An Underactuated Gripper to Unlatch Door Knobs and Handles

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Abstract—*This paper describes the development of an underactuated gripper designed to unlatch doors knobs and handles. The challenge was to create a mechanism that could manipulate a variety of door knobs and handles while using only one motor in order to create a low cost device. The final design evolved by exploring the limitations in the performance of an initial gripper prototype. In this paper, the cause of failure for the first prototype is discussed along with rationale for the changes made in the second design. The final design was capable of twisting door knobs and handles in clockwise and counter-clockwise directions. It had a collet-cone shape for compliance gripping and centering, and it utilized one motor for both gripping and twisting actions. The discussed gripper was developed for the assistive technology domain; however, this gripper mechanism could be utilized in a wide variety of robotic domains that exist today.*

1. INTRODUCTION

A gripper, otherwise known as an end effector, is commonly defined as a device that can grasp and release objects during robotic manipulation [1] or as a device that holds, handles, tightens, and releases an object [2]. Robotic grippers generally fall into one of two different categories: 1) grippers designed to handle an object of a specific size and shape, such as grippers used for manufacturing, and 2) grippers designed to handle a variety of objects, such as two-pronged clamps or human-like hands found on multi-purpose robots. This paper describes a gripper that fits into both categories. It is designed to unlatch door knobs and handles of different sizes and shapes. Such a gripper would be useful for robotic applications in healthcare, rehabilitation, reconnaissance, and rescue. Healthcare robots need to pass through rooms in order to attend to their patients and reconnaissance robots need to inspect partitioned areas in suspected buildings.

Door knobs and handles are challenging for robotic manipulators because there are many geometric and force variables to consider. A gripper that manipulates only one type of door would be useless in the real world, so the final design must be able to adjust to different shapes and be able to release the door knob or handle before causing permanent

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damage to the door. Mechanical solutions to these requirements may be a better solution approach compared to using a sensor array that could add cost, or vision systems that may be unreliable in certain lighting conditions. Two-pronged clamping grippers have been demonstrated as mechanically capable of unlatching door knobs and handles, as seen in [3, 4], but large sensor arrays and vision systems were required to control it precisely on approach. The motivation behind the design of an underactuated and compliant gripper is to keep the mechanism simple, cost effective, and easy to operate.

The gripper was developed within the assistive technology domain as part of a research project named DORA (Door Opening Robot Arm). The goal for developing DORA was to design a wheelchair-mounted robotic arm to specifically open doors for a significantly lower price than the multi-purpose wheelchair-mounted robot arms currently found on the market [5]. The two gripper prototypes were designed for integration with DORA. Therefore, the grippers were designed to use only one motor to minimize DORA's cost and weight.
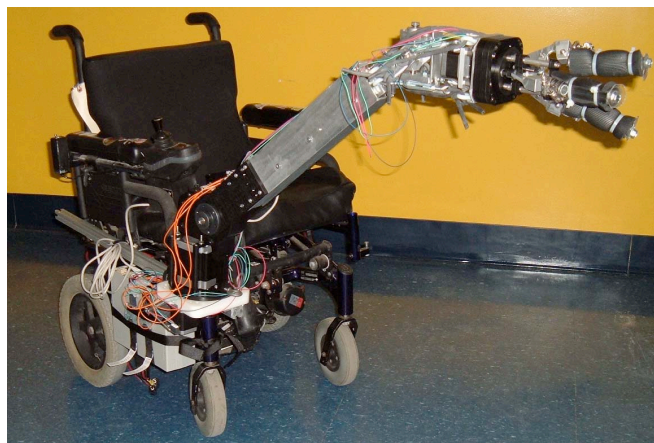

Figure 1. Photo of DORA shown with first gripper prototype (Gripper 1).

