A Low-Cost, High-Strength, Open-Source, Rapid Prototypeable Underactuated Robot Gripper

by

Daniel Jesus Gonzalez

Submitted to the Department of Mechanical Engineering
in partial fulfillment of the requirements for the degree of

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Abstract

In this work, an underactuated robot gripper was designed to meet specifications for strength, cost, and ease of manufacturing with Open-Source distribution in mind. The specifications emerged from a need for inexpensive grippers that can be used on robots that help people brace and balance. The structure and transmission of the gripper is designed to bear 150 lbs-force of static tensile and compressive loads. Gripping forces that exceed the static actuator force output are achieved by a novel method of clamping the main drive tendon by detecting dynamic overshoot and applying a self-helping cable brake, relieving the main drive actuator. The geometry, stiffness, and behavior of the gripper was designed using mathematical models and tools developed in prior art for the optimal design of underactuated hands. Apart from the actuators and waterjet machining services, the materials for the gripper can be purchased in one McMaster-Carr order. The entire structure can be cut from a single sheet of 1/16” 2024 aluminum and requires one operation on a waterjet machine, which can be found in many machine shops or through online machining services. It is the intention of the author to release the design files as Open-Source in order to allow robot researchers, engineers, and enthusiasts to use this gripper in their own work.

Thesis Supervisor: H. Harry Asada
Title: Ford Professor of Engineering

Acknowledgments

I would like to thank Tyler Hamer for his friendship all these years (and for waterjetting with me until N:00AM), Michael Alexander ”Blue” Skuhersky for being a great friend and helping me in my last-minute search for waterjet access, Nancy Ouyang at NarwhalEdu for her help with digital servos, Charles Z. Guan for teaching me the Art of the T-Nut, Rachel Bowens-Rubin for helping me get LaTeXworking, and the wonderful community at the MIT Electronics Research Society (MITERS) for providing me knowledge, encouragement, inspiration, and for showing me how fun engineering can be. I would like to thank Professor Asada and Federico Parietti for their mentorship, advice, and support throughout this project; I have grown to love robotics research as a result. Finally I would like to thank my family, especially my mother and father, for all of their help and support throughout my life, including these tedious undergrad years. Someday my robots will cook, clean, and take care of you, I swear it!

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Chapter 1

Introduction and Background

The age of the home robot assistant is upon us, as there have been many recent pushes in robotics research towards making robots that can be useful in common human environments. Advancements in autonomous perception, navigation, and planning coupled with the rise of inexpensive and robust computers, sensors, and electronics have enabled robots to become more useful and relevant in the human world than ever before.

Modern advancements in subfields of robotics often build upon each other, leading to accelerated progress. For example, the Microsoft Kinect has provided computer vision researchers with a low-cost sensor with which to implement Simultaneous Localization and Mapping (SLAM)[7]. Perception researchers, now armed with the inexpensive Kinect and Open-Source implementations of SLAM have developed methods of identifying common objects such as books and bottles in a 3D image[11]. Manipulation researchers can plan trajectories based on these perceived objects in order to achieve optimal grasps for object interaction[17]. Task-planning researchers can execute more complicated tasks such as fetching certain items for someone[1]. In order for this kind of research integration to occur, however, universal robotics hardware and software platforms are needed.

To address the need for a common, integrated platform to be able to conduct new research, robots such as the Willow Garage PR2 (see Figure 1-1), the Unbounded Robotics UBR1, and the Rethink Robotics Baxter, among others, are being designed

Figure 1-1: The Willow Garage PR2 Robot[8]
The PR2 is a human-like robot research platform used at institutions around the world to investigate robot perception, navigation, planning, and manipulation in human environments.

with the latest vision, manipulation, and locomotion capabilities. These robots are modeled upon the versatile capabilities of a human, and are meant to function alongside people, unlike specialized industrial or field robots, which are usually only suited to a few tasks like manufacturing or exploration and are often isolated from humans for safety reasons.

To enable the integration of new and improved hardware, these common robot platforms are designed to be open to customization, particularly when it comes to vision sensors and manipulator end effectors. The ability to swap end effectors is of particular importance because different end effector designs are often suited to different tasks. But unlike the subfields of perception, planning, navigation, and the design of wheeled mobile platforms and articulated manipulator arms, which have all maintained modern, robust, and reliable "go-to standards", the robotics community has yet to adopt a standard end effector more advanced than the simple parallel gripper.

1.1 Motivation

Much work has been done to create grippers that replicate the behavior and dexterity of the human hand[10], but these designs are often expensive and complicated to make and control. The robotics community has taken a turn towards investigating achieving high functionality out of simpler hands, leading to the development of optimally-designed underactuated grippers, which have more Degrees of Freedom (DOFs) than actuators. The desired underactuated behavior is often achieved by modifying design parameters such as relative joint gearing, compliance, and geometry within each finger.

Recent research on the optimal design of underactuated robot grippers has been driven by a movement to decrease the complexity and cost of grippers while maintaining the functionality of more complicated hands. Some of the earliest research on underactuation and passive conformity in robot hands comes from the work of Shigeo Hirose [9].

Underactuated grippers are now beginning to see near-standard use in modern robotics research[3] [4] [6] [5] [16]. For example, the Boston Dynamics Atlas humanoid robot, which is being used by most of the teams in the DARPA Robotics Challenge, comes stock with the i-HY Hand [13] (See Figure 1-2) which is strong enough to manipulate objects as large as power tools and basketballs yet dexterous enough handle objects as small as keys and cards.

Using these recent developments, members of the Yale Grab Lab, under Professor Aaron Dollar, have developed excellent Open-Source designs for 3D printed underactuated hands [12], which can be easily integrated with many manipulator arms. The design of the hands, while approaching optimality in its geometry and grasp behavior, is lacking in terms of its strength, stiffness, and ease of manufacturing. For example, the Yale OpenHand Model T (see Figure 1-3) consists of 3D-printed plastic structural

Figure 1-2: The i-HY Hand[13]
The i-HY hand is the stock gripper on the Boston Dynamics Atlas humanoid robot, which is being used in the DARPA Robotics Challenge. The i-HY hand has underactuated fingers which can passively adapt to a wide variety of objects.

components which are limited in their strength and stiffness. The poured urethane joints, while making for a clean final product, require meticulous preparation prior to pouring, a vacuum chamber to remove any sealed gas, and well over 24 hours to cure.

