on the dovetail mount is done in Figure 17.

The geometry of the current gripper is defined by 5 lengths and 2 pivot points (per arm). To ensure a successful grasp across the spectrum of selected YCB objects, it is necessary to adapt these lengths to accommodate the "extremes" of the selected YCB objects. These objects and their unique grip tip position requirements bounded the required range of motion that the gripper geometry was required to accommodate. The wood_block, potted_meat_can, and marker were the selected objects that provided these boundary conditions. These were the tallest, widest, and smallest objects respectively. In addition to these boundary conditions, additional design decisions had to be made to set the gripper geometry.

The layout and derivation of the simplified gripper geometry is presented in Figure (18). Length A (backplate) was set at 6" to improve manufacturability and to restrict the maximum length of the gripper arm such that it would be able to provide the required grip force to pick up the heaviest object while not overloading the selected servo motor. The servo motor had a maximum holding torque of 3.924 Nm, and the gripping force required to pick up the wood block was calculated to be 23.84 N (Table 2). Dividing 3.924Nm by 23.84N results in 0.165m or 6.496" (the maximal allowable arm length). Length E was set at 3" since it resulted in visually robust grasps during the early modeling phase, with the perpendicular connection to the grip arm moved off-center to provide increased grip tip mobility.

After calculation of these values, it was found that the grip arm and grip tip formed an equivalent radius of 6.043", while simultaneously not being long enough to pick up the marker by 0.17". This was solved with the addition of a compliant "wiper" which allows the grip arm to fully close despite the geometry interfering with the table while providing the tip with an additional 0.2" in length to scoop up the marker. This wiper concept was integrated with a TPU "skin" after testing found that the previously bare plastic grip tip did not have the required grip to pick up the hammer. This feature enabled the gripper to remain entirely 3D printed and eliminated the need for rubber tape to be applied to grip tips and backplates.

MANUFACTURING

The gripper has been designed with ease of manufacture and assembly in mind. To this end, most of the fabricated components are made by 3D printing. This approach simplifies the manufacturing process to just a few steps, primarily involving heat-set thread inserts and the assembly of the components. The structural elements of the product are constructed from PLA, ensuring robustness, while the contact surfaces on the backplate and tips are made from TPU, which offers larger friction when grasping objects.

During the experiment, the most vulnerable part is the dovetail. After the FEA of this part, aiming to increase the stiffness of this specific part, ABS was decided to use on this part fabrication. In addition to 3D printing, there are only two different parts, the Motor Mount and the Motor Block, that need to be milled in the machine shop with 6061 Aluminum, because the Motor Mount needs to be stiff and able to express heat effectively.

The cost of materials is limited to the expense of the 3D printing filaments and 6061 Aluminum sheet, making this a cost-effective solution with $18.53 for its materials cost.

According to Table 3, the estimate of the costs of all parts in the gripper including all mechanical parts, and electronic components is $589.34 (including 6061 Aluminum Bar)(Annex D Table 3).

For the labor cost in manufacturing, because most of the customized parts are made by 3D printing, the only labor cost in this process is taking care of the first printing layer, cleaning the enforcement support, and assembling after printing. Assuming each 3D printing part requires 10 minutes of labor time, there are 25 pieces of 3D printed parts in the gripper; therefore, 250 minutes are required for humans involved in the 3D printing manufacturing process. Moreover, the rest of the pieces should be milled in the machine shop: four Servo Blocks took 3 hours to manufacture in total, and two Servo Mounts took 2.5 hours each. Thus, about 12 hours would take for the manufacturing process. Assuming the team member's time cost at $100/hr, the total manufacturing cost by labor time would be $1200.

To accurately record the project development time for each team member, SCRUM time tracks the daily work hours on this project. The data compiled in the table below illustrates that each member of the team has dedicated more than 130 hours over the semester to this project. Using the same labor cost assumption above, the total cost of development by labor time would be $61,000. This extensive time investment reflects the team’s commitment and the intensive effort required to meet the project milestones and objectives.

	Aaron	Bruno	Tiffany	Yifan
SCRUM Time	161	143	134	175

Table 1. Development time

If one considers scaling the production of the gripper to 1000 units, it's clear that 3D printing, while effective for smaller quantities, may not be the most efficient or cost-effective method for mass manufacturing. Transitioning to a method like injection molding could offer several advantages.

Injection molding, though requiring an initial investment in creating separate molds for each part, can significantly reduce both time and cost for large-scale production. This method would allow us to fabricate parts much faster than 3D printing can achieve, particularly when compared to the time it would take to operate 1000 3D printers for extended periods. Ultimately, adopting injection molding for the production process would likely lead to substantial savings and improved efficiency, making it a superior choice for manufacturing at this scale.

Test plan and results

There are six predefined specifications for the product (Annex E Table 4). These specifications remained unchanged since their initial approval by both the sponsor and the supervisor, and the design successfully met all set requirements.

In terms of weight, a weight balance was used to measure the entire gripper, confirming it was more than three times lighter than the allowable weight limit (Annex E Figure 18). Additionally, the gripper's attachment to the Baxter/Sawyer robot was tested using a spring dynamometer. This testing demonstrated that the mount is robust enough to prevent detachment, even when the robot's arm moves in various directions.

There was no specific requirement to replicate object picking, so the team recorded videos of the gripper successfully grasping various YCB objects. These videos show the gripper's capability to pick up and securely hold each object for more than three seconds, thereby verifying its operational efficacy (Annex E Figure 19-28).

Furthermore, while the Arduino platform facilitates precise control over the arm's movement speed, a timer was utilized to verify that both the opening and closing actions of the gripper occur within the targeted time frame of less than one second. Although the testing phase was designed primarily for demonstration purposes, the action times of the gripper arms were recorded separately and confirmed to be within the one-second limit (see Annex E Figure 29). This testing ensures that the gripper meets the project's speed-related specifications.

For testing that the boundary conditions fall within a factor of 2, a finite element analysis was performed on the most critical part of the dovetail mount, in order to check this requirement. (Annex C Figure 17) By using 100% infill ABS on the dovetail mount, the safety factor is 17.54, much larger than 2.

Intellectual property

After a quick patent search, no exact replication of the design was found. The design is therefore likely to be patentable, as no search results for a gripper end effector with the exact backplate and gripper perpendicular and angled tips were found. The closest patent was US9486927B1 (gripper with fingers moving in perpendicular axes).

Other relevant existing patents include B25J15/10 (field with end-effectors of 3 fingers or more), B25J15/12, (field with flexible robotic fingers), B25J15/103 (gripping heads and other end effectors having finger members with three or more finger members for gripping the object in three contact points). No patents identified the use of a rigid backplate, a set of two DOF grip arms out of the plane and sprung grip ends to achieve a parallel grasp.

Societal and environmental implications

One societal implication of the rapid development of this robotic manufacturing technology is that it may cause a reduction in job positions, with companies requiring fewer human workers. Though it is cost-effective to cut labor costs, the job market will become more difficult for manufacturing technicians.

Additionally, an environmental implication is that during the project, fasteners were only sold in bulk, resulting in wasted parts when the assembly only needed one or a few fasteners of a type. The byproducts of prototyping and manufacturing are harmful to the environment, though options such as more eco-friendly plastic printing materials were considered and tried. The concept of creating more plastic is in itself unethical, as there is more than a surplus in the environment. Mass manufacturing is also unethical societally and environmentally as it makes overconsumption easier to occur.

Culturally, an implication may be that first-world countries that can afford to produce these robots will have the only access, and will drive the inequality gap between first and third-world countries.

Some ethical changes to the process can be made in the future, such as using the most eco-friendly printing material for all additively manufactured parts or using metal for efficiency and recyclability. Additionally, waste can be reduced by using fasteners of the same type when possible, to reduce the number of bulk packs needed to be purchased. The project itself can be reconsidered, and alternative options for the use of the robot that are more equity-centered can be considered, such as in the healthcare field.

Recommendations for future work

If there was an opportunity for future work on this project, the largest priorities would be to redesign the gripper more focused on lifting the hammer rather than the wood block or allow the backplate to clamp instead of allowing it to deflect. Additionally redesigning the parts to be suitable for injection molding would save time on fabrication. The team would also need to make an FEA analysis for all parts to determine the part that will fail first, in order to meet the factor of safety specification.

Acknowledgments

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Annex A

WBS/CPM

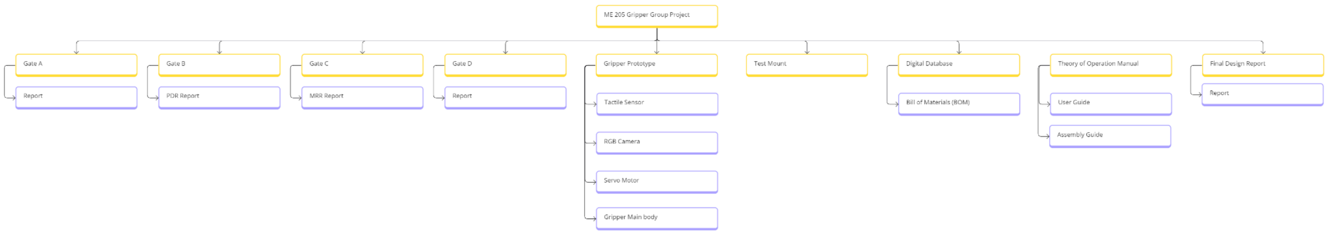


Fig 1. Work breakdown structure of primary deliverables, without activities.

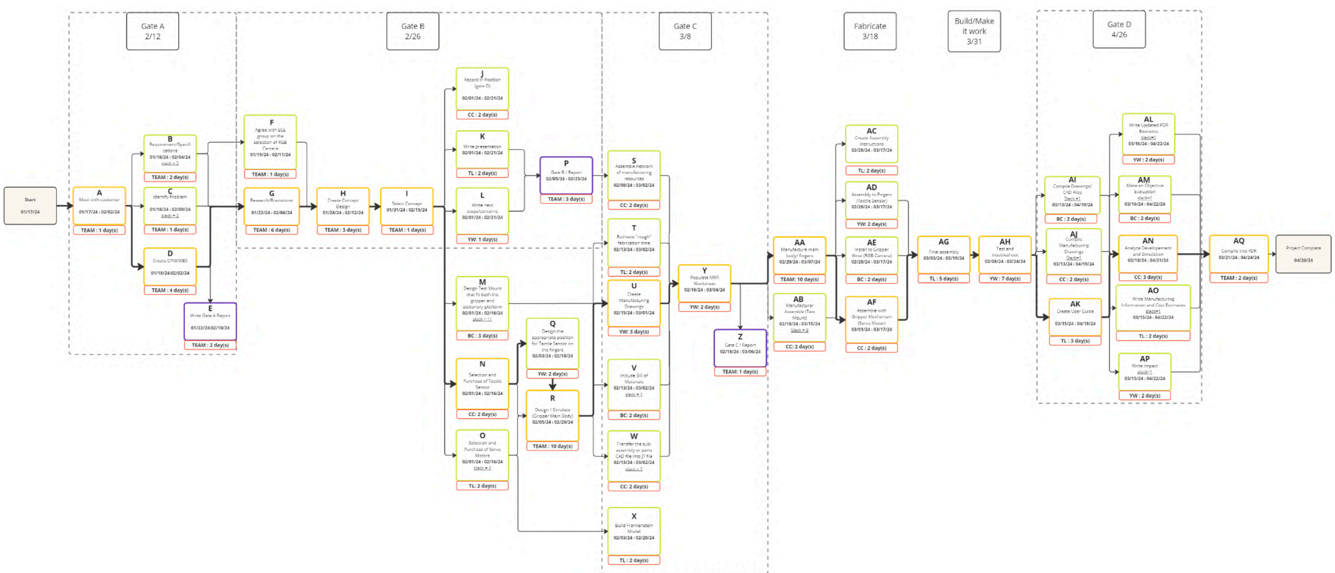


Fig 2. Critical path method with team members assigned to each task and early start/late start date.