2. RELATED WORK

Robotic grippers have been developed for a variety of purposes. Researchers at the University of Kentucky developed a one degree of freedom mechanical end-effector for an industrial robot [1]. It was based on the parallel motion of a four-bar linkage and was capable of concentrically gripping cylindrical components of different sizes. Another gripper was designed by University Laval and carried out complex grasping tasks by grouping several

robotic fingers together [6]. The object did not need a regular shape for each type of grasp because the hand automatically adapted to the rounded contours of each individual shape. Similar research involved a robotic hand that adapted to the shapes and sizes of different objects while using only one actuator [7]. Fully actuated anthropomorphic robotic hands were developed for prosthetics such as the hand on DEKA's Luke Arm [8], and for versatile tasks such as ones planned for NASA's Robonaut [9]. In the assistive technology domain, researchers at the University of South Florida developed a parallel gripper that was contoured to handle the objects commonly used for a person's activities of daily living [10]. This gripper was mounted to their custom wheelchair-mounted robotic arm.

An underactuated and compliant robotic end effector to open household doors was designed by Adeline Harris while she was a graduate student at Tufts University [11]. The Tufts gripper was designed specifically for doorknobs and handles that rotate clockwise to operate its latching mechanism. A collet-cone end effector was engineered (Figure 2) to use a single motor as an actuator, which allowed for misalignment on approach because its finger arrangement centered the door knob as it tightened on it. In addition, a door handle was manipulated by nesting it between the gripper fingers [11]. The Tufts gripper used a cam that followed a groove while the motor rotated to push a clamp over collapsible fingers arranged in a collet-cone formation. When the clamp fully compressed on the door knob, the cam could no longer follow the groove and the whole barrel released to turn the door knob.
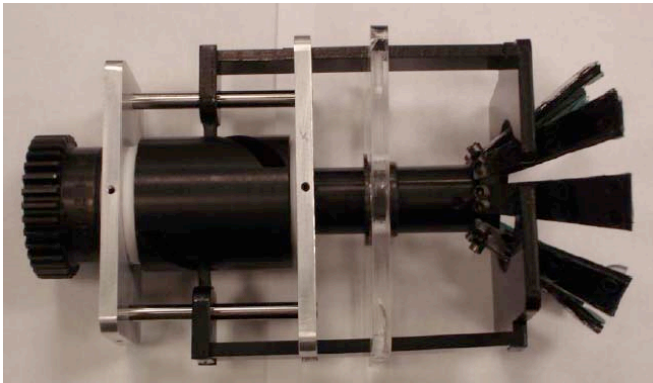

Figure 2. Tufts prototype robotic end effector to open household doors. Courtesy of A. Harris [11].

3. GRIPPER DESIGN

The design of DORA's gripper was an extension of the work completed at Tufts University. (More details about DORA's gripper concept design process can be found in [5].) Several features from the Tufts gripper were incorporated into the initial design for Gripper 1 such as its collet-cone shape for positional compliance, its use of the spaces between gripper fingers to nest a door handle, and sliding an object forward and backwards to implement the opening and closing of the collet-cone. These features were continued in the design for Gripper 2. The key difference between the Tufts and DORA gripper was DORA's ability to open and close in both

clockwise and counter-clockwise directions while utilizing a smaller and more compact mechanism.

The mechanical design on both Gripper 1 and Gripper 2 involved the combination of a planetary gearbox for rotation and a lead-screw linkage assembly that produced an opening and closing motion for its three fingered collet-cone. Both grippers were identical in this manner. The three fingered cone rotation was connected to the rotation of the outer ring of a planetary gear set. The sun gear of the planetary gear set was coupled with the lead-screw and both rotated at the same angular velocity. The planet gears reduced the angular velocity and reversed the direction of the outer ring gear. A collar was threaded around the lead-screw and was also constrained to a linear slide located along the structure connected to the outer ring gear of the gripper. The difference in angular velocities between the lead-screw collar and the gripper structure allowed the collar to move linearly, forwards and backwards, along the screw as if the collar was attached only to a linear slide. The fingers then closed and spun at the same time, spinning at the same rate as the outer ring gear and actuating due to the linear motion of the lead-screw linkage. In addition, the gripper was designed to create ease in control by allowing for misalignment on approach to the door knob or handle. The three gripper fingers were arranged in a conical pattern that acted as a collet because the fingers closed and tightened around the door knob to center it.