Research being conducted at the MIT d'Arbelloff Laboratory under Professor H. Harry Asada on eliminating worker fatigue in manufacturing through the use of Supernumerary Robotic Limbs (SRLs) [2] (see Figure 1-4) and other wearable robots requires an end effector that can not only manipulate a wide variety of objects in the surrounding human environment, but that can brace the wearer against the environment and bear any loads associated with this behavior. In this case, the Yale Open Hand does not meet the strength requirements for the MIT SRL robot. The design presented in this thesis aims to provide an alternative Open-Source underactuated gripper that is capable of bearing the forces associated with bracing a person against the environment.

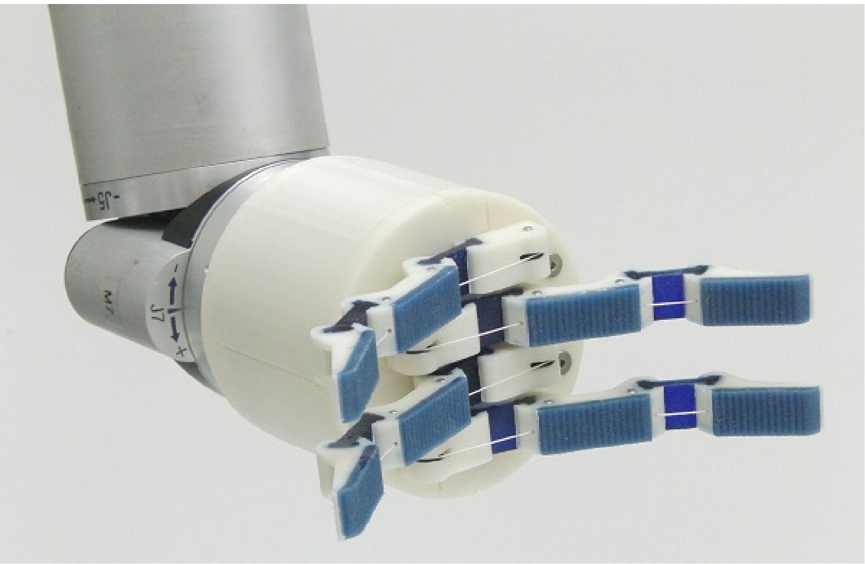


Figure 1-3: The Yale OpenHand Model T attached to a Barrett WAM Arm[12]
The Yale OpenHand Model T is an Open-Source underactuated hand with four two-link fingers driven by a single actuator. The structure is 3D printed and the flexure-based urethane joints can be poured directly into molds built into the 3D-printed fingers themselves. The Yale OpenHand Project served as inspiration for the gripper presented in this thesis.

1.2 Contributions and Overview

This thesis presents the design of an underactuated gripper (see Figure 1-5 below) whose novelty lies in its strength, cable braking mechanism, low cost, ease of manufacturing, and Open-Source availability to the greater robotics community. Specifically, the main contributions are as follows: the gripper is designed to bear a 150 lbs-force static load in tension and compression; a cable braking mechanism allows the main drive tendons to be locked during a state of dynamic force overshoot in order to achieve grasping forces higher than static motor force alone can attain; the components for the hand, including the actuators, cost less than $700.00 USD; all non-actuator components can be purchased from McMaster-Carr; the entire structure can be cut from a single sheet of aluminum on a waterjet in one operation; the whole hand can be assembled in a few hours by an unskilled machinist; the design files for making a hand will be made available as Open-Source to allow the greater robotics community to modify the design as needed and use the hand in other robotics research projects.

Figure 1-4: MIT Supernumerary Robotic Limbs Concept[2]
The Supernumerary Robotic Limbs project requires end effectors which can bear the weight of the wearer in order to brace him/her against the environment during tedious manufacturing tasks.

Chapter 2 describes the functional requirements of the gripper, the design parameters of the hand, and the mathematical models built upon prior art used to perform analysis for design. The details of the design of the geometry, structure, and transmission are then explained. Trade-offs associated with final component selection are discussed, and a final mechanical design is presented. The chapter concludes with a description the control scheme and electronics and how the gripper can integrate with a parent robot system.

Chapter 3 details the manufacture and assembly of the prototype, Chapter 4 describes the results of integrating the prototype with the MIT Supernumerary Robotic Limbs, and Chapter 5 discusses future improvements and the next steps that should