Annex B

Gripper prototype concepts and selection with YCB object demonstration

Matrix 2	Baseline (design C)	Design E	Design F
How many items can you pick (5)	0	-1	0
points of contact (4)	0	-1	-1
complexity(number of parts) (3)	0	1	1
Less changes needed (3)	0	-1	0
power issues/torque (2)	0	1	0
Total	0	-7	-1

Table 1. Pugh Matrix evaluation of design concepts presented during final concept selection

Object	Chips_ Can	Potted_Meat _Can	Banana	Spatula	Wood_Block	Padlock	Large_ Marker	Hammer	Tennis_ Ball	Foam_ Brick
Mass (g)	205	370	66	51.5	729	208	15.8	665	58	28
Clamp force (N)	6.70	12.10	2.16	1.68	23.84	6.80	0.52	21.75	1.90	0.92

Table 2. Table of selected YCB object mass and required static clamp force

Fig 3. Current parallel jaw end effector used on Baxter & Sawyer robots [1]

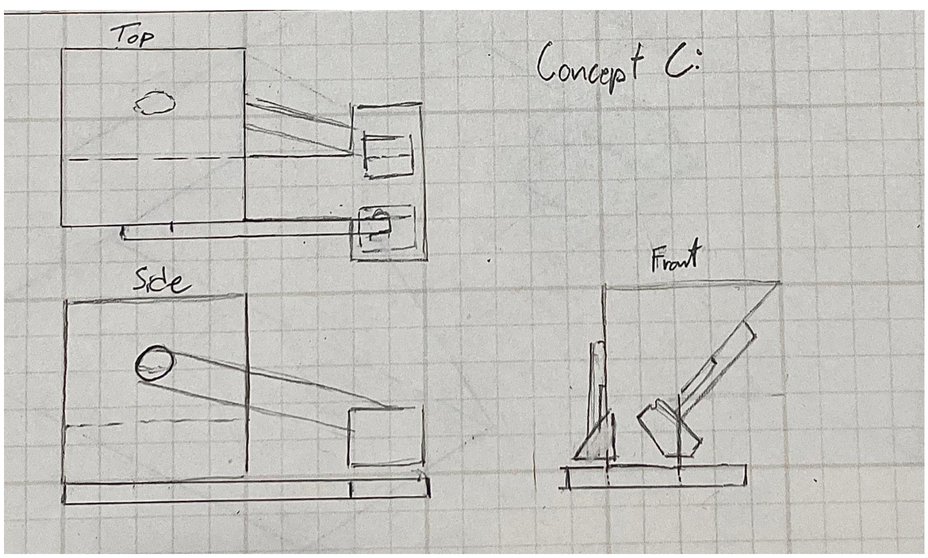


Fig 4. Concept design C - used in Final Concept Selection.

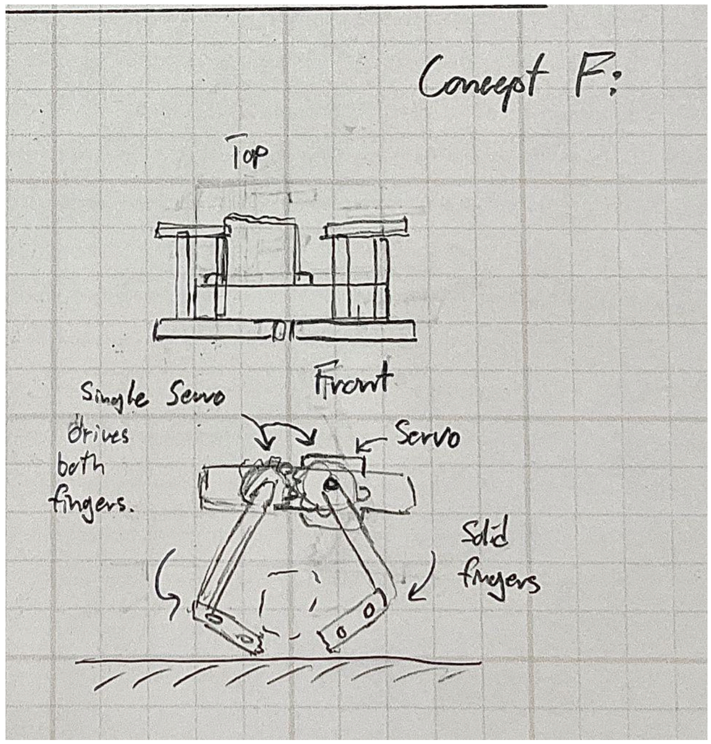


Fig 5. Concept design F - used in Final Concept Selection.

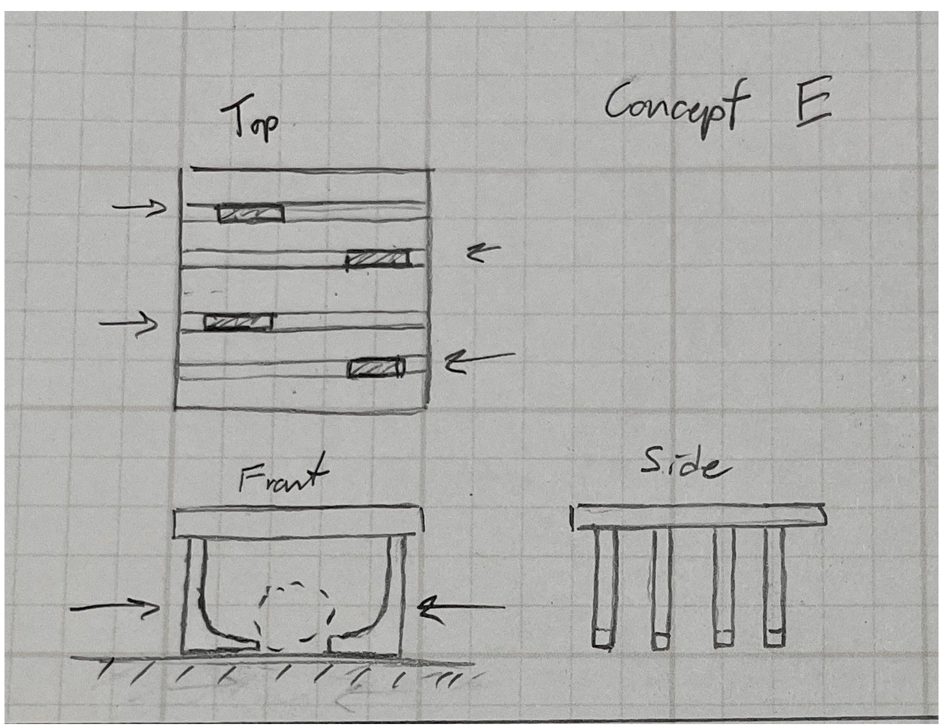


Fig 6. Concept design E - used in Final Concept Selection.

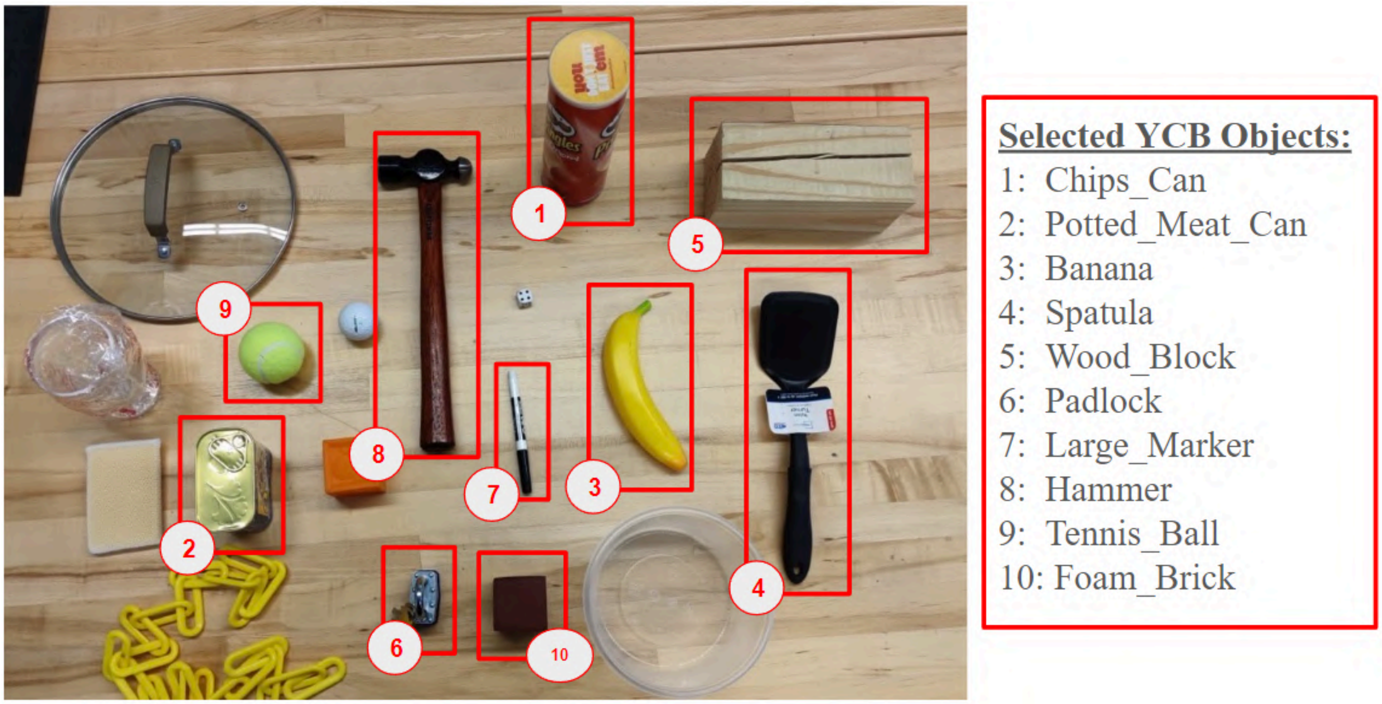


Fig 7. Selected YCB Objects - used in Final Concept Selection.

