THE DESIGN OF AN UNDERACTUATED WHEELCHAIR MOUNTED ROBOTIC ARM TO UNLATCH DOOR KNOBS AND HANDLES

BY

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ABSTRACT

Wheelchair-mounted robot arms are typically designed with many degrees of freedom to provide users with a general-purpose device for manipulating many of the objects necessary for activities of daily living. However, commercially available systems are quite expensive and are usually not covered by insurance. An underactuated door-opening robotic arm (DORA) has been developed that has the potential to increase a power wheelchair user's accessibility to indoor spaces. DORA is designed specifically to unlatch door knobs and door handles while being permanently mounted to a power wheelchair. The gripper design requires only a single motor to turn various types of door knobs and handles, and a minimized arm configuration is used to keep the cost of the robot arm low. Although DORA is able to unlatch a number of door knobs and handles with similar characteristics, there are several limitations to the design that need to be addressed prior to using the robot in a rehabilitation environment.

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1 INTRODUCTION

The American with Disabilities Act (ADA) recognizes that some people need special accommodations so they can work within their environment at a level that enables them to participate in their activities of daily living (ADL) (U.S. Congress, 1990). The ADA defines a person with a disability as “having an impairment that substantially limits one or more of their major life activities including caring for one’s self, performing manual tasks, walking, seeing, hearing, speaking, breathing, learning, and working” (Adaptive Environments, 1995). According to the 2000 U.S. Census Supplementary Survey, 39.7 million people in the United States are estimated to have a disability (Stern, 2003). As part of this survey, people were asked about their ability to participate in a community outside of their home, specifically, “Does this person have any difficulty going outside the home alone to shop or visit a doctor’s office?” This question classifies a sub-population with a go-outside-the-home disability, which comprises of 6.2% of the people with disabilities age 16 and older living in a household (Stern, 2003). People with a go-outside-the-home disability are a subset of “people who are limited from leaving their homes without assistance” (CensusScope, 2008). One reason people require assistance to go outside their homes may be because they have difficulty manipulating objects in the environment such as door knobs and handles.

The ADA acknowledges the need to accommodate people who have mobility difficulties with their wrists or arms and mandates the following guidelines for door hardware: “handles, pulls, latches, locks, and other operating devices on accessible doors shall have a shape that is easy to grasp with one hand and does not require tight grasping, tight pinching, or twisting of the wrist to operate” (United States Access Board, 2008). These ADA guidelines for door hardware explain why buildings have a large number of lever handles on their doors, push bars, and simple U-shaped handles. However, door knobs are frequently present in homes and some businesses, and outfitting every home and facility with automatic door openers could be costly. Furthermore, people who are prescribed a power wheelchair usually have limited upper body mobility, so they would not always be capable of unlatching a door knob or handle to pass between rooms without help from a caregiver (Mobilitypro, 2009).

1.1 PROBLEM STATEMENT

Wheelchair-mounted robotic arms (WMRAs) are designed to assist people who use a wheelchair and have additional complications using their arms and hands. For example, the Manus Assistive Robotic Manipulator (Manus ARM), a rehabilitation robot developed and sold by Exact Dynamics, is a 6+2 degree of freedom WMRA that can reach objects under a meter away from its mounting point (Exact Dynamics, 2008). While such general purpose devices can increase the quality of life for individuals by providing assistance in their activities of daily living (ADLs), the Exact Dynamics Manus ARM costs approximately $30,000, but robotic arms are not usually covered by insurance in the United States (Tsui, 2008).

The WMRAs that have been built to date have many different kinds of designs. Some are built with many robotic joints and human-like kinematics (e.g., (Volosyak et al., 2005)), some use horizontal links so the motors do not need to manipulate the entire weight of the robot arm (e.g., (Hillman et al., 2002)), and some use pneumatics to actuate their individual joints (e.g., (Prior & Warner, 1993) and (Ourefelli, 1993)). A WMRA operated with pneumatics adds the weight of a compressor or storage tanks onto a power wheelchair, which may drain a power wheelchair's battery. Many of the other WMRAs have between four and seven motorized joints, in addition to the gripper, to operate the robot arm about its workspace. Some of these WMRAs are sold directly to power wheelchair users and other WMRAs are purchased by researchers. Approximately 255 Exact Dynamics ARM units have been sold to this day (Tsui, 2008), a very small number compared to the number of people who use power wheelchairs. The high price to purchase a WRMA hinders the technology's acceptance among power wheelchair users.

A door-opening robot arm could enable a power wheelchair user the ability to pass between rooms independently. An underactuated door-opening robot arm can be designed to use only a few motors if the expectations for its use are targeted to a specific task. Such a device could have a more appealing price point than the WMRAs currently on the market. An underactuated system is one that has a lower number of motorized joints than degrees of freedom. An underactuated robot arm is likely to have a lower price point than an arm with many motorized joints because it would need fewer of the most expensive components such as motors, gears, and bearings. It is also known that underactuated devices tend to be more efficient, consume less power, and are generally more reliable than fully actuated devices with similar capabilities (Saliba & de Silva, 1991). For this thesis, the task at hand is to design a robot arm to unlatch a door using a minimal number of motors, gears, and bearings in its design.

There are two common sub-classes of research and development that are important for robot arms used for rehabilitation purposes: (1) mechanical design, including mobility and end-effectors and (2) programming, control, and the man-machine interface (Certec, 2009). This thesis focuses on the mechanical design of an underactuated wheelchair-mounted Door-Opening Robotic Arm (DORA) and demonstrates its capabilities while mounted to a power wheelchair.

1.2 APPROACH

A door-opening robot arm could increase a person's accessibility to unequipped indoor spaces (such as when a person in a power wheelchair enters a public building that is not ADA compliant or visits the home of a friend). There are three principal research questions to address for a successful prototype demonstration:

- How can a compliant robot gripper be designed to unlatch door knobs and handles?
- What is the ideal arm configuration that is minimized for cost but also useful for opening doors?
- How can the compliant gripper and the robot arm be joined to successfully unlatch a door?

These three questions are related because a proposed solution for one question impacts the solutions for the others. When designing the robot system, constraints for custom parts are designed based on the size and shape of previously decided upon components such as motors, shafts, bearings, flanges, drawer slides, and gears. However, this design approach is done so as to not limit DORA's capabilities; for example, different motors within a size range can fit into the current assembly. The design process for the robot arm is balanced between simulating the conceptual ideas for mechanisms, testing prototypes, making assumptions for torque and weight, using motors based on these assumptions, and making sure the actual robot arm does not weigh more than the torque calculations assumed. However, the design process began by examining similar machines such as devices that provided gripping assistance, generic robot arms, and gripper concepts implemented with other WMRA designs.

For the purpose of this thesis, the final performance metrics for DORA were to open fifteen doors that have a variety door knobs and door handles on both the left and right sides and to unlatch the door from both sides (pushing and pulling) using a push button keypad to control each individual motor on the robot arm. The fifteen doors were accessible on the UMass Lowell campus within close proximity to the lab where DORA is stored.

1.3 CONTRIBUTIONS OF THE THESIS

This thesis describes the design of a door-opening robot arm, DORA, shown in Figure 1. The contributions of this thesis include a number of innovations for a robotic gripper and an underactuated robot arm. DORA's design is:

- Capable of unlatching door knobs and handles on a number of interior doors.
- Light enough to not need counter balancing on the power wheelchair.
- Manufactured on standard milling machines and lathes.
- Able to use only one motor to both open and close the three gripper fingers and turn them in both clockwise and counterclockwise directions.

The robot arm uses three motors to serve as a Cartesian robot configuration because it only needs three controllable Degrees of Freedom (DoF). A spring-loaded universal joint serves as the non-motorized wrist (2 DoF) between the robot arm and the gripper, and the gripper both opens/closes and spins (2 DoF) using one motor. The power wheelchair serves as an additional two DoF. When mounted to a power wheelchair, DORA has a total of 7+2 DoF using only three motors in the robot arm and one in the gripper. The universal joint allows for misalignment when the gripper approaches the door knob or handle, and it allows for angle changes between the gripper and the arm when the power wheelchair pushes or pulls the door open. The robot arm was designed with mechanisms in mind that are robust, simple, and not back drivable (i.e. self-locking), so motor power is not needed to hold the arm at specific positions.

The capabilities of DORA's gripper were demonstrated on interior doors while being mounted to the underactuated robot arm. The test results yielded data for which gripper design aspects worked well and a failure analysis detailed the changes that could be made in future work (Chapter 6). For example, the gripper was unable to unlatch door knobs that require a twist angle of higher than 30° because the gripper no longer spins when the gripper fingers are fully compressed.

The resulting DORA design is a robotic arm and gripper that uses four motors (Figure 1). DORA has been successfully demonstrated to unlatch door knobs and door handles while being mounted to a power wheelchair. However, a number of failures occurred within the gripper and the universal joint. The robot arm configuration delivered the gripper to the needed position, but the universal joint did not have enough flexibility to traverse the side-to-side angle for the gripper fingers to match the plane of the door. Also, the gripper fingers sometimes slipped off the door knob or caught in a deep door jam.

More research is needed for thinner gripper fingers and a greater angle traversal for the universal joint. Aside from these details, DORA's prototype implementation proved that the concept designs for an underactuated door-opening robot arm remain a viable solution to potentially allow people who use power wheelchairs the ability to move between rooms independently. Since it uses fewer motors and gear assemblies than its predecessors, a lower price point than other WMRAs is a likely outcome if the device is manufactured in the future. DORA's materials cost is currently $1800 (not including electronics) as reported in Appendix 1.

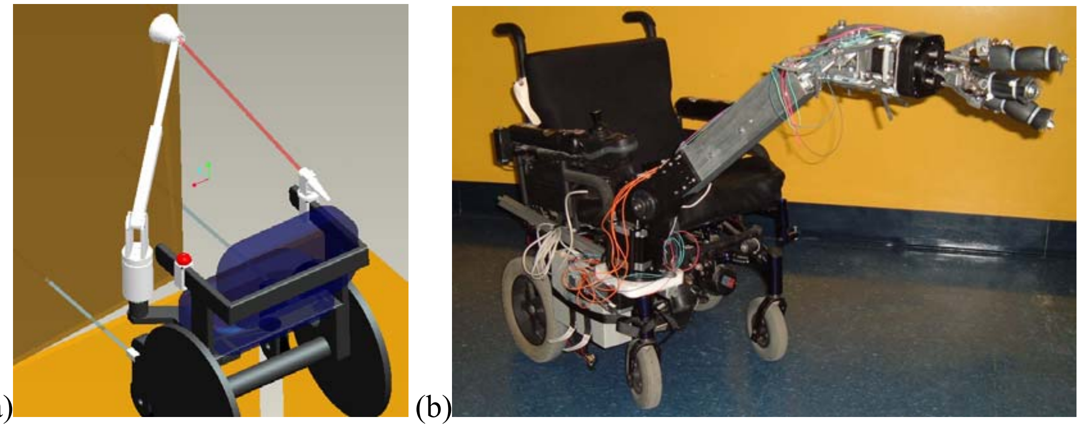

(a) (b)

Figure 1. DORA depicted as a (a) preliminary simulation and (b) the final proof-of-concept prototype.

1.4 THESIS OUTLINE

This thesis includes a survey of prior research of robots that have opened doors (Chapter 2), a look into the intended market of people who use power wheelchairs (Chapter 2), and an engineering design process that includes two major components: gripper design (Chapter 3) and robot arm design (Chapter 4). Design solutions are inspired by comparable technologies and implemented in a technical design by creating design goals for the gripper (Chapter 3) and robot arm (Chapter 4). The end result of this thesis is the design and implementation of an integrated door-opening robot arm and gripper, named DORA, that was tested on an assortment doors to discover its best design features (Chapter 5), potential design flaws (Chapter 5), and a focus for future work (Chapter 6).

2 BACKGROUND

Preliminary background research helped derive the constraints and design goals for DORA. Initially, research about people with disabilities who use power wheelchairs was conducted because they are the intended market. Next, robots that have demonstrated the ability to open doors were investigated in addition to other WMRA designs that have been implemented in the past. Finally, robotic grippers were reviewed to determine if their design could be simplified to specifically open a door. The review of these past projects helped generate design goals and define the scope and expectation for DORA's prototype performance.

2.1 INTENDED MARKET

This section describes the target user population in order to understand their needs. The actual demand for DORA among this user population is beyond the scope of this research because it would require extensive market research.

Assistive devices have the ability to increase a person's mobility and functionality in the world around them. Fully mobile people are able to move freely within indoor and outdoor environments without difficulty. People who have restricted movement in their arms or hands may have trouble moving about an environment because of doors and other obstacles. The task of opening a door requires a significant amount of strength and control, which a person with a disability may not have available. People with limited upper body mobility could increase their independence if they are provided automated assistance for unlatching door knobs and handles as shown by the presence of electric door openers seen in health care facilities (Harris, 2006).

The user population in need of a WMRA to open doors has a large variety of disabilities ranging from weakness, paralysis, missing limbs, joint problems, and spasticity (Trace, 1992). Physical impairments, such as an injury or arthritis, can prevent specific movements in the arms, hands, and other parts of the body (Trace, 1992). In addition, there are over 12,000 new spinal cord injury cases each year (NSCISC, 2008). People who are prescribed a power wheelchair have limited upper body mobility, strength, or may fatigue easily; otherwise, they would have been prescribed a manual wheelchair (Mobilitypro, 2009). People with these conditions may have difficulty manipulating doors to their homes for many reasons, such as difficulty with positioning their wheelchair relatively close to the doorknob, difficulty with squeezing to unlatch the internal spring, or difficulty with pushing down on a door handle (Harris, 2006).

Some doors are opened with pneumatic or spring-loaded door opening systems that are operated by remote control or push button. These devices serve well in controlled environments such as hospitals, nursing homes, and office buildings. However, not every door is outfitted with such a device and the technology may be too expensive to merit installing in every person’s home or workplace on every door. The ADA does not require remote controlled door opening devices (Adaptive Environments, 1995), but without them many people with limited upper body strength cannot enjoy the freedom to move themselves about an interior environment and must ask for assistance.

Creating an assistive device for people with disabilities represents a design challenge because they may also have a variety of illnesses, they may have difficulty reading, or they may be inexperienced with the product or technology (Sawyer, 1996). Many people may also be afraid to use the technology (Sawyer, 1996). The decline of vision, hearing, strength, and memory are also anticipated with age and illness (Sawyer, 1996). The FDA has emphasized the importance for a selected design to accommodate a wide range of users with varying disabilities, sometimes in stressful environments, and be less prone to error with minimal user training (Sawyer, 1996).

The ADA has placed standards for public facilities and has mandated that all new facilities have ADA compliant door hardware. A way to test for accessibility on door hardware is to do a “closed fist” test on door handles and other controls (Adaptive Environments, 1995). A “closed fist” test is when a person tries to operate a knob or button with their fist instead of their fingers. The ADA has placed other requirements such as a height limit on door hardware of 48 inches, the door should be able to open with less than a 5 lb-force, and each door should have an opening of at least 32 inches (ADA, 1995). Also, the ADA suggests 18 inches of wall space next to the pull side of a door so a wheelchair user can more easily reach the door knob or handle (Adaptive Environments, 1995). These ADA requirements are helpful in terms of what could be expected for an ADA compliant facility, but DORA is also designed for facilities that are not ADA compliant.

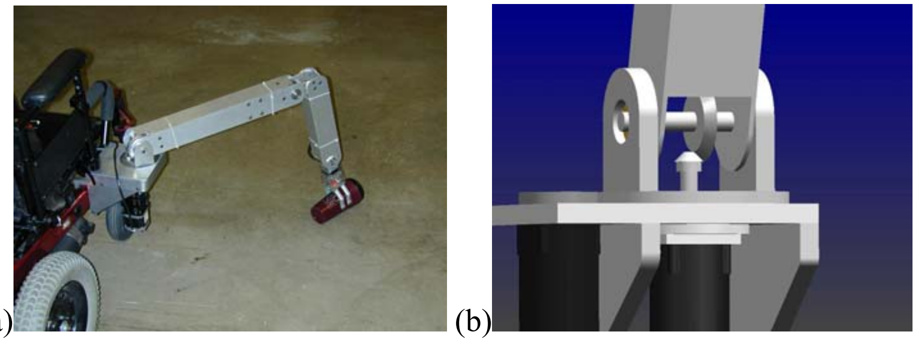
The Center for Universal Design at North Carolina State has a mission to improve environments and products through design innovation, research, education, and design assistance (Connell et al., 1997). Their Seven Principles of Universal Design challenges designers to consider usefulness among people with disabilities. The seven principals include: “equitable use, flexibility in use, simple and intuitive use, perceptible information, tolerance for error, low physical effort, and size and space for approach and use (Connell et al., 1997).” More details about the seven principles are found in (Connell et al., 1997) and are discussed as the reasons behind various robot arm design goals in Section 4.1. The review of the expectations and limitations of the intended market, along with the review of these seven principles, challenge DORA’s concept design to be potentially useful for people with disabilities.

2.2 ROBOTIC ARMS

Wheelchair-mounted robotic arms are considered a type of rehabilitation robot. Mechanical design suggestions are described for robots used in home-based environments in (Certec, 2009). The mechanical design of a robot used for rehabilitation is different than the design for robots used in industrial applications because humans occupy a workspace with the robot (Certec, 2009). Key differences include the payload on a WRMA is in a lower range than a payload on an industrial robot, the motorized joints on a WMRA require lower accuracy for motion control than on an industrial robot, the WRMA may be used a few times each day as opposed to an industrial robot that is used a few thousand times a day, and the WMRA does not need to move as fast as an industrial robot (Certec, 2009).

WMRA designs that have been brought to market are researched and explored in a presentation from the "Gateway Coalition" consisting of Ohio State University, Sinclair Community College, and Wright State University (Gateway Coalition, 2000). Their table reported on ten of the WMRAs available for purchase in year 2000, where the units were sold, and the approximate number of units sold. The Gateway Coalition claimed that the reasons many previous WMRA manufacturers failed were because they implemented a poor user interface for the robot arm, the WMRA designs appeared isolated from clinical reality, the robot arms were not portable, and the cost-benefit for these WMRAs were never justified (Gateway Coalition, 2000). For these reasons, the Gateway Coalition decided to strive for underactuation in their gripper and arm design in order achieve a lower price point than the other WMRAs available in year 2000.

The Gateway Coalition WMRA starts with a shoulder joint that twists and bends, an elbow joint located between the two arm links, and a wrist joint that connects to the gripper (Gateway Coalition, 2000). Figure 2 shows how the arm is mounted to a wheelchair and the way the motors are attached to the shoulder joint. It uses two motors in the base, one to drive a spur gear as its cylindrical joint (twist) and another to drive a bevel gear to change the angle ninety degrees between the motor shaft for the rotational joint (bend). DORA's design reflects the "Gateway Coalition's" idea of keeping the motor weight off the arm as much as possible and uses a motor to drive a spur gear as its cylindrical joint.



(a) (b)

Figure 2. Gateway Coalition WMRA (a) mounted to wheelchair and (b) shoulder joint (Gateway Coalition, 2000).

The Gateway Coalition reported that, in the year 2000, the Handy 1 had the most units sold of all the rehabilitation robotic devices (Gateway Coalition, 2000). The earliest versions of the Handy 1 system consisted of a 5 DoF robotic arm and a gripper, but it was never permanently mounted to a wheelchair (Topping & Smith, 1999). Handy 1 looks more like a work station; it enables people with severe disabilities gain independence with several important ADLs such as eating, drinking, washing, shaving, teeth cleaning, and applying make-up. At the time of its development, August 1998, no robotic system had existed that was capable of assisting people with disabilities (Topping & Smith, 1999). The Handy 1, shown in Figure 3, manipulates objects placed on a tray in front of its end effector.

Figure 3. Handy 1 (Topping & Smith, 1999).

The two most known WMRAs are the Manus ARM (Assistive Robotic Manipulator) from Exact Dynamics and the Raptor from Phybotics. The Manus ARM is mounted above the front of the castors on a user's wheelchair and folds up compactly below the level of the armrest as shown in Figure 4a. The system is the leading example of available WMRAs according to (Kara et al., 2009). However, its mount location on a user's wheelchair requires a care giver to remove the Manus ARM in order for the user to pass through a doorway. Also, the Manus ARM weighs 50 lbs and needs to be counter balanced on the power wheelchair for it to maintain lateral stability; the additional weight causes the power wheelchair batteries to drain more quickly. The Manus ARM is a 6+2 DoF robot arm which grasps objects with its 2 DoF gripper (Exact Dynamics, 2008). There are no mechanical specifications available for the Exact Dynamics Manus ARM, but one is located in the UMass Lowell Robotics Lab for research. A new control system is being researched because its current control methodology is too complex for many potential users (Tsui, 2008).

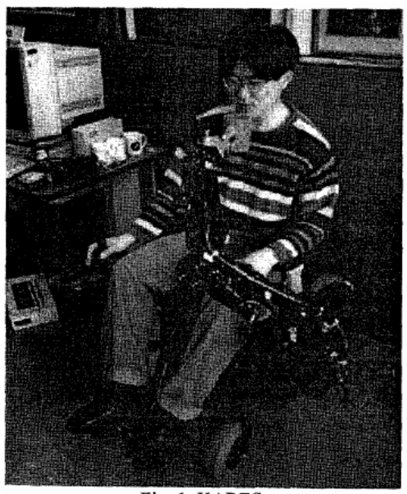
The Raptor (Figure 4b) is a commercial development of the earlier Helping Hand robot arm (Sheredos et al., 1995). The system has a limited functionality and only 4 DoF, but it is significantly lower in price than the Manus ARM and was the first commercially available FDA-approved assistive WMRA (Phybotics, 2008). It is mounted at the rear side of the wheelchair (Hillman, 2003). The Raptor was evaluated as part of a study where people used the Raptor to perform sixteen different tasks (Chaves et al., 2003). Some tasks include the opening of a refrigerator or cabinet door, but door knob and handle unlatching for passage between rooms was not evaluated. The study results indicated that the subjects were able to improve independence with the WMRA in seven of the sixteen activities (Chaves et al., 2003). The joint configuration for the Raptor was simulated as an option for DORA because it operates with a relatively low number of joints. However, the configuration was not used because its gripper could not easily match the plane of a door.

(a)  (b) 

Figure 4. (a) Exact Dynamics Manus ARM (Exact Dynamics, 2008) and (b) Raptor Arm (Phybotics, 2008).

The following two WMRAs use stepper motors for actuation. KARES (KAIST Rehabilitation Engineering System) is a rehabilitation robotic system with a 6 DoF robot arm mounted on a powered wheelchair (Figure 5a). The KARES researchers used stepper motors as its actuators because of their low cost and ease of control (Song et al., 1998). The design of the KARES arm focused on its weight, ease in assembly, workspace, load capacity, speed, repeatability, accuracy, the volume, energy efficiency, and its cost. It uses revolutionary joints with differential gears and worm gears to reduce the velocity (Song et al., 1998) and (Bien et al., 2003).

The electrical and computer engineering departments of the University of Manitoba and the University of British Columbia designed another WMRA (Farahmand et al., 2005) that uses stepper motors (Figure 5b). The robot arm was designed with 6 DoF to grasp an object on the floor and bring it to the user. Five joints are used to place the gripper and a sixth joint opens and closes the gripper. Again, stepper motors are used in each joint because of its excellent response for starting, stopping, reversing direction, and they have a high holding torque (Farahmand et al., 2005). Stepper motors and worm gears are used in DORA's robot arm design.



(a) Fig. 1. KARES.

(b)

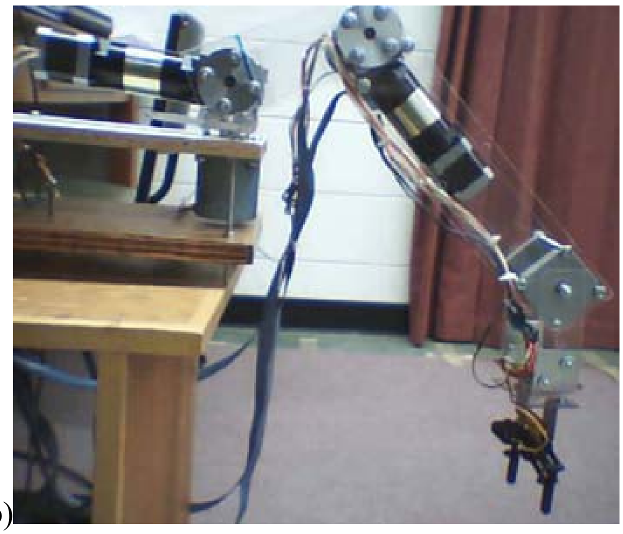


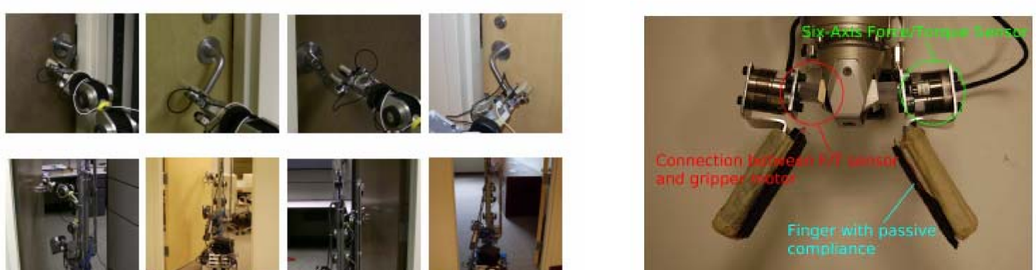
Figure 5. KARES WMRA (Song et al., 1998) and Intelligent Assistive Robotic Manipulator (Farahmand et al., 2005).

A group from the Bath Institute of Medical Engineering developed a WMRA to assist disabled users in daily activities (Hillman et al., 2002). They used an iterative design process that consists of three prototypes. Bath's robot arm configuration uses joints that operate in a horizontal plane and a single motor to actuate its vertical motion. The horizontal plane allows for less powerful motors to move the arm about a workspace (Hillman et al., 2002). DORA's sliding link uses a similar idea because the weight of the gripper is resting at an angle, not always parallel with gravity, resulting in the use of a less powerful motor. The vertical actuator on the Bath WMRA uses integral constant force springs to keep the weight of the upper arm balanced so a low power motor could be used (Hillman et al., 2002). Lastly, the gripper on the Bath

WMRA uses gearing that is not back drivable, so it maintains its gripping force when power is removed from the drive motor. This feature is also utilized on DORA by using a lead screw linkage assembly for the gripper, a lead screw for the sliding link, and a worm gear for the rotational joint.

A team from the University of South Florida (USF) designed and built a WMRA to have better performance, usability, payload, and control while being less expensive than many of the previous WMRA designs (Alqasemi et al., 2006). The price point for their WMRA was $25,000. Their robot arm is mounted as far forward and as high as possible while still in a side mount configuration so it does not significantly increase the width of the wheelchair (Alqasemi et al., 2006). Each of their robotic joints uses a high-reduction gearbox, a motor with an encoder, and spur-gear reduction (Alqasemi et al., 2006). The highly reconfigurable link lengths on the USF WMRA allow for its operation in a wide range of workspaces. The information available for the USF WMRA was insightful for its mechanical design details, gripper design details, and design implementation. However, the price point for the USF WMRA is higher than intended for DORA, so many of its design decisions are not applicable in DORA’s design because of cost, design difficulty, and power consumption. The USF WMRA is designed to be multi-purpose whereas DORA is designed to be task specific and should have a lower comparative cost.

Researchers at Georgia Tech have combined a controls solution with a mobile robot to complete an entire door opening task (Figure 6) (Jain & Kemp, 2008). They continued the work of other groups who have performed autonomous door opening research in the past such as (Nagatani & Yuta, 1995) and (Brooks, 2003). Their process works as follows: the user illuminates a door handle using a green laser pointer, the robot aligns itself with the door, the gripper uses its force sensors to detect the movable portion of the handle, the gripper unlatches the handle, the robot pushes the door open, and, to finish, the robot implements a calculated behavior to pass through the doorway while opening it (Jain & Kemp, 2008). Their gripper uses force sensing fingers, each with a six-axis force and moment sensor at the finger's base, to feel the door handle and its direction of rotation (Jain & Kemp, 2008). The system is used to open six different kinds of handled doors, over the course of thirty trials, and only failed once to locate the door handle. Although this research proved to be successful in completing the task of opening a door, the system requires a large amount of expensive hardware in order to work: an omni-directional camera, a laser range finder, a green laser with corresponding narrow-band green filter for the camera, and a powerful computer to process its autonomous commands. Also, the system is not designed to fit on a wheelchair.