The planetary gearbox and lead-screw components that were shared between the two prototypes are shown in Figure 3 (Gripper 1) and Figure 5 (Gripper 2). These parts included the planetary gear set which utilized a 48 pitch 144 tooth internal gear, 60 tooth planet gears, and 24 tooth sun gear that had a face width of 1/8 inch (3.175 mm). This gear set, along with the deep groove bearing, was housed in three plastic plates that sandwiched all of these parts together. Two plastic hubs were enclosed inside the deep groove bearing that connected the ring gear on one side to the foundations of the gripper linkages on the other. The lead-screw nut was fastened to a plastic plate that also held the other ends of the gripper linkages. Teflon bearings were nested inside the outer ends of this plastic plate and the bearings slide freely along carriage bolts to constrain the lead-screw collar's rotational motion. Therefore, the lead-screw inside the collar spins faster, and in the opposite direction, than the carriage bolts to which the lead-screw collar was connected. This design produced linear motion of the collar and, in turn, movement in the linkage that connected to the fingers. Lastly, the lead-screw was coupled to the sun gear of the planetary gearbox and was attached to the gripper motor shaft at the base of the assembly.
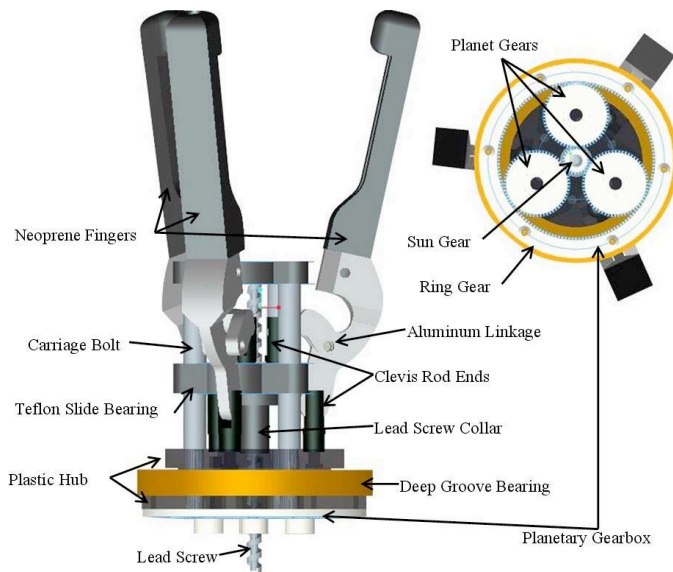
Figure 3. Mechanical assembly of Gripper 1 (housing structure for the planetary gearbox and bearings are not shown).

It was realized that, as initially designed, the gripper could not continue to spin when the fingers were fully closed around the door knob or handle because the finger linkage and planetary gearbox were directly linked. Gripper 1 compensated for this interference issue by using flexible fingers in the form of neoprene tubes surrounded by a rubber grip material for added traction around a door knob. The hypothesis was that, as the linkage closed around the door knob, the flexible fingers would bend away allowing the ring gear to continue to turn as shown in Figure 4. The Gripper 1 motor, a PK244PA 2-phase stepping motor from Oriental Motor which operated at 30 rpm and produced a torque of approximately 3.5 lb-in (0.4 Nm), was coupled to the lead-screw shaft at the base of the gripper in the final assembly.
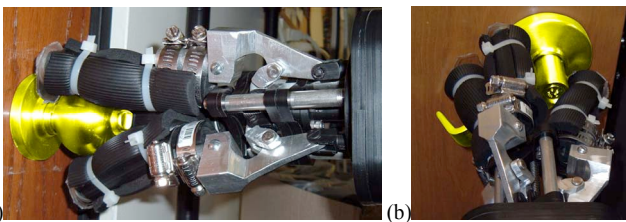

Figure 4. Gripper 1 manipulating a (a) door knob and a (b) door handle.