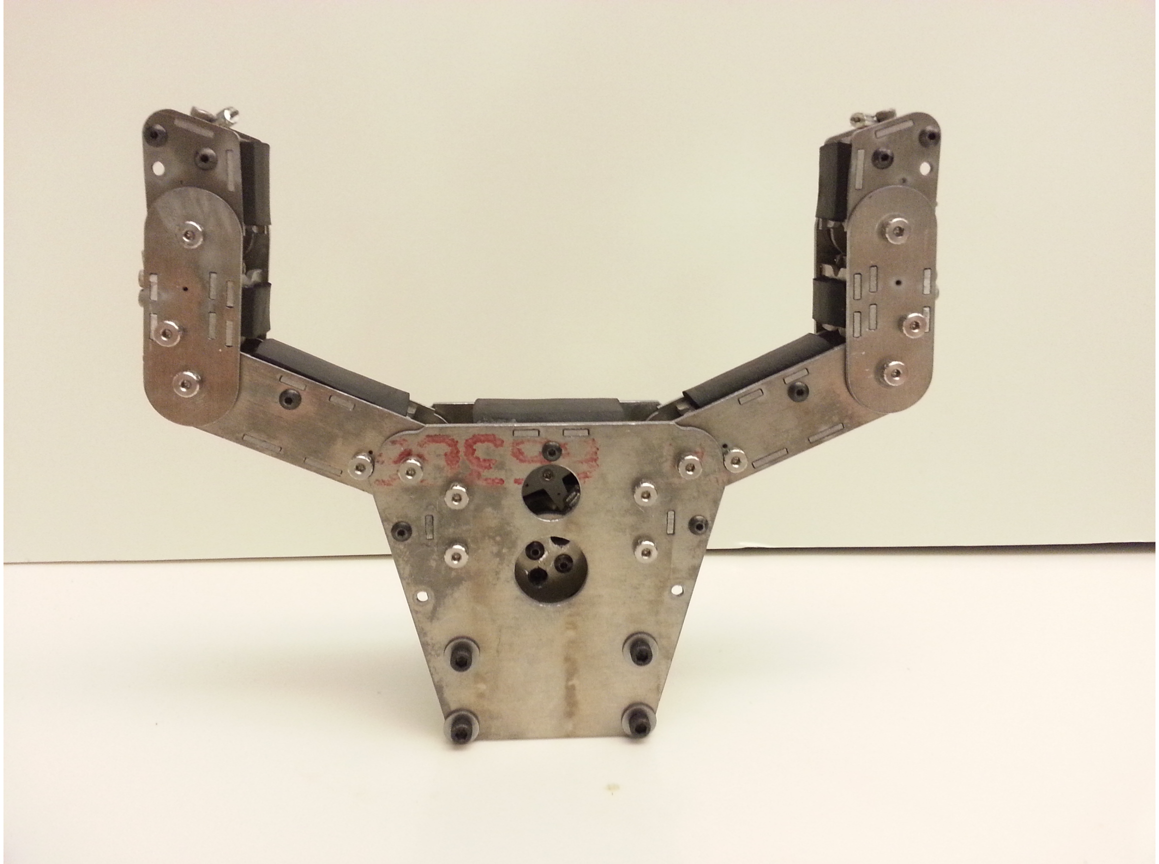


Figure 1-5: The Prototype Underactuated Gripper Designed in this Thesis

be taken to release this gripper to the Open-Source robotics community.

Chapter 2

Analysis, Optimization, and Design

2.1 Functional Requirements

The design of this underactuated robot gripper was driven by the following functional requirements:

Should Grasp a Wide Variety of Objects Designed for Human Use

In order for this gripper to be useful it should be able to successfully grasp a wide variety of objects that could exist in environments designed for humans. This will allow a robot that utilizes this gripper to complete tasks a human could. This requirement is met through the design of the hand geometry and passive complaint behavior of the underactuated fingers.

Must Grasp Objects Relavent to the MIT Supernumerary Robotic Limb project

In order for the gripper to be useful as the end effector of the MIT Supernumerary Robot Limbs (SRL) (see Section 1.1 and [2]), it must be able to grasp plates, tools, and other items relevant to manufacturing. The gripper should also be able to grasp airframe structures to brace the SRL operator/wearer against the environment while he/she performs various tasks.

Must Bear 150 lbs-force Static Load In Tension and Compression

The gripper must be able to bear some of the weight of the wearer of the MIT Supernumerary Robotic Limbs. In particular, the SRL robot is designed to brace the weight of 300 lbs against the ground, as well as carry 300 lbs while holding an overhead bar. In order to match the SRL robot's requirements, the structure and transmission of this gripper was designed to bear the load of one of the arms: 150 lbs-force in compression and 150 lbs-force while hanging from a rod.

Should Cost Less Than $700.00 USD

In order to be a cost-effective Open-Source alternative to commercial grippers, the gripper should be as inexpensive as possible. A budget of $500.00-$700.00 USD was chosen in order to make this gripper a comparable alternative to the Yale OpenHand grippers [12].

Should Require Minimal Machining Expereience to Manufacture and Assemble

In the spirit of Open-Source hardware to assist with university research, the gripper should be quick and easy for an unskilled person to manufacture and assemble. This is accomplished by designing the hand to require only one operation on the waterjet to cut the entire structure. The rest of the assembly is straightforward, with all of the pieces fitting together like a puzzle.

2.2 Geometry Parameters, Analysis, and Design

The geometry of the gripper will determine the applications for which it will be useful and the types of objects it will be able to grasp, and so it is important to consider the final application of this gripper when investigating and deciding upon the hand geometry. The design choices should optimize meeting our functional requirements, particularly the ability to grasp plates and tools on the MIT Supernumerary Robotic Limbs (SRL) and decreasing the complexity of manufacturing and assembly to allow for Open-Source distribution.

The hand morphology, namely the *number of fingers* and their *locations relative* *to each other* on the hand, must be finalized before any other design parameters are analyzed. Symmetrical and asymmetrical planar hand designs were considered: a symmetric hand with an even number of fingers could provide equal force distribution about the grasped object while an asymmetric hand morphology could incorporate a stationary finger or could stably grasp an object with two fingers while selectively triggering a function (such as a hand drill or flashlight) with a third.

Design Parameter	**Chosen Value**
Finger Locations	Symmetric
Number of Fingers	2
Number of Links per Finger	3
Total Finger Length	4.5 [inches] (114 [mm])
Link Relative Length Ratio	Inverse Golden Ratio $\frac{1}{\varphi}$
Palm Width Relative to Fingers	Inverse Golden Ratio $\frac{1}{\varphi}$
Link 1 Length	2.250 [inches]
Link 2 Length	1.391 [inches]
Link 3 Length	0.859 [inches]
Palm Width	2.781 [inches]

Table 2.1: Summary of Geometry Design Parameters and Chosen Values

A *symmetrical morphology with two fingers* was chosen in order for the hand to provide even force distribution about any grasped objects, decrease differences in stress concentrations about the gripper, and allow for more predictable behavior under load. Achieving grasps with even and symmetrical force distribution is important to achieve stable grasps of plates and other structural objects for bracing as the end effector for the MIT Supernumerary Robotic Limbs.

The next parameter to consider is the *number of links per finger*. The more links a finger has, the more it can conform to an object being grasped, leading to more frictional surface point contacts and less force required to grasp an object. Increasing the number of links leads to added complexity, however, which is undesirable in design for Open-Source.