(a) (b)

Figure 6. Georgia Tech's door opening system, (a) passing through a doorway and (b) gripper schematic (Jain & Kemp, 2008).

The Department of Homeland Security distributed a summary of small robots in March 2006 to communicate the advantages and drawbacks of various robotic systems. The Talon was shown using its multi-purpose gripper to open a door (SAVER, 2006). Bomb technicians gave the robot a subjective rating of 3.0 on a scale from 0.0 (does not have the capability) to 5.0 (can perform task easily) for its ability to open a doorknob (SAVER, 2006). It is likely that the 3.0 rating means the Talon was capable of opening a door but it could not perform the task easily because of its complex human operator system and its joint configuration.

DORA also needs to open a door; however, it needs to perform the task with less expensive hardware, be mounted to a wheelchair, and keep the human in the loop. The Talon opens a door when a driver maneuvers its robot arm joint by joint, while Georgia Tech tries to remedy a complicated robot design by using many control methods to make its operation easier. It remains clear that a two-jaw gripper on a high DoF arm is a complicated method for opening a door. In addition, the previous WMRA designs have many degrees of freedom so they could work in a large enough workspace to perform a variety of tasks as opposed to minimizing their number of joints to be task specific.

DORA's design utilizes some of the design details found from the previous WMRAs. The stepper motors and worm gears used on the KARES robot are implemented in DORA's robot arm design. The spring biasing found on the Bath WMRA is applicable to DORA's universal joint. Most importantly, the Gateway Coalition concurred that an underactuated robot arm design results in a WRMA that has a lower price point than its fully actuated counterparts (Gateway Coalition, 2000).

2.3 ROBOTIC GRIPPERS

A gripper, otherwise known as an end effector, is commonly defined as a device that can grasp and release objects during robotic manipulation (Quo et al.,

1992) or as a device that holds, handles, tightens, and releases an object (Bowman, 2008). Grippers are often part of a complete automated system. There are three different types: parallel grippers, angular grippers, and toggle grippers (Bowman, 2008). The gripper on DORA is different from conventional robotic grippers because it is underactuated, compliant, and targeted for a very specific purpose.

A gripper was designed for the USF WMRA to help people participate in their ADLs (Alqasemi et al., 2007). This gripper is different from typical robotic grippers because it uses paddles as the end effectors and a four bar linkage to produce a parallel open and close motion (Figure 7a). The paddles of the gripper are uniquely contoured to grasp a wide variety of objects with different shapes so the gripper could be used for a variety of purposes. This gripper, when mounted to their 7 DoF WMRA, demonstrates the twisting of a door knob (Figure 7b). A four-bar linkage assembly is considered for use on DORA's gripper but parallel motion of the gripper fingers is not absolutely necessary to justify integrating the extra linkages that it would require.

(a) (b)

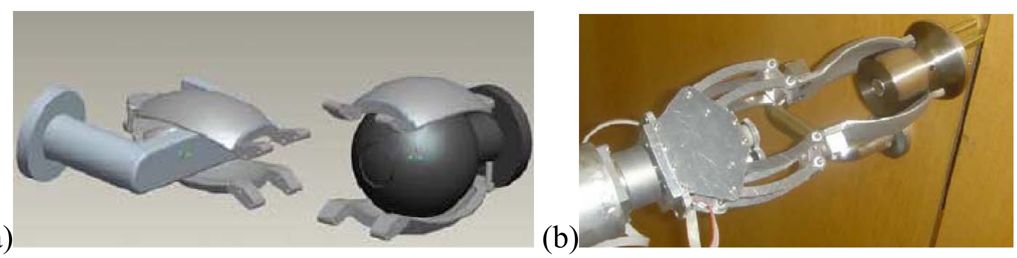



Figure 7. USF gripper design (a) simulation and (b) door knob manipulation (Alqasemi et al., 2007).

The following patent is for a robot that demonstrated a method for inserting a key, held in its end effector, into a door lock to open a door (Stone et al., 1992). This gripper uses underactuation via motions within the robot to move the key forward into the keyhole and is pictured in Figure 8. It also uses a compliant end effector to mitigate error caused by its deformation. Underactuation and compliance are also part of DORA's gripper design.

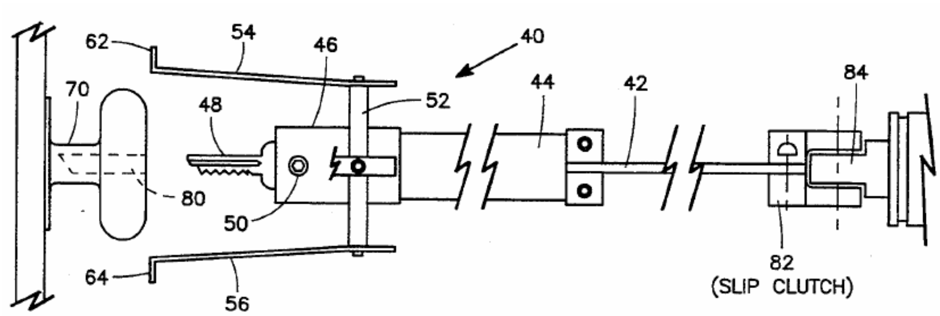


Figure 8. Hazardous materials emergency response mobile robot (Stone et al., 1992).

A Tufts University graduate student, Adeline Harris, designed a robotic end effector to open household doors. A collet end effector was engineered to use a single motor as an actuator. The collet-cone design allows for misalignment on approach because its implicated design centers the door knob as it tightens on a door knob. The gripper was also designed to twist door handles (Harris, 2006).

The Tufts gripper concept was designed for doorknobs and handles on standard household doors that rotate clockwise to operate its latching mechanism. The design of the Tufts gripper was the primary focus of the work, not a robot arm that delivers it to the door knob. Figure 9 shows how the Tufts gripper works; a cam follows a groove while the motor rotates pushing a clamp over collapsible fingers arranged in a collet-cone formation. When the clamp is fully compressed on the door knob the cam no longer can follow the groove and the whole barrel releases to turn the doorknob.

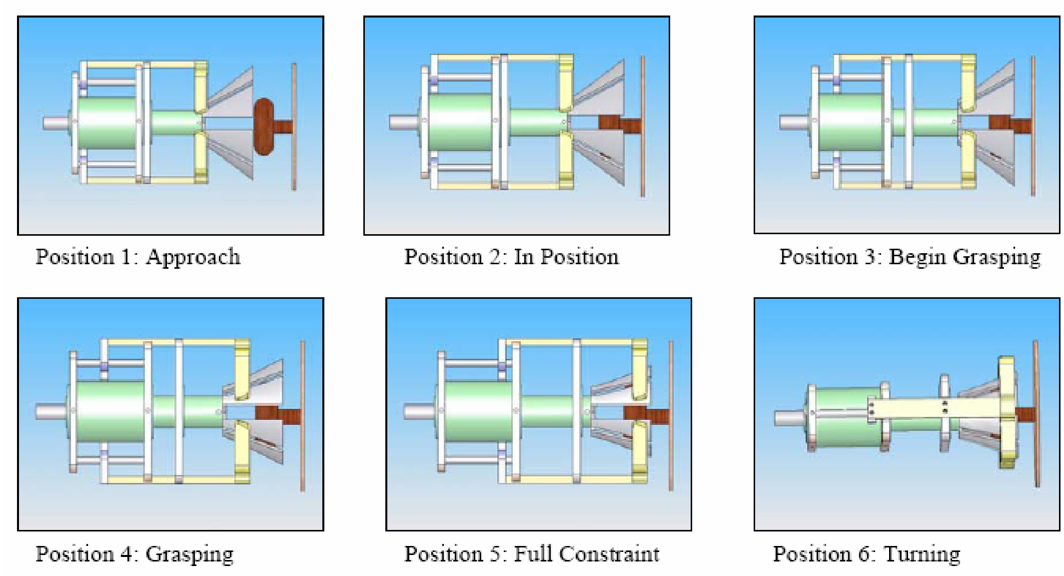


Figure 9. Doorknob opening process with Tufts gripper (Harris, 2006).

The Tufts gripper design offers many advantages such as compliance for knobs of different sizes and shapes. Compliance is defined as the ability for an object to yield elastically when a force is applied (Mirriam-Webster, 2009), and compliance gripping is typically used to grip delicate and irregularly shaped objects. The deformable compliant surface of the Tufts gripper shapes itself around a door knob so that the door can be manipulated without damaging it (Harris, 2006).

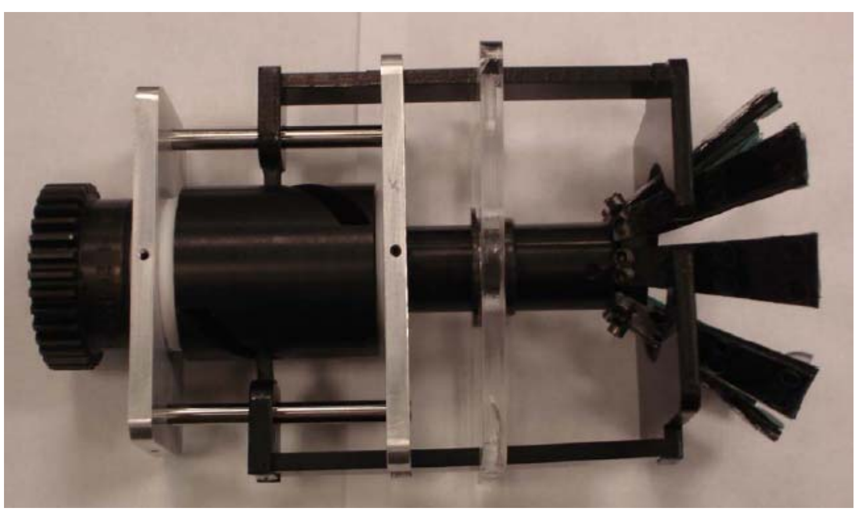


Figure 10. Fabricated Tufts gripper prototype (Harris, 2006).

The Tufts gripper design is an underactuated robotic gripper specified for the task of unlatching door knobs and handles. However, the Tufts gripper design did not consider an eventual integration with a robot arm, manufacturability, or implementation with a motor. The Tufts concept design ideas were used to initialize the concept design process for the gripper on DORA because the Tufts gripper had comparable design goals. The Tufts gripper design was required to have a "non threatening appearance, be appropriately shaped, not be damaging to doors, accommodate multiple knobs and handles, allow the user to control door manipulation, use only one actuator, and align well with the door knob or handle (Harris, 2006)." The Tufts gripper demonstrated how it is possible to include underactuation for a gripper designed to specifically open doors.

3 GRIPPER DESIGN

DORA needs an underactuated gripper designed to unlatch door knobs and handles from their respective door jams. This chapter discusses the gripper design goals, initial concept design inspirations, details in its mechanical design, fabrication, and observations regarding the prototype gripper performance. This underactuated gripper is a unique design that attempts to improve upon previously fabricated robotic grippers built to simply and compliantly unlatch a door knob or handle.

3.1 GRIPPER DESIGN GOALS

This gripper was designed specifically to manipulate door knobs and door handles. One motor for actuation is preferable to using multiple motors or other controllable devices such as solenoids. Also, the gripper is able to turn both clockwise (for all door knobs), turn counter-clockwise (for left facing handles), and close to a point if the need to press a button arises. In more detail, the gripper was designed to have:

- A cone shaped gripper finger arrangement that closes around door knobs of different diameters.
- Compliant gripper fingers to “mold” around the different contours and shapes of various door knobs and handles.

- Slots between the gripper fingers so a door handle can nest between the fingers allowing for the turning of said door handle.
- A lightweight and compact design for mounting to a robot arm.
- Uses only motors and components that are readily available for purchase and custom parts that are fabricated on a CNC milling machine or lathe.

These goals helped guide the gripper design across various concept designs discussed in Section 3.3 to produce an underactuated gripper mechanism that performs all of the functions described above.

3.2 GRIPPER DESIGN INSPIRATIONS

Many robotic grippers have been developed for a variety of reasons. Manufacturing robots have grippers that are specific to the work-piece being handled. Robotic hands were developed as research platforms for prosthetic hands or for versatile tasks such as ones planned for NASA's Robonaut (Robonaut, 2009). Many of the grippers on WMRAs and other robotic arms are two-pronged clamps that manipulate a variety of objects. The grippers and devices explored in this section inspire the underactuated gripper design for DORA.

Researchers at the University of Kentucky developed a one degree of freedom mechanical end-effector for cylindrical work-pieces for an industrial robot. It is based on the parallel motion of a four-bar linkage and is capable of concentrically gripping cylindrical components of different sizes (Quo et al., 1992). Another gripper that utilizes this concept is capable of carrying out complex grasping tasks by grouping several robotic fingers together as shown in Figure 11. The object does not need a regular shape for each type of grasp because the hand automatically adapts to the type of round shape of the object (Laval University, 2009). The fingers include underactuated DoFs that are governed by springs that actuate each connection in the finger once it comes into contact with the object. There is a mechanical limit at each connection that maintains a stable position of the following connection when no object comes into contact (Laval University, 2009). This work inspired the flexible finger design on DORA, which is useful because it allows the gripper fingers to conform around many different door knob sizes and shapes.

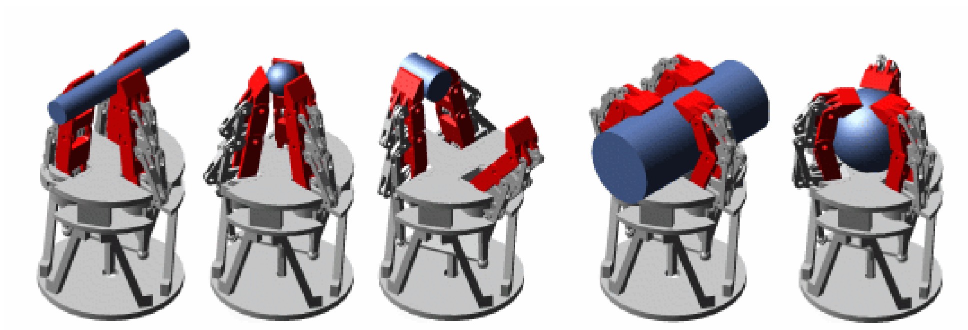


Figure 11. Types of grasp for cylindrical/round work pieces (Laval University, 2009).

Several companies developed devices and simple machines to help people open doors who have difficulty grasping or controlling their hand. Figure 12a depicts a rubber sleeve that is designed to fit over a door knob to enlarge the diameter or give a person more grip. Another problem that requires more grip strength than opening a door is the act of opening a jar where a “twist-off” hand motion is needed. Many manual solutions have been designed to assist people with the task by using flexible material or force activated shape handling as shown in Figure 12b. The gripper on DORA uses such materials and concepts for its gripper fingers.

(a)  (b) 

Figure 12. (a) Door Knob Gripper and (b) MeddaGrip Opener (Care 4U Senior Recourses, 2009).

An innovative and underactuated jar opening device is depicted in Figure 13. It uses one motor to compress two jaws: one onto the jar and a smaller one clamps around the lid. When the two jaws are fully compressed the motor turns the lid in relation to the jar to open it. This device is an excellent demonstration of underactuation by connecting compression mechanisms with a twisting ability. The gripper on DORA has a similar underactuated effect for the compression and twisting of a door knob or handle.

Figure 13. One Touch Automatic Jar Opener (One Touch Products, 2009).

The Tufts gripper uses a collet-cone claw design that has appeared in a number of other applications and artist renderings (Harris, 2006). One device is used as a sanitary means to collect and bag dog feces (shown in Figure 14a). A funnel is pulled back to open its claw and a trigger is pressed to close the grabbing claws to collect the matter (SWOOP, 2009). This claw is similar to the Tufts gripper because it slides a clamp over prongs as a means of closing them. Another simple application for the collet-cone design is a light bulb changer or remover (shown in Figure 14b). The fingers expand enough for the light bulb to fit inside the claw, the yellow rubber padding in the middle of each claw is compressive enough to enable a twisting action of the light bulb around its socket, and it can be pulled downwardly off the light bulb after insertion (Bayco, 2009). The gripper on DORA uses these concepts as a means of actuating the gripper and uses flexible material on the fingers to affect the door knob or handle.

(a) (b)

Figure 14. (a) SWOOP dog pooper scooper (SWOOP, 2009) and (b) Bayco Deluxe Light Bulb Changer Kit (Bayco, 2009).

Colin Adair, a 3D artist and web designer, has drawn the claw in Figure 14. It is a model of an “orange peel” hydraulic construction claw (Adair, 2009). Although hydraulics are not intended to be used in DORA, the pistons in Figure 14 are substituted with a linkage for actuation of the gripper fingers.

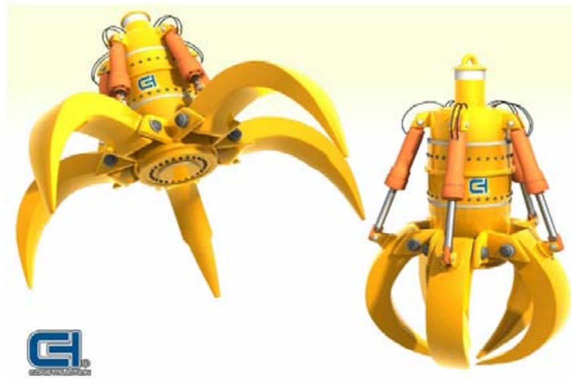


Figure 15. Colin Adair "orange peel" hydraulic construction claw (Adair, 2009).

Crane claws are common in arcade games where users control the X and Y position of a claw over a desired prize. Gamers then press a button to activate a sequence when the claw drops, closes, and returns to its home position to drop off a prize (if it has been won) into a prize chute (Muszynski & Roller, 2009). Figures 16 and 17 show how a student group from Northwestern University redesigned the claw game for an in-class assignment.

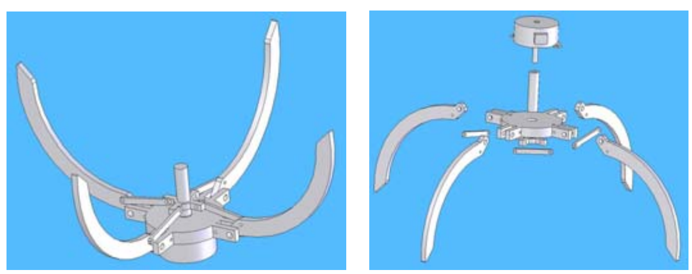


Figure 16. Solid-Works claw rendering for Northwestern crane game (Muszynski & Roller, 2009).

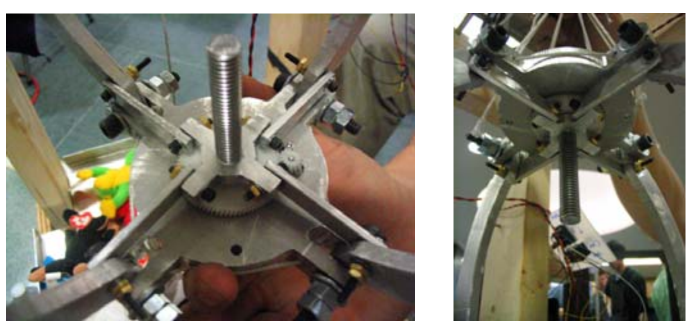


Figure 17. Northwestern crane game claw: mechanical assembly (Muszynski & Roller, 2009).

The Northwestern University claw is constructed from aluminum and consists of four large appendages that actuate as the result of the rotation of a lead screw. Their appendages are linked to the lead screw through the use of a collar that is threaded and travels along the lead screw. Simple straight linkages connected each appendage to the collar (Muszynski & Roller, 2009). The gripper on DORA uses a similar lead screw claw linkage assembly to actuate its gripper around a door knob or handle.

3.3 DESIGN CONCEPTS FOR DORA'S GRIPPER

Many of DORA's gripper concept design ideas were inspired by an analysis of the Tufts gripper. The gripper on DORA intends to be better than the Tufts gripper by making it more manufacturable, integrating it with a motor, and mounting it to a robot arm. As a starting point, the initial concept design ideas tended to be an attempt to directly improve upon the Tufts gripper design. The concept design process continued to improve upon the Tufts selected gripping solution to make it more manufacturable, packaging it in a way so it can be attached to a robot arm, add a capability for it to press elevator buttons, and add an option for counter-clockwise motion. The selected DORA gripper design was compared to the requirements sheet outlined for the Tufts gripper in Section 3.3.5 to verify whether or not there was improvement.

3.3.1 CONCEPT 1: DOUBLE BARREL CAM (1 MOTOR)

DORA's first gripper concept evolved directly from the Tufts' final barrel cam design shown in Figure 18. The underactuation of the Tufts "grip" and "twist" device is an advantage and it has been demonstrated to work on various door knobs and handles.

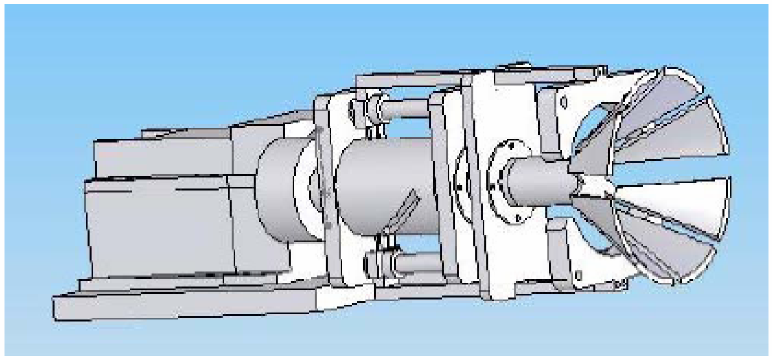


Figure 18. Cam Collet End Effector Concept (Harris, 2006).

DORA’s gripper design attempts to directly improve upon the Tufts gripper design, but this task was challenging due to the need to open handles in both clockwise and counter clockwise directions while using a single motor. DORA’s double barrel cam concept, shown in Figure 19, turns handles using stiff edges on its “fingers” that rest on a free-spinning thrust bearing biased perpendicular to gravity by use of a weight. A double barrel cam would allow for both clockwise and counter-clockwise rotation. It was discovered that in order for the collet-cone to be perpendicular to the floor, a second roll joint motor would be needed, adding redundancy. Also, barrel cams are difficult to manufacture and are expensive. Lastly, the free spinning thrust bearing used for placement would have spun the gripper counteracting the rotational motion created when the gripper tries to unlatch the doorknob. The added complexity would cause issues with manufacturability and performance, and the thrust bearing issue would have made this gripper (Concept 1) not able to function at all.

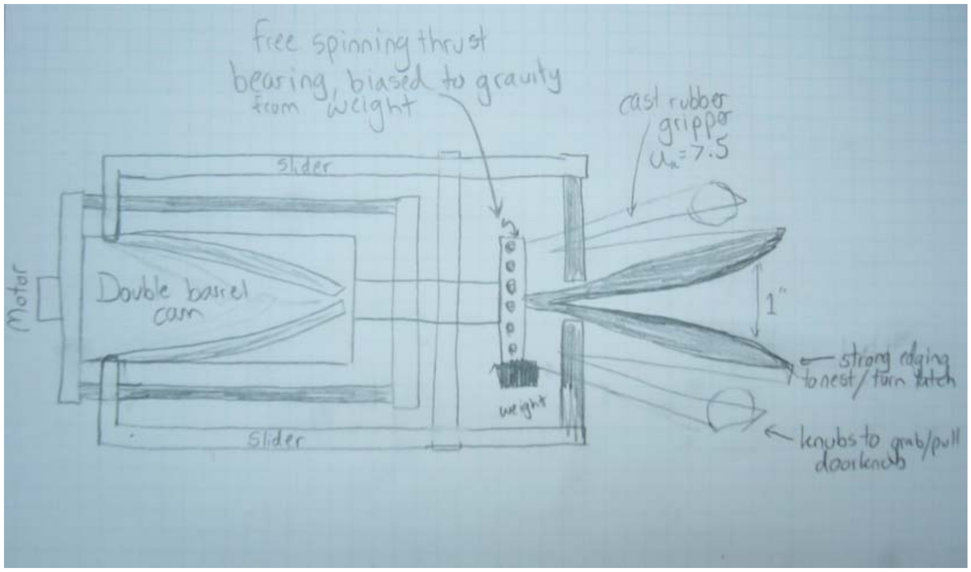
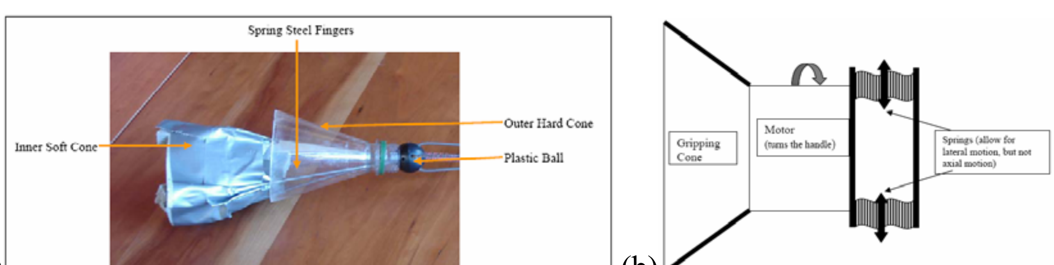


Figure 19. Concept 1: Double barrel-cam.

3.3.2 CONCEPT 2: RACK & PINION (2 MOTORS)

Explored next was the possibility of using two motors. One motor is located in the back as a roll joint both for positioning the slots for the handles parallel with the ground and applying the clockwise and counter clockwise actuation for twisting doorknobs and door handles. The second motor drives a rack and pinion to push a ring over rubber gripper fingers, similar to Tufts' concept for a Double Cone End Effector shown in Figure 20a (Harris, 2006). Figure 20b shows another of Tufts gripper ideas where a Remote Center Compliance (RCC) device is placed behind the gripper to allow for further misalignment.



(a) (b)

Figure 20. Double Cone End Effector Concept 8 and RCC Cone Gripper End Effector Concept 5 (Harris, 2006).

For the rack and pinion gripper concept shown in Figure 21, an RCC component connects the roll joint with the rest of the end effector. The cone clamp is linearly actuated by a second motor using a small rack and pinion assembly. Light sensors sense the presence of a door handle on the left or right side thereby actuating an inch long solenoid to constrain the handle inside the end effector so a door could be pulled open. The drawback is that the motor and spur gears add weight and length to the end effector. The center rod confirms the placement of a door knob in the center of the end effector and is spring-loaded in order to press a button (such as an elevator button) if needed. All unnecessary weight adds cost to the motors in the system because they would be required to handle higher torques and loads.

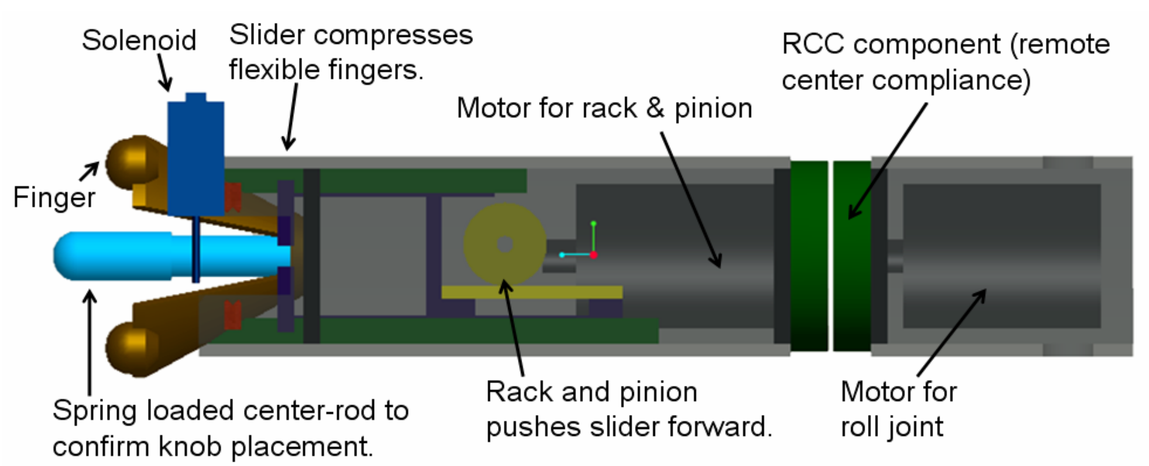


Figure 21. Concept 2: Rack and Pinion.