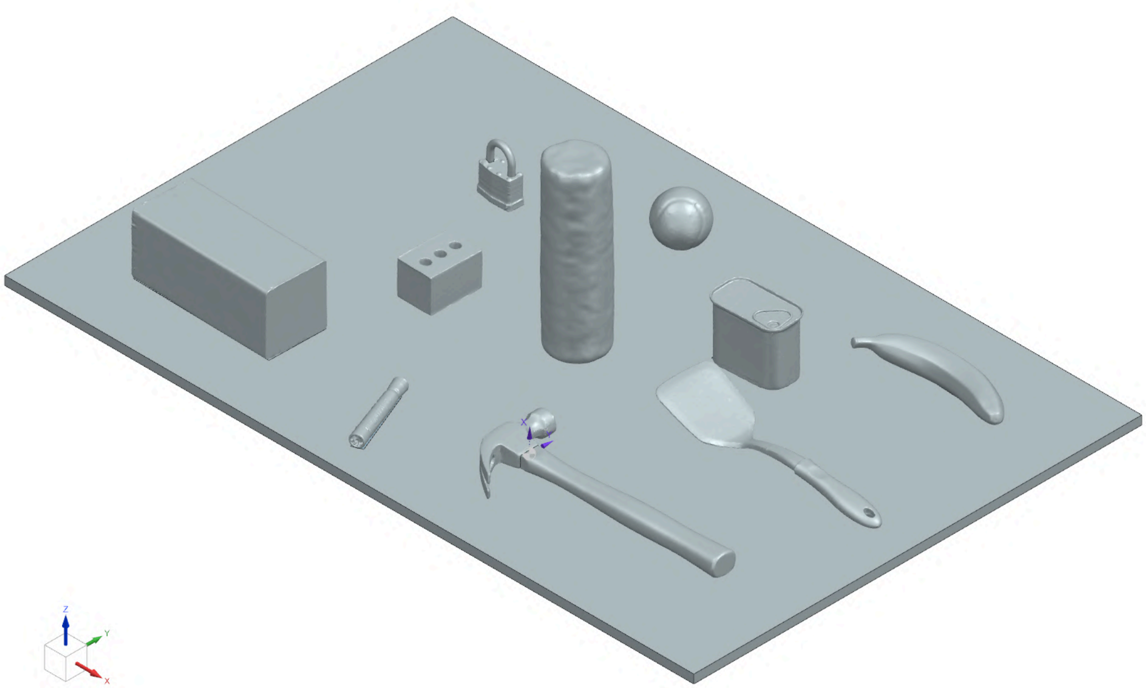


Fig 8. Selected YCB Objects in Siemens NX CAD Assembly - used in Final Concept Selection.

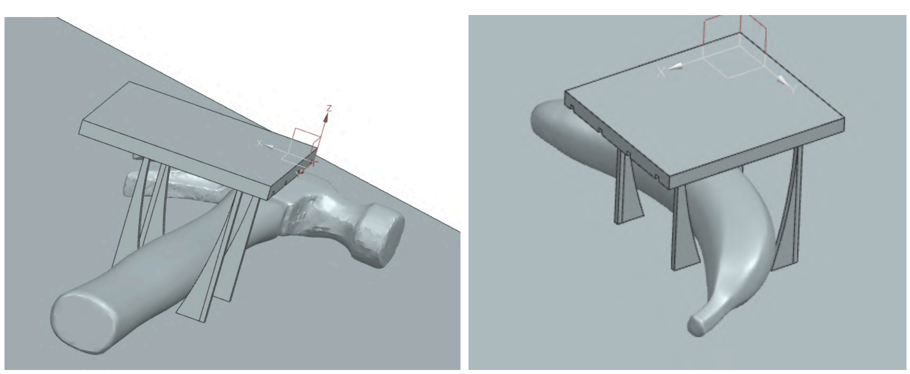


Fig 9. Concept design E around two YCB objects.

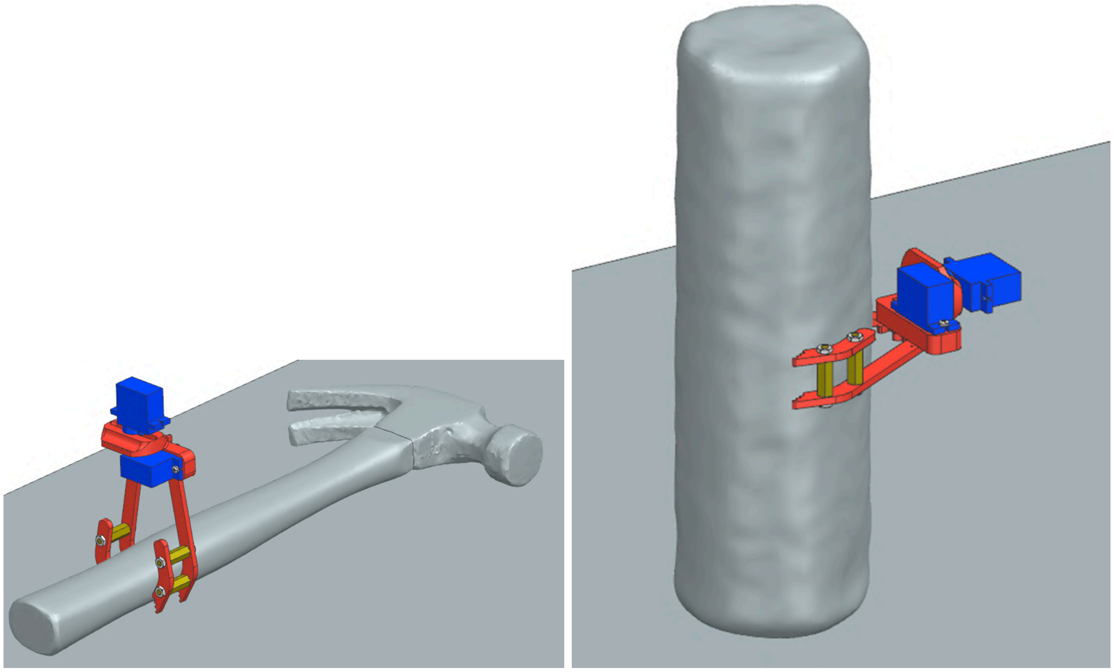


Fig 10. Concept design F around two YCB objects

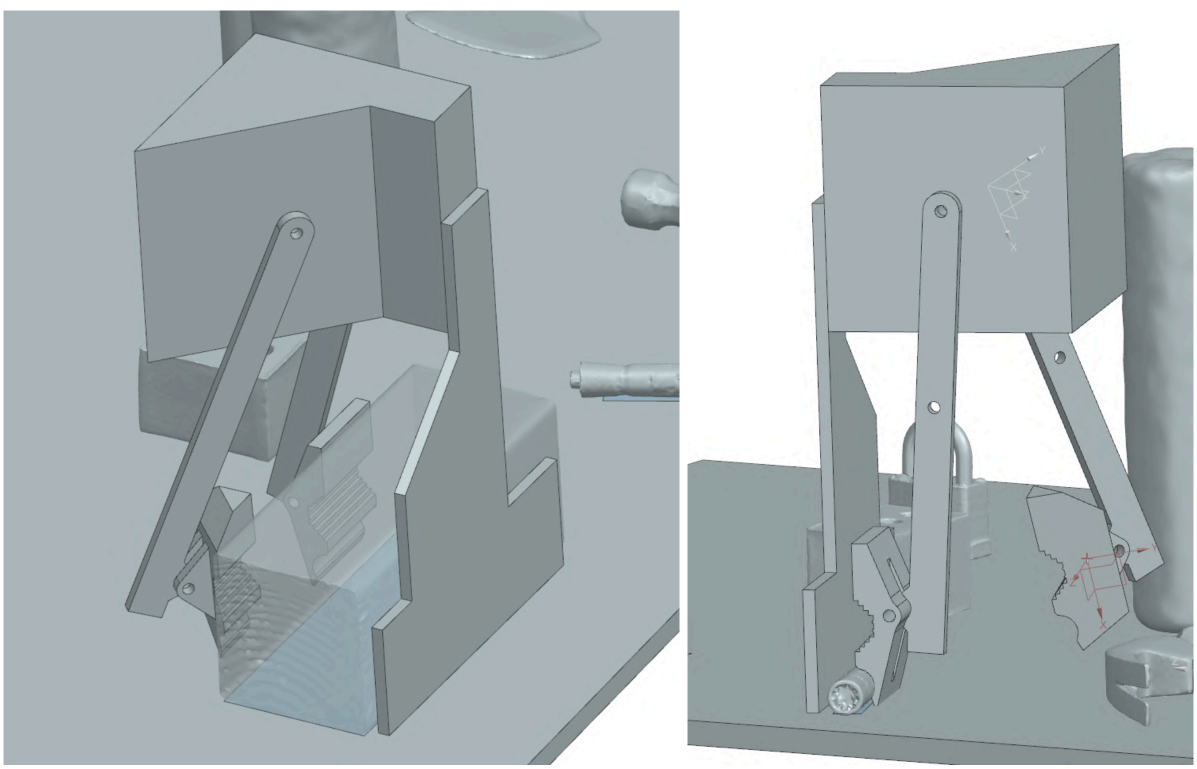


Fig 11. Concept design C around two YCB objects

ANNEX C

MECHANICAL ANALYSIS: STATIC CALCULATION OF COMPLIANT BACKPLATE

CASE 1: TRANSLATION ALONG Z-AXIS

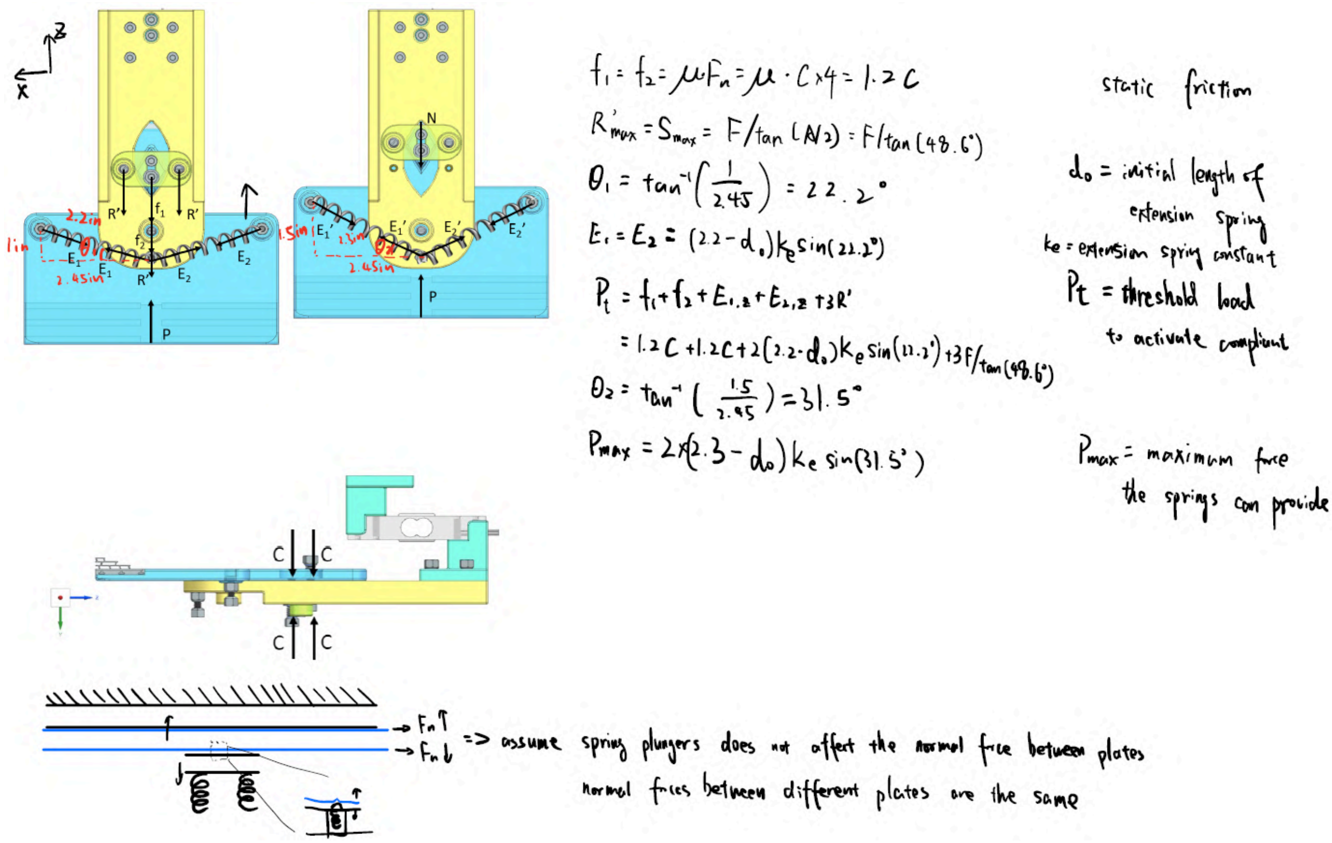


Figure 12. Compliant backplate static analysis and calculation under load in Z+ direction

In Figure 12, R' is the z component of the Reaction force in Figure 1, E is the force from the extension springs at the initial position, E' is the tensile force by stretching the extension springs, P is the force exerted on the moveable backplate(blue) in Z+ direction, f is the friction, C is the compressive force provided by the compression springs, and N is the normal force provided by the stationary backplate(yellow) to the compliant backplate(blue) when the complaint system reaches its maximum range.