The design of Gripper 2 remedied the interference issue by utilizing an adjustable slip clutch to allow the planetary gearbox to continue to rotate when the lead-screw linkage fingers were fully constrained around the door knob or handle. Figure 5 shows where the slip clutch was placed relative to the rest of the gripper assembly. The finger linkages on Gripper 1 were machined out of aluminum, were bulkier in shape, and the collet-cone opening at the end of the fingers had a larger diameter at 5 inches (127 mm). The finger linkages on Gripper 2 were thinner, machined out of Delrin, and had only a 3 inch (76.2 mm) open diameter at the end of the fingers. In addition, the overall length of Gripper 2 was increased to accommodate the size of the slip clutch.
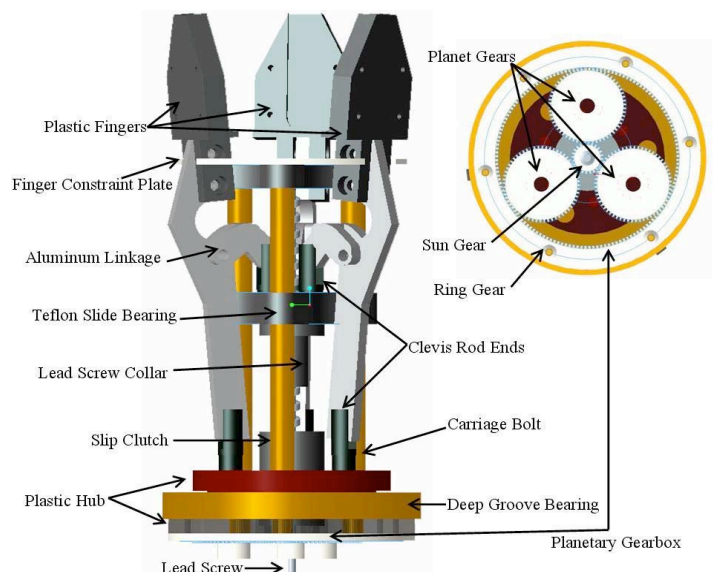

Figure 5. Mechanical assembly of Gripper 2 (housing structure for the planetary gearbox and bearings are not shown).

Other changes to Gripper 2 included the substitution of the flexible neoprene fingers with shorter fingers tips manufactured out of a solid material (Delrin). The fingers were machined to be thinner in shape so they could pass through the gap between a door knob and door jam. They were also made to be shorter to create a smaller diameter opening at the finger tips and wider to create smaller gaps between the fingers at the gripper's most open position. Figure 6 shows how rubber grip was attached to the Delrin finger to add traction. Gripper 2 used a stronger motor than Gripper 1, a PK246PA 2-phase stepping motor from Oriental Motor which operated at 30 rpm and generated a torque of approximately 7 lb-in (0.8 Nm) on the lead-screw. Also, a holding torque was placed electronically so the gripper maintained its position while the wheelchair pushed or pulled on the door. Lastly, a plate was added at the top of the carriage bolts to constrain the linkages and fingers from moving side-to-side. The reasoning behind these design changes is explained further in the Design Evaluation section.
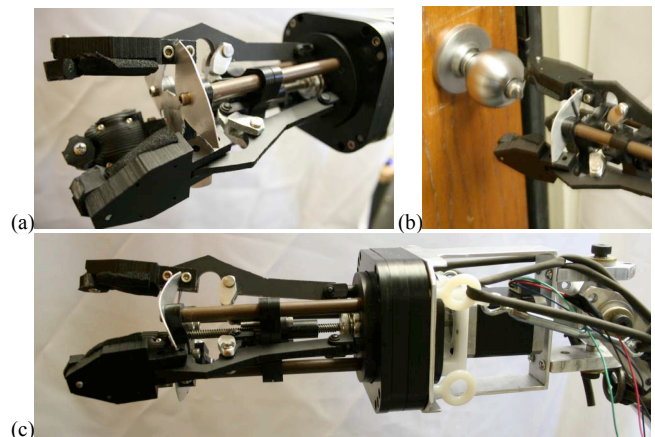

Figure 6. Gripper 2 shown at (a) an angled view, (b) on approach to a door knob, and (c) a side view including its motor and universal joint.