3.3.3 CONCEPT 3: RATCHET RACK AND PAWL (1 MOTOR & SOLENOID)

Another of the Tufts gripper design ideas, the Spider Web End Effector shown in Figure 22, is revisited because the use of two motors in DORA's gripper is not absolutely necessary (Harris, 2006). The advantage of this "spider web" concept is also its disadvantage because the placement of the door knob pushes webbing between the fingers to close them. The fingers immediately release the door knob when the gripper is pulled away. However, the use of a solenoid may be a lightweight and viable method to clamp or unclamp the fingers around a doorknob.

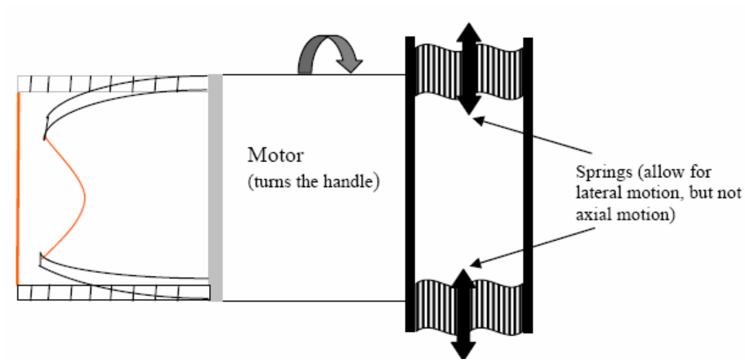


Figure 22. Spider Web End Effector with remote center compliance (RCC) Concept 7 (Harris, 2006).

Similar to the rack and pinion idea, the ratchet rack and pawl concept uses a motor to provide the roll placement and twisting actions (Figure 23). An RCC connects the roll joint to the end effector, but there would not be a second motor in the end effector. Instead, the center rod is pushed into the collet-cone as the gripper is placed over a door knob or handle. Light sensors identify the placement of a handle and solenoids constrain the handle inside the end effector (same as Concept 2). However, as the center rod is pushed in, a pawl is pushed over a linear ratchet rack to lock the collet end effector around the doorknob during the operation. After the door knob has been unlatched and, pulled open (if necessary), a solenoid that is connected to the center rod lifts the pawl off the ratchet rack so a spring nested inside the center rod could reposition the collet-cone to its original placement. Also, a switch activates when the center rod is pushed to signal to the solenoid to place the pawl down on the rack.

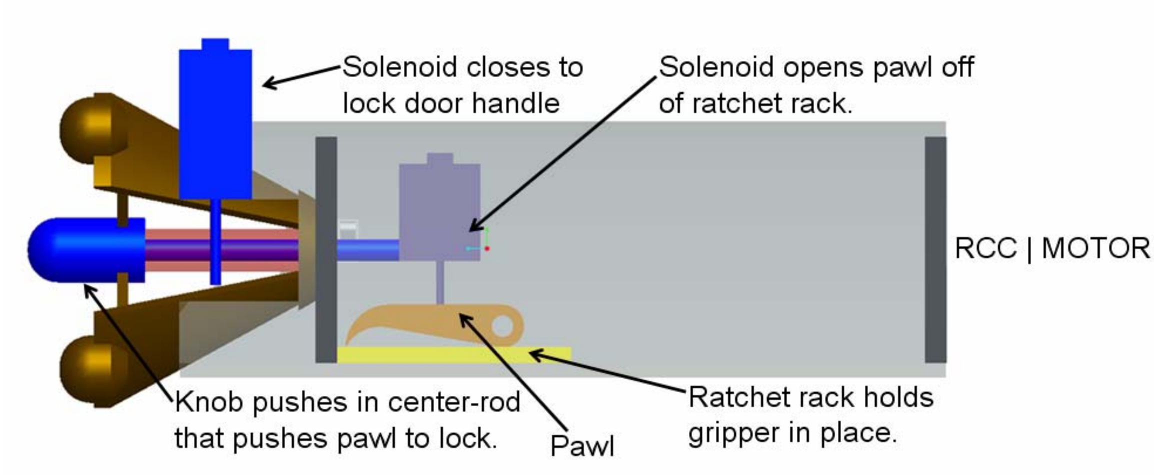


Figure 23. Concept 3: Ratchet Rack and Pawl.

The ratchet rack and pawl concept could be lightweight because it uses a minimal number of components. Also, this end effector is the shortest length of all the concept design ideas so far. It remains to have the benefits of an RCC component and centering from the collet-cone. However, the concept gripper designs for DORA continued to evolve in order to reduce the number of components and create a more robust and underactuated design.

3.3.4 CONCEPT 4: LEAD-SCREW LINKAGE CONCEPT (1 MOTOR)

The prospect of using a lead screw to provide the linear actuation of a claw linkage is revisited. It also remedies some of the manufacturability issues mentioned in the Tufts lead screw gripper concept. Similar to the Northwestern University claw game explained in Section 3.2, the lengthwise actuation of a collar around a threaded screw pulls and pushes linkages to both close and open the gripper as shown in Figure 24. The cone closes when the collar either moves forward or backwards. Manufacturability issues are resolved because the parts are simple linkages and can be fabricated from raw materials; other mechanical features are added by securing them in place. However, this design does not resolve how the rotational actuation behind the linkage would occur for the twisting and unlatching of the door knob or handle.

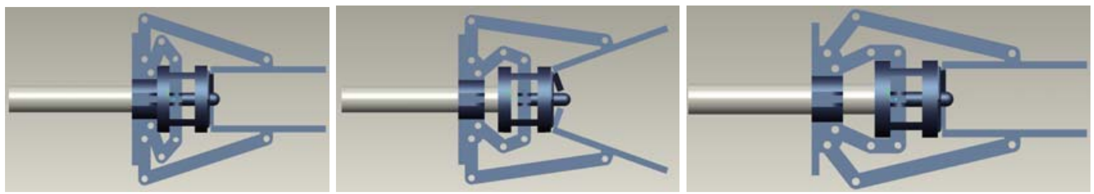


Figure 24. Concept 4: Lead screw linkages (open and closed positions).

3.3.5 CONCEPT 5: LINKAGE WITH PLANETARY GEARBOX (1 MOTOR)

The next gripper design leverages the successful aspects of the Tufts gripper design, improves upon its difficult to manufacture features, and enables rotation in both directions instead of just one. The successful aspects that are utilized include a cone gripper shape for positional compliance, the use of a single motor, the use of the spaces between gripper fingers to nest a door handle, and sliding a collar forward and backwards to implement the opening and closing of the gripper cone. The concept design of a lead screw linkage attached to a planetary gearbox is depicted below in Figure 25, as 3D models in Figure 26, and explained further in the mechanical design section (Section 3.4).

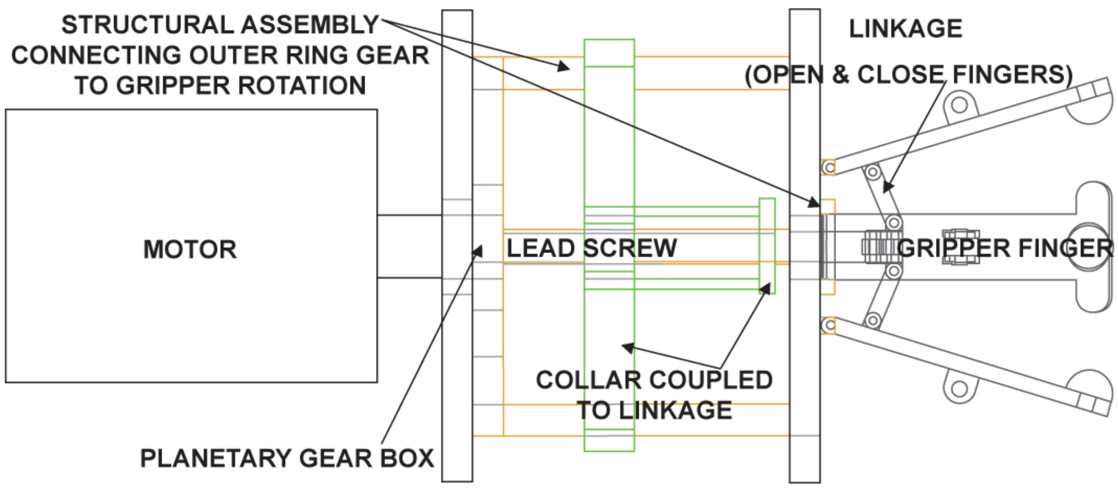


Figure 25. Selected gripper concept design with labeled parts (Concept 5).

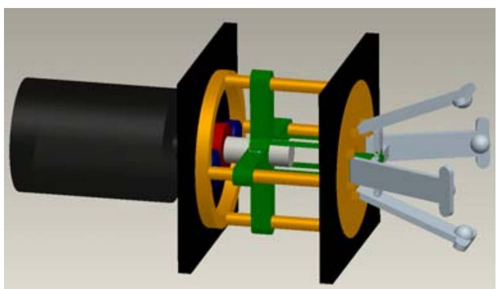
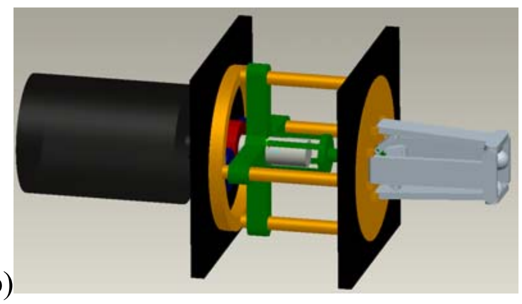
(a)  (b) 

Figure 26. 3D model of selected gripper design as (a) open and (b) closed.

This design uses a lead screw and linkages to fold gripper fingers in and out. This gripper design does not need another motor to place the gripper perpendicular to gravity because the spaces between the fingers are designed to manipulate a door handle. The handle eventually nests between two fingers as the gripper fingers are spun. The lead screw linkage attached to a planetary gearbox concept compares well to the Tufts end effector requirements in (Harris, 2006). DORA's gripper is not threatening or damaging because its flexible fingers are the only things expected to touch a door and the moving parts in DORA's planetary gearbox are fully enclosed. DORA's gripper uses the collet-cone shape to allow for some misalignment on the approach to the door knob or handle. Also, the collet-cone shape allows for an amount of positional compliance because the door knob does not need to be perfectly centered inside. The gripper accommodates knobs of different shapes and sizes because the fingers on the gripper are flexible. However, “finger tips” are added so the gripper can remain attached when it is pulled off the door knob. Finally, similar to the Tufts gripper, the DORA gripper uses only one motor for compression and rotation around the door knob or handle while having the ability to turn in both clockwise and counter clockwise directions.

3.4 MECHANICAL DESIGN OF GRIPPER

DORA uses a lead screw linkage attached to a planetary gearbox (Concept 5) as its selected gripper design. The following sections outline the detailed design, fabrication, and sub-assembly demonstrations that are performed with the underactuated gripper.

The gripper is designed to be placed over the door knob or door handle; it looks like a three-fingered cone. The mechanical design is shown in Figure 27. The cone rotation is connected to the rotation of the outer ring of a planetary gear set. The sun gear is coupled with the lead screw and both rotate at the same angular velocity. The planet gears reduce the angular velocity for the outer ring gear, which also spins in the opposite direction. A collar is threaded around the lead screw and is also fastened 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 allow it to move linearly, forwards and backwards, along the screw as if the collar is attached only to a linear slide. The fingers then close and spin 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. Nubs on the ends of the fingers hold the gripper around the doorknob so, when closed, the gripper does not slip off if pulled. For a door handle, the fingers rotate, the handle falls between two fingers, and the handle twists while the gripper spun. The fingers on the gripper must be flexible because the gripper spins and closes at the same time. Subsequently, in order for the gripper to continue to turn, the fingers must continue to flex around the door knob or handle.

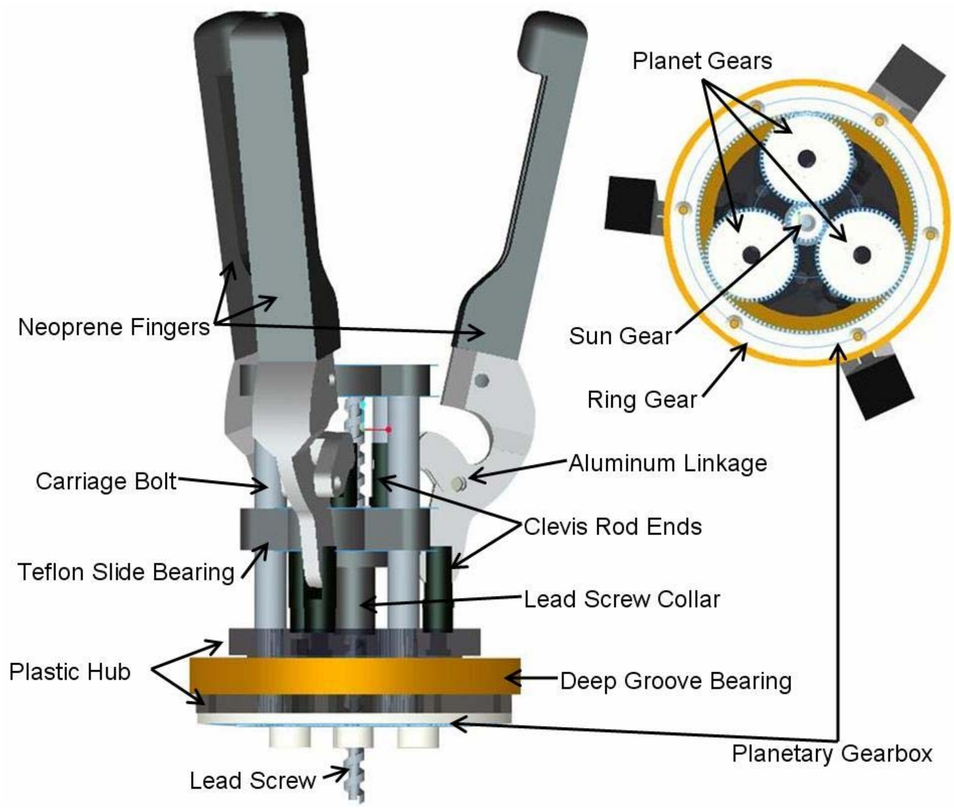


Figure 27. Lead Screw Linkage attached to a Planetary Gearbox, labeled assembly drawing.

The development of the geometrical design for the gripper involved the use of a MATLAB program to link all of the controllable and output variables in one mathematical program (Appendix 1). The first step was to enumerate the control variables in the gripper geometry (Figure 28) such as the claw opening over the door knob (4 inches), the claw base offset distance (2.13 inches), the claw finger length (5.5 inches), and the linkage connection along the finger from the base (1 inch). Next, the desired rotation was entered as a turn of 180° over 2 seconds; this number was determined through the examination and handling of doorknobs.

The outer ring gear of the planetary gear set was constrained to be a specific size because there are fewer sizes of ring gears available for purchase as compared to spur gears. Only one option was available for the gear pitch on the appropriately sized ring gear. The spur gear sizes generated by the MATLAB program were adjusted by about one tooth so they could be purchased.

Lastly, lead screw specifications based on the number of turns per inch (TPI) were entered that matched the rotation of the sun gear with the amount of travel needed in the linkage in order to open and close the fingers in the appropriate amount of time. This constraint was adjusted based on the MATLAB output for the link lengths and the components' ability to be purchased. The physical size and diameter of the lead screw was another constraint because other components in the assembly interfere with the lead screw's available space. The link lengths for the linkage assembly were generated by the use of trigonometry and angular velocities in the MATLAB program for the amount of travel in the finger tips between their fully open and fully closed positions.

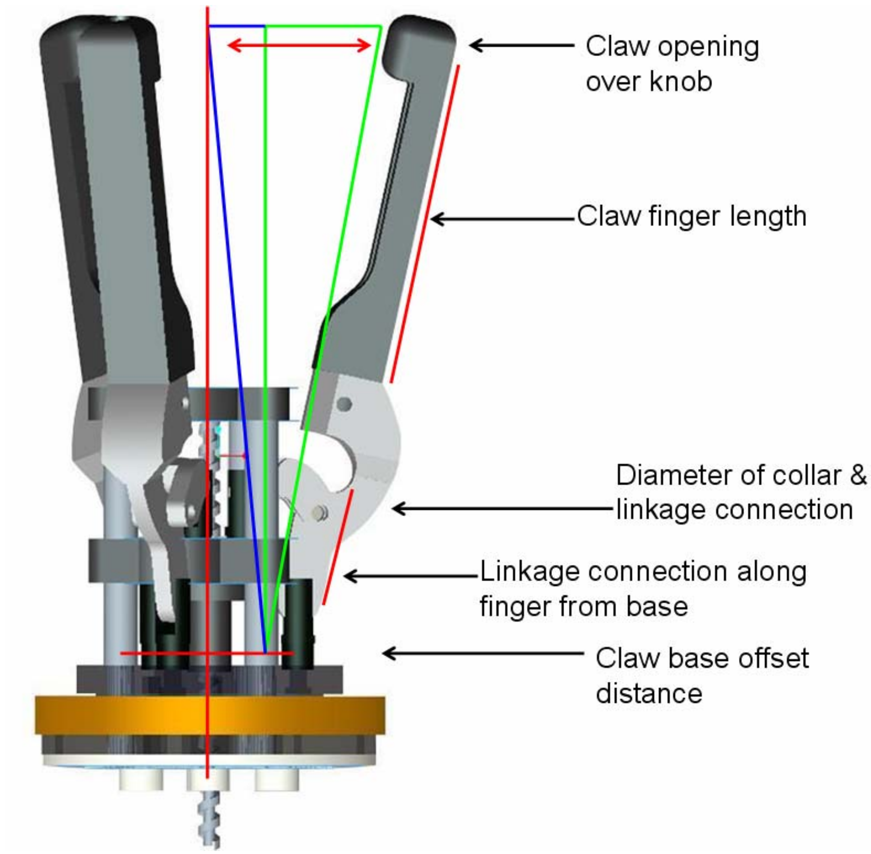


Figure 28. Gripper geometries used in MATLAB program.

The advantage of using a planetary gear set is that only a small torque is needed for the lead screw to close the linkage, but the torque is significantly multiplied between the sun gear and the ring gear for the gripper rotation to manipulate strong internal springs. The MATLAB program (Appendix 2) generated a planetary gearbox ratio of 6:1. The Tufts gripper thesis states that the torsion spring force inside door knobs and handles is in a range from 10 - 15 lb-in (1.13 – 1.7 Nm) (Harris, 2006). Based on the calculated geometries, the input torque for the motor on the system must be at least 2.5 lb-in (0.28 Nm) in order to produce at least a 15 lb-in (1.7 Nm) torque. This calculation assumes a gear ratio within the planetary gearbox of 6:1 and 100% efficiency within the planetary gears.

3.5 FABRICATION

The components for the gripper were purchased mostly from McMaster-Carr except for the planetary gears, which was purchased from WM Berg and a bearing purchased from MSC direct (see Appendix 1 for a complete parts list). The planetary gear set uses a 48 pitch 144 tooth internal gear, 60 tooth planet gears, and a 24 tooth sun gear that all have a face width of 1/8 inch. This gear set, along with the large bearing, is housed in four plastic plates that sandwich all of these parts together as shown in Figure 29 and Figure 30. Two plastic hubs clamp inside the bearing to hold the ring gear on one side and the foundations of the gripper linkages on the other as shown in Figure 31. The linkages were machined out of aluminum, and the rubber fingers were made from a 0.75 inches by 0.75 inches square neoprene bar that have a 0.25 inch hole down the middle of its length. The neoprene bars are surrounded by a rubber grip material used for lawnmower handles and are fastened by zip ties. Plastic tips protrude from the tops of the fingers to prevent the rubber fingers from sliding off the knob when the gripper is pulled backwards. The lead screw nut is fastened to a plastic plate that also holds the other ends of the gripper linkages as shown in Figure 32a. Teflon bearings are 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 (Figure 32b). Therefore, the lead screw inside the collar is spinning faster, and in the opposite direction, of the carriage bolts that the lead screw collar is connected to. This design produces linear motion of the collar and, in turn, movement in the linkage that connects to the fingers. Finally, the lead screw is coupled to the sun gear of the planetary gearbox and is attached to the gripper motor shaft. The gripper uses a

PK244PA 2-phase stepper motor from Oriental Motor at 7.5rpm which outputs a torque of approximately 3.5 lb-in (0.4 Nm). The output of the rotation for the ring gear is 21.4 lb-in (2.4 Nm), exceeding the Tufts requirement for 15 lb-in (1.7 Nm) to manipulate the internal spring force inside a door knob or handle. This motor was selected for its close proximity to the required output torque, its small size, and light weight.

Careful planning was implemented into the design detail for each fabricated component. Every custom part is capable of being fabricated on a milling machine, CNC, or lathe. Also, the gripper is assembled using only small screws (most holes are threaded for 8-32 machine screws). The assembly process begins with a Delrin plate (Figure 29a) that is used to house the bearings for the planet gears, and a bearing for the sun gear. The motor is mounted on the other side. Then another Delrin plate (Figure 29b) is fastened to the first plate in Figure 29a. This plate completely surrounds the bearings for the planet and sun gears and has a large space for housing the ring gear.

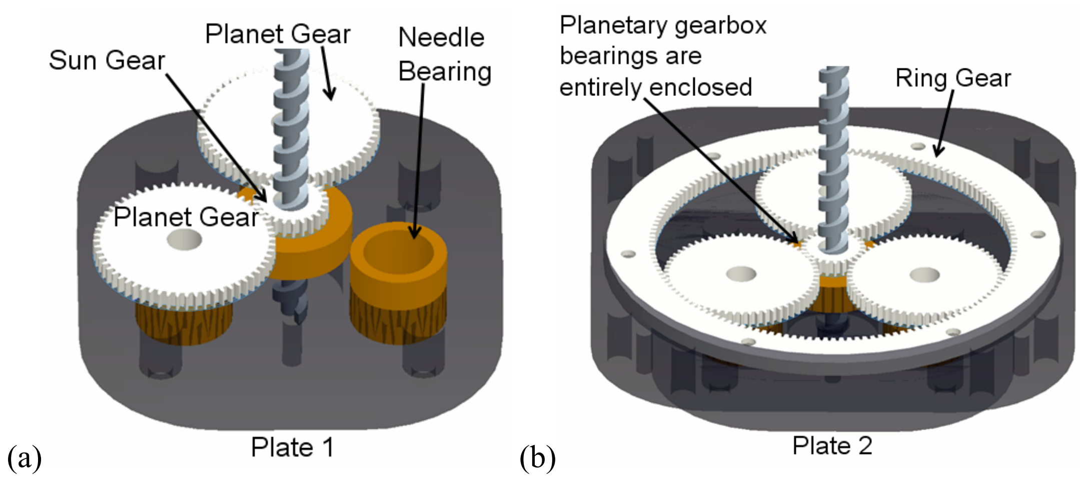


Figure 29. Delrin plates that house (a) bearings and (b) planetary gear box.

Next, two more Delrin plates were fabricated to house the large bearing between them. However, these two plates (the blue and green plates shown in Figure 30) are not fastened until the center structure that rotates with the ring gear is assembled inside the large orange bearing in Figure 31.

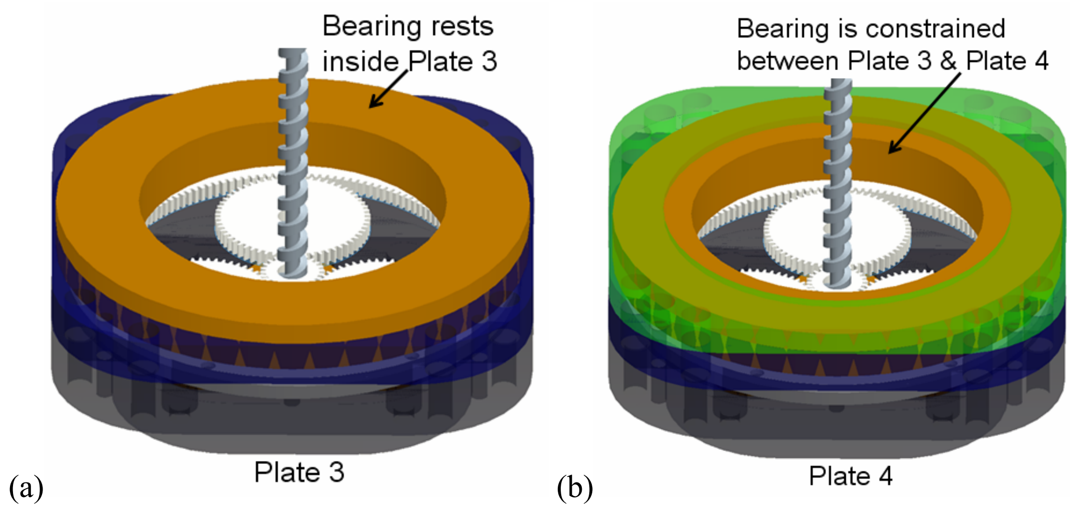


Figure 30. Two Delrin plates that house large bearing (a) bottom and (b) top.

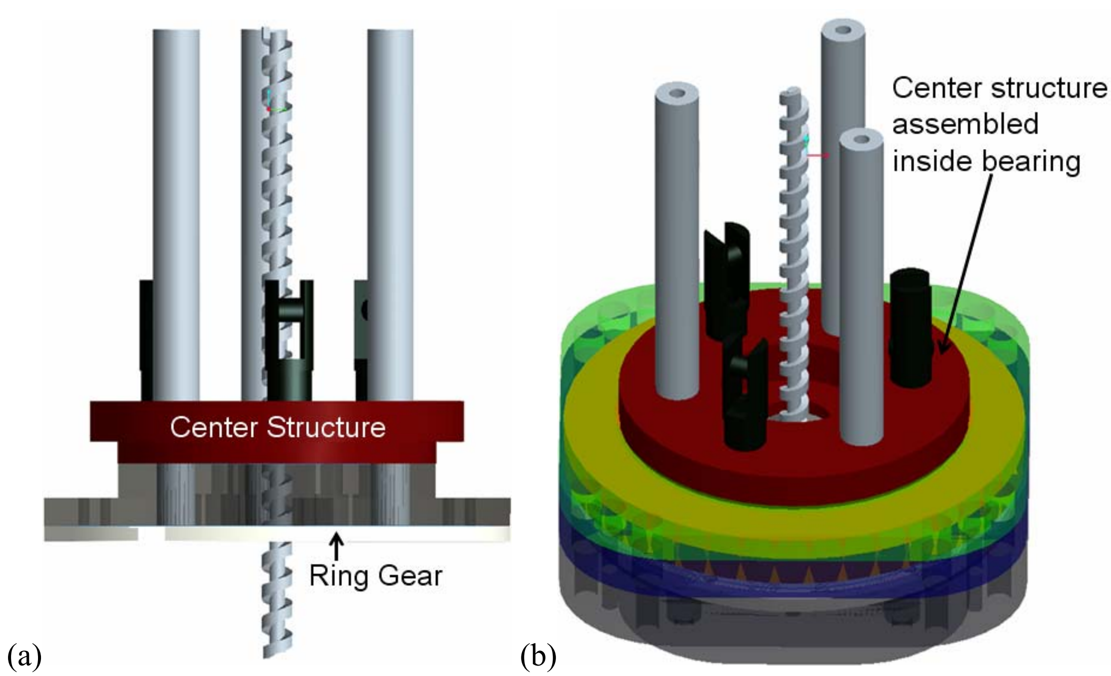


Figure 31. Center structure that (a) rotates with the ring gear and (b) located inside large bearing.