CASE 2: ROTATION ALONG Y-AXIS

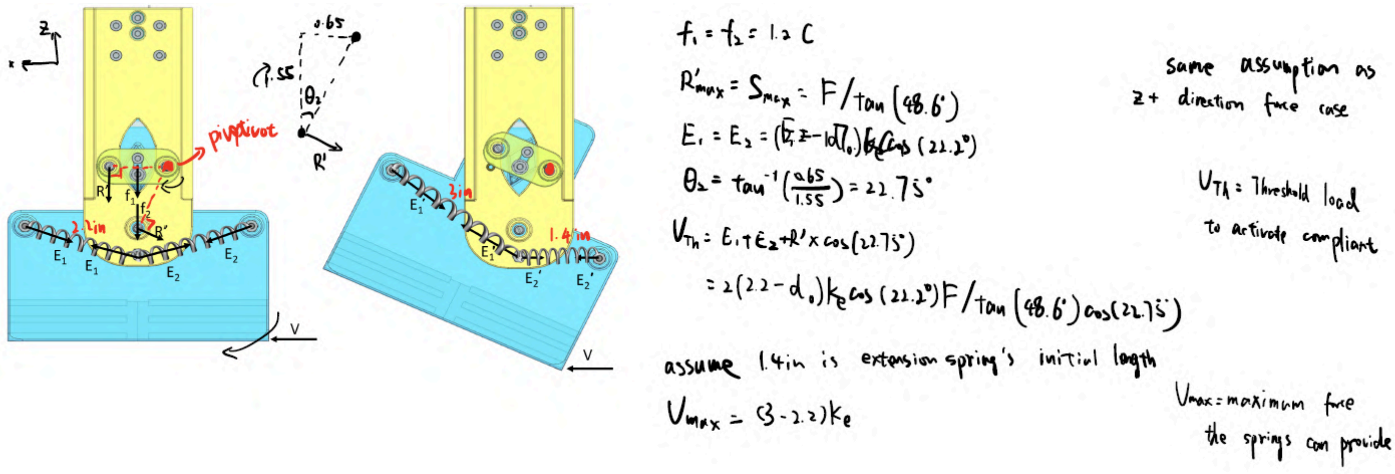


Figure 13. Compliant backplate static analysis and calculation under load in X direction

In Figure 13, V is the force exerted from the side to the moveable backplate(blue) at the bottom edge.

CASE 3: ROTATION ALONG X-AXIS

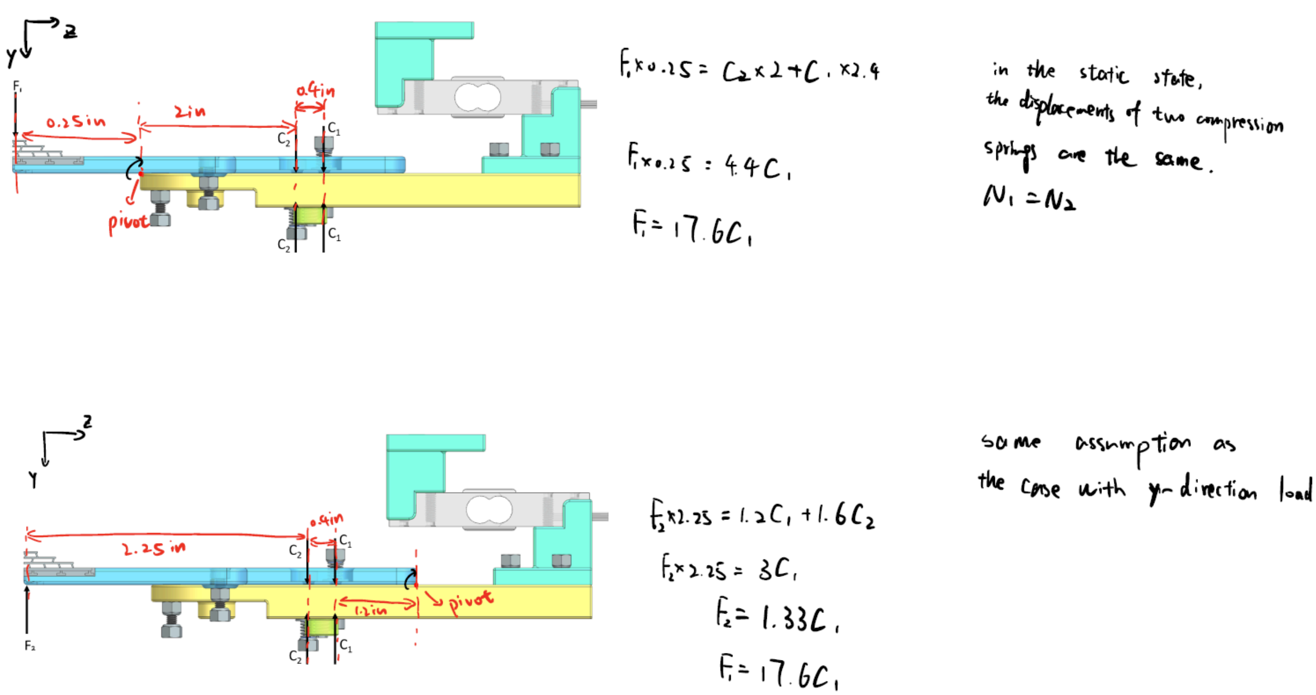


Figure 14. Compliant backplate static analysis and calculation under load in the Y direction

Requirement for Spring Sizing Based on Calculation and Design

extension spring min $d_o = 1.4\,in$

max $d > 3\,in$

	Coefficient of Friction:	0.3		Motor Max Torque	3.924	Nm
	Max Velocity (m/s):	1				
*from rest	*Time to Accelerate to Max Velocity (s	0.5		Max Clamp Force	25.07	N
*from rest	*Calculated Acceleration (m/s^2):	2				
	Acceleration of Gravity (m/s^2):	9.81				

Object Name:	Chips_Can	Potted_Meat_Can	Banana	Spatula	Wood_Block	Padlock	Large_Marker	Hammer	Tennis_Ball	Foam_Brick
Mass of YCB Object (Kg)	0.205	0.37	0.066	0.0515	0.729	0.208	0.0158	0.665	0.058	0.028
Clamp force [Static] (N)	3.35	6.05	1.08	0.84	11.92	3.40	0.26	10.87	0.95	0.46
Clamp force [Dynamic] (N)	4.04	7.28	1.30	1.01	14.35	4.09	0.31	13.09	1.14	0.55

$P_t = f_1 + f_2 + E_{1,2} + E_{2,2} + 3R'$

$= 1.2C + 1.2C + 2(2.2 - d_o)k_e \sin(22.2^\circ) + 3F/\tan(48.6^\circ) >$ weight limit

$P_t > (3kg - 0.665kg) \times 9.8 N/kg$

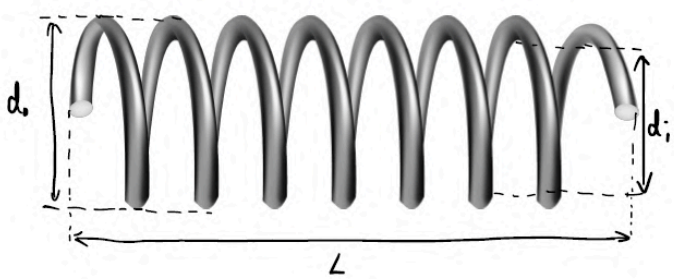
$P_t > 22.9N > 5.15lb$ slightly

$F > 25.07N$

$V_{Th} = E_1 + E_2 + R' \times \cos(22.75^\circ)$

$= 2(2.2 - d_o)k_e \cos(22.2^\circ) F/\tan(48.6^\circ)\cos(22.75^\circ) > 2lb$

According to the design



the compression spring's $d_i > 4mm$, $d_o < 7mm$, $C_1 = (L_o - 0.19\,in)k$

L_o ↳ initial length

Figure 15. Summary for the spring sizing requirement based on previous calculations in three different cases and design

Test Requirement for Selected Spring

Selected springs' parameter:

compression spring:

d_i : 0.2 in = 5.08 mm > 4 mm

d_o : 0.24 in = 6.1 mm < 7 mm

L_o : 0.25 in = 6.35 mm

k : 10.41 lb/in

max load: 1.33 lb

C_1: (0.25" − 0.19") × 10.41 lb/in = 0.625 lb

$F_1 = 17.6C_1 = 13.0\,lb = 57.8\,N > 25.06\,N$

$F_2 = 1.33C_1 = 0.83\,lb = 3.69\,N$

spring plunger:

$F = 2N = 0.45\,lb$

$S = F/\tan 48.6 = 1.76\,N = 0.4\,lb$

extension spring:

$L_o = 2\,in - 0.42\,in \times 2 + 2 \times 0.045\,in = 1.25\,in < 1.4\,in$

$k = 4.1\,lb/in$

$P_t = f_1 + f_2 + E_{1,2} + E_{2,2} + 3R'$

$= 1.2C + 1.2C + 2(2.2 - L_o)k_e \sin(22.2^\circ) + 3F/\tan(48.6^\circ)$, where $C = 0.625\,lb$

