MAGPIE^2: Designing a Robust and Manufacturable Robot Gripper with Built-in 3D Perception, Speed, Force, and Position Control for Autonomous Manipulation

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1 Abstract

This paper presents the design and development of a versatile robot gripper, the MAGPIE[2], that prioritizes strength, robustness, ease of manufacturing, and eye-in-hand capabilities. Unlike grippers tailored for specific tasks or objects, this gripper aims for generality through a linkage design. The entire gripper is designed using cheap materials like 3D-printed PLA and inexpensive fasteners, employing a simple 4-bar linkage system. Motors with speed, position, and force control capabilities are selected to drive the gripper. The developed gripper exhibits 32 Newtons of force at the fingertips and achieves tasks with tolerances below $< 0.5mm$. Extensive testing on the widely used YCB dataset demonstrates the gripper's versatility with a success rate of 93%. Moreover, 3D perception integrated at the palm of the hand enhances visual feedback throughout the grasping process. The assembly of the Siemens gear assembly problem, a sensor-based stacking, and force control experiments are conducted to evaluate the gripper's precision, strength, force control, and camera capabilities.
Keywords— YCB dataset, 3D printing, PLA, Siemens Gear Assembly, robot manipulation

2 Introduction

Robot manipulation was developed to replace dull and easy work that humans were doing. The consistency, strength, speed, and cost are some factors when considering a robot over a human. Robot arms can lift up to 1000 kg, are repeatable to 10 μm, and are faster with accelerations up to 15g[1]. Now more then ever robot arms are being used across different industries.

Currently grippers are being used in industrial settings. This can be split into categories of known and unknown environments. Grippers in known environments will rely on consistent set ups. This usually will have predefined setups and starting locations. The robot arms will also have a clear idea of what the configuration space looks like around them. These systems will have simple feedback systems. For unknown environments vision will become a huge a thing to consider. Cameras, with color and depth sensors are important to distinguish how the world looks around them. This can include classification of items and segmentation to detect the presence of objects. The environment can never be determined with absolute uncertainty so planners and probabilistic models are vital to the success of the robot arm[1].

Robot arm's are developing in agriculture because of its proposed challenge of classifying ripe foods and the fragile nature of some foods[**?**]. Fragile objects are becoming a huge design consideration because its vital to not pick up foods and deform or damage the product. This proposes the problem of force control.

Medical is becoming a huge area of research and specifically surgery because robot's ability to be more consistent then a human. It is proposed that a robot will be able to deal with more difficult hand-eye coordination, limited workspace, and restrained dexterity [2]. The problem's that arise are gripper's lack of force feedback and the repercussions of error. A robot's precision and ability to deal with small tolerances becomes a huge design consideration.

Autonomous manipulation tasks that remain a challenge include picking, placing, assembly/disassembly, and packing; and involve a large variety of compliance, for example when tightening a metal nut vs. grasping a delicate raspberry. Often, tasks of varying dexterity and compliance need to be combined, requiring a highly versatile hardware and software system. Implementing such as system is difficult. Commercially available grippers have limited capabilities, particularly the absence of torque control, and therefore lack of active compliance [**?**]. Integration with vision systems is not straightforward; wrist-mounted, table-top, and palm-mounted cameras can be occluded at different times during operation. Finally, software frameworks such as ROS take considerable effort to commission and maintain, which is often unnecessary in particular when the goal is to investigate only one aspect of a manipulation pipeline such as vision or high-level reasoning. In this paper, we present a lightweight manipulation architecture geared at researchers, educators, and hobbyists, that is able to perform a wide variety of multi-step manipulation tasks, while being simple to manufacture and affordable.

The new approach proposed is to design everything out of cheap materials and 3d printing and fasteners with the goal in mind to pick up as many objects successfully. The gripper's simple 1 degree of freedom 4-bar mechanism will allow for position control because of the feedback from the motors position and easy to use kinematic model. The gripper will also be strong enough to pick up 90% of items on the YCB data set which is a current benchmark in the robot manipulation community. The gripper will also have eye in hand 3D vision capabilities. This gripper will give the robot manipulation research community a cheap and robust option for a robot gripper. It will also move the community forward with 3D-printed grippers and the ability to make a cheaper or more robust hand in the future. The hand currently costs \$460 and the structure without the camera costs \$190 to make. The gripper can take up to 1 day to manufacture with a 3-D printer. The risks of the hand is that it can't be as stiff as metals and because of that it will never be as precise. The plastic structure gives a more compliant nature which can help with tasks that require low tolerances like the peg and hole[3].Through this research, we anticipate that the developed robot hand gripper will significantly contribute to the field of robot manipulation. The affordability, simplicity, and robust performance of the gripper will empower researchers and developers to explore novel applications, test new designs, and accelerate progress in this evolving field. The evaluation of precision will focus on the gripper's ability to execute accurate and controlled movements. Touch response tests will be conducted to assess its sensitivity in detecting subtle changes in contact forces during object interaction. Moreover, the gripper's capability to delicately manipulate thin objects will be examined, as this demands precise finger coordination and control. Strength testing will be carried out using a force gauge to measure the maximum force exerted by the gripper at the tip of its fingers. By evaluating its gripping strength, the gripper's ability to handle objects of varying weights and sizes can be quantitatively assessed.

Furthermore, the gripper's vision capabilities will be evaluated through segmentation and classification techniques. Integration with cameras will enable the gripper to analyze its surroundings, distinguish objects, and make informed decisions regarding grasping and manipulation.

In the following chapters, we will delve into the design and implementation details of the gripper, followed by a comprehensive analysis of the experimental results obtained from the conducted tests. The findings will be discussed, providing valuable insights into the gripper's performance and its potential impact on the wider manipulation community.

3 Background

3.1 Different types of Robot Grippers

The end effector, also known as a gripper, serves as the device located at the termination of a robot arm, responsible for grasping and manipulating objects. These grippers can be customized to fulfill specific tasks or designed for versatility across a range of applications. In addition to object manipulation, grippers can also serve as a means to pick up tools used in various tasks such as welding, spray painting, drilling, and more. Within the field of robot manipulation, different gripper systems have gained popularity, including the following; Soft Grippers, Suction Vacuums, Granular Vacuums, and Mechanical Gripping[4]. The selection of a gripper system depends on the specific requirements of the task at hand, considering factors such as object properties, desired grip strength, precision, and operational constraints. The development and utilization of diverse gripper systems enhance the versatility and adaptability of robotic manipulation, enabling robots to tackle a wide range of industrial, commercial, and research applications effectively.

3.1.1 Soft Grippers

Soft grippers also known as under-actuated grippers because they can't follow arbitrary trajectories because of the degree of freedom of the mechanism is greater then the actuators. They are great at picking up objects with round surfaces or complex designs. Soft grippers lack precision because of the compliant nature of the material used. They have infinite degrees of freedom because of their flexible nature. This makes position control hard to do because their kinematic model is complex. Force control can also be hard because the actuators are controlled by compressed air. The soft gripper's shown in Table 1 show that they tend to also be weaker[5][6]. Manufacturing soft gripper's is considerably more complex then 3D printing in terms of curing it. When tolerance and strength isn't a big deal this can be the best option because it will be the easiest to pick up most objects.

3.1.2 Vacuum Robot Grippers

Vacuum grippers are the best at picking up complex objects. Granular vacuums specifically will tend to struggle with objects that are flat and tasks that need high precision because of the compliant nature of the gripper when the vacuum is released [7, 8, 9, 10]. Vacuums can be harder to control with specific forces. Granular vacuums can't be precise because of its compliant nature and form fitting nature but are the best with complex objects. There can be sticking or adhesion that makes dropping objects unpredictable. Granular vacuums tends to be used with tasks that need to move objects quickly with not precise drop points. Granular Vacuums can also be harder to use with tasks.

Suction vacuums will be able to pick up flat or complex objects no different[11].Suction vacuums are successful in assembly and a good option for both precision and force. Advantages of vacuum grippers include the ability to handle many different types of items (even when those items are imperfectly positioned) and a lower price compared to other types of grippers. Disadvantages include added electricity costs to power compressed air or vacuum pumps and sensitivity to dusty conditions. You will find vacuum grippers being used to automate a wide range of tasks, but one of the most popular applications for this type of gripper is packaging and palletizing.

3.1.3 Mechanical Grippers

Mechanical grippers are great when needing a moderate amount of force and precision with high speeds. Mechanical gripper will tend to have trouble with objects that are complex or round because it can have smaller area of contact. There are a few research groups pushing the boundaries of hard grippers. They are the easiest to model the kinematic models for because they are rigid.