Now that the planetary gear box and central structure are constructed, the lead screw collar is threaded on the screw after being fastened to the assembly that slides linearly along the three carriage bolts as shown in Figure 32b. The assembly uses white Teflon sleeve bearings and consists of two Delrin plates that sandwich them together. Black Clevis rod ends are bolted to the Delrin plates as well. Delrin is used because it is half the weight of aluminum, faster to machine, and easier to press fit bearings into because the material is soft and does not need tight tolerances. Two black clevis rod ends, one on the center structure and one connected to the lead screw collars, pair up to hold the linkage for the gripper finger. The linkages are curved (Figure 32a) so the piece connecting the lead screw collar assembly and the finger can curl up into space that would have been occupied by the finger if all of the linkages had been straight.

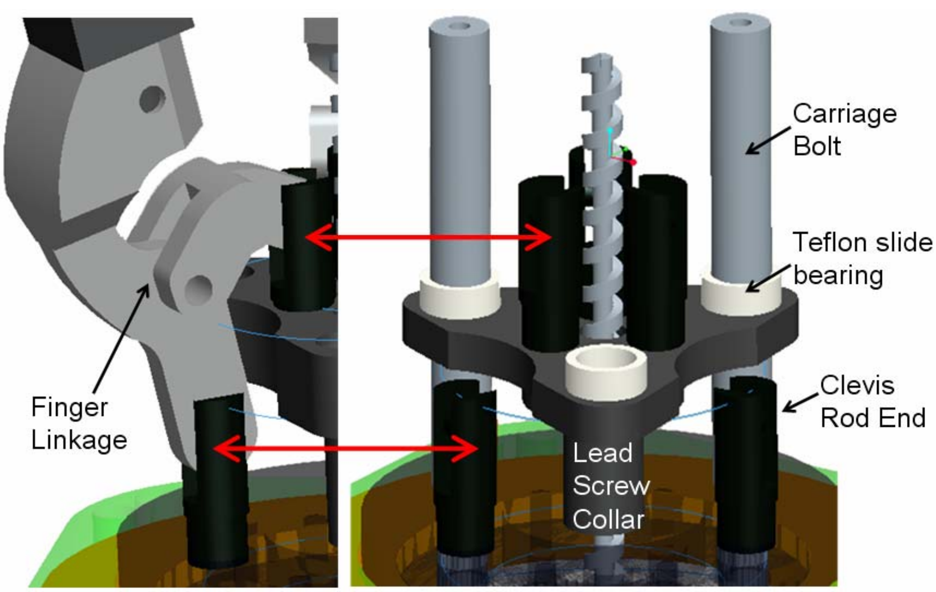


Figure 32. Lead screw collar assembly and finger linkages attached to Clevis rod ends.

Lastly, two more Delrin plates are used to create a support structure at the top of the lead screw and carriage bolts (Figure 33). The plates sandwich a bearing that holds the top end of the lead screw so it would not flex or deform during operation.

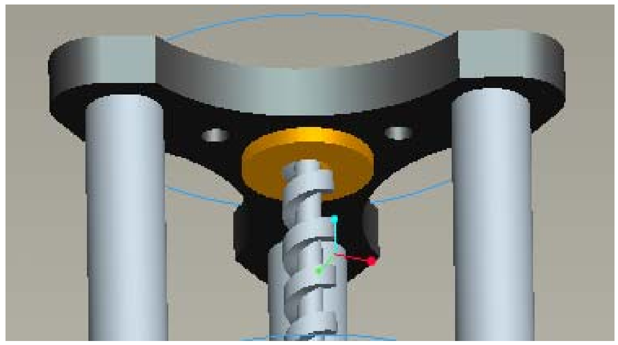


Figure 33. Support structure at the top of the carriage bolts.

The final version of the gripper is shown in Figure 34. The numbers in Figure 34 indicate areas of interest: (1) the neoprene fingers wrapped in the rubber grip, (2) the aluminum linkage assembly, (3) the lead screw collar, (4) the housing for the planetary gear box and bearings, and (5) the motor used for actuation. The gripper weighs 5.16 lbs including all of the portions seen in Figure 35.

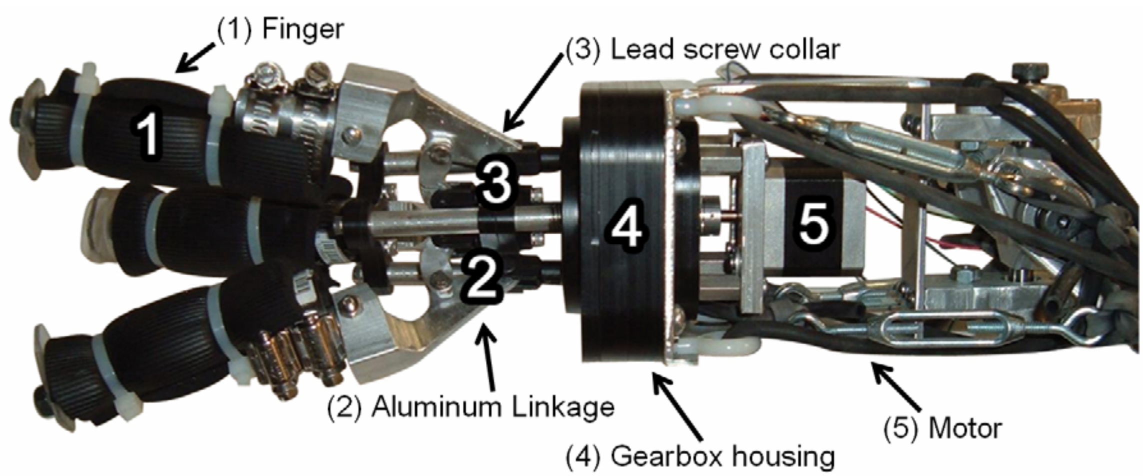


Figure 34. Final version of the gripper to unlatch door knobs and door handles using a single motor.

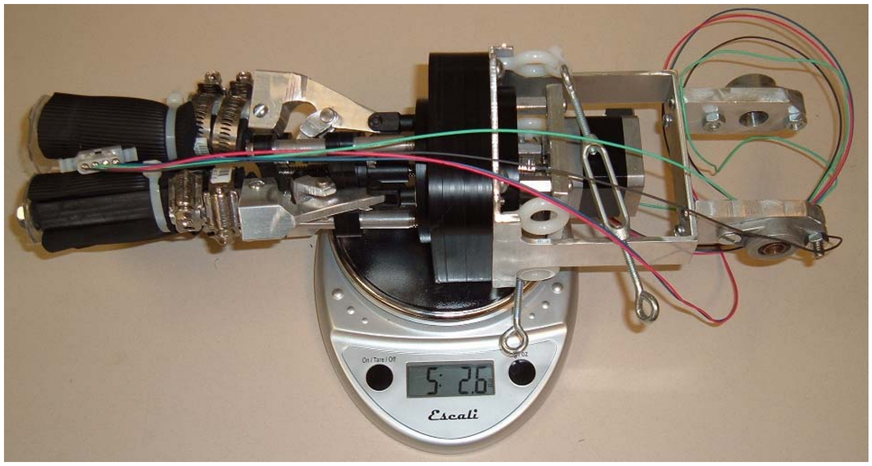


Figure 35. Gripper weight 5 lbs 2.6 ounces.

3.6 GRIPPER ASSEMBLY OBSERVATIONS

The gripper was first demonstrated on a nearby door knob and handle by twisting the lead screw by hand using a vice grip to clamp around the lead screw shaft. The gripper unlatched both the door knob and handle again when a small motor was attached to the lead screw (holding the gripper gearbox by hand). The rubber fingers twisted around the door knob and handle as seen in Figure 36. At times, when the fingers were fully constrained around the door knob, the clevis rod ends bent. One clevis rod end broke out of the assembly and was replaced. Also, chatter and backlash was heard within the planetary gear box when the fingers were fully compressed around a door knob. However, the gripper assembly was capable of unlatching door knobs and handles and was in a condition for more rigorous testing.

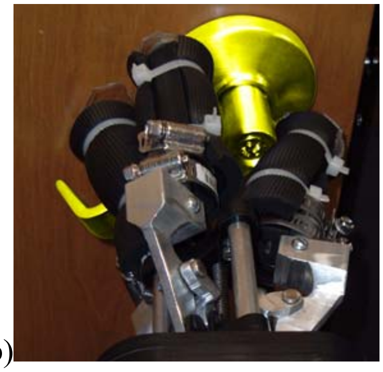
(a)  (b) 

Figure 36. Gripper manipulating a (a) door knob and a (b) door handle.

When integrated with the robot arm (see Chapter 4 for the robot arm design), the gripper had some limitations where it had difficulty operating door knobs on doors that are industrial in nature, heavy, and the gripper fingers sometimes could not fit on the door knob correctly when there was a deep door jam as shown in Figure 37. However, the gripper did work well on lighter interior doors (see Chapter 5 for more discussion of the performance testing).

(a)  (b) 

Figure 37. Failed scenarios (a) gripper slips off the door knob and (b) finger gets stuck in the door jam.

4 ROBOT ARM DESIGN

This chapter outlines the design goals that were specific for the robot arm, the joint configuration selection, and how the robot arm was technically designed so it can be fabricated, assembled, and demonstrated. The robot arm has a Cartesian joint configuration with a spring-loaded universal joint that traverses up-down and side-to-side motions to connect the robot arm with the gripper. The robot arm sub-assembly has 5 DoF, using only three motors, to mechanically deliver the gripper sub-assembly to the door knob or handle.

4.1 ROBOT ARM DESIGN GOALS

The design goals listed below are the ones that are required for the scope and success of the mechanical portion for DORA's prototype. The robot arm, pertaining to its size, shape, and motor selection, is designed to:

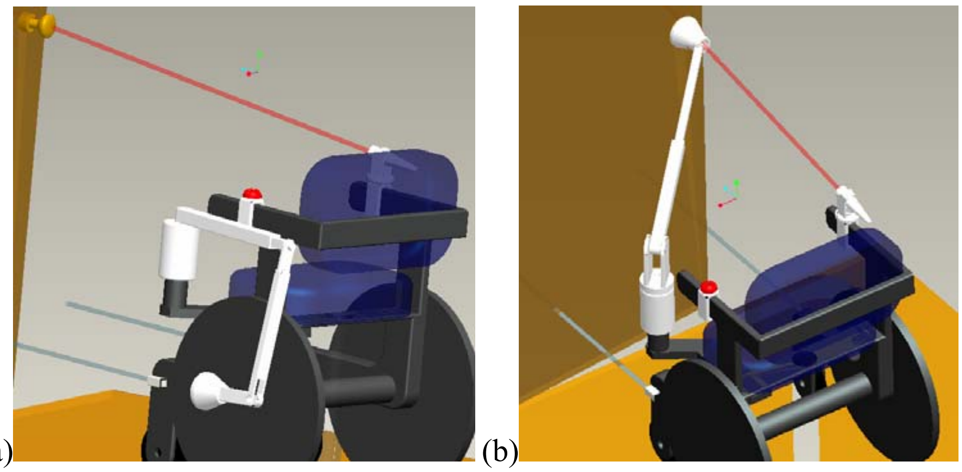
- DORA operates up to a height of 48 inches, which is the ADA requirement for maximum height of door knobs and handles (Adaptive Environments, 1995).
- DORA, when mounted to a wheelchair, does not add width that would make the system more than 32 inches wide, which is the ADA requirement for minimum width of a door (Adaptive Environments, 1995).

- The robot arm is mounted low enough so it can fit under a table, which fits under the “size and space for approach and use” principle (Connell et al., 1997).
- The robot arm has the strength and capacity to lift the gripper sub-assembly.
- To minimize hazards and avoid the unintended action of driving the robot arm near the user’s body, the robot arm has a mechanical stop that limits it from entering the user’s physical space. This fits the principle for the “tolerance for error” principle (Connell et al., 1997).
- DORA is light in weight to not cause lateral instability of the wheelchair (29 lbs), fitting the “size and space for approach and use” principle (Connell et al., 1997).
- Spring biasing was added between the gripper and the robot arm to conform to the wheelchair’s pulling or pushing action on the door, which applies to the “low physical effort” principle because this requirement helps make driving the wheelchair easier (Connell et al., 1997).
- DORA uses mechanisms that hold the robot arm at a static location if the motor power were to shut off as a safety precaution. This fits the principle for the “tolerance for error” principle (Connell et al., 1997).
- The robot arm uses only motors and components that are readily available for purchase, use custom parts that are fabricated on a CNC milling machine or lathe.

These design goals helped guide DORA's robot arm design to a successful demonstration. For example, the power wheelchair needs to remain capable of passing through a standard doorway and remain laterally stable; otherwise DORA's demonstration is not possible. In addition, as a safety precaution, DORA can not physically contact the person sitting in the power wheelchair or fall if the robot arm power deactivates. Furthermore, these design goals have helped define the workspace needed to deliver the gripper fingers to the plane of the door.

4.2 JOINT CONFIGURATION SELECTION

The robot arm needs to move in a large enough work space so it can deliver the gripper to the door knob or handle. The arm configuration and link lengths determine the robot arm's work space. First, the arm configuration was modeled in a simulation environment. The simulation environment allows for portions of the robot arm to move about a virtual room, affect a virtual door, and be mounted to a virtual wheelchair. Different joint configurations were evaluated before the final configuration was selected (see Figure 38). The final configuration has been reduced to three controllable degrees of freedom because the wheelchair's position on the floor is used to place the base of the arm relatively close to the door. The simulation environment shows that two additional degrees of freedom are needed to match the gripper with the plane of the door. This "wrist" joint does not appear to require a controllable actuator. Therefore, the arm has three motorized joints: a cylindrical joint to rotate the arm side to side, a rotational joint to swing the arm at angles up and down, and a sliding link to extend the arm to increase its length. This design is known as a Cartesian robot configuration. The gripper uses a fourth motor for actuation; it is attached to the arm using a spring-loaded universal joint, or "wrist," so the gripper fingers can match the plane of the door. The universal joint also allows for passive adjustment of the angle on approach and, after the door knob has been unlatched, while the user pushes or pulls the door open with their power wheelchair.


(a) (b)
Figure 38. Simulation environment (a) robot arm with elbow and (b) robot arm with sliding link.

The robot arm has a solvable inverse kinematic solution (IKS). As proof, a MATLAB program was used (Appendix 3) to generate joint lengths and angles so the robot arm can reach an arbitrary (x,y,z) point location in space. The Cartesian configuration generates a position workspace that looks like the shell of sphere. The shell is about a foot thick because the sliding link extends the gripper in and out 12 inches. The shell (the middle of the universal joint where the sliding link connects with the gripper) can reach down to the floor and sweep upwards to 49 inches because the arm mount height of the chair is 18 inches. The gripper link length is 16 inches. The resulting joint configuration is shown in Figure 39 and the actual position space is discussed further in Section 4.4.

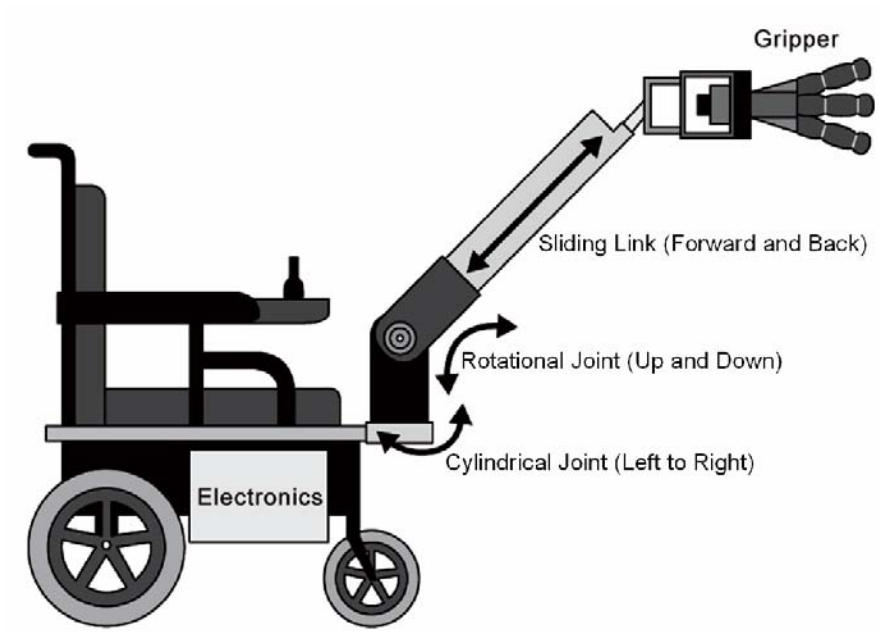


Figure 39. Location of DORA's motorized joints.

4.3 DESIGN OF INDIVIDUAL JOINTS

Stepper motors were selected for use in each joint in the robot arm because of their high holding torque and controllability. Many portions of the arm could not be designed before the motors were selected. Therefore, the motorized joints were over-designed because the motor calculations assumed heavier component weights and longer dimensions as a safety factor. In addition, the three motorized joints are intended to handle unanticipated loadings and reworked components as the prototype undergoes an iterative design process for improvement.

4.3.1 CYLINDRICAL JOINT (LEFT TO RIGHT MOTION)

The cylindrical joint is located at the very bottom of the arm and is responsible for swinging the whole arm left and right. A large gear ratio is used so that a relatively small and inexpensive motor could be selected for the function. A 72 tooth gear was selected for the base of the arm because it is the largest gear available to order and it has a large enough diameter for a circular bolt profile to fasten the rest of the arm structure onto it as shown in Figure 40. The face of the 72 tooth gear rests on top of a thrust bearing.

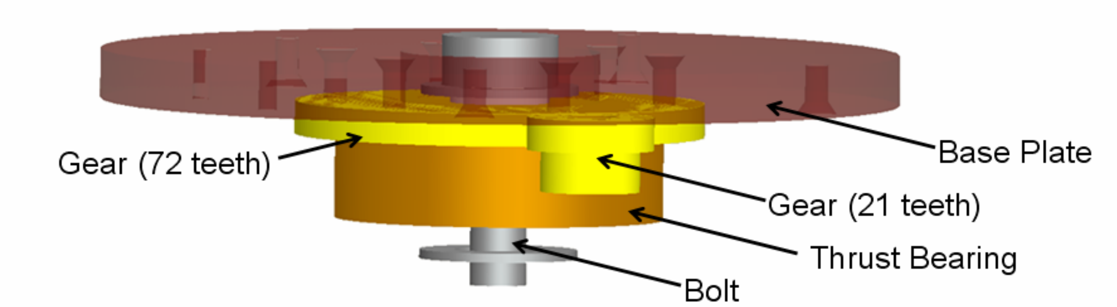


Figure 40. Gear (72 teeth) resting inside thrust bearing and mounted to circular plate.

A bolt clamps through the hub of the gear to the structure material so the arm cannot tilt, misalign, or fall. The hole inside the 72 tooth gear has been opened up so the bolt can fit a Teflon sleeve bearing around it to aid with rotation. A small thrust bearing interfaces between the nut of this bolt and the structure material so the bolt can easily spin along with the gear. The base plate of the cylindrical joint, which contains the thrust bearing, is 6 inches by 6 inches square with rounded corners. The circular plate, which fastens to the top of the 72 tooth gear, is 6 inches in diameter so it is large enough to rest the larger motor of the rotational joint. The Delrin base plate shown in Figure 41 is appropriately grooved to house all of the components, and the thrust bearing is press fit into the plate. Four threaded holes, one at each corner, are fabricated for fastening a physical block to the base plate. The physical block prevents the robot arm from driving into the power wheelchair user's immediate space.

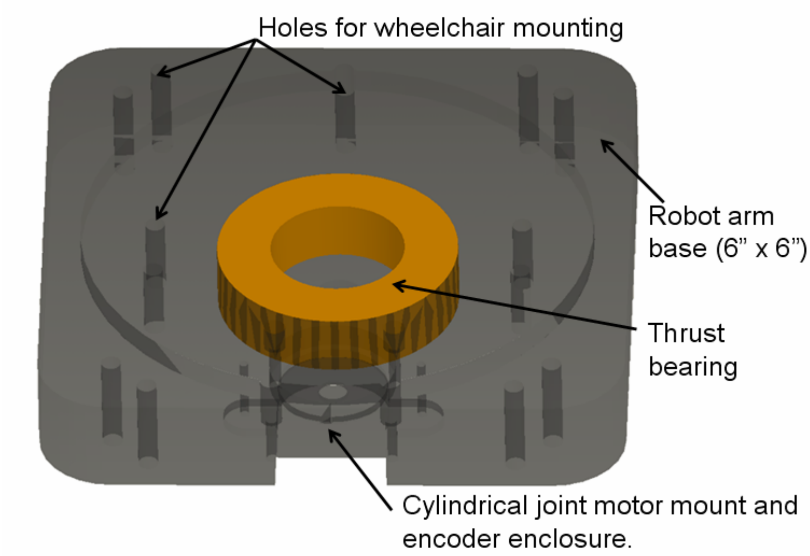


Figure 41. DORA's robot arm base plate and thrust bearing.

A 21 tooth gear is used to drive the 72 tooth gear creating a gear ratio larger than 3:1. The required angular acceleration and motion is calculated by using the assumed weights and moments of inertia for the components to estimate the minimum torque requirements of the motor. All of they cylindrical joint components are shown in Figure 42. The cylindrical joint uses a PK246PA 2-phase stepping motor from Oriental Motor at a speed of 7.5rpm which outputs a torque of approximately 7 lb-in (0.8 Nm). The resultant torque for the system, assuming 100% gear efficiency, is 24 lb-in (2.7 Nm) at a speed of 2.2rpm. The cylindrical joint weighs a total of 4.44 lbs as shown in Figure 43.

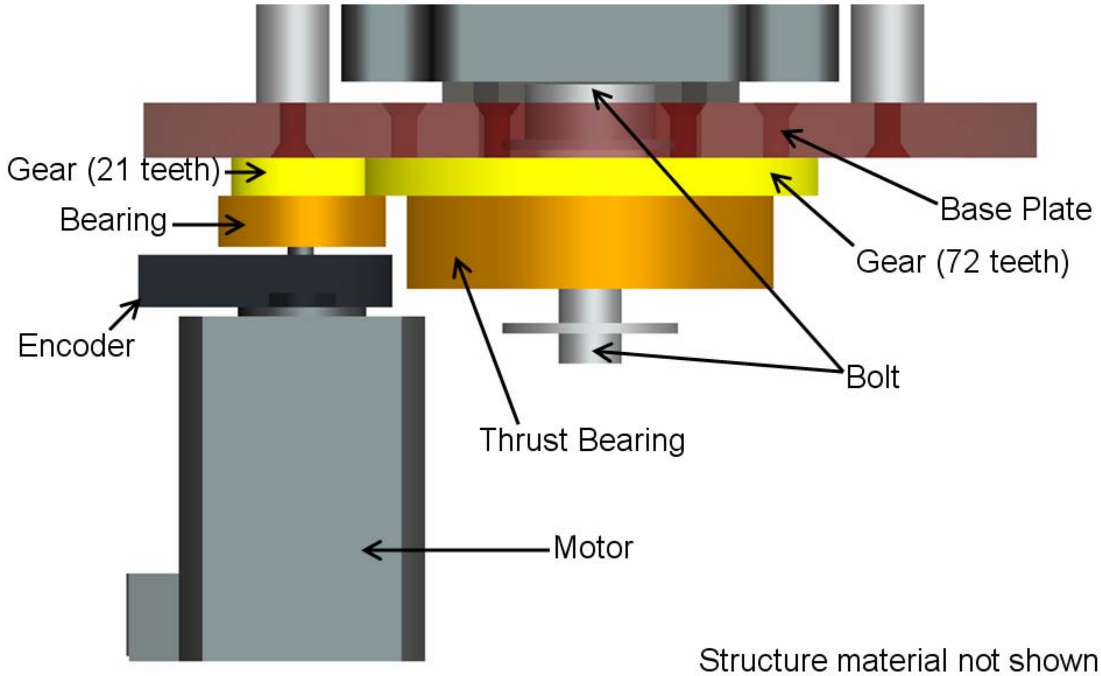


Figure 42. Cylindrical joint schematic and mechanical components.

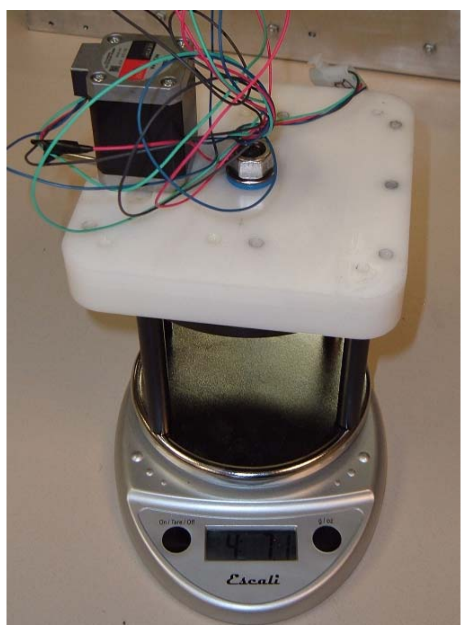


Figure 43. Cylindrical joint weight 4 lbs 7.1 ounces (pictured up-side down).

4.3.2 ROTATIONAL JOINT (UP AND DOWN)

The rotational joint for the up and down motion of the robot arm was over-designed to allow for future adjustments to the link lengths and gripper. The motor sits upright on the base of the arm in order to fit in a small envelope and not hit anything behind the base of the arm as it spins (Figure 44). A shaft collar, worm, and thrust bearing are stacked on top of the motor shaft and are connected by a keyed shaft as also seen in Figure 44. This keyed shaft rests in a needle bearing at the top of the structure so the worm does not flex or pull away from the worm gear while in operation.

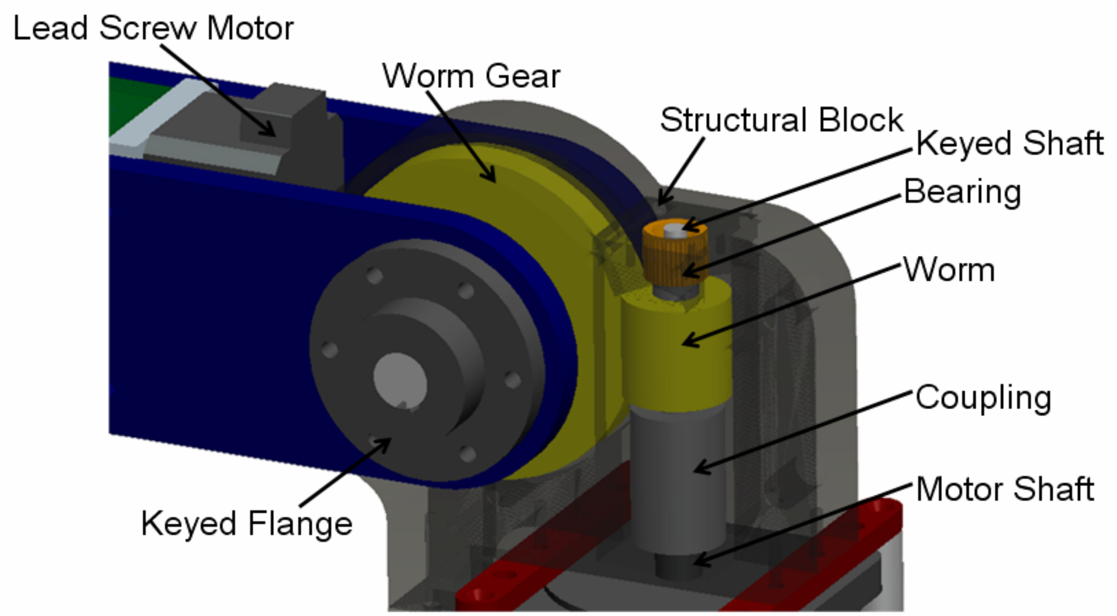


Figure 44. Rotational joint motor shaft: collar, worm gear, and needle bearing.

The worm gear connects to the rest of the sliding link structure via a keyway that goes through the worm gear and keyed flanges. These flanges mount to the rest of the sliding link portion of the robot arm. The worm gear has 40 teeth, a 40:1 gear ratio, creating a significant motor torque multiplication in a small space. The cantilevered portion of the robot arm falls (gripper, universal joint, and sliding link), rotating the worm gear, and forces the worm upwards into the top of the structure as shown in Figure 45. To compensate for this upward motion, the worm compresses a thrust bearing against the top of the structure material to allow for frictionless rotation of the worm. The motor is suspended from the structure using standoffs to help with heat dissipation and vibration as seen in Figure 46.