$= 5.6\,lb > 5.15\,lb$

$V_{Th} = E_1 + E_2 + R' \times \cos(22.75^\circ)$

$= 2(2.2 - L_o)k_e \cos(22.2^\circ) F/\tan(48.6^\circ)\cos(22.75^\circ)$

$= 2.7\,lb > 2\,lb$

Figure 16. Test requirements in Figure 15 for the selected spring

MECHANICAL ANALYSIS: FEA OF DOVETAIL MOUNT

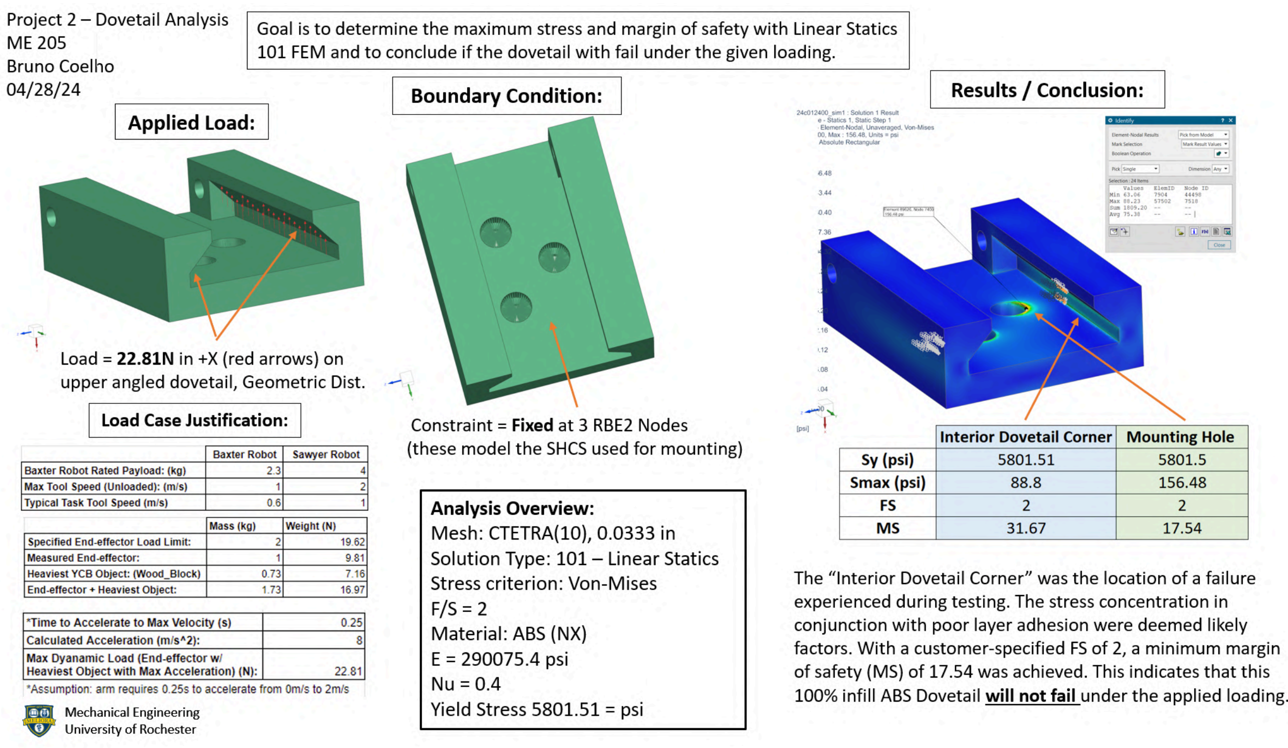
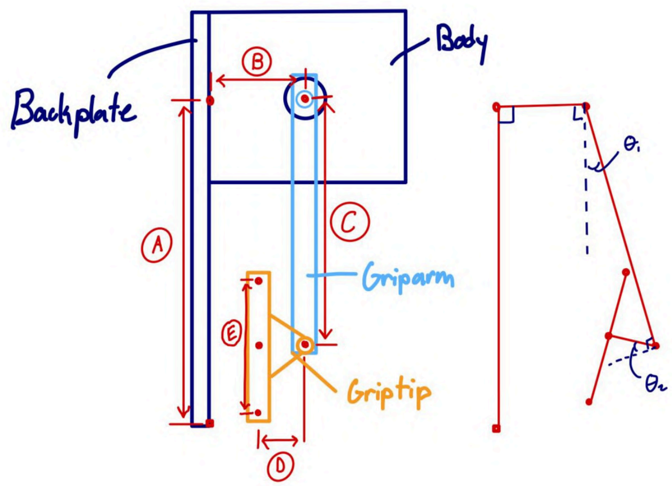


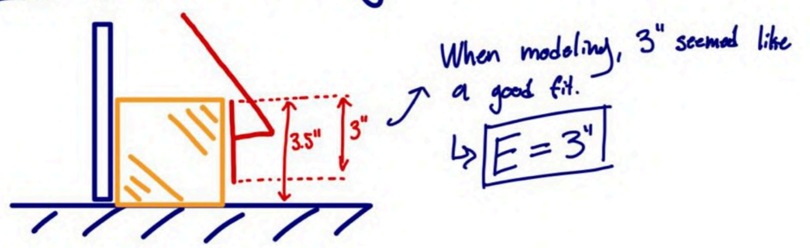
Figure 17. Tabulated results of FEA analysis of dovetail and material properties used



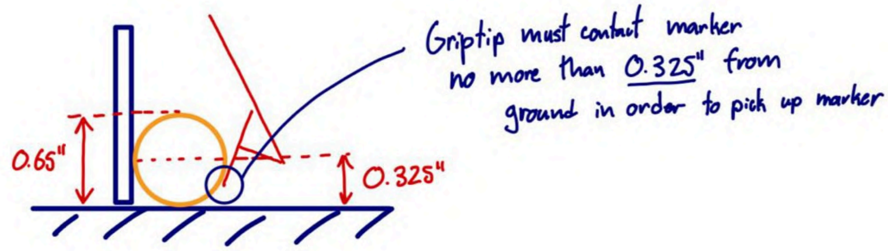
Tallest object : Wood_Block → 3.5" x 3.5"

Smallest object: marker → 0.65" ∅

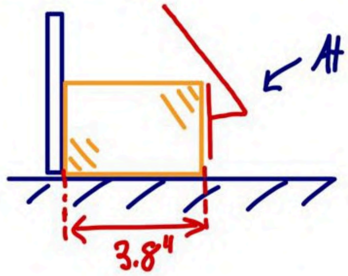
↳ Wood_block informs length of Griptip



↳ Smallest object radius = 0.65"



↳ Widest object: Potted_meat_can (sideways)



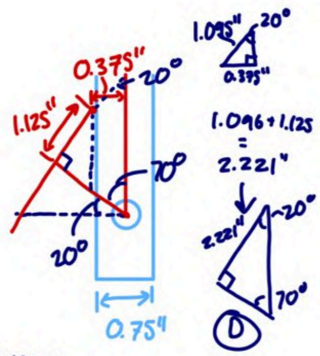
← At 3.8" away from backplate, Griptip must be able to be parallel w/ object → influences Θ_2, (B), and (C)

Starting Values:

E = 3"

$\Theta_{2(max)} = 20°$

↳ Solve for D.



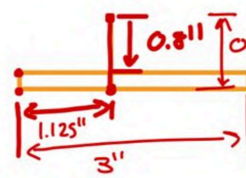
Let connection between Griparm and Griptip intersect at 90°

↳ Non-centered grip tip connection permits greater max ROM.

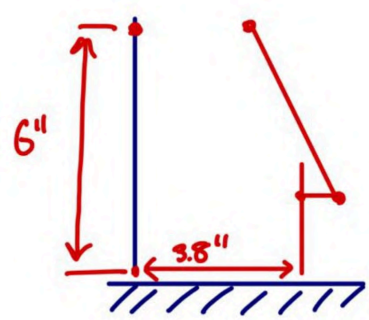
D = 0.8"

↳ Let thickness of griptip = 0.1" at tip,

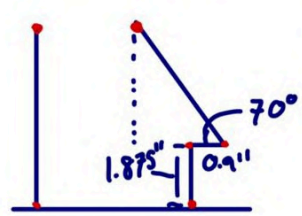
Distance between pivot and bottom face of griptip = 0.8" + 0.1" = 0.9.

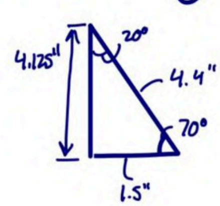


Widest Object BC:



Let backplate be 6" long.





C = 4.4"

A = 6"

B = 3.8" − (1.5" − 0.9") = **3.2"**

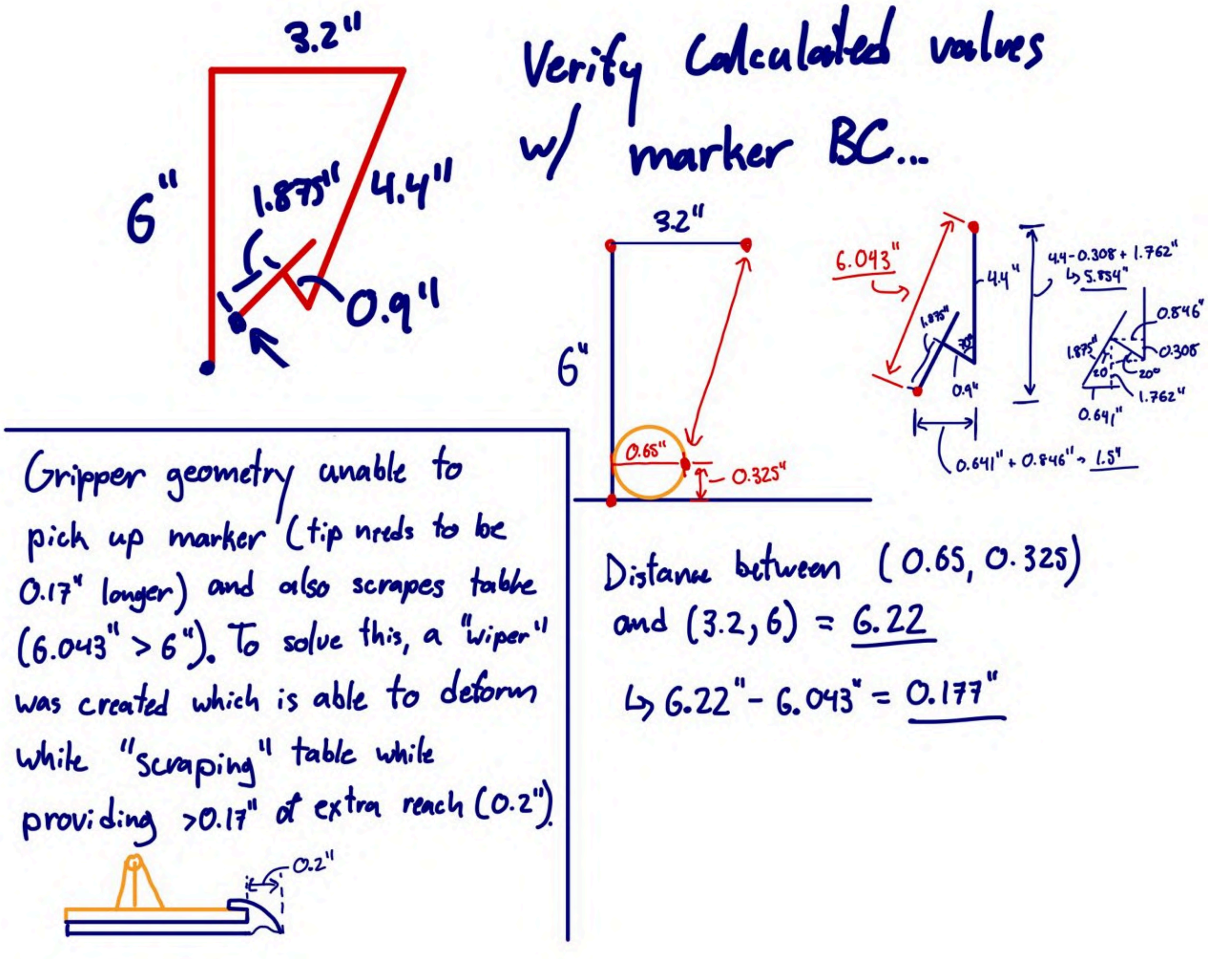


Figure 18. Derivation of primary gripper geometry

Annex D
Manufacturing
Cost of Purchased Parts

Parts Name	Quantity	Description	Cost/Each
Intel RealSense Camera D405	1	Camera	$272.00
AGFRC 40kg Waterproof Servo (A73BHLW V2)	2	Arm Servo	$76.99
25KG Digital RC Servo with U Mount Brackets (RDS3225MG)	1	Camera Servo	$17.40
Arduino Nano	1	Microcontroller	$24.90
Micro Maestro 6-Channel USB Servo Controller	1	Servo Controller	$24.95
Load Cell Weight Sensor (10kg) + HX711	1	Load Cell	$5.98
Al7075 25T Servo Horn (HSS20AG)	2	Servo Horn	$12.99
Binding Barrels and Screws 18-8 SS, 8-32, 1/4"-3/8" Matl	2	Spring Barrel	$1.47
Binding Barrel and Screw M4 x 0.7, 40-42 mm Thickness	2	Fingertip Barrel	$16.17
Torsion Spring 180 Degree Right-Hand Wound, 0.363" OD	2	Right Spring	$1.02
Torsion Spring 180 Degree Left-Hand Wound, 0.363" OD	2	Left Spring	$1.02
Ball Point Set Screws M5 x 8mm, 304 SS	3	Spring Plunger	$0.5
SS, Compression Springs 0.25" Long, 0.24" OD, 0.2" ID	2	Compression Spring	$1.08
Music Wire Spring with Loop 2" Long, 0.42" OD, 0.045" Dia.	2	Extension Spring	$3.38
Threaded Heat Insert, M3, M4, M5	~	Heat Insert	$19.88
Button Hex, M3, 8mm Screw	3	Camera-Servo	$0.09
Button Hex, M3, 12mm Screw	2	Camera Servo-Body	$0.11
Socket, M4, 10mm Screw	15	Body Mount	$0.15
Socket, M4, 16mm Screw	25	Servo Mount	$0.13