The Yale gripper uses a cable driven design with its motors. It has different positions for the gripper to be in. The pictured one is an offset of 120 degrees[12]. It also has the ability to have its fingers in parallel and anything in between. The design was influenced by the ability to be easily manufactured. It can be 3D printed and manufactured cheaply. the gripper has linkages that are a softer material. This will make the gripper more compliant but allow the object to pick up heavier objects and more complex designs of objects. The gripper is strong but also very big in comparison. This gripper showed to struggle in the YCB data set with small and thin objects.

The Tsu Hua University group is one of the leaders in the eye in hand gripper[13]. There design has multiple degrees of freedom to form around an object. This will make the gripper more compliant but allow the gripper to pick up more unique objects because of more surface contact. The Tsu Hua University group use a set of 4 bar linkages linked to each other. Eye in hand vs eye on hand has its strengths with its ability to have a better vision of the object. There is also no offset for the inverse kinematics of the gripper. The gripper uses 3 fingers to mimic a thumb. There design also allows for the gripper to be in 2 different positions for better manipulation. The one pictured is the fingers all parallel. It also has the ability to offset the fingers by 120 degrees to surround the object. The grippers actuation is a motor with a rack and pinion design. The gripper does not have force control because of 1 actuator controlling the gripper and is incredibly complex to replicate.

Robotiq has created a gripper that is very robust[14]. This gripper has 2 degrees of freedoms and 5 bar linkage for its kinematics and dynamics. This gripper is commercialized currently and used in industrial settings because of its high strength and precision. The gripper has incredible strength but the price is quite high.

3.2 Current Benchmarks

The "gold standard" in manipulation is the human hand, which is able to perform an extensive range of tasks, including tool usage and in-hand manipulation [15]. Benchmarking an end-effector design is a challenging problem and subject to research. It is difficult to disentangle grasp planning from perception [16], robot arm from end-effector performance [17], and versatility from specialization, e.g. cloth manipulation [18] or warehouse picking [19].

One way to evaluate the capability of a hand design is to subject it to a wide variety of household tasks [20] that overlap with upper-limb prosthetic applications. In such a test, underactuated designs such as the Pisa hand [**?**] and a 100-year old claw design that has only a single actuated finger [**?**] have outperformed all other designs in [20]. Although the Pisa hand's compliance is advantageous when operating scissors, e.g., a simple mechanical design is intriguing due to its manufacturability, robustness, and simpler control [**?**] while still being highly versatile.

Although versatility is not important in conventional automation using highly specialized end-effectors such as during warehouse picking or assembly of the same part, versatility will become critical for recovering from errors or when a task not only requires picking, but precise placement, e.g. during packing.

The YCB data set is a great benchmark for testing a robot gripper's capabilities because of its versatility and because it's easy to access[21]. It has an array of objects from kitchen utensils, to plastic fruits, to thin washers. It can test precision and stiffness with thin objects. It can test strength with the heavy bottles and cans. It can test the balance of compliance and stiffness with round objects such as the plastic fruit and balls. It has an array of tasks to test the overall ability and AI of the gripper. Some of these tasks include a gear assembly and stacking blocks. A gripper with vision capabilities, strength, and stiffness should succeed in most of these objectives. [22] [23] [24]

Figure 1: The list of items on the YCB data set

3.3 Comparison

Gripper	Style	Force/Actuators	Aperture	DOF/finger	Weight
Tsing Hua University [13] 2a.	Linkage	50N/1	160mm	4+	1.5 kg
Yale Open-Hand[25] 2b.	Linkage	12N/1	200+mm	3	.5 kg
Robotiq Hand-e[14] 2c.	Linkage	20-185N/	50mm	2	1 kg
Robotiq 2F-85[14] 2d.	Linkage	20-235N/	85mm	2	.9 kg
Robotiq 2F-140[14] 2e.	Linkage	10-125N/	140mm	2	1 kg
Robotiq 3-F[26] 2f.	Linkage	3-70N/	155mm	2	2.3 kg

Barret Hand[27] 2g.	Linkage	20N/2	335mm	2	.98 kg
Schunk SVH 5-F[28] 2h.	Hand	N/A	200+mm	2	1.3 kg
Schunk EGU[28] 2i.	Linear	450N/	41mm	2	1.47 kg
i-HY[29] 2j.	Linkage	15N/5	200+mm	2	1.39 kg
Reflex[30] 2k.	Linkage		200+mm	2	.8 kg
Onrobot RG2[11] 2l.	Linkage	40N/	110mm	2	.78 kg
Onrobot RG6[11] 2m.	Linkage	120N/	160mm	2	.8 kg
Onrobot 2FG7 [11] 2n.	Linear	140N/	49mm	1	1.1 kg
Onrobot 3FG15 [11] 2o.	Linear	240N/	150mm	1	1.15 kg
Onrobot VGC10 [11] 2p.	Vacuum	6-15kg/1	Inf	1	.81 kg
Onrobot SG-a-H [11] 2q.	Soft	380N/1	40mm	Inf	.77 kg
Nanjing University [6] 2r.	Soft	2.4N/1	50mm	Inf	.06 kg
Bio-Inspired Hand [31] 2s.	Hand	/1	200+	3kg	
Magic Ball Gripper [10] 2t.	Vacuum	18/1	Inf	Inf	.1kg
Polypus [9] 2u.	Vacuum		200+	Inf	
Octopus Sucker Gripper [7] 2v.	Vacuum	46N/1	N/A	Inf	
Flexible Vacuum Gripper [8] 2w.	Vacuum	19.6N/1	N/A	Inf	
ANFIS Gripper [32] 2x.	Linear	/1	N/A	Inf	
Three-Fingered Prismatic Gripper[12] 2y.	Linear	40-60N/1		3	.7kg
GTAC 4-finger[33] 2z.	Linkage	/4		2	
3-Finger Soft Gripper[5] 2aa.	Soft	4.2kg/1	80mm	Inf	1.2kg
Reconfigurable Gripper [34] 2ab.	Linkage	100N/3	72mm	2	.82
Robotic Materials Hand [35] 2ac.	Linkage	/2	106.6mm	1	.25kg

Table 1: A comparison of recent development of grippers in recent research or industry

Table 1highlights the problem in robot manipulation which is not all information is transparent. Not every gripper show in Table 1 has all the information easily accessible. The categories in Table 1 are important because it gives an idea of the strength, weight, and targeted application. A gripper with 1 DOF will target simple objects and one with multiple degree of freedoms will want to pick up complex shaped objects. There are a lot of hidden variables that aren't shown in Table 1. These include dimensions, voltage, current, actuator selection, price, and a possible camera. These hidden variables can deceptively make some grippers a way better choice. The important ones to look at are GTAC and Yale Grippers [33][25][12]. The GTAC and Yale grippers have a benchmark associated to them and make comparing to them a lot easier. All are mechanical mechanisms which will be the basis of the gripper being designed. Vacuum Gripper's can be strong which is shown in Table 1 but its infinite degrees of freedom will cause issues with precision. The soft gripper's will tend to be weaker because research isn't at the point of making precise and strong soft gripper's. All the gripper's with more then 2 finger's struggle with small and thin object's except Yale's gripper[12]. Most gripper's in Table 1 are between .5-1.5kg and pictured with UR robots when using. For smaller robot arms it can be important to get closer to the .5kg range.

Figure 2: a.Tsing Hua University b.Yale Open-Hand Project c.Robotiq Hand-e d.Robotiq 2F-85 e.Robotiq 2F-140 f.Robotiq 3-F g.Barret Hand h.Schunk SVH 5-F i.Schunk EGU j.i-HY k.Reflex l.Onrobot RG2 m.Onrobot RG6 n.Onrobot 2FG7 o.Onrobot 3FG15 p.Onrobot VGC10 q.Onrobot SG-a-H r.Nanjing University s.Bio-Inspired Hand t.Magic Ball Gripper u.Polypus v.Octopus Sucker Gripper w.Flexible Vacuum Gripper x.ANFIS Gripper y.Three-Fingered Prismatic Gripper z.GTAC 4-finger aa.3-Finger Soft Gripper ab.Reconfigurable Three-Finger Robotic Gripper ac.Robotic Materials Hand

3.4 Eye in hand

Looking at Table 1 there are only 2 grippers with camera capabilities. The robotiq grippers have a wrist attachment that allows for a camera[14]. The Tsing Hua University gripper has eye in hand capabilties[13]. Currently Eye-in-Hand shows easily calculations and excellent results. The transformation from the end effector is a lot easier to calculate then a separate camera in the configuration space relaying information to the robot arm. National Taiwan University of Science and Technology demonstrates a simple look and control strategy with capabilities of overall error of 1.2 mm for positioning and 1.0° for orientation angle[36]. An active vision system is also preferred because of the ability to get different perspectives on objects. The ability to also perceive features until the final movement phase can also increase success and ease of calculation with an accuracy of 95% success rate[13].