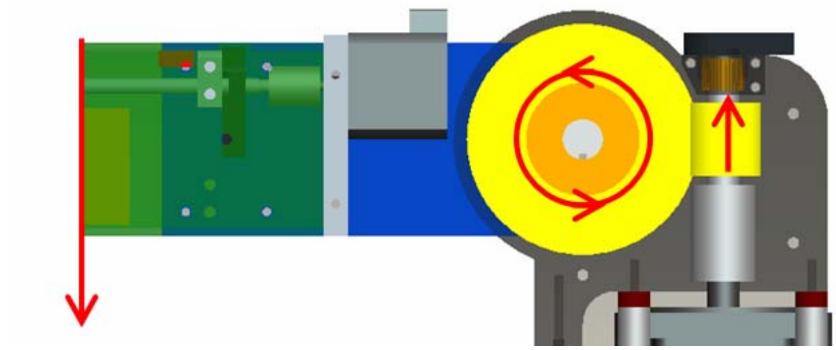


Figure 45. Sliding link falls, spinning worm gear, which pushes worm upwards.

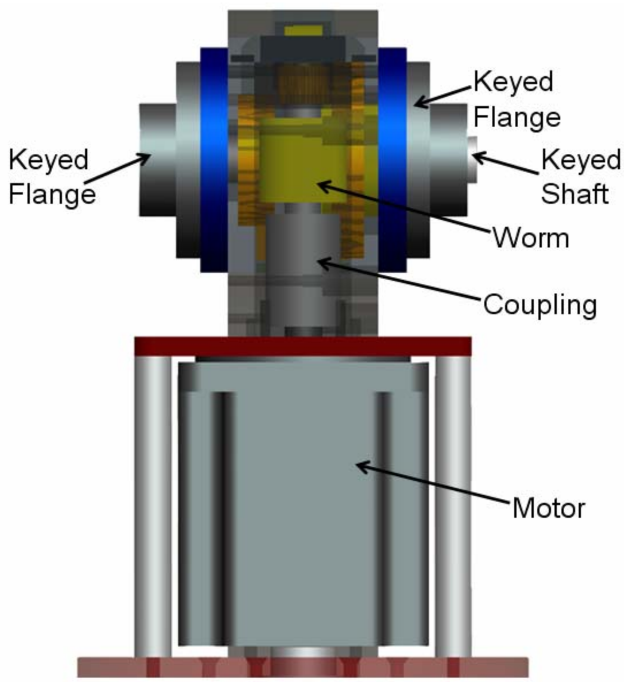


Figure 46. Rotational joint motor connection to sliding link structure and motor mount.

The Delrin structure that surrounds the worm gear and nests the bearings for the shaft that passes into the sliding link structure has many features for manufacturability. The structure consists of three pieces: one that looks like the letter “I” (Figure 47a) and acts as a standoff between the rotating plate and the rest of the structure and two halves of a structure that sandwiches around the worm gear and motor shaft (Figure 47b). Also, the rounded edge around the worm gear allows for the lead screw motor to be very close to the joint as seen in Figure 48 along with a depiction of all the components located in the rotational joint.

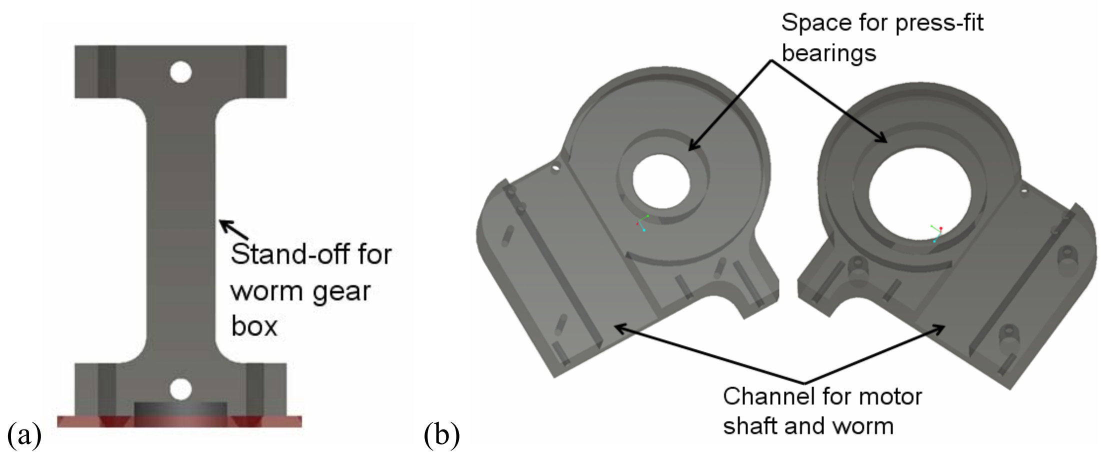


Figure 47. Rotational joint structure (a) acts as an “I” beam and (b) houses the worm gear.

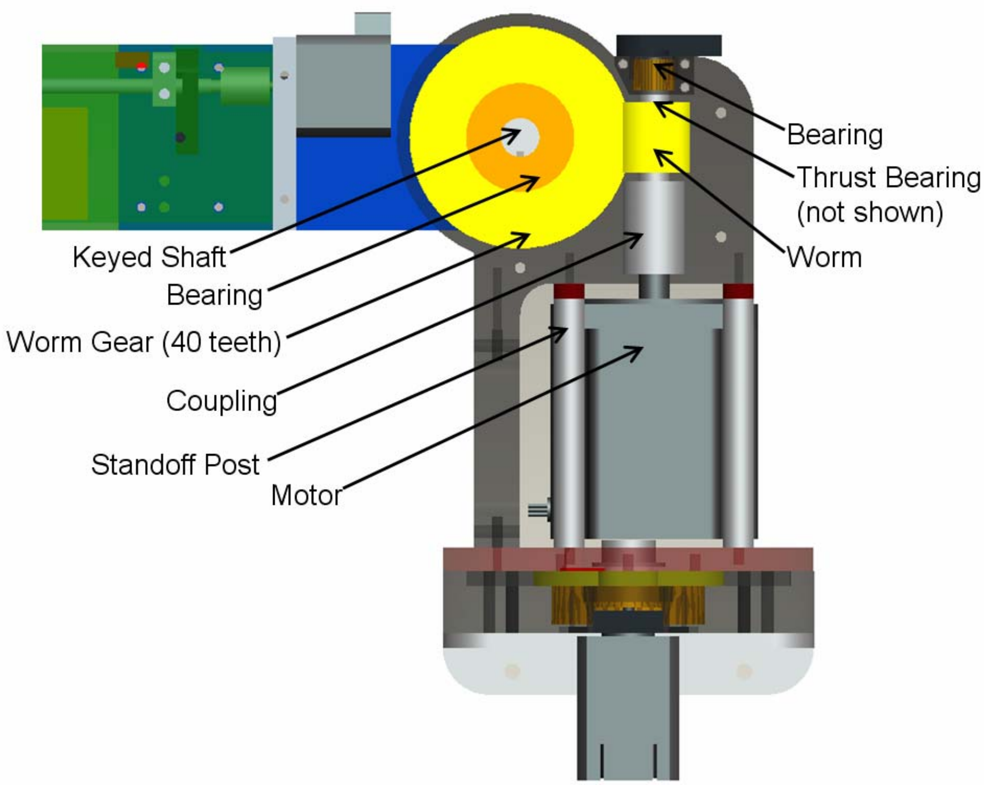


Figure 48. Rotational joint schematic and mechanical components.

Lastly, it is a safety advantage that the worm gear system is self-locking (cannot back drive) when the motor power is shut off. The sliding link portion of the arm is always held at its driven position via the rotational joint and cannot disengage if the robot arm were to lose power. This joint is designed with an assumed required output torque of 500 lb-in (56.5 Nm) and a desired output speed of 1.5rpm. The 500 lb-in torque requirement stems from a combined sliding link and gripper weight assumption of 13 lbs at an extension point of 36 inches. Using the arm estimated weight at the furthest extension for its torque requirements served as a greater safety factor than adding up the weight at its incremental extensions. The Slocum design book is used as a reference for best design practices and torque calculations for the various mechanical assemblies (Slocum, 2008). The corresponding Slocum excel spreadsheets indicate a need for a motor output torque of 37.6 lb-in (4.25 Nm) for the worm gear system to lift the intended weight at its intended speed.

The rotational joint uses a PK299-03AA 2-phase stepping motor from Oriental Motor at a speed of 30rpm which produces a torque of approximately 53 lb-in (6 Nm). The resulting torque for the system, assuming 100% efficiency, is 2124 lb-in (240 Nm) at a speed of 1.3rpm. However, the Slocum design book suggests the efficiency for the worm gear is far lower, approximately 30%-50%, because of its sliding contact between the teeth (Slocum, 2008). Therefore, the resulting minimum output torque created in the system is 637 lb-in (72 Nm) which satisfies the 500 lb-in (56.5 Nm) requirement and allows a combined weight of 13 lbs on the gripper, universal joint, and sliding link components. The lack of efficiency in the worm gear system is countered by the fact that it is not back drivable so the motor power may be removed when the joint is not in operation. The rotational joint weighs a total of 12.7 lbs as shown in Figure 49 and cantilevers a combined weight of nearly 12 lbs.

(a) (b)

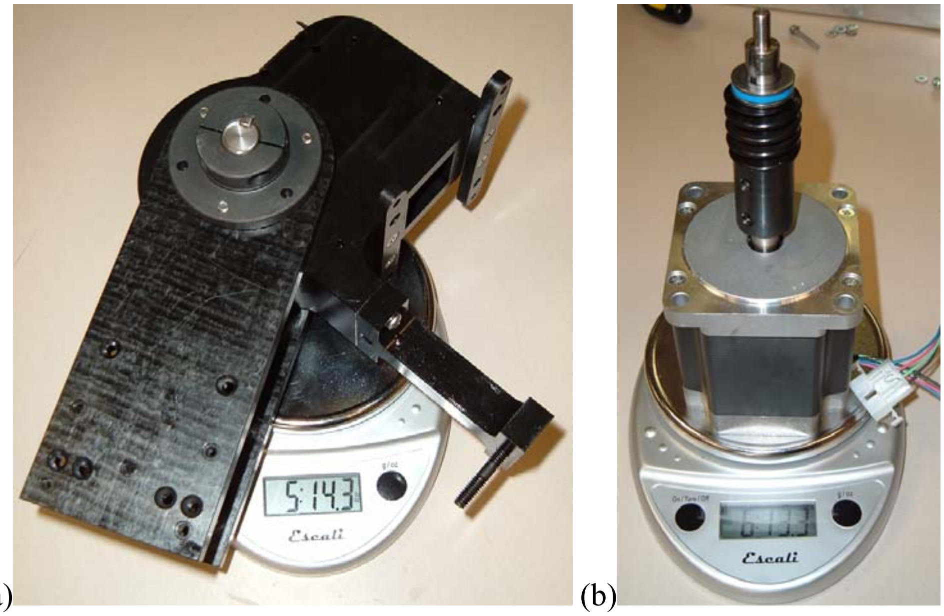


Figure 49. Weight of rotational joint 12 lbs 11.6 ounces, (a) worm gearbox and sliding link connection and (b) motor, coupling, worm, and keyed shaft.

4.3.3 SLIDING LINK (FORWARD AND BACK)

The sliding link utilizes a pair of steel drawer slides that extend from 12 inches to 24 inches for forward and backward motion of the gripper. Aluminum tubing is fastened to the extending portion of the drawer slides, and a lead screw drives a collar to create the sliding link as shown in Figure 50. The lead screw collar is attached to one end of the aluminum tube and the gripper is attached to the other. The motor is attached at the end closest to the rotational joint so its weight has a minimal impact on the torque limitations. Using spreadsheets from (Slocum, 2008), the preliminary calculations for the lead screw assume the gripper and linkage assemblies need a 9 lb-force to lift it upwards. The gripper assembly weighs approximately 5 lbs and the lead screw needs to overcome friction created in the drawer slides. The output torque for the system motor needs to be at least 0.97 lb-in (0.11 Nm). The lead screw calculations assume a lead of 0.25 inches (4 turns per inch, or TPI), coefficient of friction of u= 0.2, the lead screw has a thread angle of 30 degrees, and a motor efficiency of 90%.

The sliding link uses a PK244PA 2-phase stepper motor from Oriental Motor at 7.5rpm which produces a torque of approximately 3.5 lb-in (0.4 Nm) on the lead screw. The safety factor caused by using a motor that is four times more powerful than needed means that the efficiency in the system, the lead screw and friction in the drawer slides, can be as low as 20%, and the system will still operate. The sliding linkage and the majority of the universal joint weigh a total of 6.5 lbs as shown in Figure 51.

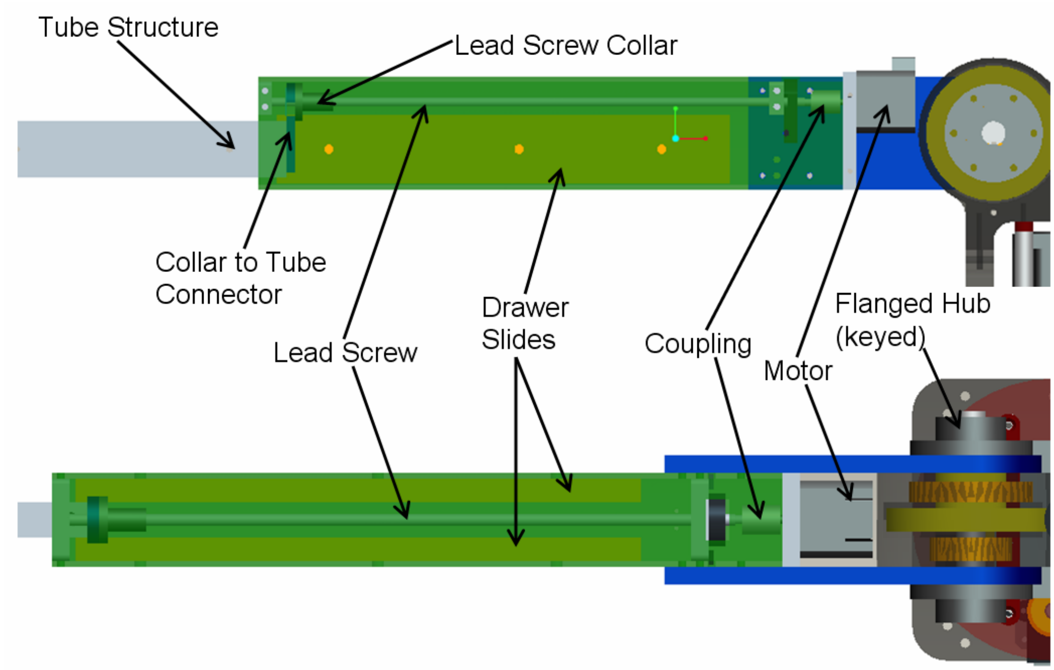


Figure 50. Sliding link schematic and mechanical components.

(a)  (b) 

Figure 51. Weight of (a) sliding link, universal joint, and (b) lead screw motor, 6 lbs 7.4 ounces.

4.3.4 UNIVERSAL JOINT (2 DOF "WRIST")

The universal joint is needed to traverse the gripper angle from being in line with the sliding link portion of the arm to the plane of the door. This feature is especially needed to open a door knob or handle on the left side of a door when the robot arm is mounted to the right side of the chair. It is custom made out of aluminum, brass sleeve bearings, and bolts that protrude from the central block through the bearings as shown in Figure 52. The universal joint connects the gripper to the sliding link end of the arm and falls to hit a hard stop that places the gripper at an angle relatively parallel with the floor. Eight plastic eyebolts are used as locations to fasten surgical tubing, four connected to the universal joint and four connected to the gripper. The surgical tubing is tensioned using turnbuckles. Additional tubing is tied around the eyebolts to enable the gripper assembly to easily move to different angles when the arm compresses it against the plane of a door.

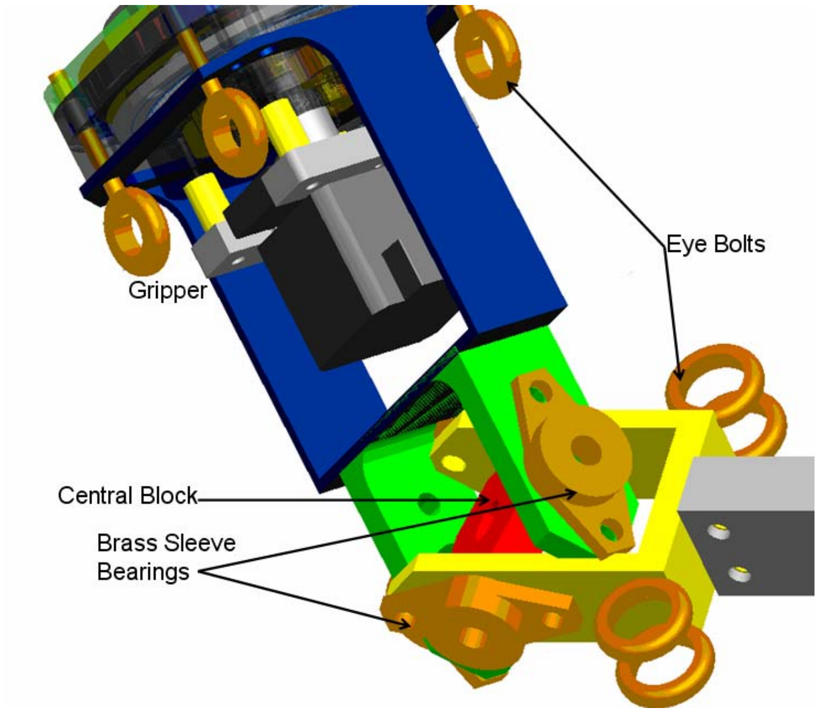


Figure 52. Universal joint schematic and mechanical components.

4.3.5 WHEELCHAIR MOUNTING

The mount that fastens the robot arm on the wheelchair is an aluminum tube that connects to the base cylindrical joint of the robot arm as shown in Figure 53. The mount needs to be parallel with the floor for the cylindrical joint to work because its motor has trouble overcoming the moment of inertia caused by the arm rotating on an axis and gravity's pull. The mount is suspended from the wheelchair frame using holes that are already drilled into the frame for seat pan and arm rest adjustments. However, the aluminum tube deforms when the arm's full weight swings outwards so additional clamps are used to prevent material deformation. It is best for the function of the wheelchair mount when the cylindrical joint spins the robot arm only when the sliding link structure is vertically positioned by the rotational joint.

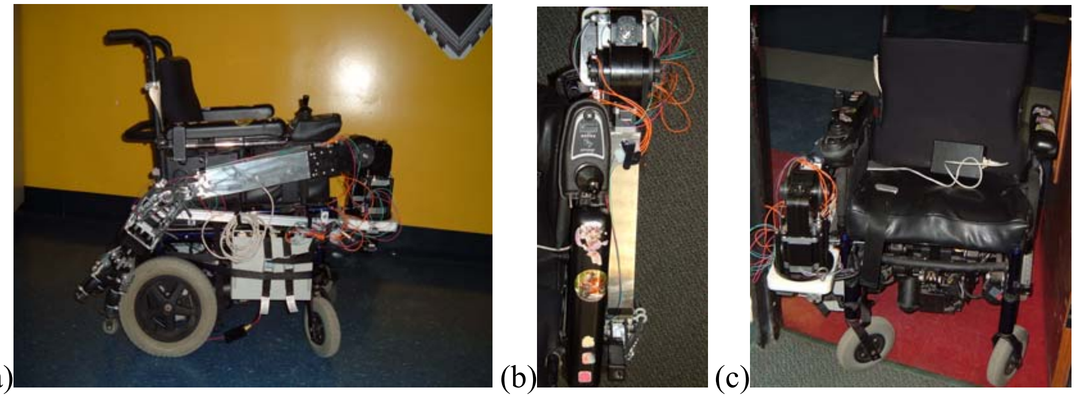
(a)(b) (c)

Figure 53. Wheelchair mount and DORA location (a) stowed side view, (b) stowed top view, and (c) passing through doorway.

4.4 ROBOT ARM PERFORMANCE OBSERVATIONS

DORA is mounted to a Quickie S525 power wheelchair by Sunrise Medical (Figure 54) and is capable of passing through doors and navigating tight spaces while mounted. The motorized operation on DORA uses custom designed electronics and a numeric keypad that controls the individual motors. The total weight of the robot arm (with gripper) is 28.8 lbs.

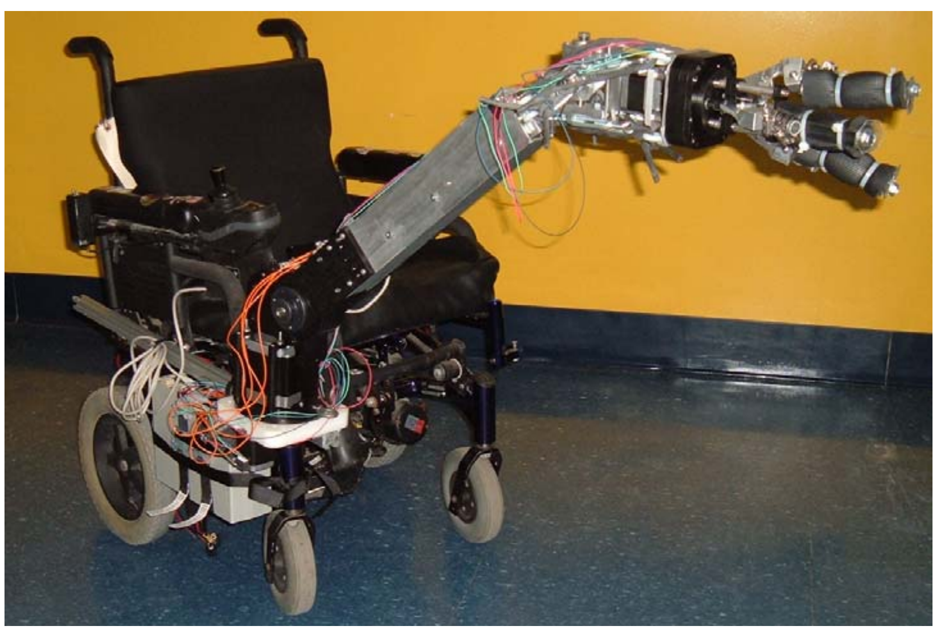


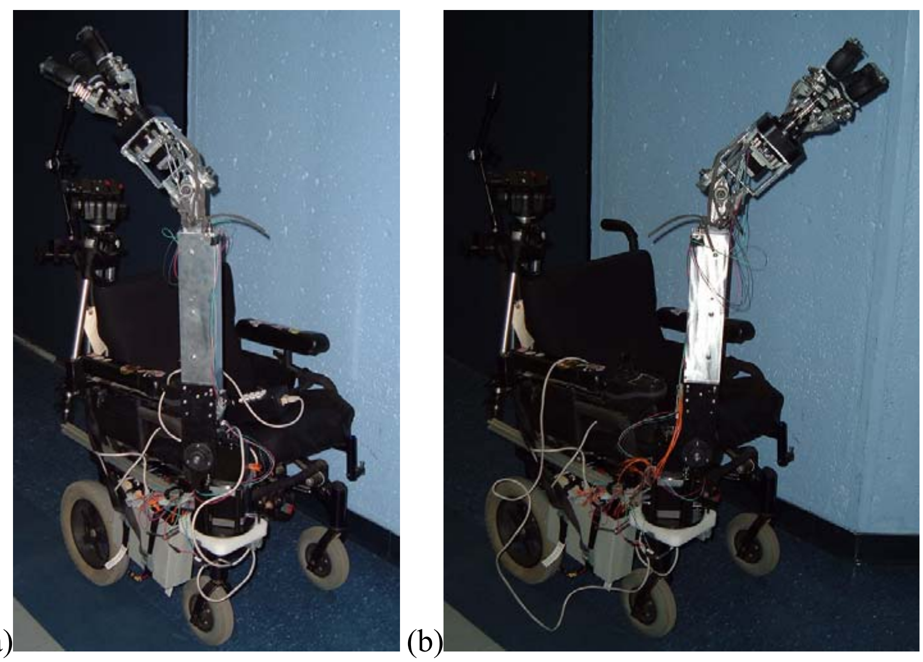
Figure 54. Photo of the wheelchair-mounted robotic arm to open doors.

The motors on the robot arm are able to handle the expected loads so that it can drive the gripper to the location of the door knob or handle. The motor for the cylindrical joint appears to be slightly underpowered, but this can be remedied in future work. The mass of the robot arm, when driven at a horizontal position, is capable of overcoming the holding torque in the cylindrical joint motor causing the arm to spin side-to-side unexpectedly. The cylindrical joint works best when the sliding link portion arm is raised to its vertical position before it is spun (as opposed to horizontal position as when stowed) because the motor does not need to overcome the larger moment of inertia created by the arm's weight and extension at its horizontal position (as shown Figure 53a). The thrust bearing for the 21 tooth gear in the cylindrical joint was removed because the set screw for the gear could not be accessed as designed. In addition, the spur gears in the cylindrical joint skip and cause a clicking noise possibly because of the chatter in the stepping motor and backlash in the gear teeth.

The sliding link portion of the arm is able to move the gripper back and forth at an angle, but lifting the gripper weight straight up remains a challenge because of the mass of the gripper and the friction in the drawer slides caused by slight misalignment. The coupling that connects the motor shaft with the lead screw in the sliding link consistently breaks apart when the gripper, while mounted to the sliding link, is incidentally pulled away from the rotational joint. Furthermore, the rotational joint remains the most reliable joint because it consistently raises and lowers the sliding link and gripper portion of the arm.

At times, the heads of the eyebolts on the universal joint had snapped off their shafts when the universal joint was over tensioned. The plastic eyebolts that are mounted into the gripper work well because the tension is in the lengthwise direction of the eyebolt. However, the eyebolts at the back end of the universal joint are tensioned laterally, which can cause for detachment. The plastic eyebolts were replaced at with steel eyebolts the back end of the universal joint and have since not caused any issues.

The robot arm was driven to the corners of its operable position space to determine its mechanical mobility limitations. The robot arm joint arrangement at its vertical position (Figure 55) and along the floor (Figure 56) show the right-most and left-most limitations of the robot arm's spherical workspace. Figure 57 shows how the sliding link gives the spherical workspace a shell 12 inches thick.


(a) (b)
Figure 55. DORA's workspace at vertical position (a) turned to the side and (b) turned to the front.

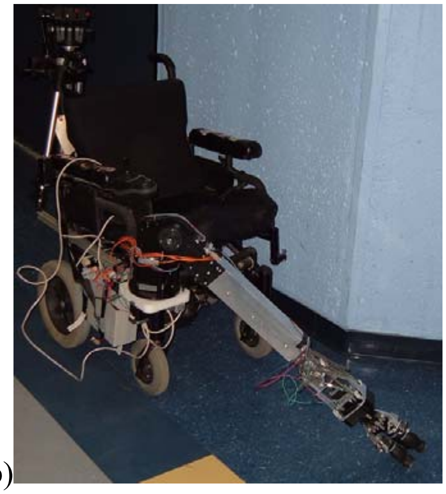
(a)  (b) 

Figure 56. DORA’s capability to reach the floor (a) to the side and (b) out in front.