Socket, M4, 25mm Screw	2	Dovetail Mount	$0.20
Socket M6, 10mm Screw	4	Dovetail Mount	$0.11
M3 Medium Nylon Locknut	2	Camer Servo-Body	$0.05
M4 Medium Nylon Locknut	19	Backplate M4	$0.06
Female-Female Jumper Wire	~	Jumper Wire	$6.98
Multipurpose 6061 Aluminum Bar	~	Motor Mount	$4.34
		Total Cost	$589.34

Table 3. Cost of purchased mechanical and electronic components

Cost of 3D Printed Parts

Part Name	Usage	Material	Time (hour, minutes)	Used Filament (g)
24c012500.stl	Camera Mount	PLA	9m	0.95
24c026053.stl	Baxter Mount	PLA	5h25m	49.32
24c026052.stl	Sawyer Mount	PLA	3h24m	26.19
24c012400.stl	Dovetail Mount	ABS	2h46m	19.46
24c012401.stl	Body Back	PLA	3h15m	29.23
24c012402.stl	Body Front	PLA	2h28m	22.38
24c012406.stl	Electronic Mount	PLA	1h18m	10.58
24c012407.stl	Electronic Mount Clip1	PLA	7m	0.62
24c012408.stl	Electronic Mount Clip2	PLA	14m	1.20
24c012405.stl	Body Bottom	PLA	2h53m	24.86
24c013842.stl	Vertical Arm	PLA	2h0m	15.71
24c013843.stl	Angle Arm	PLA	1h34m	13.20
24c012409.stl	Servo Bushing	PLA	5m	0.44
24c013845.stl	Vertical Fingertip	PLA	5h40m	36.76
24c013846.stl	Angle Fingertip	PLA	4h22m	27.48
24c013844.stl	Vertical Skin	TPU	3h54m	18.56
24c013847.stl	Angle Skin	TPU	23m	1.80
24c044513.stl	Load Cell Block	PLA	1h34m	10.55
24c044519.stl	Stationary Backplate	PLA	5h1m	45.59
24c044522.stl	Movable Backplate	PLA	7h34m	73.14
24c044526.stl	Support Plate	PLA	40m	4.73
24c044524.stl	Backplate Skin Left	TPU	1h28m	6.63
24c044525.stl	Backplate Skin Right	TPU	1h28m	6.63
		Total Cost	57h42m	PLA: 392.93g / $10.61 ABS: 19.46g / $0.53 TPU: 33.62g / $3.05

Table 4. Cost and printing time of 3D print parts(In PrusaSlicer; 0.15mm QUALITY; Supports: Everywhere; Infill: 30%)

ANNEX E
SPECIFICATIONS

	Required Value	Description	Method of Test	Real value	Pass/Fail
1	3 kg	The weight of the gripper with the end effector adapter must be smaller than this value	Weight balance	0.8813 kg	Pass
2	3 sec	Every YCB benchmark object must not fall/drop or move after the gripper grasp	Video Assessment	>3 second	Pass
3	2 kg	The connection between the gripper and the baxter & sawyer robot must be fastened and connected preventing detachment when the arm is oriented downward under this load	spring dynamometer	>2 kg	Pass
4	$1000	Must stay under budget	check the money spreadsheet tab	$777.77	Pass
5	1 sec	The end-effector must close and open within the range	Timer	0.31s/0.24s	Pass
6	2 FS	Materials and Boundary Conditions' Uncertainty must be under this factor of safety	FEA assessment of critical part	17.54	Pass

Table 5. Specification

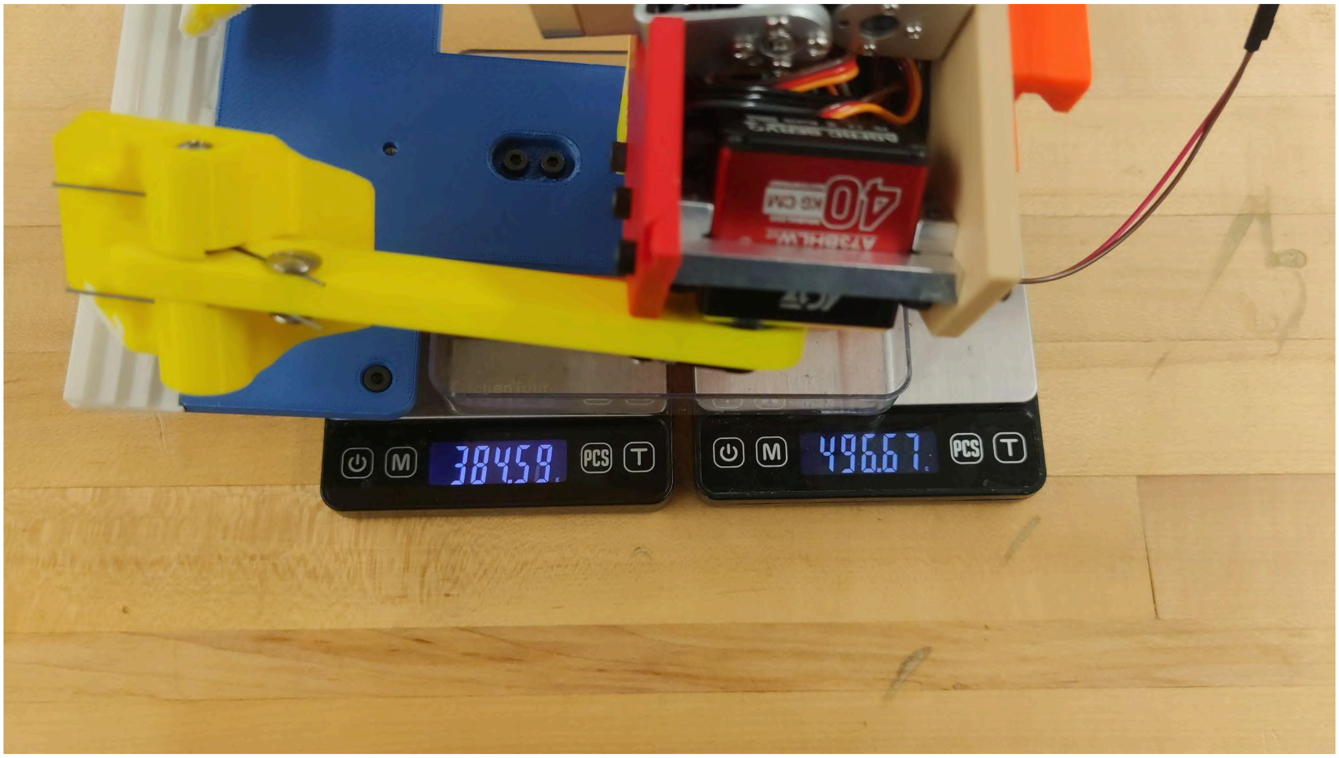


Figure 19. Test of Specification 1(Weight limit)

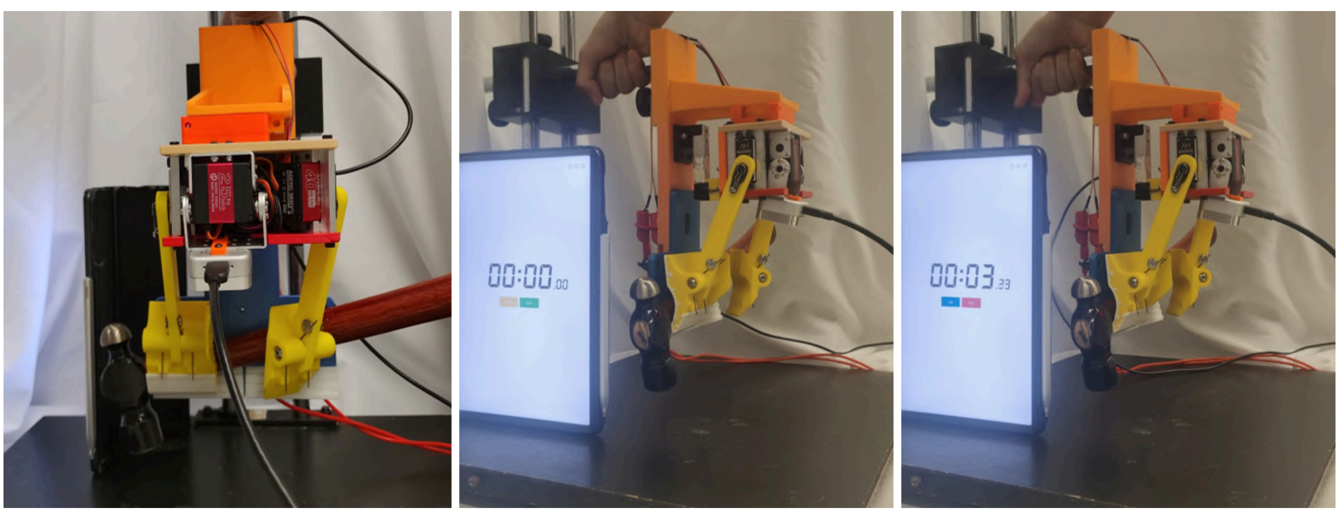


Figure 20. Test of Specification 2(Hammer)

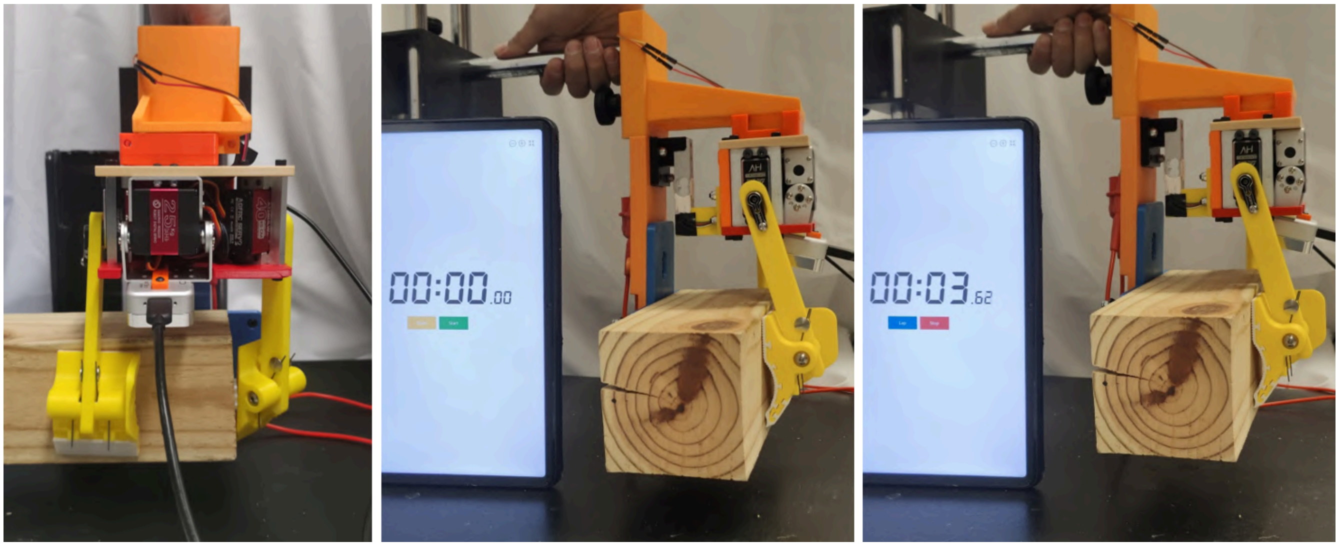


Figure 21. Test of Specification 2(Wooden Block)