According to work done in TU Delft by Jasper Schuurmans, fingers with 3 links perform 21% better than fingers with 2 links [16] based on a metric of the grasp wrench force required to forcibly remove the object from a stable grasp per unit joint torque. Fingers with a fourth link added only performed 8% better than their 3-linked counterparts. Based on trade-off of grasp efficiency versus mechanical complexity, *it was decided this gripper would have 3 links.*

Once the hand morphology, number of fingers, and number of links per finger has been finalized, the specific lengths and sizes of the hand components must be chosen. The *length of each finger*, the *length of each link*, and the *width of the palm* determines the average size of object that the gripper is able to grasp.

The finger length must be optimized in order to meet the requirement of being able to grasp a wide variety of human-sized objects. *A total finger length of 4.5 inches (114 mm) was chosen* based on the size limitations that emerged from packing the transmission elements and the optimal value results from prior art. This size is similar to the prototype grippers that resulted from simulation-based optimization work done by Schuurmans (100 mm)[16], Ciocarlie (118 mm) [4], and Ma (115 mm)[12], among others.

The length of each link and the width of the palm must now be chosen to allow for a wide variety of human objects to be grasped efficiently. It is interesting to note that much of the prior art on simulation-based optimization of underactuated geometry [16] [3] [6] [4] converges on φ, the Golden Ratio (~ 1.618), as the optimal ratio between finger link lengths, which is highly similar to the geometry of the human hand[14]. Given the optimal results achieved by prior work, the *Link Relative Length Ratio was decided to be* φ.

The length of an individual link in a 3-link finger is:

$$l_n = f(n) = l_f \cdot \varphi \cdot \frac{3-n}{1+\varphi+\varphi^2} \tag{2.1}$$

where n is the link number (1 is proximal, 2 is middle, 3 is distal), l_f is total length of the finger, and φ is the Golden Ratio.

The *optimal width of the palm* based on prior work was also found to be related to φ. Particularly:

$$w_{palm} = \frac{l_f}{\varphi} \tag{2.2}$$

where l_f is the total length of the finger and φ is the Golden Ratio.

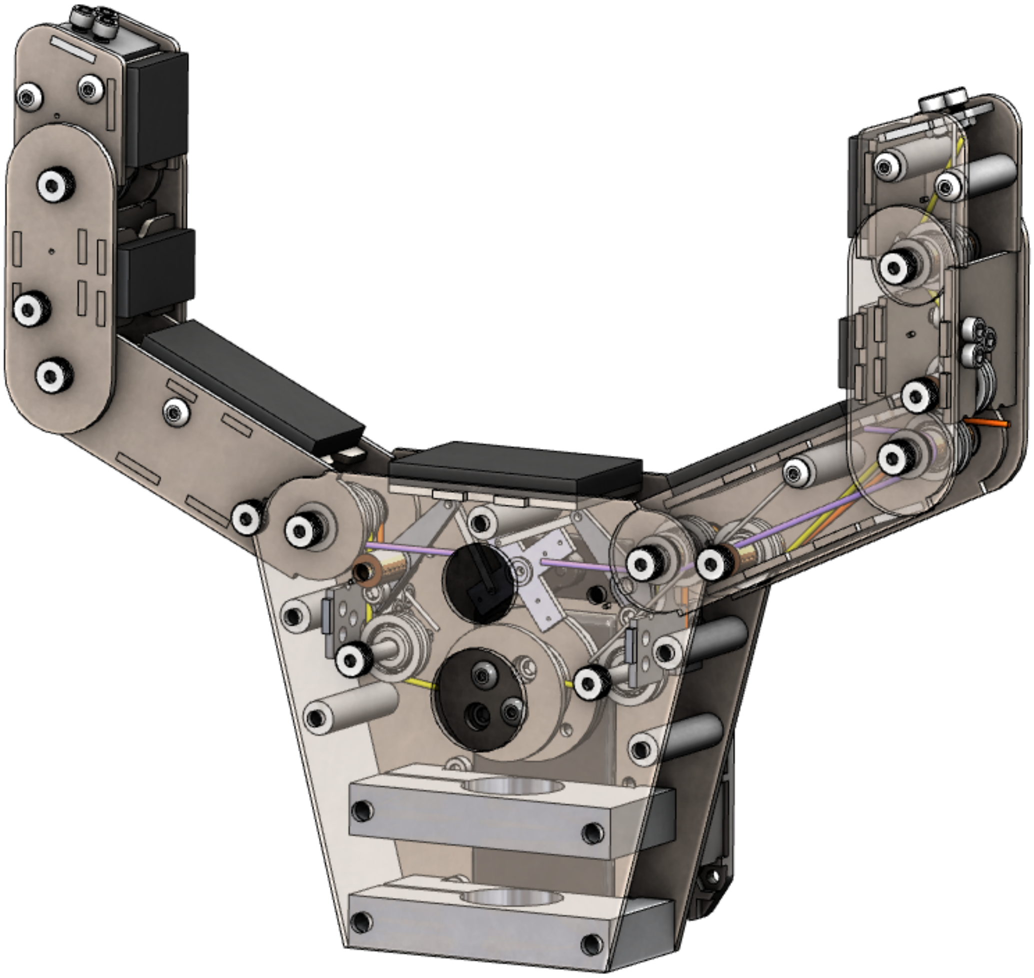


Figure 2-1: Solid Model Rendering of the Gripper

2.3 Transmission Analysis and Design

The parameters that relate to the motion and behavior of the hand while grasping must be finalized. The *rest angles* of the fingers and links determine the largest possible object the gripper can grasp, as well as provide the initial conditions for the rest of the grasp to occur. The *joint stiffnesses* and *joint torque ratios* between the links of each finger determine the passive grasp behavior achievable through the underactuation. The *size and type of drive tendon* must also be decided upon based on the expected grasp forces.