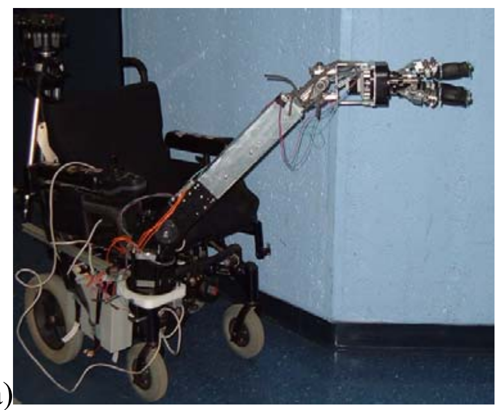
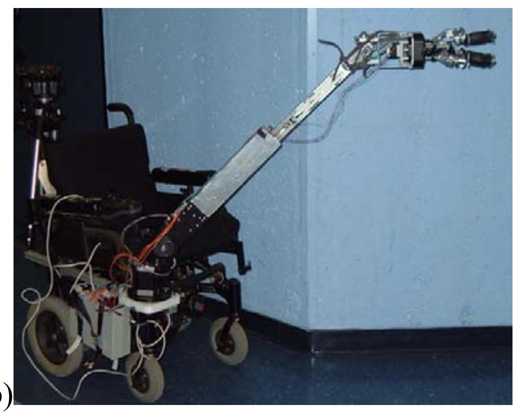
(a)  (b) 

Figure 57. DORA’s extension of its sliding link (a) fully stowed and (b) longest extension.

The robot arm is mechanically capable of delivering the gripper to a large spherical workspace; however, the universal joint limits the gripper capability of matching the plane of a door from side-to-side and up-down angles to match the plane of a wall or door. Figure 58 shows the actual operable spherical position space of DORA.

(a) (b)

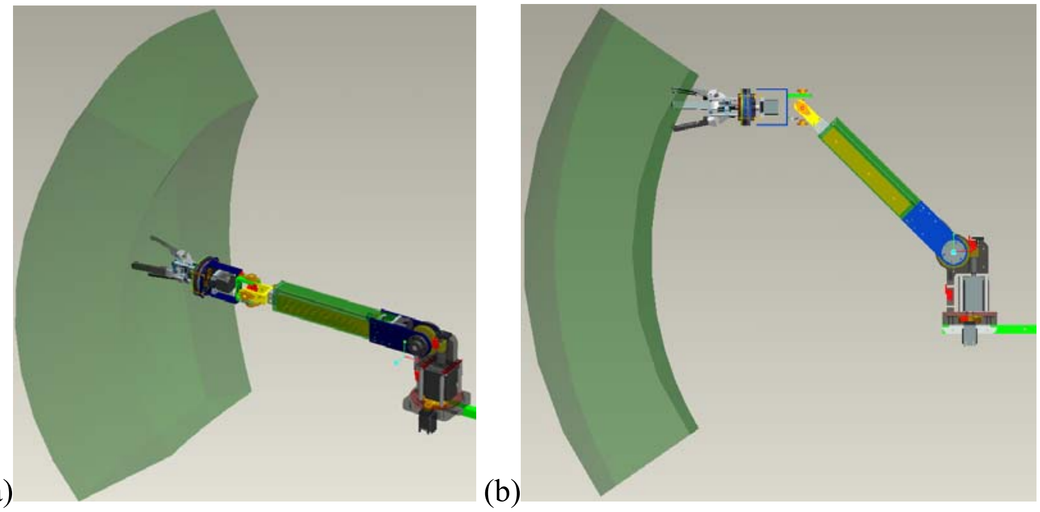


Figure 58. (a) Orthogonal view and (b) side view of DORA position space.

According to the models, DORA's optimal approach to a door (while mounted to a wheelchair), referenced from the center of the robot arm, is between 36 inches and 44 inches. This model assumed an average door knob height of 39 inches and that the front of the wheelchair and the plane of the door were parallel. As shown by the green position space in Figure 59, the model displays how the gripper fingers can also be placed on the plane of the door for areas above and below the height of 39 inches. The remainder of the position space is unused because door knobs and handles are not typically placed above 48 inches or below 30 inches. In addition, the position space changes according to the exact mount height of the robot arm above the floor (DORA is currently mounted 18 inches off the floor as seen in Figure 59). Furthermore, the wheelchair may be positioned at angles less than 30° on approach to the door because the universal joint traverses 30° angles side-to-side. However, the position space of the robot arm always remains in relation to the position robot arm's base, not the location of the door, so DORA's position space for a door approached at an angle is far narrower.

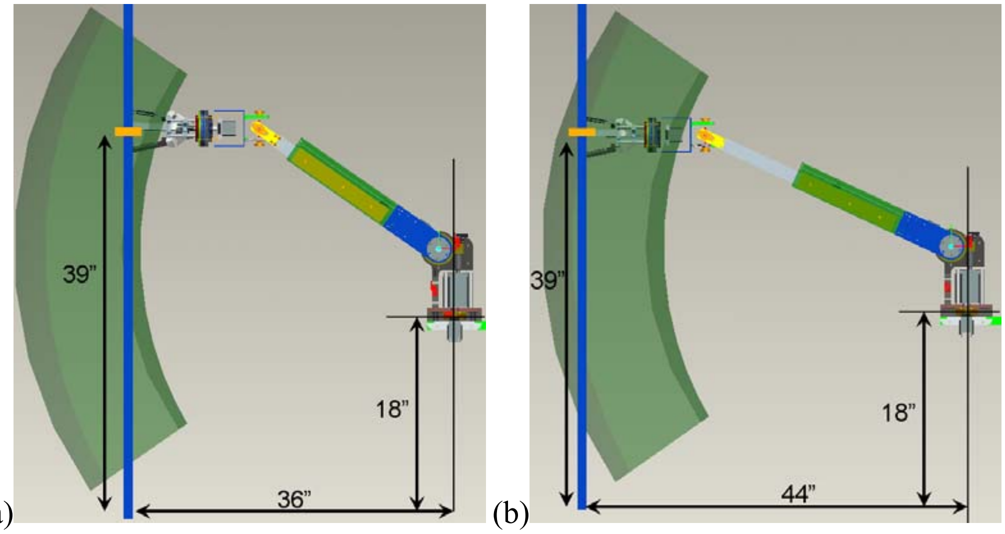
(a) (b)


Figure 59. Optimal distance between DORA and the door to approach a door knob height of 39 inches (a) closest approach to a door 36 inches and (b) furthest approach to a door 44 inches.

The robot arm was demonstrated on three different doors to verify DORA’s robot arm design capabilities. The majority of performance issues within the robot arm are attributed to the mass of the components made out of aluminum which add a significant amount of weight to the suspended portions of the arm such as the sliding link, universal joint, and gripper. In addition, the universal joint did not traverse a great enough angle for the robot arm to cross in front of the wheelchair to grasp a door knob on the left side of the door, nor did it traverse the angle without being directly handled by the operator. However, the robot arm was capable of delivering the gripper to the door knob or handle that was directly in front of the robot arm base and was in an acceptable mechanical condition for more rigorous testing.

5 DORA PEFORMANCE TEST

A more extensive test was needed to verify DORA's design. First, fifteen doors on the UMass Lowell campus were selected for testing: five 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 to push the door open. The purpose of this test was to quantify which of DORA's design characteristics work for most doors and which failure trends occur due to a door's specific geometric or force characteristics. This chapter outlines the test procedure and presents the door characteristics, followed by the data and a resulting discussion based on the findings.

5.1 TEST PROCEDURE FOR OPENING DOORS

In this test, the powered wheelchair was used to position the base of the robot arm directly in front of the door knob or handle. This action negated any performance results that may be 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 vary so the rotational joint and sliding link were used to deliver the gripper to its destination. Forward and backward motion of the wheelchair was used to reposition the gripper on the door knob or handle between trials. Five trials on each side of the door were performed to determine the success rate of the gripper actuation on the door knob or handle being tested. Each trial ended with the pushing or pulling of the wheelchair to verify if the door knob or handle had been unlatched. The robot arm was realigned after the wheelchair moved backwards or forwards between each trial. The gripper was again positioned on the door knob or handle between each trial to guarantee a "new" attempt.

DORA was tested on fifteen different doors located on the UMass Lowell campus. Five of the doors had handles and ten of the doors had door knobs. 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 fifty trials. The door handles were tested using both directions: clockwise if the door handle was on the left side of the door (handle points right) and counter-clockwise if the door handle was on the right side of the door (handle points left). All of the door knobs were tested using the gripper in a clockwise direction.

5.2 DOOR CHARACTERISTICS

The fifteen doors selected have varying characteristics. As a means to quantify DORA's performance attributes, the selected doors are characterized by the following statistics:

A. Does the door have door knob or handle?
B. Is the door knob/handle on the pull side of the door on the left or right?
C. Is the door knob/handle on the push side of the door on the left or right?
D. Height of center of door knob/handle from floor (see Figure 60).

E. Distance from the center of the door knob to the edge of the door from both pull/push sides of the door (see Figure 60).

F. The depth of the door jam from plane of the door (see Figure 60).

G. The offset between the widest part of the door knob and the plane of the door (for a knob) or the distance between the outside surface of a door handle and the plane of the door for a handle (see Figure 60).

H. The largest diameter of a door knob (see Figure 60).

I. Shape of door knob (see Figure 60 and Figure 61).

J. Length of door handle (see Figure 62).

K. Thickness of door handle (see Figure 62).

L. The space between the edge of the door knob or handle and the door jam at the door knob's widest diameter (see Figure 63).

M. The minimum angle needed to unlatch the door knob or handle from the door jam (see Figure 64).

N. The force needed to push open the door (see Figure 65).

O. The torque needed to unlatch the door knob or handle (see Figure 66).

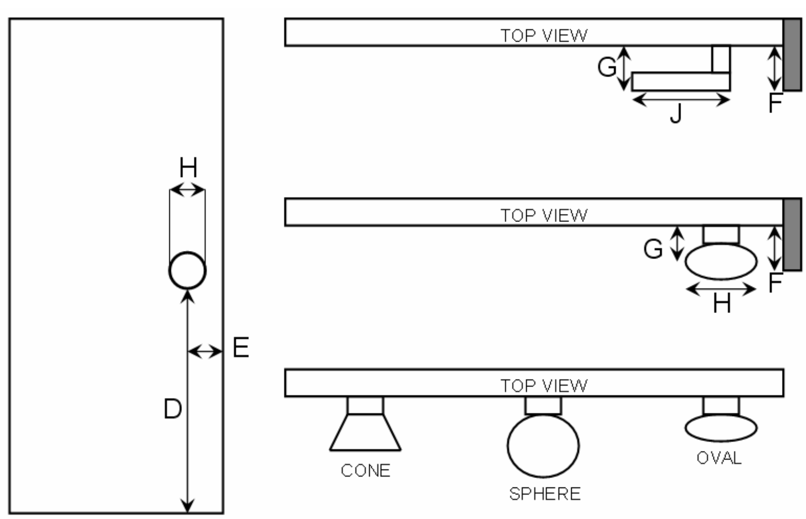


Figure 60. Door knob and handle dimensions for test.


Figure 61. Types of door knobs (a) oval, (b) sphere, and (c) cone.

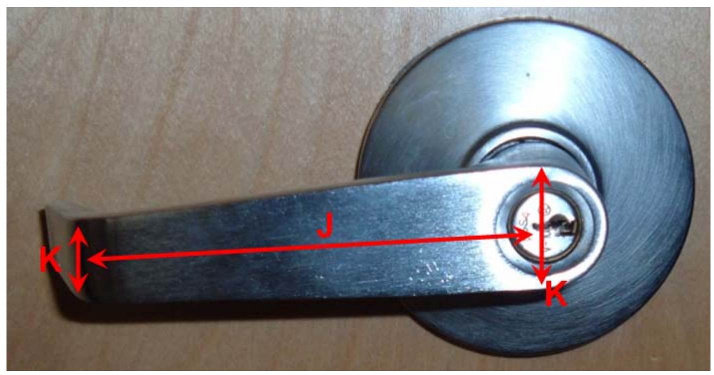


Figure 62. Length ‘J’ and width ‘K’ dimensions on a door handle.

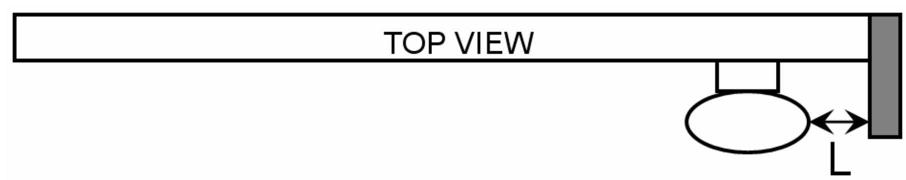


Figure 63. Distance between edge of the door knob or handle and the door jam.

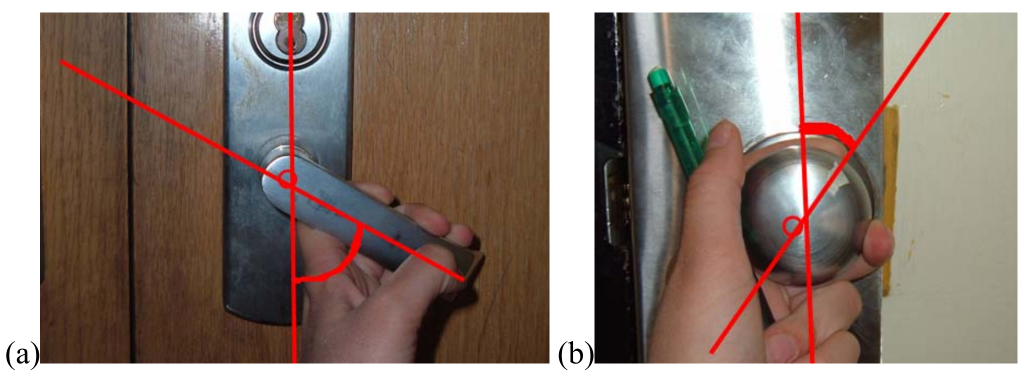


Figure 64. Angle (a) for door handle (90° minus angle) and (b) for door knob.

Figure 65. Method of measuring force to push open a door.

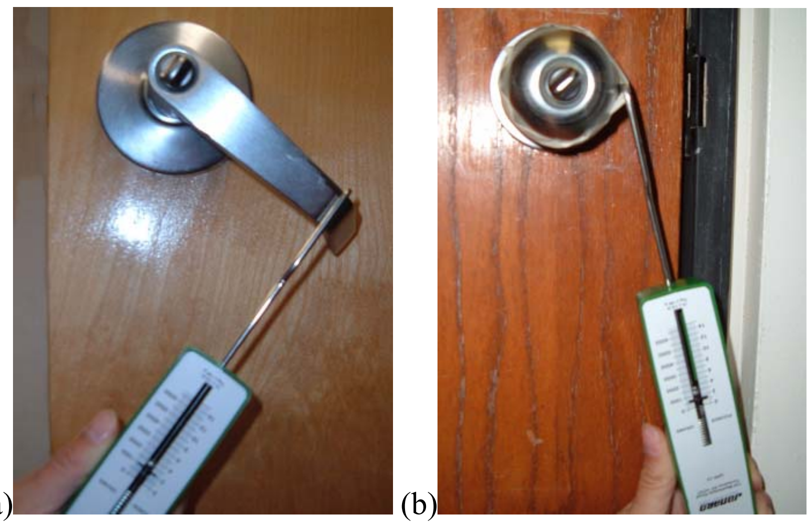
(a)  (b)

Figure 66. Method of measuring torque from (a) door handles and (b) door knobs.

The characteristics for each handled door are listed in Table 1. The door handles have heights between 37 inches and 40 inches, most of them have a taper from 1 inch thick at the axis of rotation to 0.75 inches thick at the end, and all have generous gap between the axis and the door jam. Door 2 is slightly different because it is actually a set of two doors that pull open where one has a handle on the left, one has a handle on the right, and the push side of each door has a push bar. The handle on

Door 2 does not have a taper (see Figure 64a above); instead it is consistently 1 inch thick. Lastly, the door handles need to be twisted at angles between 30° and 60° at torques between 9 lb-in and 21.25 lb-in.

Table 1: Door Handle Characteristics

	A	B	C	D	E (pull side)	E (push side)	F (pull side)	F (push side)	G
DOOR #	Type	Pull	Push	Height (inches)	Knob cender to edge (inches)	Knob cender to edge (inches)	Door jam depth (inches)	Door jam depth (inches)	Height off door plane (inches)
1	handle	right	left	38.00	5.00	5.00	0.00	0.00	2.50
2	handle	both	none	37.00	3.38	3.38	0.00	0.00	2.88
3	handle	right	left	39.75	3.00	2.50	0.00	1.00	2.50
4	handle	right	left	40.00	3.00	2.50	0.00	1.00	2.50
5	handle	left	right	38.75	2.75	2.50	0.00	1.13	2.50

Table 1: Door Handle Characteristics (continued)

	H	J	K	L	M	N	O
DOOR #	Max diameter around axis (inches)	Handle length (inches)	Handle thickness (inches)	Space between handle & door (inches)	Rotation_angle (degrees)	Force-open (lbs)	Torque-unlatch (lb-in)
1	1.00	4.00	.75 - 1	4.50	60.00	10.00	12.00
2	1.00	4.25	1.000	2.88	30.00	3.50	21.25
3	1.00	4.50	.75 - 1	2.00	35.00	0.80	11.25
4	1.00	4.50	.75 - 1	2.00	40.00	0.80	9.00
5	1.00	4.25	.75 - 1	2.00	50.00	0.80	12.75

The characteristics for each knobbed door are listed in Table 2. These doors have heights varying between 37.25 inches and 40.13 inches and have diameters varying from 1.75 inches (conical style) to 2.25 inches (spherical and oval styles). The widest part of the door knob ranges from 1.5 inches off the door plane to 2.5 inches off the door plane. There is no depth of a door jam on the pull side of the door so there is no risk of the finger catching between the door knob and door jam on the pull side of the door. Lastly, the door knobs need to be twisted at angles between 14° and 82° with torques ranging between 1.75 lb-in and 4.5 lb-in.

Table 2: Door Knob Characteristics

	A	B	C	D	E (pull side)	E (push side)	F (pull side)	F (push side)	G
DOOR #	Type	Pull	Push	Height (inches)	Knob cender to edge (inches)	Knob cender to edge (inches)	Door jam depth (inches)	Door jam depth (inches)	Height off door plane (inches)
6	knob	right	left	37.25	3.00	2.50	0.00	1.75	2.00
7	knob	right	left	38.75	2.50	2.50	0.00	1.13	2.50
8	knob	left	right	37.50	2.88	2.25	0.00	1.25	2.00
9	knob	left	right	37.75	2.88	2.25	0.00	1.25	1.50
10	knob	left	right	38.00	2.88	2.00	0.00	4.00	1.63
11	knob	right	left	38.00	3.00	2.50	0.00	1.00	2.00
12	knob	right	left	38.13	5.00	5.00	0.00	2.50	2.00
13	knob	left	right	39.00	2.63	1.75	0.00	2.25	1.75
14	knob	left	right	40.13	2.75	2.38	0.00	1.00	2.00
15	knob	left	right	38.50	2.50	2.00	0.00	1.75	1.88

Table 2: Door Knob Characteristics (continued)

	H	I	L	M	N	O
DOOR #	Max diameter around axis (inches)	Shape	Space between handle & door (inches)	Rotation_angle (degrees)	Force-open (lbs)	Torque-unlatch (lb-in)
6	2.13	sphere	1.44	29.00	0.80	2.13
7	2.13	oval	1.44	58.00	0.40	8.50
8	2.25	sphere	1.13	32.00	4.50	2.25
9	2.00	oval	1.25	36.00	6.00	3.00
10	2.13	oval	0.94	82.00	6.00	3.19
11	2.25	sphere	1.38	37.00	1.00	3.38
12	2.25	oval	3.88	38.00	0.00	3.94
13	2.25	oval	0.63	14.00	8.00	4.50
14	1.75	cone	1.50	21.00	0.80	1.75
15	2.25	oval	0.88	30.00	0.20	4.50

5.3 TEST RESULTS

One hundred and fifty trials were performed on fifteen doors. There were six observed behaviors that occurred during the test. These behaviors are listed below in greater detail beside their respective column heading. For 46% of the trials, two or more of the failure behaviors (b-f) were observed to contribute to DORA's lack of performance on the door being tested.

a. A successful opening happens when the arm delivered the gripper to the door knob or handle, the gripper twisted the knob or handle enough to unlatch it out of the door jam, and the gripper maintained the unlatching action while the robot arm pushed or pulled on the door to open it (14% of trials).

b. The trials when the gripper was not capable of twisting the door knob or handle far enough (past the required rotation angle) to unlatch the door from the door jam (49% of trials). This result is caused by having enough clamping force in the gripper but not enough twisting action.

c. The trials when gripper fails to twist the door knob or handle at all (31% of trials). This result is attributed to a lack of both clamping and twisting forces in the gripper.

d. The trials when a finger got stuck between the door knob or handle and the door jam (13% of trials). This result is attributed to the finger being wider than the available space (door characteristic “L”).

e. The trials when the gripper was not capable of holding onto the door knob or handle. When the wheelchair drove backwards to pull the door open, the gripper fell off the door knob or handle (25% of trials). This result is attributed to not having enough clamping force on the gripper fingers and the nubs at the end of the fingers were not capable of wrapping around the knob/handle enough to be effective.

f. The trials when the gripper twisted itself off the door knob or handle (17% of trials). This result is attributed to the wide gap between the gripper fingers, wide enough a door knob or handle passes through them, and the universal joint’s incapability to counteract the forces generated while the gripper attempts to manipulate a high torque.

The test results are presented in Tables 3, 4, and 5 along with more detailed discussions based on the results from each door. An ‘x’ in the table denotes the behavior had occurred according to the criteria defined above as behaviors a-f.

5.3.1 RESULTS, DOORS WITH HANDLES

Door 1 is a handled door that requires a 60° rotational angle to open. It is the heaviest door to open (10 lbs) and requires 12 lb-in to twist the handle. In all ten trials the gripper was able to twist the door handle, but the gripper also twisted itself off the handle four of the ten times: one trial on the pull side of the door (counter-clockwise) and three trials on the push side of the door (clockwise). DORA failed to open this door because the gripper could not twist the handle for a long enough time to push the heavy door open and it could not grip the handle well enough to pull the door.

Door 2 was a handled door that requires a 30° rotational angle to open. It had the highest torque required to unlatch (21.25 lb-in) and needed a 3.5 lb-force to push it open. This door was different because it was two equal doors with two handles, one pulled open from the left (clockwise) and one pulled open from the right (counter-clockwise). A push bar was located on the push side of the two doors so only the pull sides were tested. For three of the trials, the gripper did not twist the handle at all, and, for seven of the trials, the gripper twisted the handle a few degrees. The gripper twisted itself off the handle four times. DORA failed with this door because of the high torque needed to twist the handle.

Door 3 was a handled door that required 11.25 lb-in torque to unlatch, a 0.8 lb-force to open, and a rotation angle of 35°. The gripper was able to twist and push (clockwise) and twist and pull (counter-clockwise) the door open in nine of the trials. The gripper twisted off the handle in one trial. However, this door did not fully latch itself into the door jam. Due to this fact, this is not truly a successful opening of a handled door because it did not need to hold the handle at a rotated position for a long period of time. However, this sample demonstrated that DORA is capable of twisting a handle to push or pull a door open. This result suggests that the gripper is unable to hold the handle at its unlatched position for a long enough time to unlatch the other handled doors.

Door 4 was a handled door that needed 40° and a 9 lb-in torque to unlatch and a 0.8 lb-force to push open. The gripper twisted the handle in nine of the ten trials and twisted off the handle in two out of the ten trials. The gripper briefly twisted the handle past the 40° mark on the pull the door open (counter-clockwise) for four of the trials but was unable to hold the handle at that angle for a long enough time because of the high torque to unlatch. Also, the gripper pulled off the handle when the wheelchair drove backwards because it could not grasp the handle well. Furthermore, the gripper was unable to twist past the 40° mark on the push side of the door (clockwise) because of the high torque required to unlatch.

Door 5 was a handled door that needed 50° and a 12.75 lb-in torque to unlatch and a 0.8 lb-force to push open. For all five occasions on the pull side of the door (clockwise) the gripper twisted itself off the handle. The gripper did not twist the handle far enough for the five trials on the push side of the door (counter-clockwise). DORA failed because of the high rotation angle and torque needed to unlatch the handle.

Table 3: Test Results for Doors 1-5 (handles)

				a	b	c	d	e	f
TRIAL_ID	DOOR_ID	Trial_Number	Side	Success	Twists_small_angle	No_twist	Finger_stuck_in_door_jam	Pulls_off_knob	Twists_itself_off_knob
1	1	1	pull		x				
2	1	2	pull		x				x
3	1	3	pull		x				
4	1	4	pull		x				
5	1	5	pull		x				
6	1	1	push		x			x	
7	1	2	push		x				x
8	1	3	push		x				x
9	1	4	push		x				x
10	1	5	push		x			x	
11	2	1	pull l		x				
12	2	2	pull l		x				
13	2	3	pull l		x				
14	2	4	pull l			x			
15	2	5	pull l		x				x
16	2	1	pull r			x			x
17	2	2	pull r		x				x
18	2	3	pull r		x				
19	2	4	pull r			x			x
20	2	5	pull r		x				
21	3	1	pull	x					
22	3	2	pull	x					
23	3	3	pull	x					
24	3	4	pull	x					
25	3	5	pull	x					
26	3	1	push	x					
27	3	2	push						x
28	3	3	push	x					
29	3	4	push	x					
30	3	5	push	x					
31	4	1	pull		x				
32	4	2	pull					x	
33	4	3	pull					x	
34	4	4	pull					x	
35	4	5	pull					x	
36	4	1	push		x				
37	4	2	push		x				
38	4	3	push						x
39	4	4	push		x				x
40	4	5	push		x				
41	5	1	pull			x			x
42	5	2	pull		x				x
43	5	3	pull		x				x
44	5	4	pull		x				x
45	5	5	pull		x				x
46	5	1	push		x				
47	5	2	push		x				
48	5	3	push		x				
49	5	4	push		x				
50	5	5	push		x				

5.3.2 RESULTS, DOORS WITH KNOBS

Door 6 was a door with a knob that was 2.13 inches in diameter, had a spherical shape, needed 29° and 2.13 lb-in to unlatch, and required 0.8 lb-force to push open. DORA was successful in unlatching the door knob from the pull side of the door for the first two trials, but was not able to turn the knob far enough for the remaining three trials because of gripper placement. DORA was unable to twist the door knob for four of the trials on the push side of the door because the finger stuck in the space between the knob and the door jam (1.44 inches); the gripper managed to twist the door knob slightly for one other trial on the push side of the door. DORA was partially successful with this door because of the low rotation angle and torque needed to unlatch the door, and the gripper grasped the knob well enough to pull the door open because of the door's low push force. The failures on the push side of the door were because of the small space between the knob and the door jam.

Door 7 was a door with a knob that was 2.5 inches in diameter, had a oval shape, needed 58° and 8.5 lb-in to unlatch, and required 0.4 lb-force to push open. On the pull side of the door, the gripper did not turn the knob at all and twisted itself off the door knob for the first two trials. The gripper did not turn the knob far enough for two more trials, did not turn the knob at all for one trial, and pulled off of the knob as well for three of the five trials. On the push side of the door, a gripper finger consistently got stuck in the space between the knob and door jam (1.44 inches) and failed to turn the door knob at all. DORA failed on this door because of the high angle, the torque needed to unlatch the knob, and the fingers stuck between the knob and the door jam.

Door 8 was a door with a knob that was 2.25 inches in diameter, had a spherical shape, needed 32° and 2.25 lb-in to unlatch, and required 4.5 lb-force to push open. The gripper was unable to twist the door knob far enough for all five trials on the pull side of the door. DORA pushed the door open on the push side of the door for two of the five trials, but it is questionable whether or not the door was entirely latched during those trials. The gripper was unable to twist the door knob far enough to unlatch the door in the remaining three trials because the finger stuck in the space between the knob and the door jam (1.13 inches). DORA failed on the pull side because the door was heavy, therefore the gripper pulled off the door. The trials on the push side of the door failed because the finger stuck between the knob and the door jam.

Door 9 was a door with a knob that was 2 inches in diameter, had a oval shape, needed 36° and 3 lb-in to unlatch, and required 6 lb-force to push open. The gripper was unable to twist the knob far enough except for one trial on the push side of the door; in that trial, the finger stuck in between the knob and the door jam (1.25 inches) and twisted itself off the knob. DORA failed because of the higher rotation angle and torque needed to unlatch the door knob on the pull side of the door and the finger stuck between the knob and the door jam on the push side of the door.