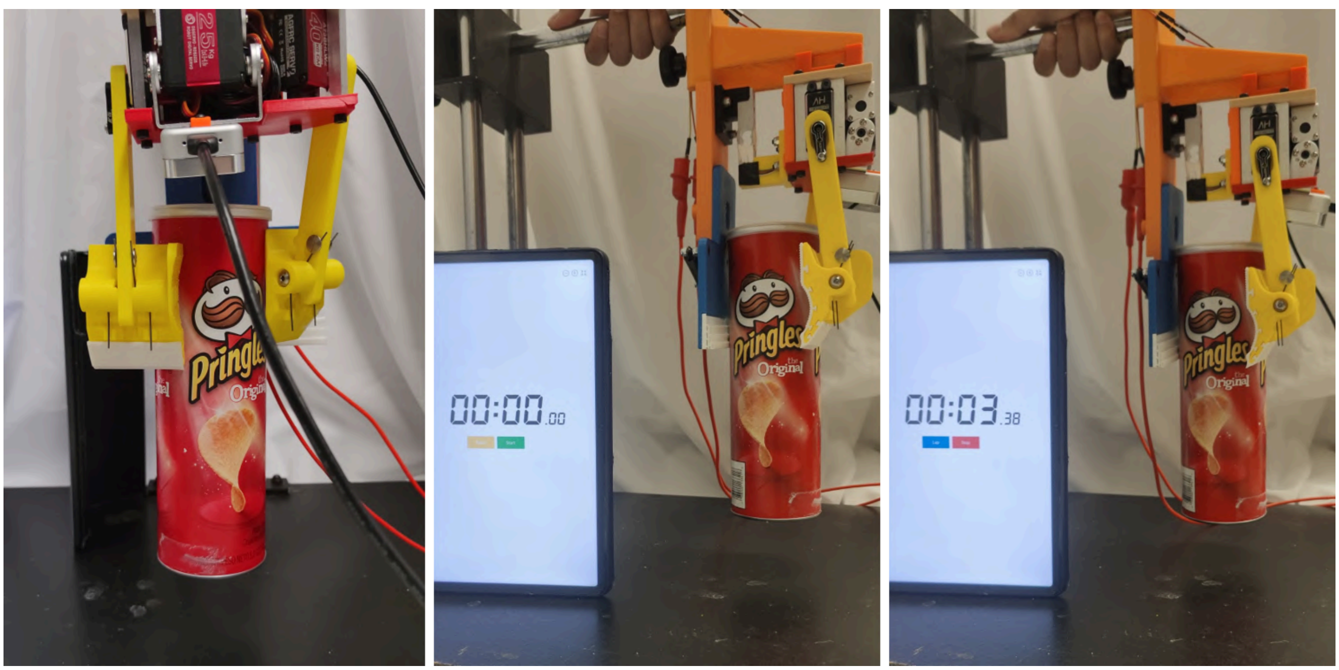


Figure 22. Test of Specification 2(Chip Can)

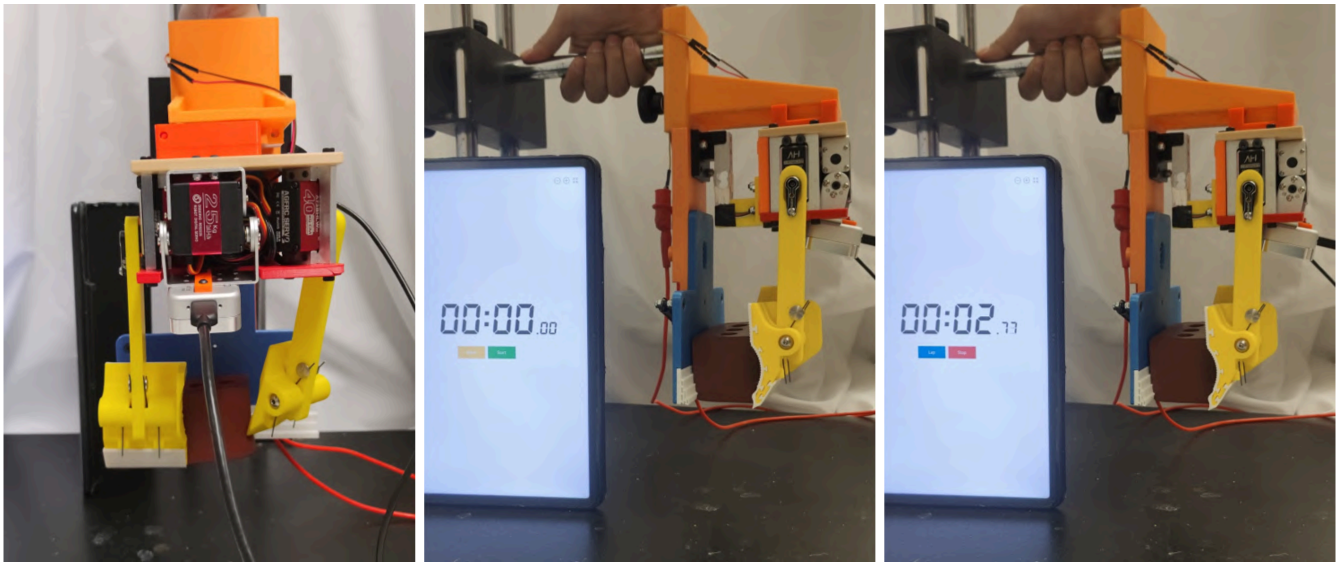


Figure 24. Test of Specification 2(Foam Block)

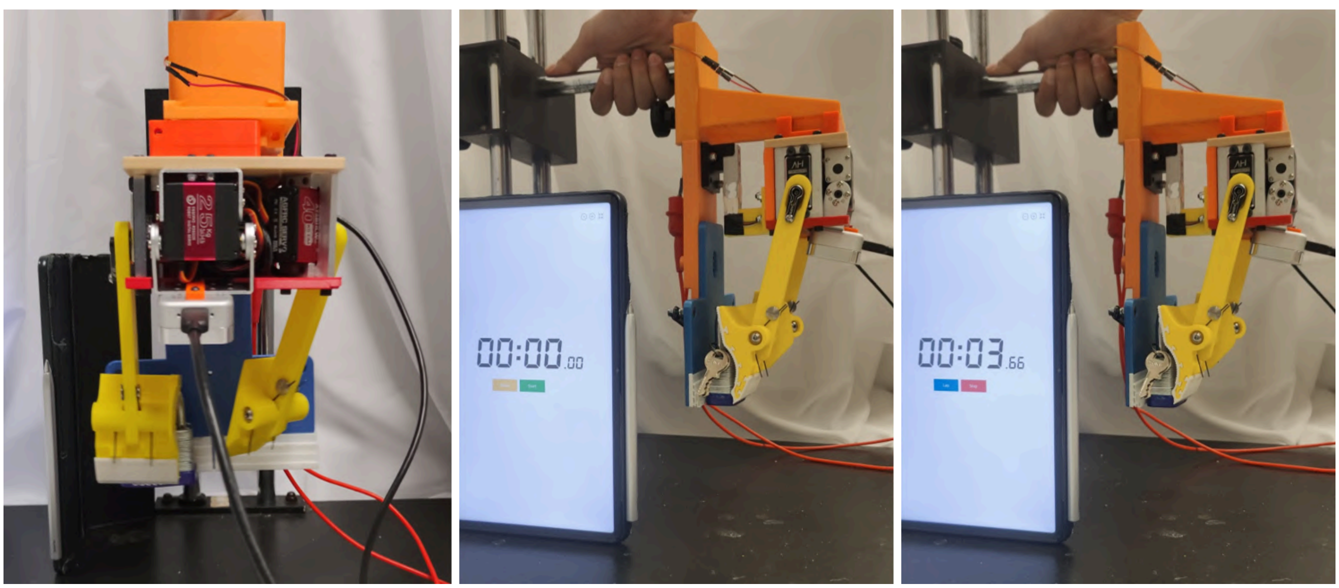


Figure 25. Test of Specification 2(Padlock)

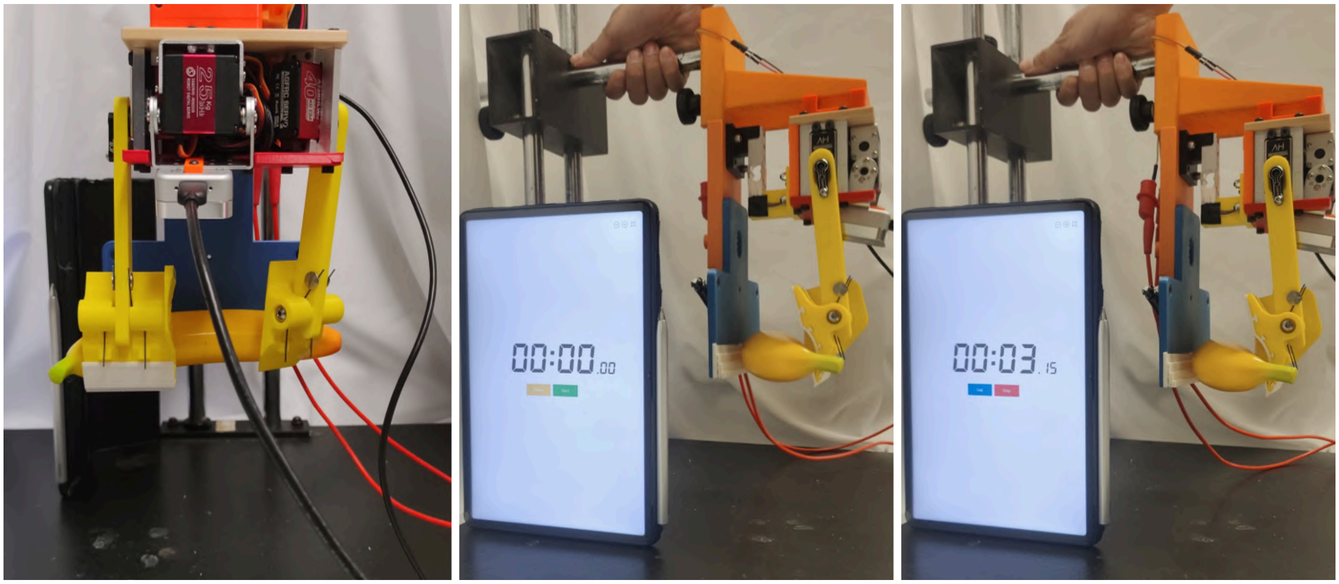


Figure 26. Test of Specification 2(Banana)