4. DESIGN EVALUATION

The following section explains the test procedure used to evaluate both gripper designs and discusses the results in accordance to the design changes made for Gripper 2. Both gripper prototypes were delivered to the door knob or handle by DORA during their evaluation periods. DORA included a motorized Cartesian robot configuration (Figure 7) that was driven, joint-by-joint, to the door knob or handle. DORA utilized a motorized side-to-side joint, a motorized up-down joint, and a motorized sliding link that extended the gripper forwards and backwards. The gripper was attached to the sliding link portion of the robot arm via a spring-loaded universal joint used to traverse the face of the gripper to the plane of the door. The purpose of using the spring-loaded universal joint was to keep motor usage and costs low within the entire DORA design. However, the universal joint did not work as intended so its impact (in terms of evaluating the gripper) was kept to a minimum [5]. Likewise, the cylindrical joint was underpowered and unable to hold its position against any side-to-side forces placed on the arm [5].
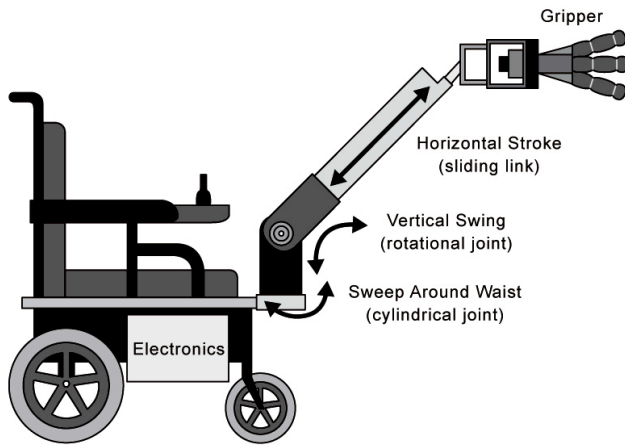

Figure 7. The Cartesian arm configuration and gripper as incorporated into the DORA design.

A power wheelchair (Quickie S525 by Sunrise Medical) was used to position the base of the robot arm directly in front of the door knob or handle for gripper testing. This action negated any performance results that may have been affected by the use of the cylindrical joint and the universal joint's traversal from the sliding link to match the gripper with the plane of the door. The heights of the door knobs and handles varied so only the rotational joint, the sliding link, and the wheelchair wheel platform were used to deliver the gripper to the door knob or handle of interest. In the prototyping state, DORA was controlled via a custom built stepper motor controller by driving each motor joint individually using a push button keypad.

Fourteen doors on the UMass Lowell campus were selected for testing: four with handles and ten with door knobs. The doors had varying characteristics such as door knob or handle height, diameter, unlatching torque, distances from their respective door jams, and force required to push the door open. Figure 8 displays the location of the gap between a door knob and door jam. The purpose of this test was to quantify which of DORA's design characteristics were effective and which were not due to a door's specific geometry or its required force characteristics.
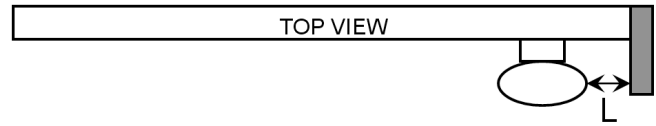

Figure 8. Location of gap between the door knob and door jam (known as dimension "L" in [5]).

Ten "door-opening" trials were performed on each door, five on the pull side of the door and five on the push side of the door, for a total of one hundred and forty trials for each gripper design. Each trial ended with the pushing or pulling of the wheelchair to verify if the door knob or handle had been twisted far enough to unlatch and allow the door to open. The gripper was again positioned on the door knob or handle between each trial to guarantee a "new" attempt. All of the door knobs were tested by operating the gripper fingers in a clockwise direction. The door handles were tested in a clockwise direction if the door handle was on the left side of the door (handle pointed to the right) and in a counter-clockwise direction if the door handle was on the right side of the door (handle pointed to the left). Table 1 shows the results of the 140 trials for Gripper 1 and Gripper 2 along with the door characteristics that most affected their performance evaluation.