Door 10 was a door with a knob that was 2.13 inches in diameter, had an oval shape, needed 82° and 3.19 lb-in to unlatch, and required 6 lb-force to push open. The gripper was unable to twist the knob far enough except for one trial on the push side of the door when the gripper was able to successfully open the door. It is questionable whether or not the door was fully latched into the door jam for this trial especially since the gripper fingers stuck in the space between the knob and the door jam (0.94 inches) in all other four trials on the push side of the door. DORA failed because of the high rotation angle needed to unlatch the door knob; however, the successful trial demonstrated that the robot arm is capable of pushing open a door with a 6 lb-force.

Table 4: Test Results for Doors 6-10 (knobs)

				a	b	c	d	e	f
TRIAL_ID	DOOR_ID	Trial_Number	Side	Success	Twists_small_angle	No_twist	Finger_stuck_in_door_jam	Pulls_off_knob	Twists_itself_off_knob
51	6	1	pull	x					
52	6	2	pull	x					
53	6	3	pull		x			x	
54	6	4	pull		x			x	
55	6	5	pull		x			x	x
56	6	1	push		x				
57	6	2	push			x	x		
58	6	3	push			x	x		
59	6	4	push			x	x		x
60	6	5	push			x	x		x
61	7	1	pull			x			
62	7	2	pull			x			
63	7	3	pull		x			x	
64	7	4	pull		x			x	x
65	7	5	pull			x		x	x
66	7	1	push			x	x		x
67	7	2	push			x	x		x
68	7	3	push			x	x		x
69	7	4	push			x	x		
70	7	5	push			x	x		
71	8	1	pull		x			x	
72	8	2	pull		x			x	
73	8	3	pull		x			x	
74	8	4	pull		x			x	
75	8	5	pull		x			x	
76	8	1	push	x					
77	8	2	push	x					
78	8	3	push		x				
79	8	4	push		x				
80	8	5	push		x				
81	9	1	pull		x				
82	9	2	pull		x				
83	9	3	pull		x				
84	9	4	pull		x				x
85	9	5	pull		x				
86	9	1	push			x	x		
87	9	2	push		x				
88	9	3	push		x				
89	9	4	push		x				
90	9	5	push		x				
91	10	1	pull		x			x	
92	10	2	pull		x			x	
93	10	3	pull		x			x	
94	10	4	pull		x			x	
95	10	5	pull		x			x	
96	10	1	push	x					
97	10	2	push		x		x		
98	10	3	push		x		x		
99	10	4	push		x		x		
100	10	5	push		x		x		

Door 11 was a door with a knob that was 2.25 inches in diameter, had a spherical shape, needed 37° and 3.38 lb-in to unlatch, and required 1 lb-force to push open. The gripper failed to turn the door knob at all for all ten trials. DORA failed because of the higher rotation angle and the larger diameter of its door knob.

Door 12 was a knobbed door with a knob that was 2.25 inches in diameter, had a oval shape, needed 38° and 3.94 lb-in to unlatch, and required 0 lb-force to push open because it naturally swung outward when unlatched. The gripper failed to turn the door knob at all for all ten trials. DORA failed because of the high torque needed to unlatch the door.

Door 13 was a door with a knob that was 2.25 inches in diameter, had a oval shape, needed 14° and 4.5 lb-in to unlatch, and required 8 lb-force to push open. The gripper either did not turn the knob far enough (two trials) or at all (three trials) on the pull side of the door. The gripper finger stuck between the door knob and the jam for all five trials on the push side of the door and did not turn the knob at all. DORA failed to open the pull side of this door because of the high torque to unlatch the door and high force needed to open the door, despite the small rotation angle, and failed on the push side of the door because of the small space between the knob and the door jam.

Door 14 was a door with a knob that was 1.75 inches in diameter, had a conical shape, needed 21° and 1.75 lb-in to unlatch, and required 0.8 lb-force to push open. The gripper successfully unlatched the door knob for eight of the ten trials. The two failures occurred on the pull side of the door where the gripper was unable to twist the knob far enough to unlatch. DORA's success with this sample is because of the low rotational angle, low torque, low push force on the door, and small diameter of the door knob.

Door 15 was a door with a knob that was 2.25 inches in diameter, had an oval shape, needed 30° and 4.5 lb-in to unlatch, and required 0.2 lb-force to push open. The gripper either did not twist the knob at all (two trials), did not twist the knob far enough (two trials), or twisted itself off the knob (one trial) for the five trials on the push side of the door. The gripper failed to twist the knob far enough for all five trials on the pull side of the door because the high torque needed to unlatch.

Table 5: Test Results for Doors 11-15 (knobs)

				a	b	c	d	e	f
TRIAL_ID	DOOR_ID	Trial_Number	Side	Success	Twists_small_angle	No_twist	Finger_stuck_in_door_jam	Pulls_off_knob	Twists_itself_off_knob
101	11	1	pull			x			
102	11	2	pull			x			
103	11	3	pull			x			
104	11	4	pull			x			
105	11	5	pull			x			
106	11	1	push			x			
107	11	2	push			x			
108	11	3	push			x			
109	11	4	push			x			
110	11	5	push			x			
111	12	1	pull			x		x	
112	12	2	pull			x		x	
113	12	3	pull			x		x	
114	12	4	pull			x		x	
115	12	5	pull			x		x	
116	12	1	push			x			
117	12	2	push			x			
118	12	3	push			x			
119	12	4	push			x			
120	12	5	push			x			
121	13	1	pull			x		x	
122	13	2	pull			x		x	
123	13	3	pull		x			x	
124	13	4	pull			x		x	
125	13	5	pull		x			x	
126	13	1	push			x	x		
127	13	2	push			x	x		
128	13	3	push			x	x		
129	13	4	push			x	x		
130	13	5	push			x	x		
131	14	1	pull	x					
132	14	2	pull	x					
133	14	3	pull	x					
134	14	4	pull		x			x	
135	14	5	pull		x			x	
136	14	1	push	x					
137	14	2	push	x					
138	14	3	push	x					
139	14	4	push	x					
140	14	5	push	x					x
141	15	1	pull		x			x	
142	15	2	pull						
143	15	3	pull		x			x	
144	15	4	pull			x		x	
145	15	5	pull			x		x	
146	15	1	push		x				
147	15	2	push		x				
148	15	3	push		x				
149	15	4	push		x				
150	15	5	push		x				

5.4 PERFORMANCE DISCUSSION

DORA successfully and verifiably unlatched and opened two out of the fifteen doors. The two doors that were unlatched were comparable such that they needed rotation angles below 30° (the other 30° door had a high twisting torque), the doors were easy to push open using a 0.8 lb-force (the other doors below 0.8 lb-force had a high twisting torque), and the two lowest torque requirements, 2.13 lb-in and 1.75 lb-in, of the ten knobbed doors (Door 8 with a 2.25 lb-in torque failed because the heavy door could not be pulled from one side and the finger stuck in the door jam on the push side). Coincidentally, the two successful samples, the doors with the lowest combination of unlatching torques, push forces, and twisting angles, were the doors used for incremental design verification during the design process because they are located in the lab where DORA was developed. Figures 67, 68, 69, and 70 show the success and failure rate of the doors according to its torque and rotation characteristics.

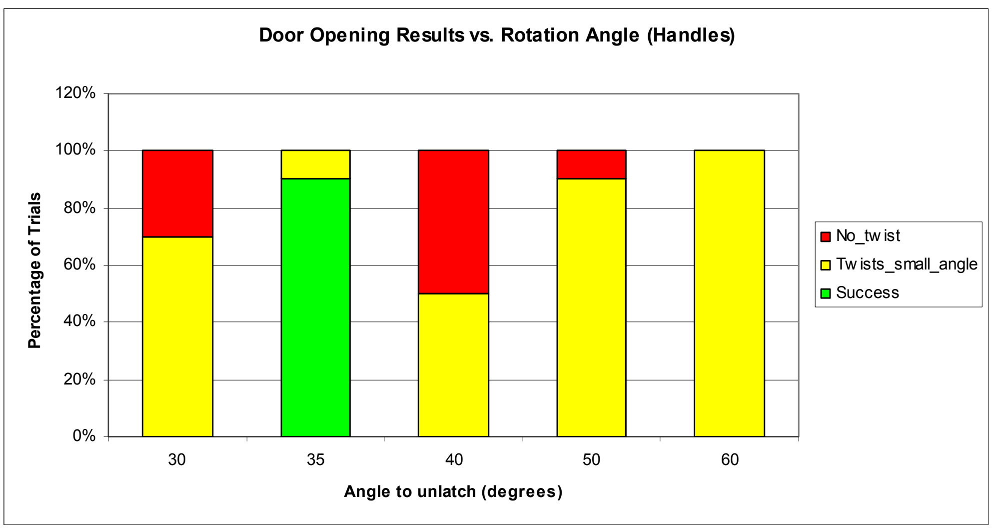


Figure 67. Success and failure mode for handled doors according to its unlatching angle.

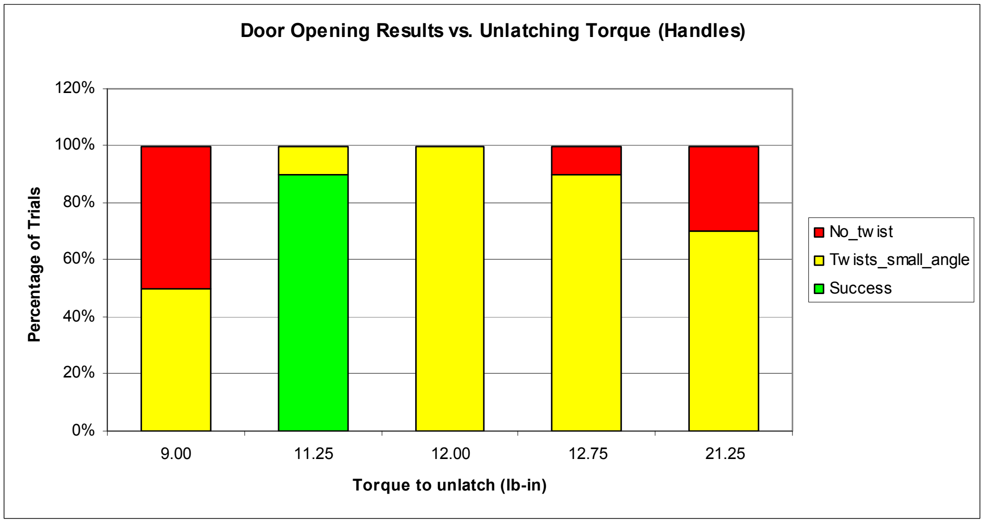


Figure 68. Success and failure mode for handled doors according to its unlatching torque.

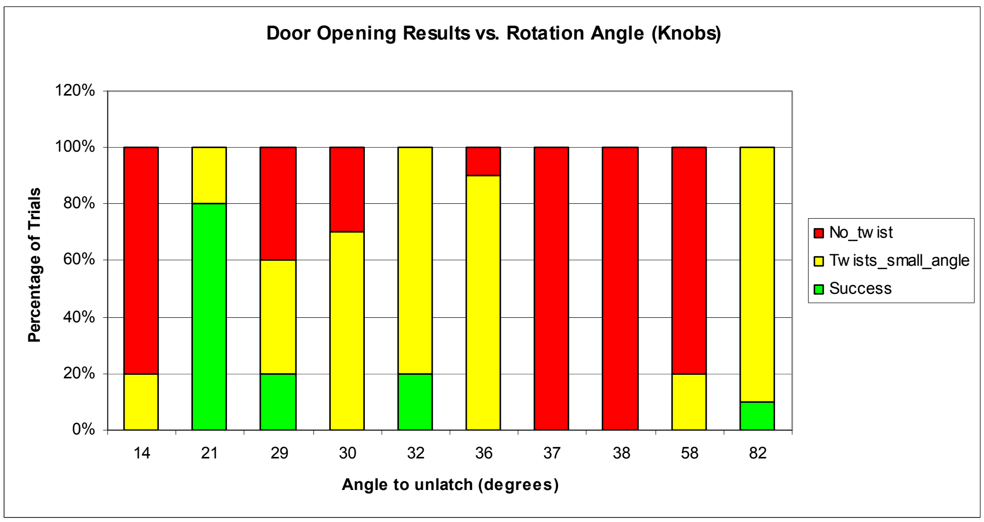


Figure 69. Success and failure mode for knobbed doors according to its unlatching angle.

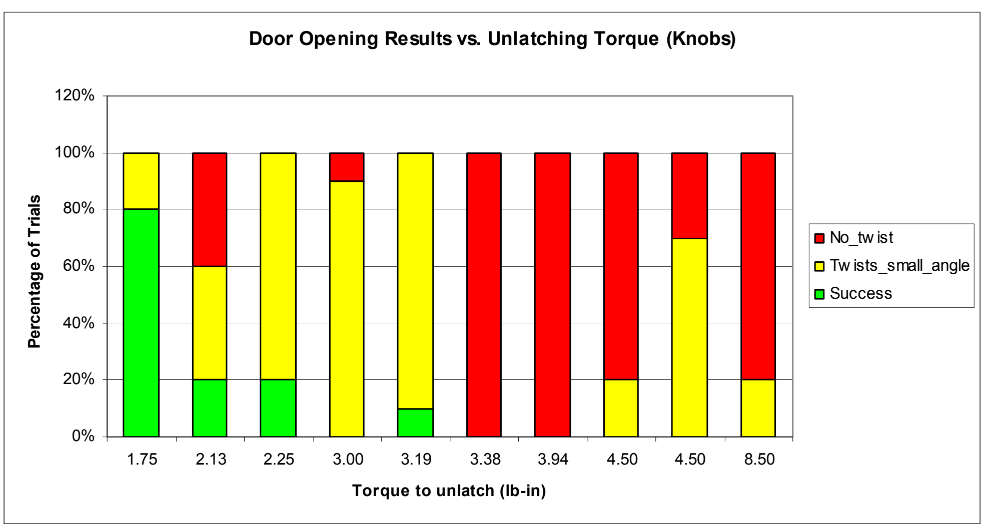


Figure 70. Success and failure mode for knobbed doors according to its unlatching torque.

Generally speaking, handled doors could not be pushed or pulled open because the gripper could not hold the twisted handle for a long enough time to unlatch it from its door jam. When DORA pushed the door open, the universal joint allowed the gripper to move to the side, releasing the handle. DORA could not pull a handled door open because the gripper could not clamp around it tightly enough. Most knobbed doors could not be unlatched from the push side because the fingers were too wide to fit between the door knob and the door jam. Knobbed doors could not often be pulled open because the flexible fingers and finger-tip nubs could not tightly clamp onto the knob so they easily slipped off the knob when DORA pulled on the door backwards.

Many of the doors in the test scenario gave insights into issues with DORA's current design because the data has produced noticeable trends. Fingers only stuck between the door knob and the door jam when the space between was less than 1.44 inches (the fingers are about 1.5 inches wide) as shown in Figure 71. The finger did not catch in the gap of 1.5 inches on Door 14 because the widest part of the door knob was off the door plane by 2 inches whereas the depth of the door jam was only 1 inch.

In addition, the gripper more frequently twisted itself off the door knob or handle when the unlatching torque was higher than 8.5 lb-in. The gripper twisted itself off the door knob or handle three times at torques lower than 8.5 lb-in (nine doors, all knobs) and twisted itself 23 times at torques 8.5 lb-in and higher (six doors; five handles and one knob) as shown in Figure 72. The gripper likely twisted off the higher torque door handles because the spring-loaded universal joint was not tensioned strongly enough to counteract the force generated from the gripper finger downward on the handle. The universal joint allowed the whole gripper to climb up on the handle and twist itself off.

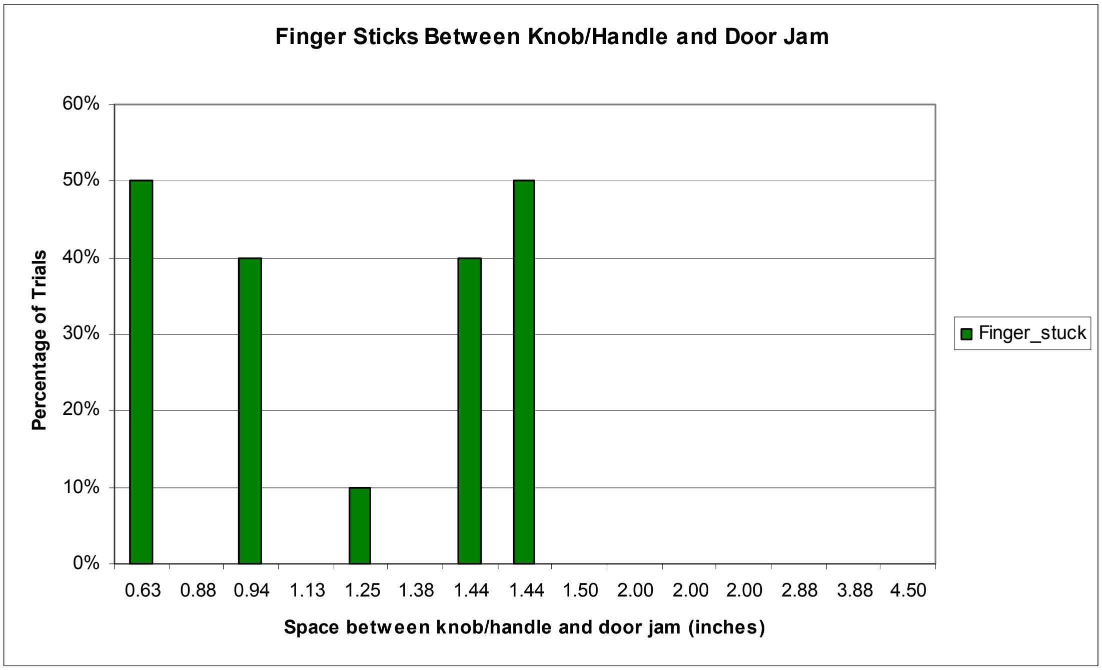


Figure 71. Percentage of trials the finger was jammed according to the space available.

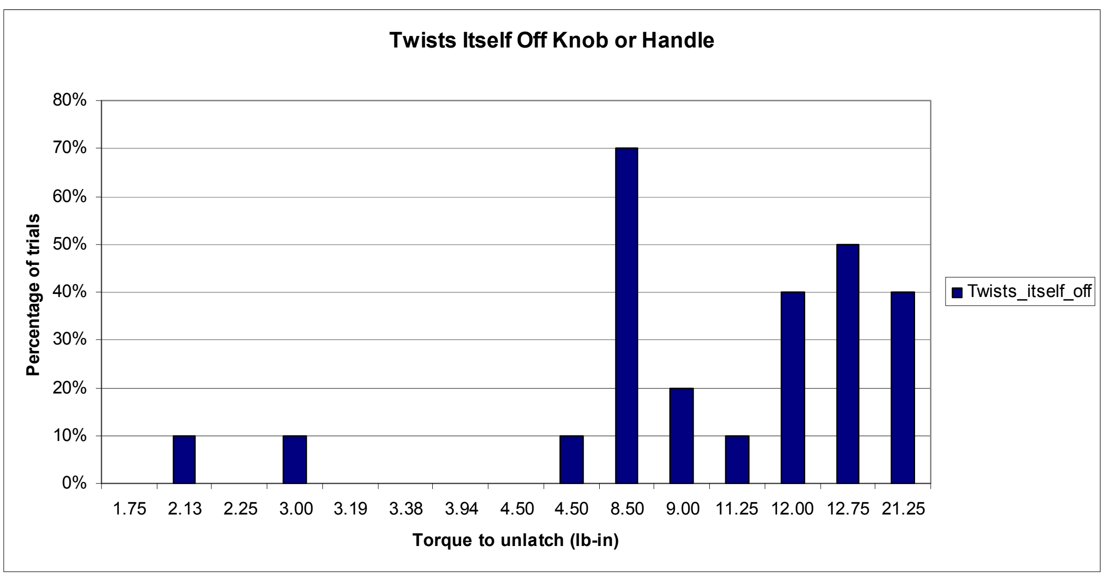


Figure 72. Percentage of trials when the gripper twisted itself off the knob/handle according to unlatching torque.

It is questionable whether or not the door knob geometries (shape, diameter, and distance from the door plane) have an effect on DORA's performance. The failures are more likely attributed to the door characteristics such as rotation angle, holding torque, and force to pull the door open. An earlier understanding of the angles and torques needed to open the doors around campus may have resulted in significant changes earlier for the design phase. However, significant design changes in the gripper design would not have been discovered if not for testing the current gripper prototype on the robot arm, which was not available earlier in the time line of the project.

As a clarification, this test did not demonstrate DORA's capabilities on a door knob or handle located on the left side of the door where the robot arm needs to cross in front of the wheelchair to manipulate it. Also, it did not test the universal joint's capabilities of traversing side-to-side angles, only up-down angles, because the robot arm was placed directly in front of the door knob or handle to fairly test the gripper's performance while being delivered by a spring loaded "wrist" joint for passive up-down motions. As mentioned in Section 4.4, the universal joint needed to be externally manipulated to traverse large side-to-side angles and DORA's performance could not be quantified in a test that required external manipulation for some of its components. However, as a precursor to this test, the gripper did manage to unlatch Door 14 while cantilevered by the robot arm and crossing in front of the wheelchair to the left side of the door.

5.5 FAILURE ANALYSIS

A failure analysis was conducted to better examine the mechanical reasons why the gripper failed to unlatch a high percentage of doors. This failure analysis allows for a better focus for significant design changes and future work. The fault tree analysis in Figure 73 shows how the failures trend under three categories: issues with clamping the knob or handle (lead screw and linkage), issues with twisting the knob or handle (planetary gear box or fingers), or not enough torque produced from the motor.

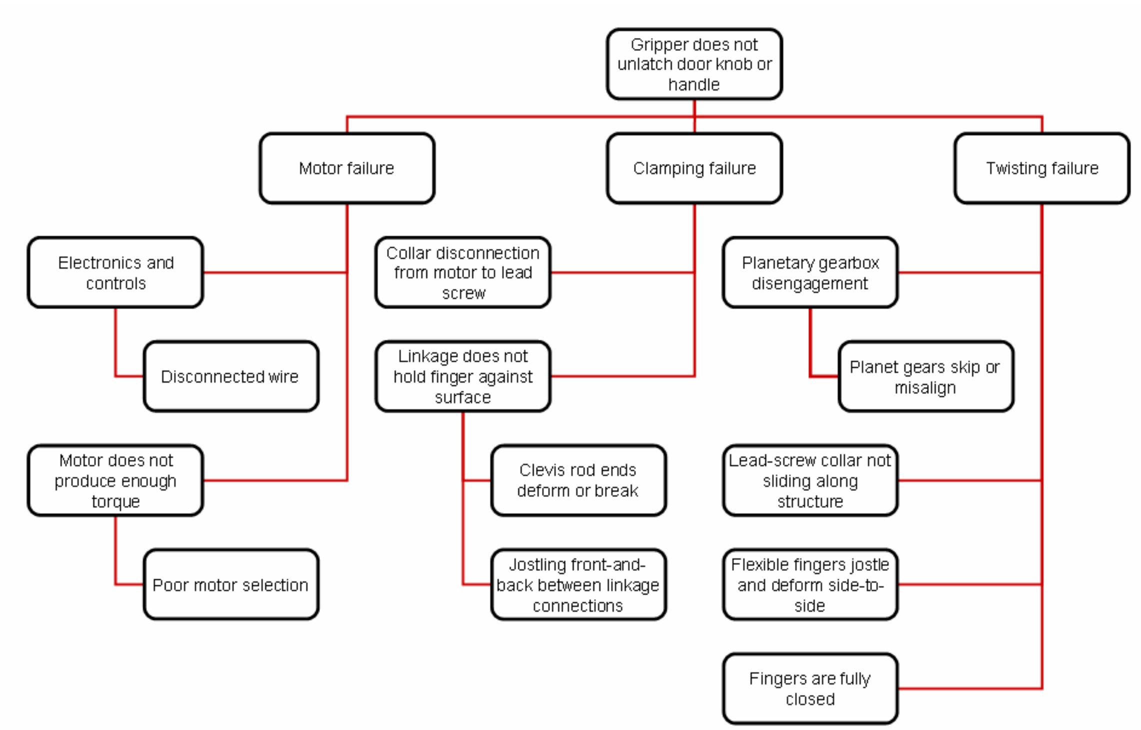


Figure 73. Fault tree analysis of gripper failures.

The biggest gripper design issue was its inability to continue to turn after the fingers have fully closed, which is why the gripper worked only on door knobs that required a small angle for unlatching. The flexible rubber fingers were supposed to remedy this issue, but the design of flexible fingers is difficult considering the requirements that the fingers must flex front-to-back enough to allow the gripper to turn, they must not flex side-to-side at all to allow for the constraint of a door handle, and they must apply enough of a compressive force and/or finger tips need to constrain a door knob or handle when the robot pulls on a door. There is no guarantee that a flexible gripper finger design that meets all of these criteria would be small enough to fit between the widest edge of a door knob and a door jam.

The finger linkages were tightened and refurbished prior to the test; however, the jostling between the linkages increased as the tests were performed. Coincidentally, the two successful doors (Door 6 and Door 14) were unlatched early in the testing process. Video of the trials confirm that the finger linkages were pushed side-to-side when the finger stuck between a door knob and the jam (see Figure 74a). The compressive forces on the linkages were so great that the clevis rod ends pulled off of the threads of the screws holding them into place allowing them to move (see Figure 74b). Furthermore, the fingers were seen to compress the door knob, but the rubber material itself twisted along with the gripper at their foundation while the tips remained static on the door knob.

(a)  (b) 

Figure 74. The clevis rod ends (a) allowing the whole finger linkage to twist side-to-side and (b) pulling out of the plastic hub.

A combination of issues with the universal joint and the gripper allowed for failures involving the twisting off of the gripper around the door knob or handle. It is questionable whether or not the issue remains present if the gaps between the gripper fingers are small enough to not allow the door knob or handle to pass through them. Likewise, the gaps need to be small in order for the universal joint to be constrained around a door knob or handle and passively adjusted by compressing the robot arm into the plane of the door. The side-to-side motion of the universal joint was not formally tested so it is not known if the side-to-side traversal of the gripper from the universal joint would add more issues with the design.

The testing did not identify specific issues regarding the cylindrical joint, the rotational joint, and the sliding link portions of the robot arm that may have contributed to the failures. All of the failures are caused by the universal joint and the gripper. The robot arm is capable of delivering the gripper to the door knob or handle at multiple heights within a four inch range. It is possible that the weak cylindrical joint motor further allowed the universal joint to traverse and twist off a door knob or handle because, as the gripper compresses into the plane of the door, the cylindrical joint may have broken away when side-to-side forces were introduced.

In summary, the design attributes most responsible for the high number of failures include:

- The gripper’s inability to continue to twist once the fingers are fully constrained.
- The large spaces between the gripper fingers which allow the door knob handle to pass through them.
- The large diameter/width of each individual gripper finger.
- The universal joint’s inability to constrain its motion when the gripper is manipulating the high torque of a door knob or handle.

A solution to these design issues may be the separation of the clamping action and the twisting action without the use of a second motor. This would allow the fingers to be stiff, solid, and smaller to allow for more design options because the lead screw and the planetary gear box motions would not be dependent on each other. Also, this separation would allow for smaller gaps between the fingers, a smaller open cone diameter at the finger tips, or possibly more fingers so a door knob or handle would not be capable of passing through the gripper's collet-cone. All other design issues could be remedied with better manufacturing, a better understanding of the actual gearbox efficiencies, and the inclusion of an iterative test plan for each sub-assembly.

6 DISCUSSION AND FUTURE WORK

DORA is currently functional but there are several areas for improvement. The failure analysis outlined in Section 5.5 suggests several areas for gripper improvements such as better motor selection, separating the clamping and twisting actions without adding a second motor, making the fingers a narrower shape, arranging the fingers so a door knob or handle could not pass through them, and improving the overall fabrication of the finger linkage assembles. In terms of improving the gripper concept design, a slip clutch could be added between the sun gear and the lead screw so the gripper can continue to turn when the maximum clamping force around the door knob or handle has been encountered (Figure 75). The gripper motor would directly connect to the sun gear but a slip clutch would disengage when the maximum torque is achieved within the lead screw when the collar can no longer turn, allowing the sun gear to continue to rotate the ring gear. This design also allows the gripper fingers to be somewhat stiff so they may compress and hold the door knob better, have a smaller shape, and be better arranged so the door knob or handle cannot pass through its gaps.