4 Procedure

4.1 Constraints

There are a lot of different variables that can go into the design of a new gripper. It is important to set boundaries for these specifications to have an idea on what purpose you want the gripper to have. For example a smaller and lighter gripper will need less power and allow the robot arm to move at faster velocities and accelerations but can lack strong forces to pick up big objects. The constraints considered in the design for the MAGPIE^2 are size and weight, price, manufacturability, vision, strength, and precision.

4.1.1 Size and Weight

What items you are going to pick up and in what space you are going to pick them up are going to vary. Most manipulators have a weight capacity due to the gravitational forces applied to the joints. Most grippers are made for acceptable use with industrial grade robot arms like the UR3 and UR5 both in Figure 3. These both have large payloads of 3kg and 5kg respectively[37, 38]. Weight then becomes a small constraint for the design of the gripper but these robot arms create a large barrier to entry because of the high price. Robot arms that are smaller will have smaller payloads such as the Dorna 2 and the Wlkata which are in Figure 3. For the gripper to be usable on these arms a tighter weight constraint needs to be made. Both these arms have a payload of 1.5kg[39, 40]. Creating a gripper that can be used on these arms will allow the robot manipulation community to grow. I created a constraint of .5 kg for the robot gripper to allow for a 1 kg pickup for small robot arms[39, 40]. 3D-printing and PLA will allow the MAGPIE^2 to fit under this weight. Limiting the metal to structural and tolerance uses will have to be minimal in order to keep the weight down. Keeping the system to a simple 4 bar mechanism and 1DOF allows the robot's structure to be minimal and keep to under the weight constraint.

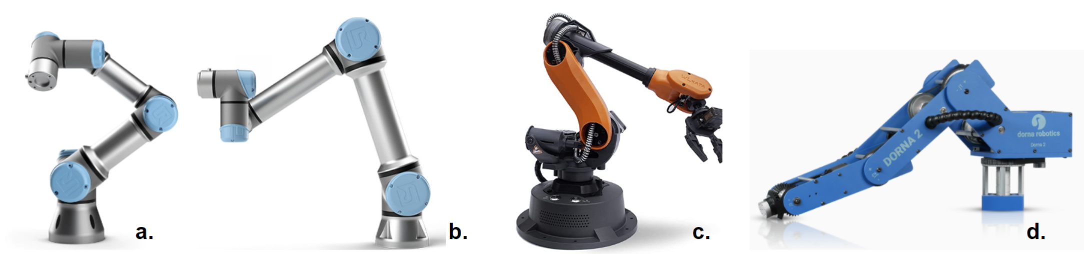

Figure 3: a.UR3 robot made for industrial purposes b. the UR5 robot made for industrial purposes c. Wlkata Mirobot uses for educational purposes d.Dorna 2 robot made for industrial and educational purposes)

The size of the gripper was not considered an important constraint in the development of the gripper. The length, width and height were set to a limit of 250mm, 250mm, and 100mm respectively.

4.1.2 Price

The price of robot grippers can be several thousand dollars[14, 26, 11]. There are different factors that can be contribute to the price such as hardware, materials, and manufacturing. When considering hardware. A motor with force, speed, and position control was a must. Working backwards from the Robotic Materials Hand[35] I considered the motor it used to be strong and have all the capabilities needed[41]. The motor used on the Robotic Materials Hand had a torque of 2.5Nm. The company was reliable with performance and the motor would be downgraded for a better price. The robotis Dynamixel's cheapest motor is the AX-12A4 which has 1.5Nm which will suffice and can act as strong as the XD430-T210-R motor4 with design changes to the 4-bar mechanism to allow for more grip force. The OpenRB-150 board4 is able to control the AX-12A motors and was the cheapest option from Dynamixel[41]. The camera is an important piece to the capabilities of the robot gripper. 3D perception at the palm of the hand is the basis of this robot gripper's concept. The camera would need to be small in order to not effect the gripper's 4-bar linkage system and would need to be accurate enough to allow for precision pickups. The Intel® RealSense™ Depth Camera D4054 was chosen because of its small size, relatively reasonable price, close-range vision, and sub-millimeter accuracy[42]. Manufacturing can vary in price due to the material that needs to be cut or produced or the

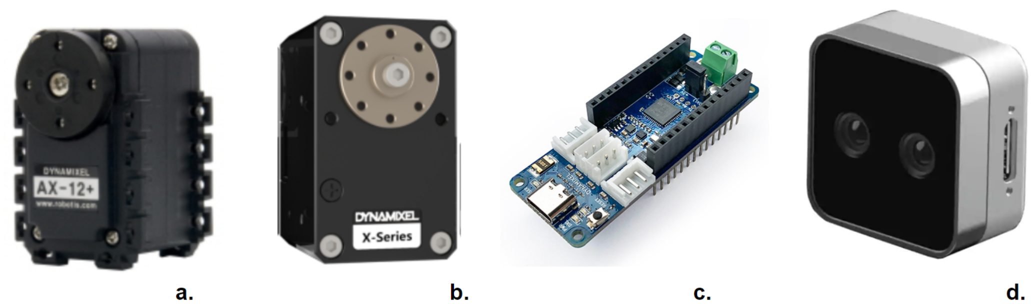

Figure 4: a.Ax-12A motor b. XD430-T210-R motor c. OpenRB-150 board d.Intel D405 Camera with depth and color capabilities

tolerances that need to be achieved. Materials considered for this gripper were carbon fiber, ABS plastic, PLA plastic, aluminum, and steel. An expensive machine would need to be used in order to produce a gripper with the materials steel, aluminum, or carbon fiber. These materials would take more time to produce because a third party manufacturer would need to be used. Because of this 3D printers are considered the best option for this application due to accessibility and speed of production. The gripper can be made in either ABS or PLA plastic. The Creatility Ender3 printer is in Figure5 and was used to print all the pieces because of it's large community and low price. The tolerance is +/- .1mm.

Figure 5: The Creatility Ender3 3-D printer

4.1.3 Strength

The coefficient of friction will directly be related to the material. This can also give more force for the gripper to pick up heavier items. In order to pick up 90% of the items in the Table2 the gripper will need a force of 30 Newtons exerted from the fingers for a factor of safety of 2. There are 58 items so a total of 52 items need to be picked up. The coefficient of friction was assumed to be .4 for all objects. The mustard bottle is the heaviest object the gripper will be able to pick up on the list of items theoretically with a force of 30.15 Newtons needed.

$$F_{Normal} = m * g * F.S./\mu \tag{1}$$

Item	Mass(g)	Width(mm)	Force Needed
Pringles	205	76.372	10.25
coffee can	414	104.92	20.7
Cheeze-it box	411	58.072	20.55
sugar box	514	34.16	25.7
tomato soup can	349	73.2	17.45
mustard bottle	603	53.68	30.15
tuna fish can	171	82.96	8.55
jello pudding box	187	30.5	9.35
gelatin box	97	30.5	4.85
spam can	370	51.24	18.5
plastic lemon	66	48.8	3.3
apple	18	73.2	.9
pear	68	73.2	3.4
orange	29	73.2	1.45
banana	33	48.8	1.65
peach	49	73.2	2.45
strawberry	47	24.4	2.35
plum	25	61	1.25
pitcher	244	24.4	12.2
bleach cleanser	1131	68.32	56.55
glass cleaner	1022	63.44	51.1
wine glass	133	24.4	6.65
metal bowl	147	36.6	7.35
metal mug	118	24.4	5.9
sponge	6.2	68.32	.31
cooking skillet	950	48.8	47.5
metal plate	279	24.4	13.95
knife	31	24.4	1.55
spoon	30	24.4	1.5
fork	34	24.4	1.7
spatula	51.5	52.948	2.575
white table cloth	20	48.8	1
power drill	895	73.2	44.75
wood block	729	73.2	36.45
scissors	82	48.8	4.1
padlock	304	39.04	15.2
keys	10	7.32	.5
markers	15.8	19.52	.79
wrench	252	30.5	12.6
screw driver	97	42.7	4.85
wood screws	98.4	12.2	4.92
nails	5	12.2	.25
bolts	4	12.2	.2
nuts	1	12.2	.05
hammer	665	61	33.25
spring clamp	60		3
mini soccer ball	123	207.4	6.15
softball	191	97.6	9.55
baseball	148	73.2	7.4
tennis ball	58	63.44	2.9
racquetball	41	52.46	2.05
golf ball	46	39.04	2.3
plastic chain	98	48.8	4.9
washers	50	24.4	2.5
foam brick	28	73.2	1.4
dice	5.2	6.1	.26
marbles	4	24.4	.2

rope	18.3	97.6	.915

4.1.4 Precision/Compliance

The PLA will cause the gripper to be compliant. A gripper with a softer and more elastic material will have an easier time picking up items but will be less precise when using or dropping the items. A hard gripper will be more precise but lack the capabilities to deform to better complete a task as shown in[3] where the compliance in the gripper allows for the peg and hole task to be a lot easier to complete. The MAGPIE^2 will be designed in order to not rely on 3D printing tolerances and instead rely on fasteners for tolerances. The gripper will have the ability to pick up objects with precision because of its vision capabilities. It can see the object while grasped and before grasping because of its eye-in-hand position. The Intel® RealSense™ D405 has .1 mm tolerances[42]. The resolution of the AX-12A motors chosen is 0.29 ° which allows for precision control of the position of the linkage system[41].