Table 1: Evaluation Results for Various Doors

Door ID	Type	Distance between door knob and door jam (inches)	Rotation angle to unlatch door knob/handle (degrees)	Push force required to open the door (lbs)	Torque to unlatch the door knob/handle (lb-in)	Push/Pull	Gripper 1	Gripper 2
							Percentage of successful trials (5 trials on each side of the door) Space is left blank if zero	
1	handle	4.5	60	10.0	12.0	push		60%
						pull		
2	handle	2.9	30	3.5	21.3	pull left		
						pull right		
3	handle	2.0	40	0.8	9.0	push		100%
						pull		80%
4	handle	2.0	50	0.8	12.8	push		100%
						pull		
5	knob	1.4	29	0.8	2.1	push		100%
						pull	40%	80%
6	knob	1.4	58	0.4	8.5	push		
						pull		
7	knob	1.1	32	4.5	2.3	push		100%
						pull		
8	knob	1.3	36	6.0	3.0	push		80%
						pull		100%
9	knob	0.9	82	6.0	3.2	push		100%
						pull		100%
10	knob	1.4	37	1.0	3.4	push		100%
						pull		100%
11	knob	3.9	38	0.0	3.9	push		100%
						pull		100%
12	knob	0.6	14	8.0	4.5	push		100%
						pull		100%
13	knob	1.5	21	0.8	1.8	push	100%	100%
						pull	60%	100%
14	knob	0.9	30	0.2	4.5	push		100%
						pull		100%

Table 1 shows a direct comparison between Gripper 1 and Gripper 2. Gripper 1 unlatched the mechanisms on two doors out of the fourteen doors (10 of 140 trials, 7%) whereas Gripper 2 unlatched the mechanisms on twelve of the fourteen doors (100 of 140 trials, 71%). The two doors that were unlatched by Gripper 1 were similar such that they had the lowest required twisting angles, lowest required push

forces, and the two lowest torque requirements of the ten knobbed doors. Also, the two successful doors were evaluated early in the testing process when Gripper 1 had not yet experienced much mechanical fatigue.

Gripper 1 could not push or pull open handled doors because it could not hold the twisted handle for a long enough time to unlatch it from its door jam. This occurrence was increased since a holding torque had not been programmed for the gripper motor when the power command was removed. In addition, DORA could not pull a handled door open because the rubber fingers on Gripper 1 could not hold the handle tightly enough. Most knobbed doors could not be unlatched from the push side because the fingers were too wide to fit in the gap between the door knob and the door jam (Figure 8). Knobbed doors were not often pulled open because the flexible fingers and fingertip nubs did not tightly clamp onto the knob. The rubber fingers easily slipped off when DORA pulled the gripper backwards.

Many of the door statistics from the test scenario gave insight into Gripper 1 design flaws because the data produced noticeable trends. The gripper fingers often caught in the gap between the door knob and the jam (Figure 8) because the fingers were often wider than the space allowed. The fingers were 1.5 inches (38.1 mm) wide and therefore, as compared to Table 1, could not pass through the space available on many of the samples. This observation lead to a design change for the fingers on Gripper 2; they were made thinner than the smallest gap found within the sample. In addition, the finger linkages and clevis rod ends on Gripper 1 jostled side-to-side after the fingers were being constantly forced into that area. To remedy this, a constraint plate was implemented on Gripper 2 to limit side-to-side motion if the fingers happened to hit any kind of obstacle.