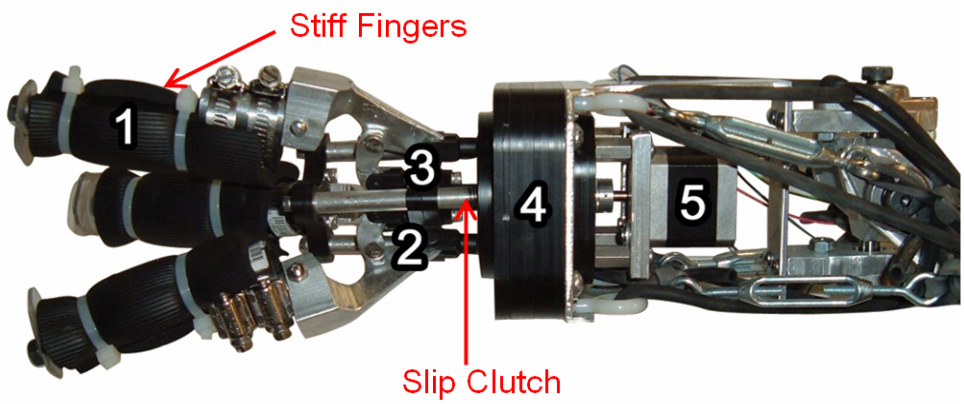


Figure 75. Gripper design improvements.

The universal joint supplied a number of performance issues affecting both the gripper and robot arm. First, the universal joint was not fabricated correctly; the intent was to spring bias the universal joint well enough so the gripper holds in-line with the sliding link. However, the gripper was too heavy for the spring biasing to work. In addition, it is difficult to spring load a “wrist” joint when the gripper and the robot arm move between horizontal and vertical positions because the gripper needs to be tightly tensioned backwards. Instead, a hard stop was placed so the gripper always rests at an angle somewhat parallel with the floor. The conceptual idea of using a universal joint as a spring-loaded “wrist” is one of the concepts that were tested in this thesis (Research Question 3: How can the compliant gripper and the robot arm be joined to successfully unlatch a door*?*). As such, the universal joint demonstrated in the testing that it was capable of traversing the gripper small angles up and down for matching the gripper fingers with the plane of the door without external manipulation. However, the universal joint allowed for the gripper to twist off the door knob or handle when the manipulation torque was high. The concept of using a universal joint, or any kind of spring loaded “wrist,” should be revisited when the gripper design improvements are made and the gripper is lightened. Also, any future universal joint designs could be made to traverse larger side-to-side angles to allow for a larger position space of the robot arm.

The robot arm generally worked well, but it could be further lightened to allow for a variety of wheelchair mount design options and better performance from the cylindrical joint. To achieve this, DORA could use lighter drawer slides in its sliding link and all of the aluminum parts could be substituted with plastic. Also, the cylindrical joint was the only joint that was back drivable and required a holding torque from the motor. The next design should include a not back drivable cylindrical joint so the robot arm can be mounted at any angle relative to the floor, the cylindrical joint could better compress the gripper into the plane of a door to hold the universal joint at its necessary side-to-side angles, and allow for a longer wheelchair battery life because the motor power could be shut off when not in use.

The wheelchair mount needs to be revisited because there is currently no standard method of mounting hardware to a power wheelchair and all wheelchairs have different structures to interface with. Also, the wheelchair mount twisted and bent when the robot arm swung outwards. A lighter robot arm and better material selection for the wheelchair mount would allow for more stability. Furthermore, a lighter robot arm allows for more wheelchair mount design options because the mount would not need to handle high loads.

A better assessment of the requirements is needed if the device is refurbished or rebuilt. Actual door knob and handle size, torque, force, and twist characteristics within the facilities of interest should be better characterized prior to re-designing the gripper. These ranges are especially needed because these door characteristics were poorly defined early in the DORA design phase, which is why only two out of the fifteen doors worked in the test. The current gripper could be used to test new finger designs and to quantify the finger's pull and push forces needed to clamp around the door knobs and handles of interest. The linkage assemblies and clevis rod ends (if used again) should be cycle tested to discover any failures due to fatigue. The actual motor outputs and gear efficiencies should be measured so a proper motor, within the size limitations of the current design, can be selected and integrated. This exercise may result in the selection of smaller motors and more reliable components, which would help lower the overall cost.

7 CONCLUSIONS

This thesis outlines the decision making process behind a new design for a robotic gripper and a simple wheelchair-mounted robotic arm. DORA's purpose was to improve upon the cost-benefit ratio of wheelchair-mounted robotic arms by being designed for a specific task. The gripper concept improves upon a standard robotic gripper's ability to open a door because it is underactuated and compliant. The gripper on DORA is a continuation of the Tufts gripper design because, although the two grippers have similar requirements for underactuation and compliance, DORA's gripper is also mounted to a robot arm, actuated with a motor, and spins in both clockwise and counter clockwise directions.

DORA's gripper demonstrated its capability to unlatch door knobs in a clockwise direction, using a single motor, while being mounted to a robot arm. It was able to unlatch two door knobs that had a low twisting torque and rotation angle. Door handles were a challenge because of the high unlatching torque they require and the universal joint often let the gripper twist itself off during actuation.

DORA, when mounted to the power wheelchair, is a 7+2 DoF system using four motors plus the wheelchair base. The robot arm portion of DORA is 5 DoF but it uses only three motors as 3 DoF. The other 2 DoF in the robot arm are achieved from movement in the spring-loaded universal joint that connects the robot arm with the gripper. A further 2 DoF are achieved by the opening/closing and twisting action of the gripper equaling a total of 7 DoF using only four motors. Finally, the +2 DoF are achieved from the movement of the power wheelchair motors.

Further testing and iterative design will result in better performance from the gripper and a more optimized motor-joint design will reduce the costs of motors and internal components. DORA's materials cost is currently $1800 (Appendix 1), but the price of components and motors drop when they are ordered in larger volumes. Nevertheless, the mechanical concepts integrated into this proof-of-concept prototype remain a viable solution to help people with limited upper body mobility achieve further independence. The further investigation and implementation of these design concepts may enable individuals who use power wheelchairs the ability to move between rooms, without the help from a care giver, for a lower cost than the general-purpose higher degree of freedom WRMA's currently on the market.

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9 APPENDIX

9.1 PARTS LIST (APPENDIX 1)

	Total Cost	Part Number	Description	Class	Distributor
TOTAL	$1,773.74				
hardware	$3.81	91259A544	Alloy Steel Shoulder Screw 1/4" Shoulder Dia, 1-1/4" L Shoulder, 10-24 Thread	arm	mcmaster
hardware	$6.96	92865A560	Grade 5 Zinc-Plated Steel Hex Head Cap Screw 1/4"-20 Thread, 4-1/2" Long, Fully Threaded, Packs of 10	arm	mcmaster
hardware	$3.45	90272A197	Zinc-Pltd Stl Pan Head Phillips Machine Screw 8-32 Thread, 3/4" Length, Packs of 100	arm	mcmaster
hardware	$5.68	90273A245	Zinc-Plated Stl Flat Head Phil Machine Screw 10-24 Thread, 3/4" Length, Packs of 100	arm	mcmaster
hardware	$4.29	90273A197	Zinc-Plated Stl Flat Head Phil Machine Screw 8-32 Thread, 3/4" Length, Packs of 100	arm	mcmaster
hardware	$11.68	3014T45	Steel Eyebolt with Shoulder for Lifting 1/4"-20 Thread, 500# Wll, 1" Thread Length	arm	mcmaster
hardware	$2.53	90272A192	Zinc-Pltd Stl Pan Head Phillips Machine Screw 8-32 Thread, 3/8" Length, Packs of 100	arm	mcmaster
hardware	$1.75	90480A195	Zinc-Plated Steel Machine Screw Hex Nut 10-32 Thread Size, 3/8" Width, 1/8" Height	arm	mcmaster
hardware	$2.33	92005A118	Metric Pan Head Phillips Machine Screw Zinc-Plated Steel, M3 Size, 8mm Length, .5mm Pitch, Packs of 100	arm	mcmaster
hardware	$7.50	5234K963	Super Soft Latex Rubber Tubing 5/32" ID, 1/4" OD, 3/64" Wall, Opaque Black (Same as 5234K96)	arm	mcmaster
hardware	$3.50	90273A194	ZINC-PLATED STL FLAT HEAD PHIL MACHINE SCREW, 8-32 THREAD, 1/2" LENGTH	arm	mcmaster
hardware	$5.12	93075A194	ZINC-PLATED STEEL HEX HEAD MACHINE SCREW, 8-32 THREAD, 1/2" LENGTH	arm	mcmaster
hardware	$4.87	95263A158	METRIC CLASS 12.9 SOCKET HEAD CAP SCREW, ZNC-COATED ALLOY STL,M3 THRD,16MM L, .5MM PITCH	arm	mcmaster
hardware	$12.43	98017A215	18-8 STAINLESS STEEL AN 960 FLAT WASHER, 5/8"SZ,NO. C1016, .640"ID, 1.188"OD,.059"-.067"THK	arm	mcmaster
hardware	$3.54	90272A827	ZINC-PLTD STL PAN HEAD PHILLIPS MACHINE SCREW, 10-32 THREAD, 3/8" LENGTH	gripper	mcmaster
hardware	$6.25	92196A192	18-8 STAINLESS STEEL SOCKET HEAD CAP SCREW, 8-32 THREAD, 3/8" LENGTH	gripper	mcmaster
hardware	$7.16	92196A194	18-8 STAINLESS STEEL SOCKET HEAD CAP SCREW, 8-32 THREAD, 1/2" LENGTH	gripper	mcmaster
hardware	$5.60	92210A105	18-8 STAINLESS STEEL FLAT HEAD SCKT CAP SCREW, 4-40 THREAD, 1/4" LENGTH	gripper	mcmaster
hardware	$5.55	92735A120	18-8 SS GROOVED CLEVIS PIN W/RETAINING RING, 3/16" DIAMETER, 3/4" LENGTH	gripper	mcmaster
HARDWARE	$104.00				
material	$71.41	8739K64	White Delrin Rectangular Bar 1-1/4" Thick X 6" Width	arm	mcmaster
material	$6.76	6023K121	Multipurpose Anodized Aluminum (Alloy 6061) 1/4" Thick X 1/2" Width, 1' Length (Same as 6023K12)	arm	mcmaster
material	$5.44	8497K213	Acetal Copolymer Rod 1/2" Diameter, Black, Lengths of 4 Ft. (Same as 8497K21)	arm	mcmaster
material	$15.28	88935K533	Architectural Aluminum (Alloy 6063) Rect Tube, 3/4" X 1-1/2", 1/8" Wall Thk, 3' L (Same as 88935K53)	arm	mcmaster
material	$28.49	88935K683	Architectural Aluminum (Alloy 6063) Rect Tube, 2" X 3", 1/8" Wall Thk, 3' Length (Same as 88935K101)	arm	mcmaster
material	$31.26	8662K35	Black Delrin Rectangular Bar 3/8" Thick, 3" Wide	arm	mcmaster
material	$13.98	8982K154	Multipurpose Aluminum (Alloy 6061) 90 Deg Angle, 3/16" Thick, 1" X 1" Legs, 4' Length (Same as 8982K15)	arm	mcmaster
material	$18.27	8662K53	Black Delrin Rectangular Bar 3/4" Thick, 2" Wide	arm	mcmaster
material	$10.86	8575K1	Black Delrin Sheet 1/2" Thick, 6" X 6"	arm	mcmaster
material	$6.79	8662K16	BLACK DELRIN RECTANGULAR BAR, 1/8" THICK, 4" WIDE	gripper	mcmaster
material	$12.66	8662K26	BLACK DELRIN RECTANGULAR BAR, 1/4" THICK, 4" WIDE, 1' LENGTH	gripper	mcmaster

material	$19.85	8662K36	BLACK DELRIN RECTANGULAR BAR, 3/8" THICK, 4" WIDE, 1' LENGTH	gripper	mcmaster
material	$22.15	8662K46	BLACK DELRIN RECTANGULAR BAR, 1/2" THICK, 4" WIDE, 1' LONG	gripper	mcmaster
material	$13.57	9986K11	BLACK DELRIN ROD, 3" DIAMETER, 1/2" LENGTH	gripper	mcmaster
material	$14.90	9986K21	BLACK DELRIN ROD, 4" DIAMETER, 1/2" LENGTH	gripper	mcmaster
MATERIALS	$291.67				
part	$16.90	11435A12	Full-Extension Lever Release Drawer Slide 12" L, 12" L Travel, 71 lb/Pr Load Rating	arm	mcmaster
part	$7.89	6655K17	Steel Ball Thrust Bearing Carbon Steel, for 1/2" Shaft Diameter, 15/16" OD	arm	mcmaster
part	$35.48	5912K42	Aluminum Mounted Bronze Sleeve Bearing Flange Mounted, for 3/8" Shaft Dia, 2-1/4" L Base	arm	mcmaster
part	$3.06	91259A622	Alloy Steel Shoulder Screw 3/8" Shoulder Dia, 3/4" L Shoulder, 5/16"-18 Thread	arm	mcmaster
part	$3.08	91259A624	Alloy Steel Shoulder Screw 3/8" Shoulder Dia, 1" L Shoulder, 5/16"-18 Thread	arm	mcmaster
part	$75.52	90268A009	18-8 Stainless Steel Coupling Nut 8-32 Thread Size, 5/8" Length, 3/8" Width	arm	mcmaster
part	$8.05	5905K41	Steel Needle-Roller Bearing Single Sealed for 1/4" Shaft Dia, 7/16" OD, 3/8" W	arm	mcmaster
part	$12.48	1497K107	FULLY KEYED 1045 STEEL DRIVE SHAFT, 5/8" OD, 3/16" KEYWAY WIDTH, 6" LENGTH	arm	mcmaster
part	$4.36	2380K13	ZINC-PLATED STEEL TWO-PIECE CLAMP-ON COLLAR, 1/4" BORE, 5/8" OUTSIDE DIAMETER, 9/32" WIDTH	arm	mcmaster
part	$11.74	2780T24	HIGH-LOAD STEEL BALL BEARING, OPEN, FOR SHAFT DIA 5/8" X 1-3/4" OD X 1/2" WIDTH	arm	mcmaster
part	$60.14	57545K517	14-1/2 DEG PRESSURE ANGLE WORM GEAR, CAST IRON, 12 PITCH, 40 TEETH, 3.33" PITCH DIA	arm	mcmaster
part	$22.37	57545K527	STL WORM,12 PITCH,W/ 1/8"X 1/16" KWY FOR, 14-1/2 DEG PRESSURE ANGLE WORM GEAR	arm	mcmaster
part	$7.39	57785K16	UHMW BEARING, SLEEVE, FOR 5/8" SHAFT DIA, 3/4" OD, 3/4" LENGTH	arm	mcmaster
part	$4.36	5905K23	STEEL NEEDLE-ROLLER BEARING, OPEN FOR 1/2" SHAFT DIAMETER, 11/16" OD, 1/2"WIDTH	arm	mcmaster
part	$15.38	5905K41	STEEL NEEDLE-ROLLER BEARING, SINGLE SEALED FOR 1/4" SHAFT DIA, 7/16" OD, 3/8"W	arm	mcmaster
part	$31.82	60355K24	STEEL BALL BEARING--ABEC-1, OPEN BEARING NO.R24 FOR 1-1/2" SHAFT DIA, 2-5/8"OD	arm	mcmaster
part	$24.76	60715K28	STEEL BALL THRUST BEARING, FOR 1-3/8" SHAFT DIAMETER, 2-15/32" OD, SHIELDED	arm	mcmaster
part	$38.08	6325K67	STEEL PLAIN BORE 14-1/2 DEG SPUR GEAR, 24 PITCH, 72 TEETH, 3" PITCH DIAMETER, 1/2" BORE	arm	mcmaster
part	$13.62	6350K31	1/4"-16 SIZE, 4 TPI, STANDARD NUT FOR, ULTRA-SMOOTH THREADED RODS	arm	mcmaster
part	$10.20	6391K122	SAE 841 BRONZE SLEEVE BEARING, FOR 3/16" SHAFT DIAMETER, 1/4" OD, 1/4" LENGTH	gripper	mcmaster
part	$9.51	6412K41	STEEL ONE-PIECE SET-SCREW COUPLING, 1/2" BORE, 1-1/2" LENGTH, 1" OD, WITH KEYWAY	arm	mcmaster
part	$4.10	6655K19	STEEL BALL THRUST BEARING, CARBON STEEL, FOR 3/4" SHAFT DIAMETER, 1-1/4" OD	arm	mcmaster
part	$31.47	6867K21	STEEL FINISHED BORE 14-1/2 DEG SPUR GEAR, 24 PITCH, 21 TEETH, .875" PITCH DIA, 3/8" BORE	arm	mcmaster
part	$7.53	7398K4	FULLY KEYED 304 STAINLESS STEEL DRIVE SHAFT, 1/2" OD, 1/8" KEYWAY WIDTH, 3" LENGTH	arm	mcmaster
part	$6.32	90089A305	GRAY HARD FIBER FLAT WASHER, 1/64" THICK, 3/16" SCREW SIZE, 3/16" ID, 3/8" OD	arm	mcmaster
part	$3.50	91259A792	ALLOY STEEL SHOULDER SCREW, 5/8" SHOULDER DIA, 3/4"L SHOULDER, 1/2"-13 THREAD	arm	mcmaster
part	$2.16	92530A100	18-8 STAINLESS STEEL KEY STOCK, UNDERSIZED, 1/8" X 1/8", 12" LENGTH	arm	mcmaster
part	$57.74	9684T2	MOUNTING FLANGE ONE-PIECE SHAFT COLLARS, 5/8" BORE, 1-1/2" COLLAR OD, 13/16" OVERALL WIDTH	arm	mcmaster
part	$11.20	99374A100	TYPE 416 STAINLESS STEEL KEY STOCK, 3/16" X 3/16", 12" LENGTH	arm	mcmaster
part	$79.02	88051875	65MMX100MMX11 SINGLE ROW DEEP GROOVE BB	arm	mcmaster
part	$7.47	1520T21	NEOPRENE RUBBER SQUARE BAR, HOLLOW, 3/4" SIZE, 1/4" ID, 6" LENGTH	gripper	mcmaster
part	$19.50	2449K11	CORROSION-RESISTANT NYLON CLEVIS ROD END, 10-32 FEMALE THREAD SIZE, 0.787" LENGTH	gripper	mcmaster
part	$9.06	2639T12	PTFE SLEEVE BEARING, FOR 3/8" SHAFT DIA, 1/2" OD, 3/8" LENGTH	gripper	mcmaster
part	$20.85	5905K43	STEEL NEEDLE-ROLLER BEARING, SINGLE SEALED FOR 1/2"SHAFT DIA, 11/16"OD, 9/16"W	gripper	mcmaster
part	$13.62	6350K31	1/4"-16 ACME SIZE, 4 TPI, STANDARD NUT FOR, PRECISION MODIFIED-ACME THREADED ROD	gripper	mcmaster
part	$4.29	6383K17	STEEL BALL BEARING, PLAIN OPEN FOR 7/16" SHAFT DIA, 7/8" OD, 1/4"W	gripper	mcmaster

part	$4.87	6455K2	MAINTENANCE-FREE DELRIN BALL BEARING, SS BALLS, 1/4" SHAFT DIA, 5/8" OD, .196" WIDTH	gripper	mcmaster
part	$2.98	90281A095	BLACK-OXIDE STEEL BOTH-ENDS THREADED STUD, 1/4"-20 THREAD, 1-1/2" OVERALL LENGTH	gripper	mcmaster
part	$30.60	97042A352	18-8 STAINLESS STEEL ONE-END THREADED STUD, 3/8"-16 THREAD, 4" OVERALL LENGTH	gripper	mcmaster
part	$21.00	LC2U10B	Motor Cable (1 m)	elec	oriental motor
part	$63.10	2adn3	Coupling,4 Beam Cla	arm	Small Parts
part	$38.92	99030A700	1018 Carbon Steel Precision Acme Threaded Rod 1/4"-16 Sz, 1/4" Travel/Turn, 4 Starts, 3'L, Rh Thread	arm	mcmaster
part	$10.93	P48A26-24	SPUR GEAR PIN HUB<=3 ALUMINUM	gripper	WM Berg
part	$27.19	N48A4-144	INTERNAL SPUR GEAR> 3 ALUMINUM	gripper	WM Berg
part	$47.46	P48A26-60	SPUR GEAR PIN HUB<=3 ALUMINUM	gripper	WM Berg
PARTS	$941.07				
motor	$150.00	PK244PA	2-Phase Stepping Motor	motor	oriental motor
motor	$81.00	PK246PA	2-Phase Stepping Motor	motor	oriental motor
motor	$206.00	PK299-03AA	2-Phase Stepping Motor	motor	oriental motor
MOTORS	$437.00				

9.2 MATLAB PROGRAM FOR GRIPPER GEOMETRY (APPENDIX 2)

```
---------------------------------------------------------------------------------------
%WORK IN RADIANS
%------ INPUTS ------------
%Gripper Geometry-
Gb=2.125;                                    %INPUT: claw base offset (inch)
Gf=5.5;                                      %INPUT: claw finger length (inch)
Gto=4;                                       %INPUT: claw opening over knob (inch)
Gl=1;                                        %INPUT: linkage connection along finger
                                             from base (inch)
Fth=0.75;                                    %INPUT: Finger thickness
%Gripper Specs for Rotation-------
DegT=180;                                    %INPUT: degrees of gripper travel (deg)
TimT=2;                                      %INPUT: time for gripper travel (seconds)
%Lead Screw & Collar Specs------
TPI=4;                                       %INPUT: turns per inch for selected ACME
                                             lead screw (inch)
Dc=.375;                                     %INPUT: crest diameter of ACME lead screw
(inch)
Bdg=29;                                      %INPUT: thread angle (degrees)
m=4;                                         %INPUT: number of threads (one)
Clr=0.75;                                    %INPUT: diameter of collar, linkage
connection
%Gearbox Specs-
Pg=48;                                       %INPUT: gear pitch for all gears
N3=144;                                      %INPUT: ring gear # of teeth (based on
size in assembly)
To=15;                                       %INPUT: desired gripper turning-torque
(lb-in)
%---------- Gripper Linkage Geometry ----------------
Go=Fth+Gto;                                  %finger opening over knob with finger
                                             thickness involved
Acl=acos(((Gb/2)-(Fth/2))/Gf);               %finger angle when gripper is closed,
                                             finger=hypotenuse, base=base (rad)
AclD=180-(Acl*(180/pi))
Aop=asin(((Go-Gb)/2)/Gf);                    %finger angle when gripper is open,
                                             finger=hypotenuse, base=base, need to add
                                             90 (rad)
AopD=90-(Aop*(180/pi))
Lf=(Gl*sin(Aop))+(Gb/2)                      %link length if no collar
Ll=(Gl*sin(Aop))+(Gb/2)-(Clr/2)              %link length at open (inch)
```

```
%plot(Gl,Ll)                                 %PLOT linkage connection location with
                                             linkage length
Hlk=(Gl*cos(Aop))                            %distance/height of link at center when
                                             open (inch)
TtVa=asin((Gb/2)/Gf);                        %Tip to vertical angle when closed (rad)
aLbTs=asin(((Gf-Gl)*(sin(TtVa)))/Lf);        %Angle from link bottom to screw (rad)
ThwD=Ll*cos(aLbTs)                           %throw down along screw
Tt=ThwD*2;                                   %total travel for lead screw and collar,
excel geom (inch)
NutClear=((Gf-((Hlk-ThwD)/(cos(TtVa))))*sin(TtVa))-(Clr/2)
%---------- Lead Screw Characteristics (travel) -------------
TRA=(DegT/360)*2*pi;                         %total rotation angle for gripper (rad)
No1=(TPI*Tt)/2                               %number of revolutions for desired travel
(one direction)
No2=(TPI*Tt);                                %number of revolutions for desired travel
                                             (two directions, total throw)
Li=((2*pi)*No1)/TimT;                        %lead screw ideal velocity, if fixed
                                             collar (rad/sec)
Lv=ThwD/TimT;                                %linear velocity of collar around screw
(inch/sec)
%---------- Gearbox Calculations (velocity) ---------------
W3=((DegT/360)*2*pi)/TimT;                   %rotational velocity of gripper output
                                             (rad/sec)
W1=Li+W3;                                    %lead screw actual veloicty (rad/sec)
N1=N3*(W3/W1)                                %sun gear # of teeth (ERROR LINE when
                                             plotting!)
P1D=N1/Pg                                    %sun gear pitch diameter (inch)
P3D=N3/Pg                                    %orbit gear pitch diameter (inch)
P2D=(P3D-P1D)/2                              %planet gear pitch diameter (inch)
N2=P2D*Pg                                    %planet gear # of teeth
-------------------------------------------------------------------------------------
```

9.3 MATLAB PROGRAM FOR IKS OF ROBOT ARM (APPENDIX 3)

```
-------------------------------------------------------------------------------------
% XYZ derived from laser-pointer joystick input
D=40;                                        %INPUT measured laser distance
AngleR=45;                                   %INPUT angle offset from rotational joint
                                             DEGREES
R=AngleR*(pi/180);                           %RADIANS, rotational joystick joint
AngleC=-45;                                  %INPUT angle offset from cylindrical
                                             joint DEGREES
C=AngleC*(pi/180);                           %RADIANS, cylindrical joystick joint
yy=D*sin(R);                                 %y location of object
d2=D*cos(R);
xx=d2*sin(C);                                %x location of object
d3=sqrt((xx^2)+(yy^2));
zz=sqrt((D^2)-(d3^2));                       %z location of object
Pobject=(xx,yy,zz)
Ad=25;                                       %INPUT measured offset to arm base
AngleAr=0;                                   %INPUT measured angle offset from
                                             rotational joint to arm base DEGREES
Ar=AngleAr*(pi/180);                         %RADIANS, rotational measure joystick to
                                             arm base
AngleAc=-90;                                 %INPUT measured angle offset from
                                             cylindrical joint to arm base
Ac=AngleAc*(pi/180);                         %RADIANS, cylindrical measure joystick to
                                             arm base
Ayy=Ad*sin(Ar);                              %y location of arm base
Ad2=Ad*cos(Ar);
Axx=Ad2*sin(Ac);                             %x location of arm base
Ad3=sqrt((Axx^2)+(Ayy^2));
Azz=sqrt((Ad^2)-(Ad3^2));                    %z location of arm base
ParmBase=(Axx,Ayy,Azz)
Ky=yy-Ayy;                                   %Object location y with respect to arm
base
```

```
Kx=xx-Axx;                               %Object location x with respect to arm
base
Kz=zz-Azz;                               %Object location z with respect to arm
base
Lee=12;                                  %INPUT end effector length
Lzz=Kz-Lee;                              %Z normal to XY object plane offset by
                                         end effector
PinverseKS=(Kx,Ky,Lzz)                   %Point normal to XY object plane offset
by end effector
L1Dist=sqrt((Kx)^2+(Ky)^2+(Lzz)^2)       %Distance between two points, arm length
L1angleR=asin(Ky/L1Dist)*(180/pi)        %Angle offset from rotational joint of
                                         Arm Base DEGREES
L1angleC=atan(Kx/Lzz)*(180/pi)           %Angle offset from cylindrical joint of
                                         Arm Base DEGREES
Vx=(Kx-xx);
Vy=(Ky-yy);
Vz=(Lzz-zz);
Veffector=(Vx,Vy,Vz);                    %Vector of the end effector location
MagPinverseKS=norm(PinverseKS)           %Normalized magnitude of PinverseKS
vector
MagVeffector=norm(Veffector)             %Normalized magnitude of Veffector
DDot=dot(Veffector,PinverseKS)           %Dot Product between vectors
L2angleR=acos(DDot/(MagPinverseKS*MagVeffector))
                                         %Angle offset from sliding link arm to
                                         manipulator arm
L2angleDeg=L2angleR*(180/pi)             %Angle of end effector motor connected to
                                         sliding link
-------------------------------------------------------------------------------------
```