4.1.5 Manufacturability

A good gripper will want to be replicated for others to use. What goes into replicating a new gripper will be materials, labor, and time. A gripper which is less complex will be cheaper and easier to manufacture. An example of materials that can vary are steel and plastic. The ability to build from steel and plastic will vastly differ because of the different temperatures needed to mold or cut each material. If the extra strength isn't needed then going with hard plastics will be the better choice because of its ability to be mass produced. If the gripper is not dependent on small tolerances. This can allow the gripper to be manufactured with cheaper machines. The design cannot have complex designs and relies on thick features will stress will be applied. Steel fasteners can help give strength to places where the robot gripper needs to be strong and durable.

4.2 Kinematics and Dynamics

4.2.1 Kinematics

The structure of the 4 bar mechanism was important. It was important to keep the fingers always parallel with the camera at all times for a better grasp of items[43]. The strongest position of the 4 bar mechanism would be one that has the crank parallel to the camera. It was important to have the parallel position be somewhere between fully closed and fully open because the servo motors were not powerful and every Newton of force would add to the value of the robot gripper. The robot would not be grasping most items at a fully closed position. The ground for the 4 bar mechanism would not parallel to the front of the gripper to minimize space and reduce the width of the gripper overall. A 30 Newton Force was aimed for the design because it would allow to pick up 90% of the items on the YCB data-set benchmark. The assumption for this would be a weak coefficient of friction and a factor of safety of 2 to allow for any error to be accounted for. Error could include under-powered motors, worse coefficiton of friction, and frictional forces for the 4-bar mechanism going against the motion of the servos.
The structure of the fingers will impact the kinematics and dynamics of the gripper. The systems is going to be a 4-bar linkage system. For the case pictured a 4 bar mechanism will have 1 degree of freedom meaning that the trajectory of the system is 1 dimensional[44, 45]. In Figure 6 Joint 2 is an output link driven from the servo motor. Joint 3 is the coupler link attaching to Join 2 to Joint 4. Joint 4 is the output link. Joint 1 is the ground or fixed link. Joint 3 will be a large component that will also act as the finger for the robot gripper.

$$J_2 + J_4 = J_1 + J_3 \tag{2}$$

$$J_2 * cos(\theta_1) + J_4 * cos(\theta_4) = J_1 * cos(\theta_2) + J_3 * cos(\theta_3) \tag{3}$$

$$J_2 * sin(\theta_1) + J_4 * sin(\theta_4) = J_1 * sin(\theta_2) + J_3 * sin(\theta_3) \tag{4}$$

The robot gripper will succeed with picking up items if the fingers can remain parallel at all times with the gripper. In order to do this Equation 9 is needed. The length of the crank is joint 4.
First we will solve for the aperture or position of the width of the gripper at specific angles. Figure6c. shows the servo is offset from the middle. Offset servox is the difference between the camera's x position and servo motor. Offset fingerx is the difference between the cranks x position and finger base's x position.

$$length_{crank} = 45mm$$

$$offset_{servox} = 38mm$$

$$offset_{fingerx} = -24.32mm$$

$$aperture = 1 * cos(theta) * length_{crank} + offset_{fingerx} + offset_{servox}); \quad (5)$$

Next we will solve for the position of the finger tip for the y axis. This will allow us to know the depth of the finger in respect to the camera. Figure6c. is showing how we got the equations. Offset of servoy is the difference between the camera's y position and the servos position. Length of fingetip is the length of the fingers base.Offset of fingery is the difference between the cranks y position and the base of the finger.

$$offset_{servoy} = -21mm$$

$$length_{fingertip} = 80mm$$

$$offset_{fingery} = 1.32mm$$

$$L2 = sin(theta) * length_{crank} \quad (6)$$

$$L1 = length_{fingertip} + offset_{fingery} \quad (7)$$

$$y_{fingertip} = L2 + L1 + offset_{servoy}); \quad (8)$$

To pick the two lengths we can work backwards from the strength found from Table 2. I used a genetic algorithm library 'ga' in Matlab to find a minimum for the mass selected and the width needed to pick up 90% of the items.

$$J_2 = J_4 J_1 = J_3 \quad (9)$$

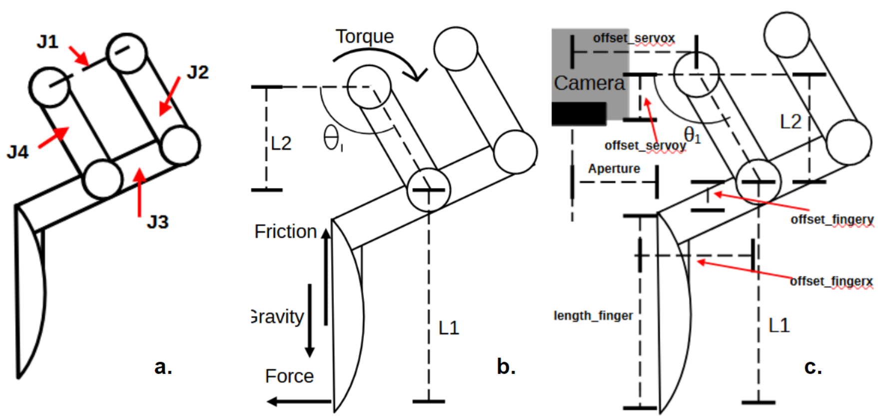

Figure 6:

4.2.2 Dynamics

The position of each joint will cause a different normal force from the finger. Figure6b. shows that the normal force can be calculated given the angle of the servo crank joint or Joint 4 from Figure6a. J4 is 45mm long. L1 is a combination of the offset of the crank to finger base and the point of contact on the finger(0-80mm). The gripper will give a different strength depending on how the distance is from the motor. Along the fingers base increments of 20mm were tested because some object will be preferred to be picked up at different locations. The gripper's theoretical is a max force of 12Newtons from each finger all the way to 33Newtons of force. This gives a total force range from 12-66Newtons as shown in Figure7.

$$Force = \tau/(J4 * sin(\theta) + L1) \quad (10)$$

$$Force_{Normal} = Force * sin(\theta) \quad (11)$$

$$F_{Friction} = \mu F_{Normal} = \tau/(L_2 \sin(\theta) + L_1) \quad (12)$$

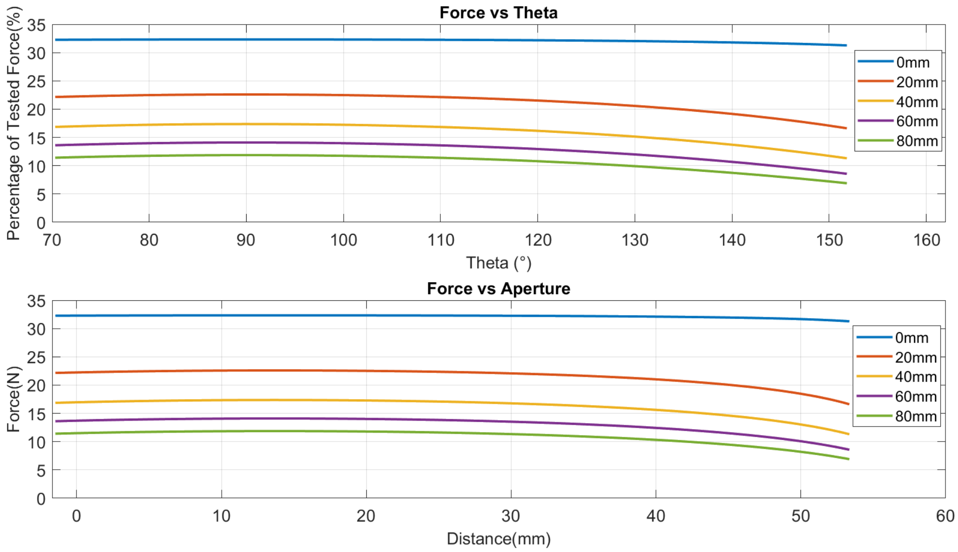

Figure 7: The top is Force vs Theta. The bottom is the Force vs Aperture.