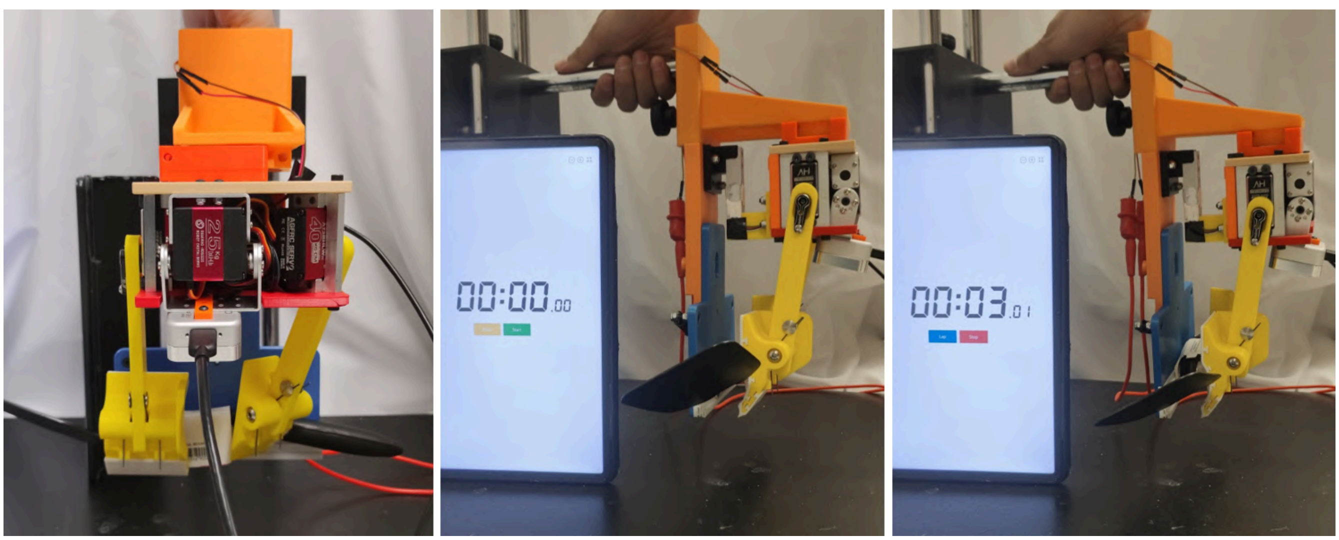


Figure 27. Test of Specification 2(Spatula)

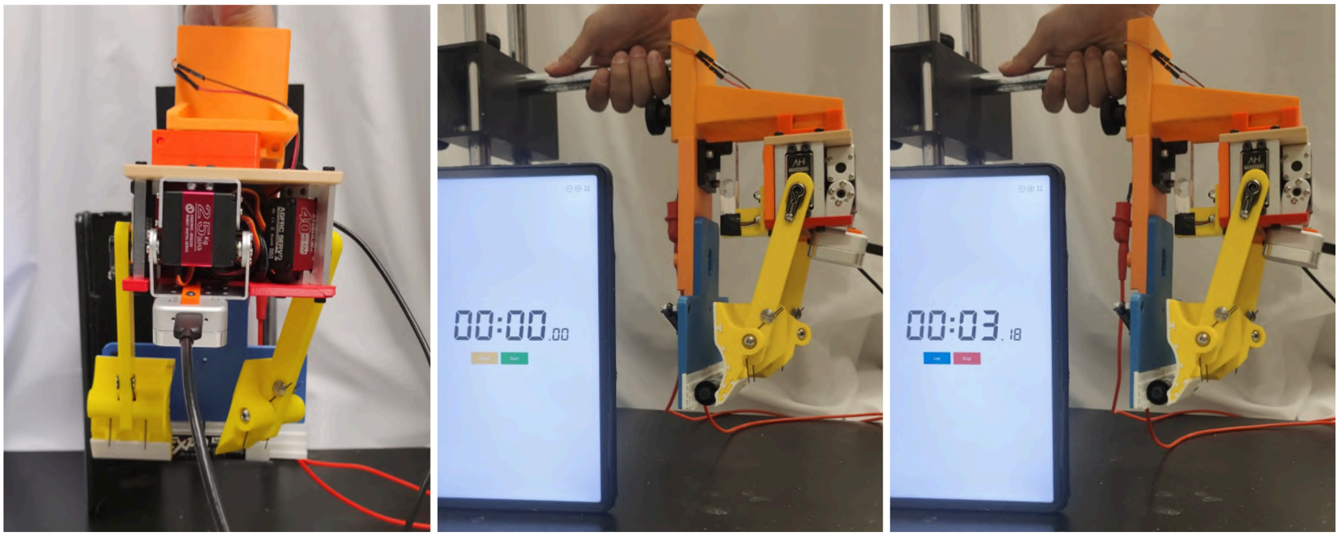


Figure 28. Test of Specification 2(Marker)

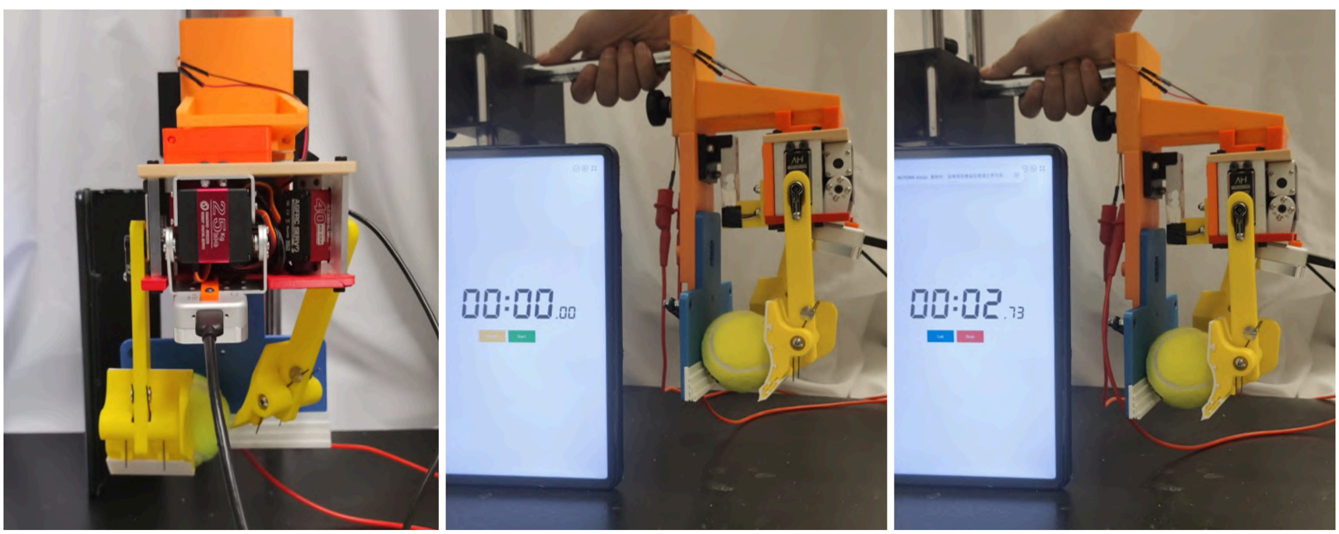


Figure 29. Test of Specification 2(Tennis Ball)

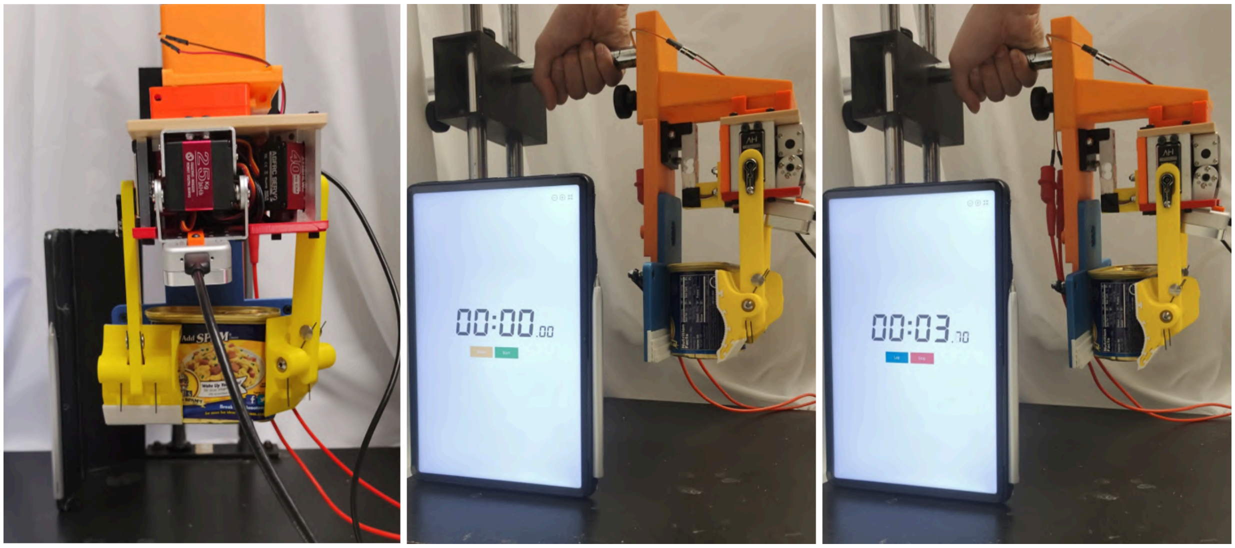


Figure 30. Test of Specification 2(Spam)

Week	Parts	Services			Burn		Burn Line
1/15/24					$ -	1	0.0
1/22/24					$ -	2	66.7
1/29/24					$ -	3	133.3
2/5/24					$ -	4	200.0
2/12/24					$ -	5	266.7
2/19/24					$ -	6	333.3
2/26/24					$ -	7	400.0
3/4/24					$ -	8	466.7
3/11/24					$ -	9	533.3
3/18/24	370.39				$ 370	10	600.0
3/25/24	243.2				$ 614	11	666.7
4/1/24					$ 614	12	733.3
4/8/24	101				$ 715	13	800.0
4/15/24	52.57				$ 767	14	866.7
4/22/24					$ 767	15	933.3
4/29/24	10.61				$ 778	16	1000.0

Figure 31. Test of Specification 4(Budget)

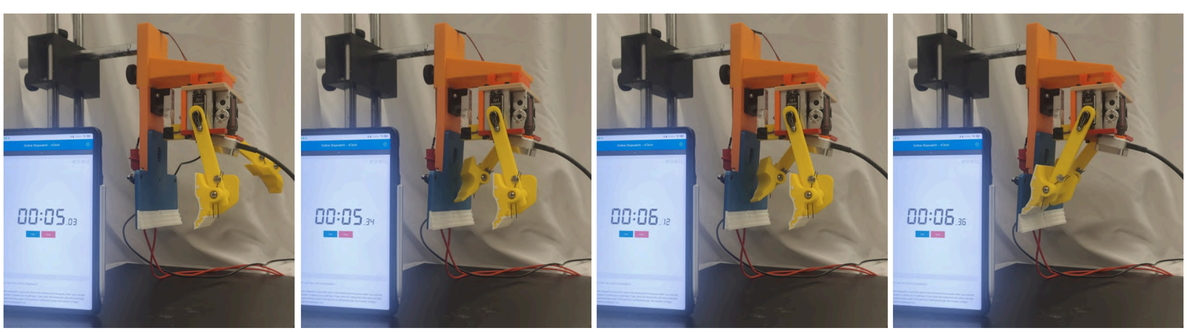


Figure 32. Test of Specification 5