The Robotis Dynamixel MX-64 smart servo was chosen as the main drive actuator due to its high fidelity design and construction, its ability to output 6 Newton-meters when driven by 12 Volts, and the ability to receive position, velocity, and torque feedback for data logging and control applications. It is the most expensive component of the entire gripper, however, at $300.00 USD. The torque output of the MX-64 is sufficient to allow for the direct drive of a spool pulley for the Main Drive Tendon of both fingers simultaneously. In order to be able to output the highest force possible on the Main Drive Tendon while still being able to attach to the MX-64 output horn, *a spool pulley radius of 0.6875 inches was chosen.*

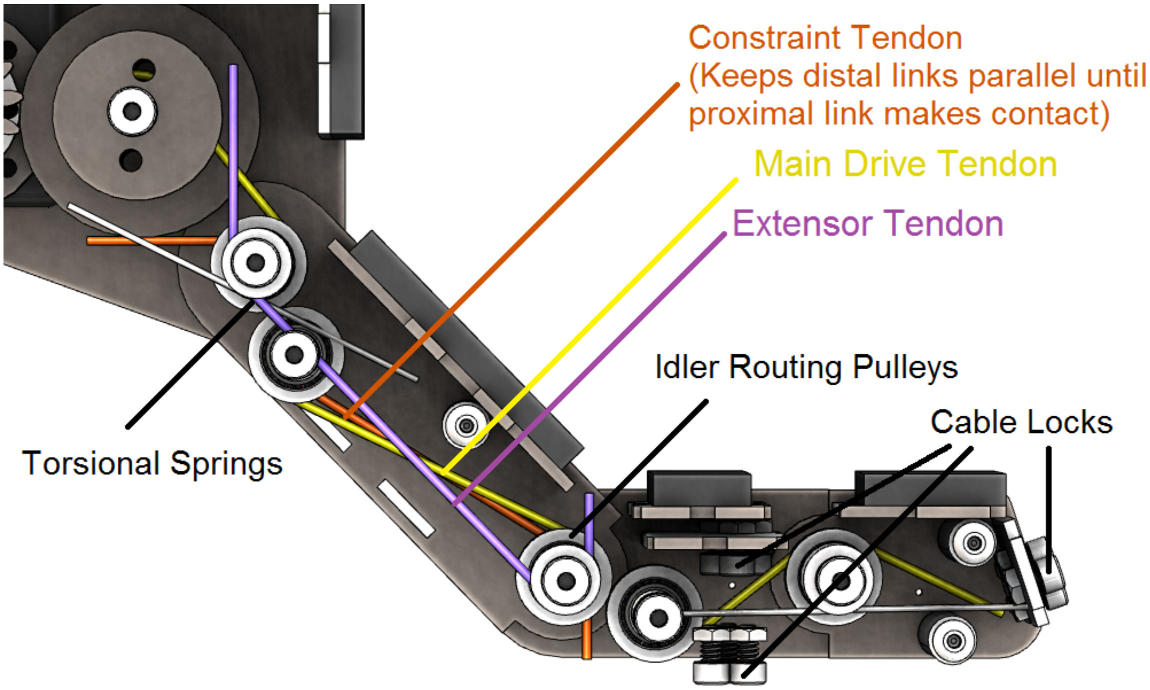


Figure 2-2: Finger Transmission Details

The desired behavior was chosen based the functional requirements that the gripper be able to grasp metal plates and other flat surfaces, as well as a wide variety of other human objects. A parallel pinch grasp is ideal for clamping onto plates while an enveloping power grasp is ideal for most other human objects. A design similar to that of the WillowGarage Velo Gripper [4] was used, which utilizes a passive Constraint Tendon and a spring Extensor Tendon coupling the palm and the middle link

(See Figure 2-2). This enables parallel behavior as the Drive Tendon is pulled taught until the gripper encounters resistance, in which case the other joints break away and complete the passive grasp (see Figure 2-3). The Middle and Distal links are parallel in their rest position and the proximal link is 25 degrees up from the horizontal at rest in order to allow the gripper to grasp sufficiently large objects.

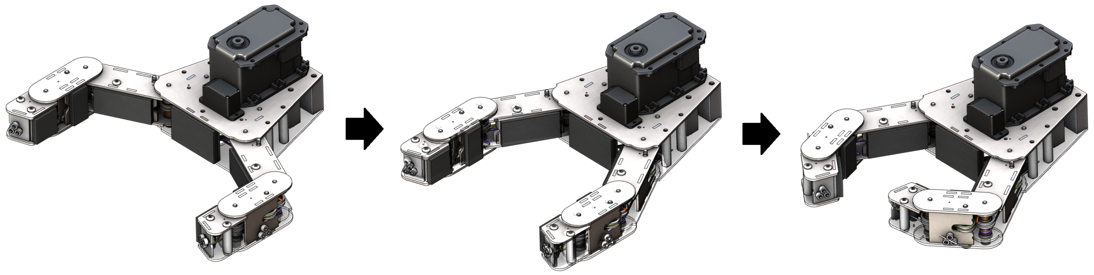


Figure 2-3: Typical Grasping Scenario
The gripper will close with the Middle and Distal links parallel until the Proximal link encounters resistance. The Middle and Distal links will then comply to the object and complete the grasp.

In order for the finger to close and apply the proper amount of force required to enclose and grasp an object, we must be able to design how much torque is transferred from the actuator to each joint in the finger. Attaining a torque ratio between each joint in a finger can be achieved in a variety of ways. One way to achieve a torque ratio, used in a majority of prior work [9][16][4] is to design for specifically-sized pulleys at each joints. The practical trouble in this case is the commercial availability of specifically-sized wire rope idler pulleys on McMaster-Carr. Custom idler pulleys can be machined from a waterjet, but the only usable bearings available from McMaster-Carr were not small and inexpensive enough to meet our requirements.

Instead, a single commercially-available type of steel wire rope idler pulley was chosen, and rather than alter the diameter, the relative locations of the various idlers along the finger were modified in order to achieve a desired torque ratio (see Figure 2-2).