4.2.3 Optimization

A genetic algorithm was used in order to find lengths to all the joints. There were too many variables and choosing them would be random[46]. There were two iterations for the optimization. The first was to find the ratio of joint lengths I would need to keep the finger parallel to the robot gripper. Using vector math we can solve for theta B in Figure8. As long as theta 3 doesn't change throughout all the different values of theta2 in the figure. Theta 2 was chosen incremented by 1 degree from 160 to 30 degrees. After running the program their were global minimums found. As long as the R2 = R4 and R1 = R3 then the kinematics would allow the finger to stay parallel to the gripper. The cost function was directly related to the maxtheta3 -mintheta3. It came out to less than .001 when R2 = R4 and R1 = R3.

$$R_i = R1 + R2 \tag{13}$$

$$r_4^2 = r_i^2 + r_3^2 - 2 * r_i * r_3 * cos(\theta_B) \tag{14}$$

$$\theta_B = cos^-1((r_i^2 + r_3^2 - r_4^2)/2 * r_i * r_3) \tag{15}$$

$$\theta_3 = arg(Ri) - \pi + \theta_B \tag{16}$$

After the ratio was found, a minimum of 110mm of aperture and 15 Newtons of force at 50mm on the finger along the finger was set using R2 = R3 and R1 = R4. Increments of 1 mm from 20mm to 30mm for Joint1 and Joint 4 were used and from 35 to 60mm for Joint 2 and Joint 3. Given the list of Joint lengths, I chose 22mm for Joint 1 and Joint 4 and 45mm for Joint 2 and Joint 3. The gripper seemed to wide when going over 25mm for Joint 1 and Joint 4. 22mm gave a compact design as long as the Joint 1 had an offset angle from being perpendicular to the gripper. 45mm just barely cleared the aperture limit with 113mm opening and gave the 16.2Newtons of force.

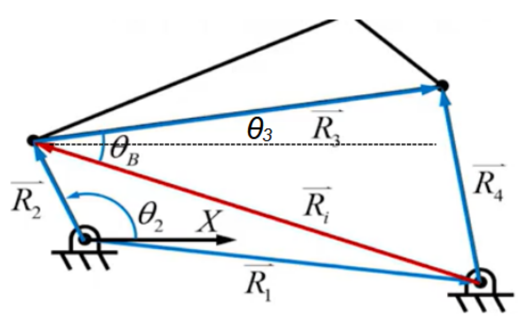

Figure 8: The graph showing the vector math to solve for joints.

4.3 Design Process

4.3.1 Inspiration

The inspiration for the current robot gripper came from Nicolaus Correll's Lab at University of Colorado Boulder. The Robotic Materials Hand in Figure 1i. is the current gripper for the lab which is manufactured from metal and used the Intel Real Sense Camera. It used a 4 bar mechanism with two 2.5 N*m servomotors. The camera was offset from the palm and was capable of controlling each finger separately. It had a Jetson for processing the camera data and a OpenCM micro controller from Dynamixel for controlling the motors. The motors have the ability to control speed, torque, and position.

4.3.2 Initial Design

The first design was replicating this hand but in a way that everything could be easily manufacturable as shown Figure 9a. The idea was to keep a 4 bar mechanism because it allowed for a stiff pickup from the gripper. The gripper would already be compliant due to the material nature of PLA plastic. Adding any new degree of freedom would make the gripper excessively compliant and lose precision. The new gripper would have the camera centered instead of offset at the palm of the hand. This would allow for easier calculations and better vision on the item being picked up. The cost for the new gripper would be significantly lower due to the cost of materials. Materials that would be used would be PLA and metal fasteners. The servo motors would be reduced in specification with a torque of 1.5N*m to be more affordable but still allow for the user to pick up heavy items. The servo motors would need force sensing, speed control, and position control. The servo motors would need to be driven separately for better control.

4.3.3 Iterations

An idea from a paper showed that vibrations could be reduced if the centroid of the whole system was stationary[47]. This design is showed in Figure9. This meant adding weight in certain joints to move the centroid towards the middle of the system. After prototyping there was no noticeable difference in the performance of the gripper and the design choice was dropped. The idea would be that anyone could 3d print the parts and buy the rest of the parts off of Amazon for a low price. When prototyping the gripper, problems with the gripper's compliance became a problem. While the motors were stuck in place a noticable displacement could be seen in all 3 axis of the gripper's fingers. This meant that the gripper could not be precise. The gripper's first iterations relied on the 3D printers ability to have low tolerances. The Joints had holes that would rotate around standoffs and it could be seen that the joints were not showing one degree of freedom because of their tolerances. 3D printers would not be consistent enough for holes that needed something to spin freely in the hole. The design could be made out of plastic materials for most of the base but would need metal parts to add structure and reduce tolerances. Bearings were added to the design because the tolerances of them would be superior[48]. The tolerances are not shared but can be assumed to be better then a 3D printer. The bearings could be super glued in place inside the hole of the joints. Tolerances for the rest of the holes on the structure were tested to see what would be the best for screws on the gripper. Holes tested for a 3M screw were 3.1,3.15,3.2,3,25, and 3.3. It was found that a .25mm tolerance allowed for fast assembly and hole that could keep the screw in place. The first iterations also had the micro-controller on the same side as the motors. This was unnecessary. The micro-controller was moved to the opposite side of the gripper, which added 10mm height to the gripper but reduced the width by 30mm because the servo motors could be closer together.

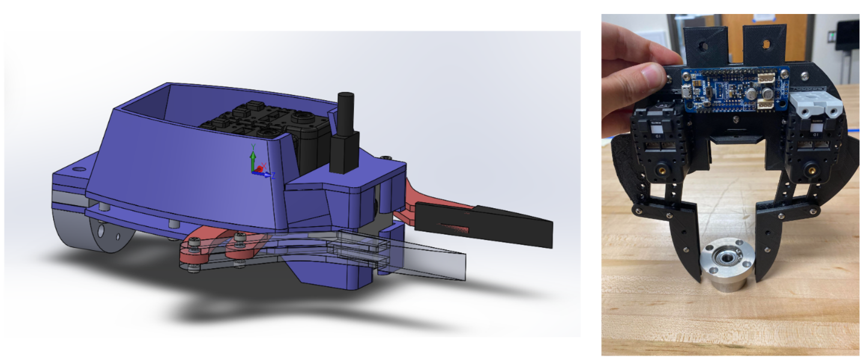

Figure 9: The left is a picture of the first design of the gripper. The right is a design after some iterations and a working prototype.

4.3.4 Final Design

The overall dimensions of the gripper are a maximum width of 211.56mm and a minimum length of of 169.64mm when the robot gripper is fully open and a minimum width of 133.68mm and a maximum length of 193.32mm when the crank is parallel to the gripper. The height of the gripper is 65mm. An infill percentage of 100% was used in order to be on the safe side for structural strength. The mass of the gripper is 0.411 kg. The dimensions of size are within the constraints of 250mm, 250mm, and 100mm. The mass constraint of .5kg has been fulfilled. The final design has been shrunk down to the smallest footprint possible. The gripper has a maximum aperture of $w = 106.24mm$ which can pick up the coffee can which was the limitation for 90% of the items to be picked up at 104.92mm.The last iteration relies on bearings and metal standoffs for motion because the tolerances a CNC machine can reach are much higher than 3D printers. Steel is also not flexible and can't morph over time. Every tolerance on the gripper that was important is now dependent on manufacturers from the fasteners. The last iteration was given a cover for both the motors on the top and the micro-controller on the bottom. This allows for the camera, servo motors, and micro-controller to be safe. The cover is also acting as a palm to allow the gripper to press into an object if the user wants to. Rubber material was added to the palm and fingers for a higher coefficient of friction from .4 to .95 assuming steel to rubber. The gripper needs 9-12Volts, .2 Amps, and a functioning computer. The camera can see the object at all points in the robot manipulation planning process. The final gripper is estimated at $458.63 shown in Figure4.3.5 and will take 1 day to manufacturing using a 3D-printer.

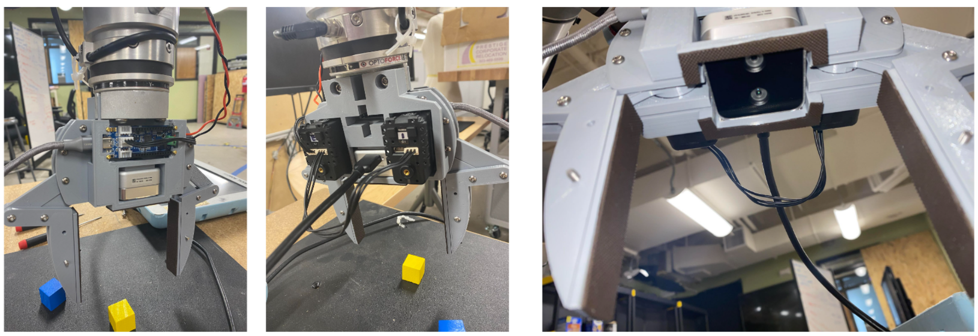

Figure 10: The final gripper pictured on the UR5 robot.