Occasionally, Gripper 1 twisted itself off the door knob or handle while trying to actuate it. This action occurred when one of the fingers jammed and was unable to move. Gripper 1 frequently twisted itself off the door handles because its geometry allowed for the finger to act as a pivot point on the top surface of the handle. The rotational portion of the handle passed through the gaps between the other fingers while the gripper pivoted around it. To fix this twisting-off problem, the fingers on Gripper 2 were designed to be wider which resulted narrower gaps at the gripper's open position. The gaps between fingers on Gripper 1, at its most open position, were about 4 inches (101.6 mm) whereas the gaps on Gripper 2 were 2 inches (50.8 mm). The testing confirmed that this twisting-off issue was eliminated for Gripper 2.

Gripper 1 used rubber fingers because of an interference issue between the lead-screw linkage and planetary gearbox. The gripper design was unable to continue to turn after the fingers were fully constrained around a door knob or handle. However, Gripper 1 was only capable of manipulating the two door knobs that had a small angle for unlatching. The conclusion was that rubber fingers were not the optimal approach. The use of flexible fingers was difficult

considering the number of requirements to make it a successful design: 1) the fingers must flex front-to-back enough to allow the gripper to turn; 2) they must not flex side-to-side at all to allow for the constraint of a door handle; and 3) they must apply enough of a compressive force to constrain a door knob or handle when DORA pulls on a door. There was no guarantee that any flexible gripper finger design could meet all of these criteria while being thin enough to fit in the gap between a door knob and its door jam (Figure 8). Also, flexible materials are known to wear out more quickly than solid materials. The design of Gripper 2 remedied this interference issue by separating the clamping and twisting actions with an adjustable slip clutch. This change allowed for more design options because the lead-screw and the planetary gearbox motions were no longer dependent on each other. The use of solid material for the fingers on Gripper 2 enabled a finger design that eliminated many of the design flaws found in Gripper 1.

Gripper 2 was tested in an identical manner to Gripper 1. The results are shown in Table 1; there was a significant improvement in performance. Gripper 2 was capable of pushing or pulling open ten of the doors that Gripper 1 failed to manipulate.

Although there was a dramatic performance increase between Gripper 1 and Gripper 2, the gripper design requires another iteration to improve certain failed scenarios. Gripper 2 failed on the pull side of the three handled doors because the sides of the fingers managed to slip off the handle. This issue could be remedied by adding nubs on the edges of the fingers to allow for a mechanical constraint instead of just relying on compression. Gripper 2 did fail to manipulate two of the door knob samples for very specific reasons. The door knob on Door 6 would not continue to turn after the point where it unlatched, and Gripper 2 pulled off of the knob on Door 7 because the door stuck in its door jam.

5. CONCLUSION AND FUTURE WORK

This paper described the iterative design of an underactuated gripper used to unlatch doors knobs and handles. This research yielded a mechanism that was capable of twisting door knobs and handles in clockwise and counter clockwise directions. It had a collet-cone shape for compliance gripping and centering, and it utilized one motor for both gripping and twisting actions. The gripper combined a planetary gearbox and a lead-screw linkage to open, close, and turn three gripper fingers connected to a linkage assembly.

The two iterations of the gripper design were evaluated by direct comparison through a rigorous test. The test was completed on fourteen doors found on the UMass Lowell campus which all had varying characteristics. Gripper 1 unlatched the mechanisms on two out of the fourteen doors (10 of 140 trials, 7%) whereas Gripper 2 unlatched the mechanisms on twelve of the fourteen doors (100 of 140 trials, 71%). Gripper 2 had a far higher success rate on the tested doors than Gripper 1.

Continued research and improvement in the specific gripper finger design would likely yield a higher success rate. The testing of Gripper 2 showed that the gripper pulled off many of the handled doors. One potential solution would be to create fingers with a contour or curve to constrain the door handle instead of relying on only compression on the sides of the fingers. In addition, a more optimized motor, lead-screw, and linkage assembly would result in a tighter grip. This exploration into the design of an underactuated gripper for unlatching door knobs and handles yielded a final prototype that was intrinsically compliant, simple, used a single motor, and was compact for mounting to a robotic arm.

6. ACKNOWLEDGEMENTS

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