A static model was developed in order to determine the torque applied about a joint as a function of the idler pulley locations along the link. This model extends the one used by Cabas [3]. A graphical explanation of the parameters relevant to the following derivation can be found in Figure 2-4. The moment M applied about a

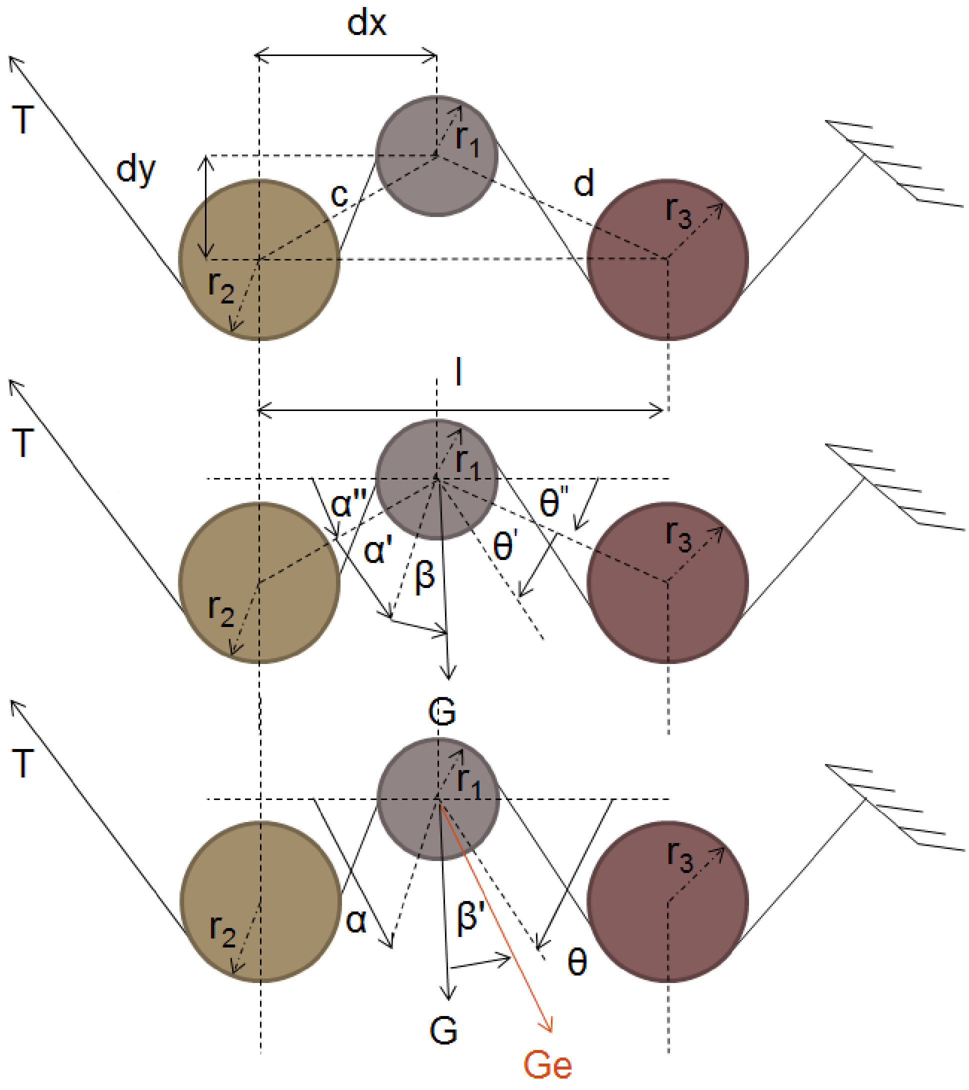


Figure 2-4: Geometry and Parameters Relevant To Evaluating Force Ge

joint to a link is given by:

$$M = c \cdot Ge \tag{2.3}$$

where c is the distance from the center of the joint to the center of the middle idler pulley, and Ge is the tangential component of the force G applied to the middle idler pulley, given by:

$$Ge = G \cdot \cos\beta \tag{2.4}$$

$$\beta = \alpha' + \beta' + \frac{\pi}{2}, \beta' = \frac{\pi - \alpha - \theta}{2} \tag{2.5}$$

$$\alpha = \alpha' + \alpha'', \quad \theta = \theta' + \theta'' \tag{2.6}$$

$$\alpha' = \arcsin \frac{r1 + r2}{d}, \alpha'' = \arctan \frac{dy}{dx} \tag{2.7}$$

$$\theta' = \arcsin \frac{r2 + r3}{d}, \theta'' = \arctan \frac{dy}{l - dx} \tag{2.8}$$

$$c = \sqrt{dx^2 + dy^2}, d = \sqrt{(l - dx)^2 + dy^2} \tag{2.9}$$

where l is the length of the link, dx and dy are the coordinates of the middle pulley relative to the first pulley, $r1$, $r2$, and $r3$ are the radii of the pulleys (but in our case all three pulleys are the same radius r), and $\alpha, \alpha', \alpha'', \theta, \theta', \theta'', \beta$, and β' are intermediate angle values used to relate the angle of Ge with the rest of the link geometry.

By inputting the pulley radii ($r = 0.1875$ inches), the direct drive servo spool diameter (11/16 inches), and the maximum main tendon drive servo torque at 12 Volts (6 Newton-meters), and optimizing dx and dy to have the greatest difference in torque ratios between the joints in a finger, *we achieve the results detailed in Table 2.2.*

Parameter	**Value**
Main Drive Spool Radius r (all)	0.6875 [inches]
Ilder Pulley Radius r (all)	0.1875 [inches]
Mid Pulley dy (all)	0.1875 [inches]
Mid Pulley dx (link 1, link 2, link 3)	0.4682, 0.4682, 0.8594 [inches]
Maximum Force Ge at middle of link (link 1, link 2, link 3)	71.54, 136.16, 319.6 [lbs-force]
Maximum Joint Moment M (link 1, link 2, link 3)	9.09, 10.70, 15.52 [Newton-meters]
Link2/Link 1 and Link 3/Link2 Joint Torque Ratios	1.176, 1.160

Table 2.2: Joint Torque Ratio Optimization Results

3/64-inch diameter steel wire rope was chosen because it is rated to beyond the maximum load the main drive servo could apply to it.

2.4 Structural Parameters, Analysis, and Design

A first-order stress analysis was conducted in order to ensure the structural components of the gripper would be able to meet the strength requirements for the MIT

SRL robot while bracing a human-sized load. The requirements state the gripper must be able to bear 150 lbs-force of static load in both tension and compression.