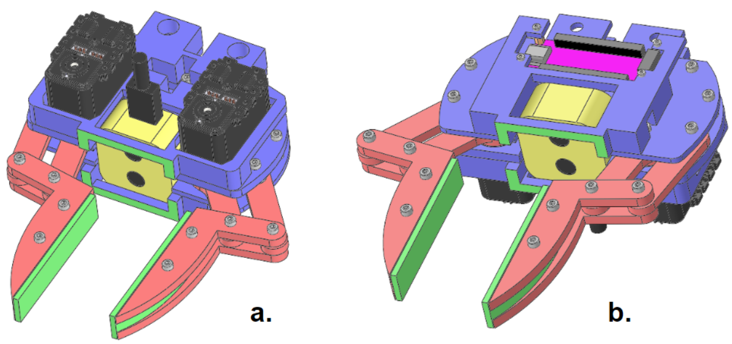

Figure 11: a. top view of the final gripper assembly b.bottom view of the final gripper assembly

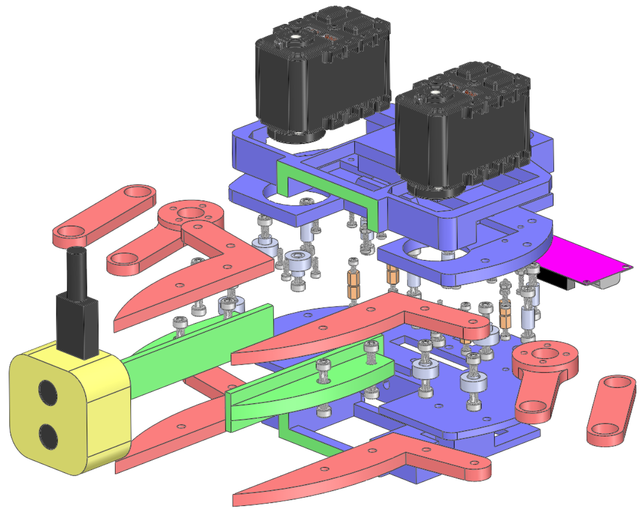

Figure 12: An exploded view of the robot gripper(22 unique parts and 120 total parts)

4.3.5 Bill of Materials

Bill of Materials			
ID	Item	Quantity	Cost
1	Top Base(PLA)	1	$ 1.51
2	Top Base Cover(PLA)	1	$ 2.05
3	Bottom Base(PLA)	1	$ 1.17
4	Bottom Base Cover(PLA)	1	$ 1.15
5	Servo Crank(PLA)	2	$ 0.47
6	Servo Coupler(PLA)	4	$ 1.56
7	Servo Rocker(PLA)	2	$ 0.28
8	Finger	2	$ 0.86
9	OpenRB-150 board	1	$ 24.90
10	Intel® RealSense™ D405	1	$ 272.00
11	AX-12A Servo Motor	2	$ 99.80
12	3M 6mm standoff	4	$ 9.99
13	3M 8mm standoff	8	$ 9.99
14	2.5M 10mm standoff	4	$ 9.99
15	Electrical Wire	2	$ 0.45
16	3M Nuts and Bolts	32	$ 12.49
17	2M Nuts and Bolts	8	$ 9.99
18	5M bearings	8	$ 9.99
		Total	$458.63

4.4 Mechatronics System

4.4.1 Hardware

The user would need a power supply that gives a steady .2 Amps and 9-12 Volts. A computer and robot arm will also be needed to connect the camera and micro-controller as well as move around the robot arm.

4.4.2 Vision

The camera can see from a range of 70mm to 500mm. Figure 13 shows that the gripper will be able to see an object from start to finish for the grasping process. The red pictured is the depth of the camera in which it is blind. The yellow is the camera's working range for vision. y in Figure 13 can vary from 5.52(Fully Open) to 21.32 mm(Servo Crank Parallel t Gripper). The camera has full range of view when the gripper is fully open.

Currently Open3D library has been incorporated with the gripper's vision in order to get pose and dimensions of the world around it[49].

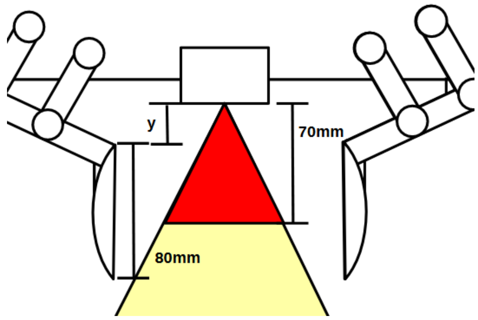

Figure 13: The red is the depth the camera is blind to and the yellow is depth the camera can see. The dimension of the finger is

4.4.3 API

The Dynamixel sends packets of data and not bits to the controller. This means that specific commands need to be made to grab the data from Dynamixel's micro-controller. A page of all the commands possible are pulled to the main Python script. All the kinematics of the gripper have been coded to allow knowledge of the position of the finger in the y dimension and x dimension[50]. This information can be used to program the robot gripper to move in relative way towards or away from the item. There are three commands for closing to the gripper. Closing the servos simultaneously with the force asked. The second is getting close to the width with little force and then closing with the given force to allow for more accuracy against items that can slip. The last is closing one finger til it touches the item and then closing both fingers. This command gives the best results for precision. There is simple image processing using the Open3D library. The flat surface and object is lying on is removed from the image. The image is downscaled for faster calculations. Pose, width, length, and height are calculated in the script[50].

5 Experiments

5.1 Torque Test

I conducted a force test to get the normal force of the fingers at different values from the Dynamixel AX-12A. The test was conducted at 11.1 Volts for one of the fingers. I recorded the force at the strongest position of the servo crank which is parallel to the robot gripper. The aperture is 28mm from the center and has the servo crank parallel to the camera. The location of contact was 10mm from the tip of the finger towards the camera along the finger.

$$Force = \tau/(cos(0) * (L1 + L2 * cos(0))) \tag{17}$$

$$Force_{Normal} = Force * cos(0) \tag{18}$$

The Dynamixel Servo were tested at values of 100, 110, 125, 150, 200, 300, 400, 500, 600, 700, 800, 900, 1000. Three trials were conducted for each value. The value range was from 0-1023. I locked the force gauge into a vice with Styrofoam to be secured and not damage the sensor. The force gauge read the max force at each interval. The Shimpo Force Gauge FGV-10XY has a tolerance of +- .2%. As we can see from Figure 14 the max force is around 16 Newtons for each finger. This gives a combined force of 32 Newtons. From observation, the Dynamixel AX-12A will overload when set to 14 Newtons or above after a short time. The gripper exhibited compliance and visible flexion when subjected to a force of 14 Newtons or higher. The error could arise from the motor being specified to exceed the deliverable of 1.5Nm. The motor could also be tested at a lower voltage or a lower input torque. This graph shows the gripper will over perform the theoretical calculations by 31.1% for max force(16N) and 14.7% for usable max force(14 Newtons) . This experiment has also shown that the grippers PLA structure and base can withstand the stress of 32 Newtons of force because of its compliant nature. The motors force is best modeled to a polynomial showing in Equation 19. The $R^2 = .99$ showing that is a great fit for the experimental results.

$$y = -1.889e - 05x^2 + .038399x - 3.4073 \tag{19}$$

The motors exhibit changes over time with increased usage, resulting in decreased strength and increased temperature. This variability leads to a slight variation in the minimum torque required, ranging from 90 to 110 bits out of the total torque necessary to move the 4-bar mechanism. This variation could potentially impact force touch control. To address this, a programming approach can be implemented to detect changes in position based on different bit values. Accurate determination of the minimum torque requirement is crucial for precise object manipulation. This capability allows the gripper to position one finger against the object while the other finger adjusts its position, minimizing any unintended displacement or movement of the object.

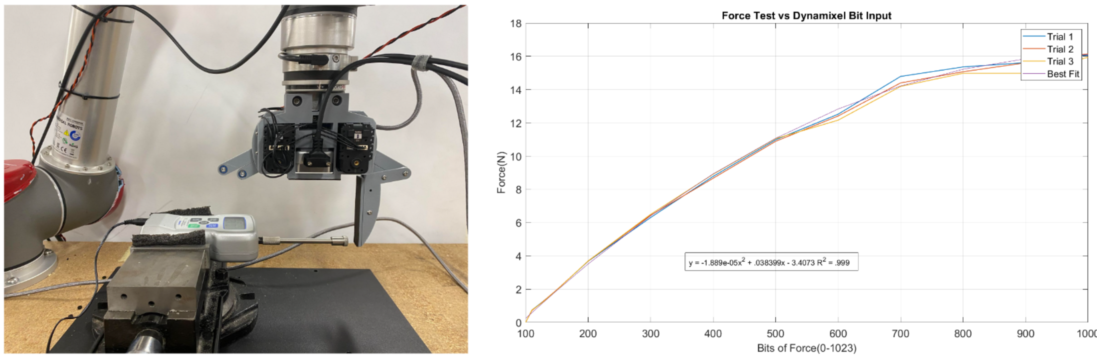

Figure 14: On the left the setup for the torque test using 1 finger actuated with 1 finger removed. The Shimpo Force Guage is cushioned in a vice to prevent moving.On the right a parabolic curve of the torque input in bits vs Normal Force recorded from the tip of the finger.)

5.2 YCB dataset

In this experiment, we grasped each item from a flat surface and moved it directly up along the z-axis, as well as forward and backward along the x and y axes. The items we grasped were sourced from the YCB dataset, and we obtained all the necessary information from the referenced paper[21]. The main objective of this experiment was to determine whether the gripper can safely transport the items when grasped correctly.
The "Precise" category in Table 3 holds significant importance as it provides insights into the specific areas where proper grasping is essential to prevent slipping. I introduced this category because certain items, like the pitcher, can pose significant challenges due to the uneven weight distribution around the grasping location. During the experiment, if the pitcher was not grasped properly, it would swing about the grasping location. Vibrations caused by robot movements could also induce movement in the item. Similarly, other items such as forks or spoons can cause problems if not picked up at their centroids.
It is worth noting that movements perpendicular to the robot gripper result in more slipping compared to parallel movements, primarily due to the higher compliance of the mechanism in the perpendicular direction. The gripper's ability to handle "Precise" items is limited due to having only two contact areas. While an additional point of contact could allow for more precise grasping, it would overly complicate the design.
Items marked with Yes* were successfully held initially, but over time they would either slip or cause the servo motors to overload. We conducted the experiment using 11.9 Volts with varying torques to prevent object crushing. However, when the motors needed to exert a force exceeding 14 Newtons, as observed in Figure 14, the constant torque would cause motor overload.
Due to limited materials, we couldn't test every item. However, we can assume that the untested items yield similar results to the theoretical predictions. Items like balls and plastic fruit, which do not exhibit differing material coefficients or irregular shapes, can be assumed to follow the expected behavior. On the other hand, items like the wood block and hammer have a decent chance of deviating from the theoretical predictions due to the bleach and glass cleaner being 30 percent heavier, resulting in a short holding period. The force required for grasping these items would remain below the 14 Newton threshold observed in the torque experiment. Moreover, the wood block and hammer would exhibit a greater coefficient of friction (0.95) due to the rubber-to-wood contact, and provide a better surface area for grasping.
To enhance the certainty of grasping items, we would need to introduce or modify a feature in the gripper. However, this would compromise simplicity, manufacturability, or the price of the gripper. Increasing the torque of the motors would significantly raise the cost and potentially strain the gripper's fingers. While considering alternative 3D printing materials, we must prioritize accessibility, as most 3D printers excel in printing ABS and PLA due to temperature and hardware constraints.

Visually, the gripper exhibits strain at torques exceeding 14 Newtons. Introducing an additional finger or degree of freedom to the actuator would improve contact but reduce simplicity and compromise precision due to increased error tolerance.

Any improvement made to the gripper would have a considerable impact on its simplicity, manufacturability, or price. While specific use cases may warrant design changes, targeting the YCB dataset is crucial for overall performance due to its generalizability.

Item	Weight(g)	Width(mm)	Precise?	Theoretical	Actual
Pringles	205	76.372	No	Yes	Yes
coffee can	414	104.92	No	Yes	Yes
Cheeze-it box	411	58.072	No	Yes	Yes
sugar box	514	34.16	No	Yes	Yes
tomato soup can	349	73.2	No	Yes	Yes
mustard bottle	603	53.68	No	No	Yes
tuna fish can	171	82.96	No	Yes	Yes
jello pudding box	187	30.5	No	Yes	Yes
gelatin box	97	30.5	No	Yes	Yes
spam can	370	51.24	No	Yes	Yes
plastic lemon	66	48.8	No	Yes	N/A
apple	18	73.2	No	Yes	Yes
pear	68	73.2	No	Yes	Yes
orange	29	73.2	No	Yes	Yes
banana	33	48.8	No	Yes	N/A
peach	49	73.2	No	Yes	Yes
strawberry	47	24.4	No	Yes	Yes
plum	25	61	No	Yes	N/A
pitcher	244	24.4	Yes	Yes	Yes
bleach cleanser	1131	68.32	No	No	Yes*
glass cleaner	1022	63.44	No	No	Yes*
wine glass	133	24.4	No	Yes	Yes
metal bowl	147	36.6	No	Yes	Yes
metal mug	118	24.4	Yes	Yes	Yes
sponge	6.2	68.32	No	Yes	Yes
cooking skillet	950	48.8	Yes	No	No
metal plate	279	24.4	Yes	Yes	Yes
knife	31	24.4	Yes	Yes	Yes
spoon	30	24.4	Yes	Yes	Yes
fork	34	24.4	Yes	Yes	Yes
spatula	51.5	52.948	Yes	Yes	Yes
white table cloth	20	48.8	No	Yes	Yes
power drill	895	73.2	Yes	No	No
wood block	729	73.2	No	No	N/A
scissors	82	48.8	Yes	Yes	Yes
padlock	304	39.04	No	Yes	Yes
keys	10	7.32	No	Yes	Yes
markers	15.8	19.52	No	Yes	Yes
wrench	252	30.5	Yes	Yes	Yes
screw driver	97	42.7	Yes	Yes	Yes
wood screws	98.4	12.2	No	Yes	Yes
nails	5	12.2	No	Yes	Yes
bolts	4	12.2	No	Yes	Yes
nuts	1	12.2	No	Yes	Yes
hammer	665	61	Yes	No	N/A
spring clamp	60	N/A	No	Yes	Yes
mini soccer ball	123	207.4	No	Yes	N/A

softball	191	97.6	No	Yes	N/A
baseball	148	73.2	No	Yes	N/A
tennis ball	58	63.44	No	Yes	N/A
racquetball	41	52.46	No	Yes	N/A
golf ball	46	39.04	No	Yes	Yes
plastic chain	98	48.8	No	Yes	Yes
washers	50	24.4	No	Yes	Yes
foam brick	28	73.2	No	Yes	Yes
dice	5.2	6.1	No	Yes	Yes
marbles	4	24.4	No	Yes	Yes
rope	18.3	97.6	No	Yes	Yes
				51/58	46/48

5.3 Credit Card

We conducted an experiment to assess the gripper's capability of picking up a credit card from a flat surface. The credit card had a width of 55mm and a thickness of 1mm. In the experiment, we positioned the gripper away from the card and moved it towards the card in a linear motion. Subsequently, we closed the gripper using approximately 20 Newtons of total force. To successfully pick up the credit card, the position of the gripper's z-axis could only deviate by +-0.5mm, as determined during testing.
The gripper exhibited optimal performance when its kinematic motion allowed it to exert force against the table. Due to its compliant nature and plastic material, the gripper flexed instead of causing damage to the table or the robot gripper. Overcoming friction with the table required a slightly stronger force than just holding the credit card, ensuring a good surface area contact.
Picking up such a thin item poses a significant challenge in the field of robot manipulation. It is important to consider how the robotics community approaches this problem. Many solutions resort to alternative gripper styles such as suction-based grippers. Others employ complex maneuvers like flip-and-pinch, which we aim to avoid due to their inherent complexity[51]. The gripper we developed strikes a strong middle ground between stiffness and compliance, allowing us to circumvent such maneuvers and successfully handle the task at hand.