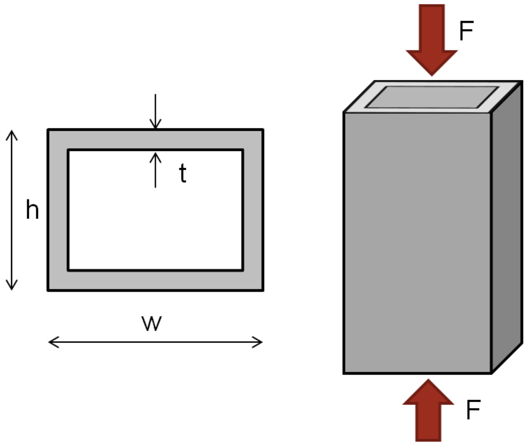


Figure 2-5: Rectangular Tube Extrusion Model Used for Analysis

First, the thickness of the wall material that makes up the bulk of the gripper's structure is analyzed. An assembled finger can be modeled as square tube extrusion with a cross section of 1-inch width and 3/4-inch length (see Figure 2-4). Aluminum sheet with a thickness of 1/16 inches is considered for the main structure due to its availability and ease of cutting on a waterjet machine, and we assume a yield strength of 275 MPa. The stress under maximum static load at any point in the structure must be less than half of the yield strength (137.5 MPa)

The tensile stress σ in a rectangular extrusion is given by:

$$\sigma = \frac{Force}{Area} = \frac{F}{2 \cdot t \cdot (l + w - 2 \cdot t)} \tag{2.10}$$

where F is the applied load and l, w, and t are the length, width, and thickness, respectively.

By substituting 75 lbs-force for F (on account of half of the full gripper load being distributed through each finger) and the aforementioned values for l, w, and t, the stress σ comes out to be a mere 3.5 MPa, which is far less than half the yield strength of the material. *1/16-inch aluminum sheet is more than sufficient for this application.*

The next components with the most stress concentration are the shoulder screws which comprise the axles about which each joint and transmission pulley moves. The shoulder screws act as pins under shear loading when.

The expression for shear stress τ in a pin joint with a circular cross-sectional area is given by:

$$\tau = \frac{Load}{Area} = \frac{P}{\pi \cdot \left(\frac{d}{2}\right)^2} \tag{2.11}$$

where d is the diameter of the cross-sectional area of the pin.

When substituting 102 MPa (half the yield stress for type 316 Stainless Steel, the material of the shoulder screws) for τ, and 75 lbs-force for P, a minimum diameter d for the shoulder screws was found to be 0.057 inches, or just under 1/16 inches. *A standard shoulder screw size of 1/8 inches was chosen*, which is more than sufficient to meet the gripper force requirements.

The design of the integrated structure was driven by the waterjet manufacturing process. Use of slots and tabs in the walls allow for rapid "puzzle-piece" assembly, and the structure is held together by the shoulder bolts and 4-40 standoffs.

2.5 Control and System-Level Design

The control software for the gripper was designed to be simple and easy to modify and integrate with other robot projects. The control software needs to, at the very least, receive a command from a higher-level system, close the gripper by commanding the Dynamixel MX-64 servo to apply a certain torque, and open the gripper to its rest position when commanded to do so.

The control software was implemented on an Arduino Board Nano for this project due to the microcontroller's availability and widespread use in both the academic robotics research and Open-Source communities. The Arduino hardware platforms have the advantage of integrating timing, power management, and programming hardware on a single board, and the software is easily customizable and compatible with a variety of Arduino hardware. The code used in this thesis can be easily modified