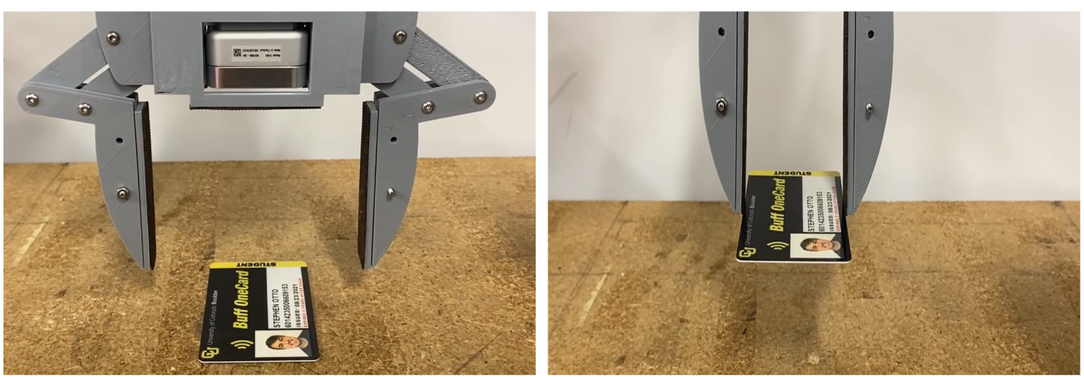

Figure 15: The left shows the gripper before pickup of the credit card. The right shows the grippers ability to pick up from a flat surface after the robot arm moved in every direction.)

5.4 Touch Test

The gripper demonstrates the ability to sense force/torque. There are two different approaches to sensing touch. This can be from finger sensors or by actuation measurements. It has been shown that it is possible to get accurate force control from actuation measurements by understanding the system model dynamically and kinematically[52]. Figure **??** shows the force profile for the right ('Motor 1') and the left ('Motor 2') finger vs. gripper aperture as the gripper closes on the mustard container from the YCB dataset. The container was placed off-center, with the right motor making contact first. This was intentional to show that the gripper could compensate for errors in vision or robot arm movement because of its ability to have force control on each actuator. Instead of moving the mustard, the finger remains in position until the second finger makes contact. We observe minimal torques while moving the finger, with Motor 1 having more friction than Motor 2 due to slight variations in manufacturing. Figure 16 shows at a dashed line where the robot gripper changes contact. The response is quick from the motors with at most a .2 second delay. This ability to have force control will be important for delicate items such as strawberries[53].

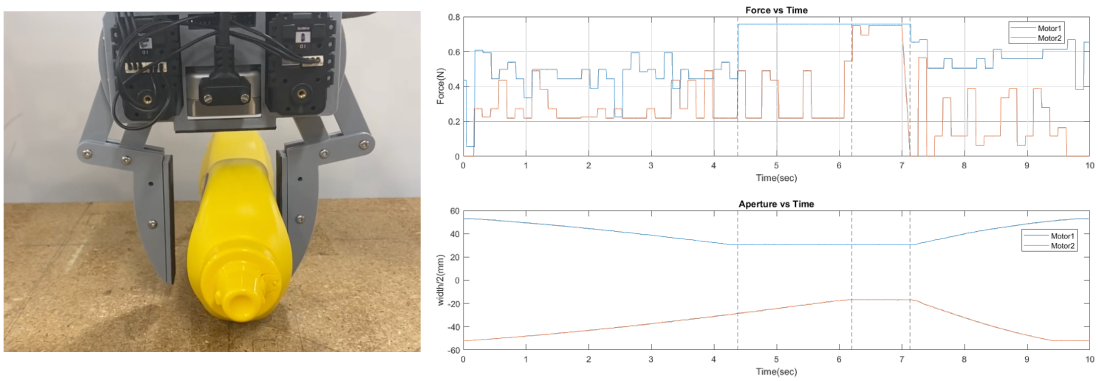

Figure 16: Gripper grasping the mustard container from the YCB dataset from an off-center position (left). Limiting torque during approach prevents the mustard from moving as the right finger makes contact. Dashed vertical lines indicate contact by the right finger, contact with both fingers, and opening (from left to right).

5.5 User Studies

The robot gripper has also been evaluated by Dylan Kriegman and James Watson as well. The API is shown to be easy with two colleagues using the gripper's capabilities.
Dylan evaluated the system using a tower-assembly task using three colored, wooden cubes from [21]. Figure 17 shows snapshots of the experiment, a view of the camera image, the resulting labeled 3D objects, and the corresponding PDDL domain. A task planner was adapted to show an example of computer vision incorporated with the gripper. The camera can allow for segmentation through deep learning models and location from the depth sensors using Yolo[54]. The camera's capabilities gave Dylan knowledge of the location and pose of the boxes in the table space.

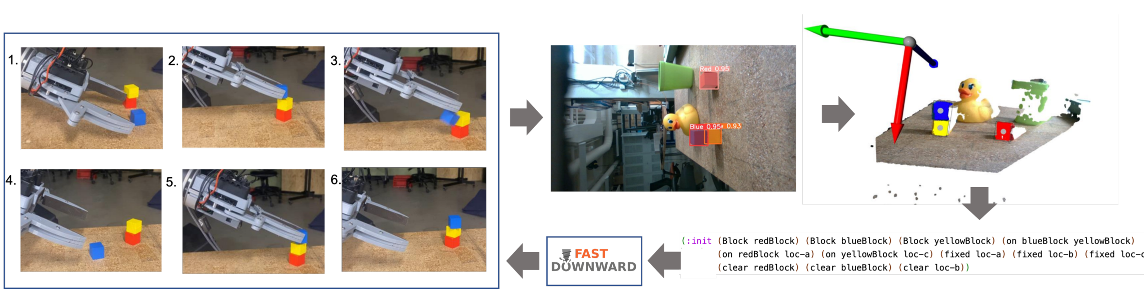

Figure 17: Snapshots from a tower construction task that is solved by continuous replanning. The robot accidentally hits the tower (1) while placing the blue block (2), which fails as the tower has moved (3), the robot re-analyzes the scene (4), and places the blue block (5). Point cloud and image data are used for object identification and segmentation, resulting into a labeled scene that gets parsed into a PDDL 2.1 problem description and solved by FastDownward. The plan is repeated until the problem is solved.

To demonstrate the precision and accuracy of the design, James Watson performed a robotic assembly task with tight tolerances ($< 0.5mm$). Snapshots of the task are shown in Figure 18. Precision and accuracy of grasping the elements from a known position on the table(modeling the industrial assembly challenge requirements from [55]) is sufficient to reliably assemble all parts into a functioning mechanical system. The assembly task succeeded 8 out of 10 trials; with one failure each due to an angular misalignment of the small peg and the large gear becoming jammed on the large peg. These are on par with previous results [56] which was used by a metal gripper with more stiffness. The compliant nature was able to allow James to wiggle the pieces into to the slots.

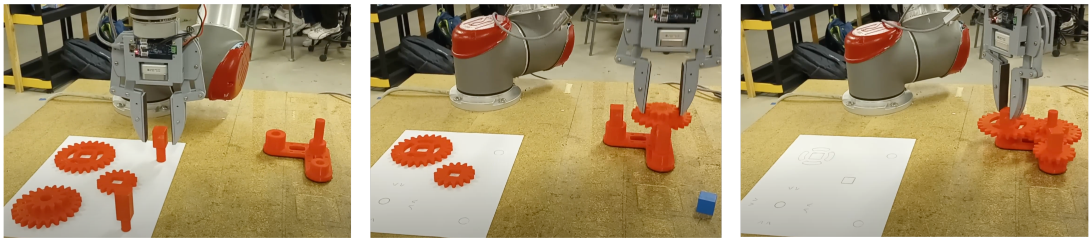

Figure 18: Demonstration of accuracy and precision by reliably assembling the "Siemens gear assembly problem" [57] with sub-millimeter accuracy requirements.

6 Conclusion

In conclusion, the developed gripper has demonstrated impressive capabilities in robot manipulation tasks. It has shown strength and precision, successfully completing challenges such as the Siemens gear assembly and effectively grasping delicate objects like credit cards. The utilization of 3D printing technology has enabled the creation of an inexpensive gripper with high tolerances. Furthermore, the gripper offers position, speed, and force control capabilities, providing flexibility in various applications. The user-friendly API has facilitated its adoption by fellow researchers in the field of robot manipulation, as evidenced by the positive feedback from colleagues James Watson and Dylan Kriegman. The combination of 3D printing, accessible motors, and cameras has opened up new possibilities for developing versatile and easily manufacturable grippers with enhanced strength, precision, and vision capabilities. As a result, the gripper no longer needs to be tailored to specific objects or tasks, but instead, it can be utilized for a wide range of applications, showcasing its versatility in the field.

7 Future Work

Future Work can include a way of adding a retractable 3rd finger. This would allow the gripper to have a better time picking up heavier and more complex objects. As well, more tests could be run on the gripper to understand the system better. The compliance of the gripper should be tested to see how much the deflection the system has in each axis. The speed of the Dynamixel motors could also be tested to understand the kinematic model better with inputs. Thickness in all the parts for the 3D prints and infill percentage can be changed to bring down the weight. A selection of better better bearings are worth considering because the tolerances are reliant on them. The gripper could also try different lengths for the 4 bar mechanisms to see if the compliance changes from longer or shorter lengths.

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