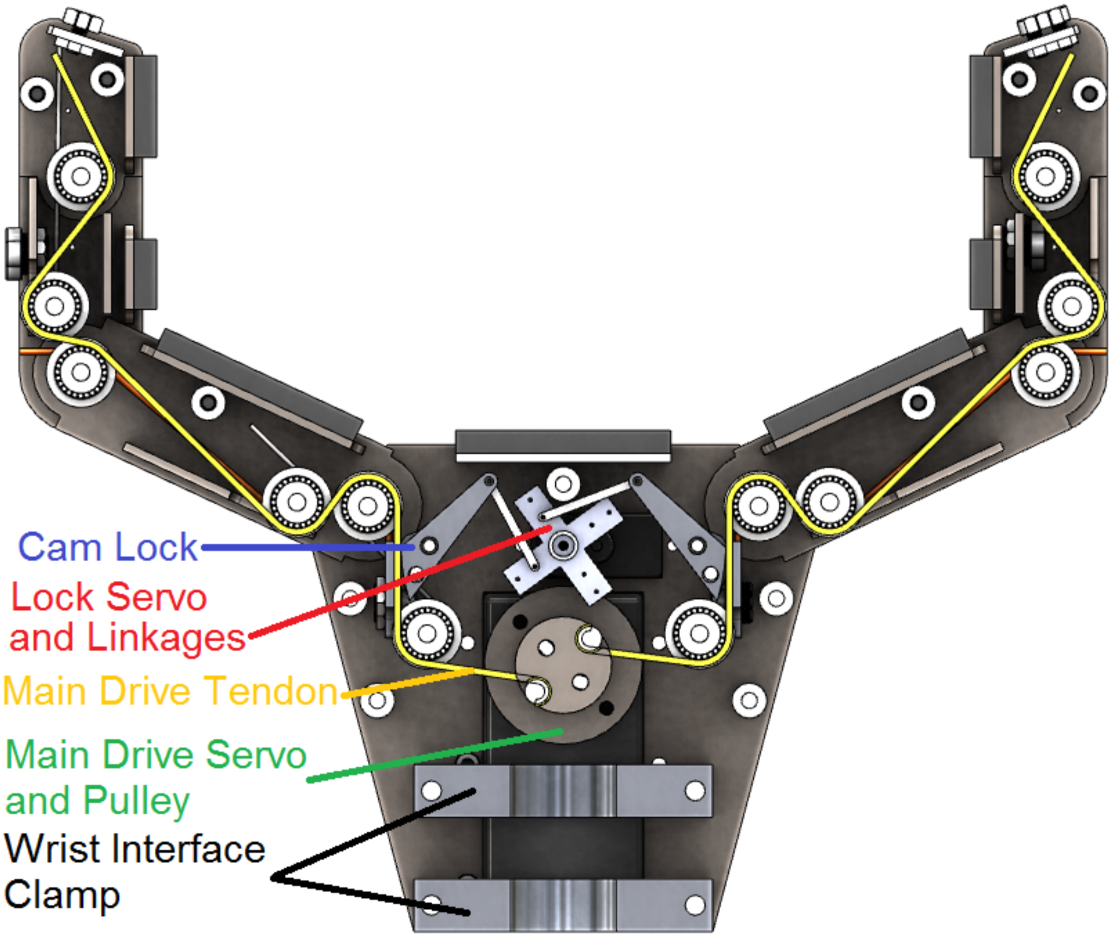


Figure 2-6: Cross Section View of the Gripper
The idler pulleys routing the Main Drive Tendon are all the same size, and their relative locations are modified in order to achieve the desired Torque Ratio.

to suit the needs of a higher-level project. For example, rather than detect a digital signal to close, a parent project can send specific desired torque commands to shake someone's hand in one moment, then crush a can of soda in the next, or extend the gripper's functionality by introducing pressure sensing.

The software runs a state machine which waits for a digital input command from a button press or a higher-level system. The MX-64 is then commanded to a desired torque, and the gripper begins to close. In order to take advantage of the dynamic force overshoot from the changing momentum when the gripper contacts the object, the Arduino must apply the Cam Brake when there is the most tension in the Main Drive Tendon (see Figure 2-7). This occurs right when the MX-64 has stopped turning

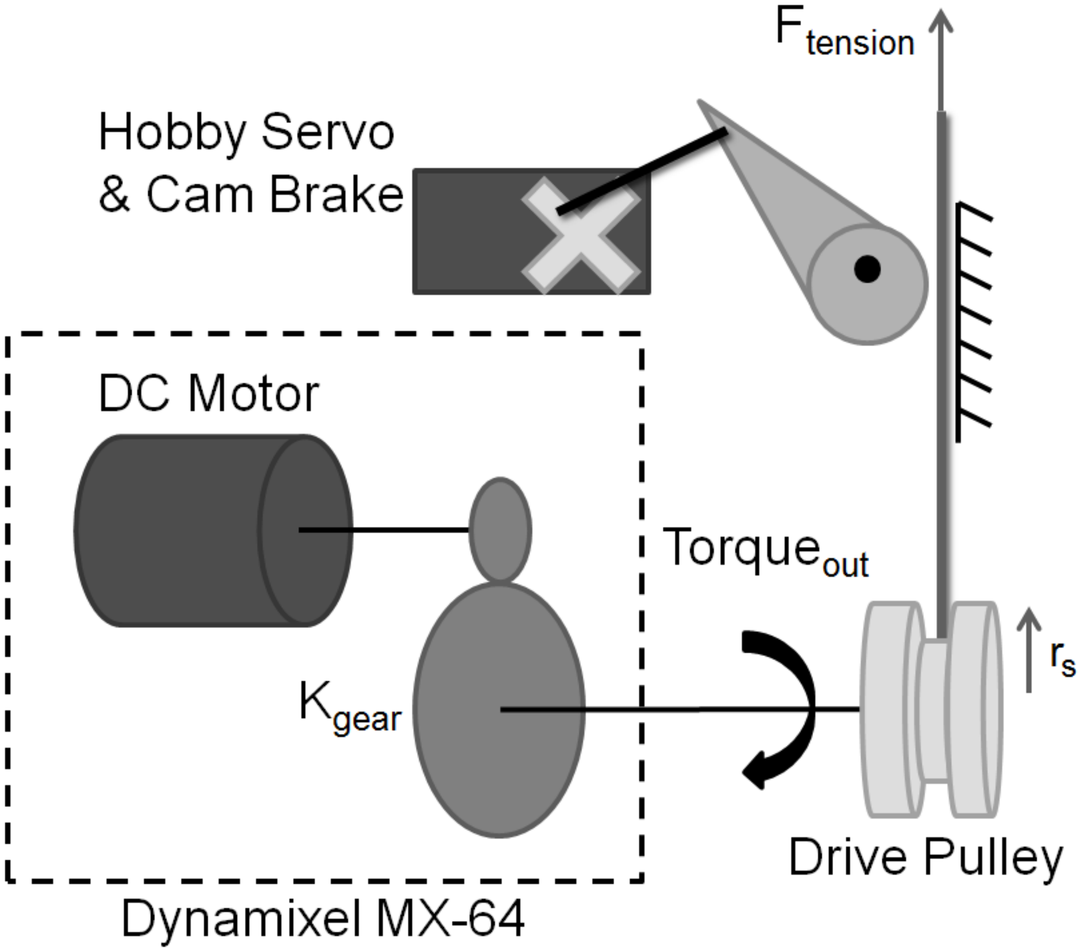


Figure 2-7: Diagram of Transmission Components
The Dynamixel MX-64 contains a Maxon DC motor and outputs $Torque_{out}$ through a 200:1 gear reduction ratio. The output horn of the MX-64 is coupled to a Drive Pulley of radius r_s which results in a force $F_{tension}$ in the Main Drive Tendon. A self-helping Cam Brake can be applied to the Main Drive Tendon by driving an ES08DE Digital Hobby Servo.

completely and right before the Main Drive Tendon springs back to its deflection under static motor force. To detect the peak tension, the Arduino requests velocity feedback from the MX-64 and applies the Cam Brake when the velocity reaches 0.

Once the Cam Brake is applied, the MX-64 is commanded to 0 torque and the grasp procedure is complete. The Arduino detects whether or not the application of the Cam Brake was successful by monitoring the motion of the MX-64. If the tension from the grasp forces the MX-64 back into motion, the brake did not successfully take, and the servo is driven back to the desired torque, which is still capable of successfully grasping the object. When the gripper is commanded to open, the Dynamixel MX-64 is driven a full torque again to remove load from the Cam Brake. The brake is then released, and the servo is commanded to return to the home position.

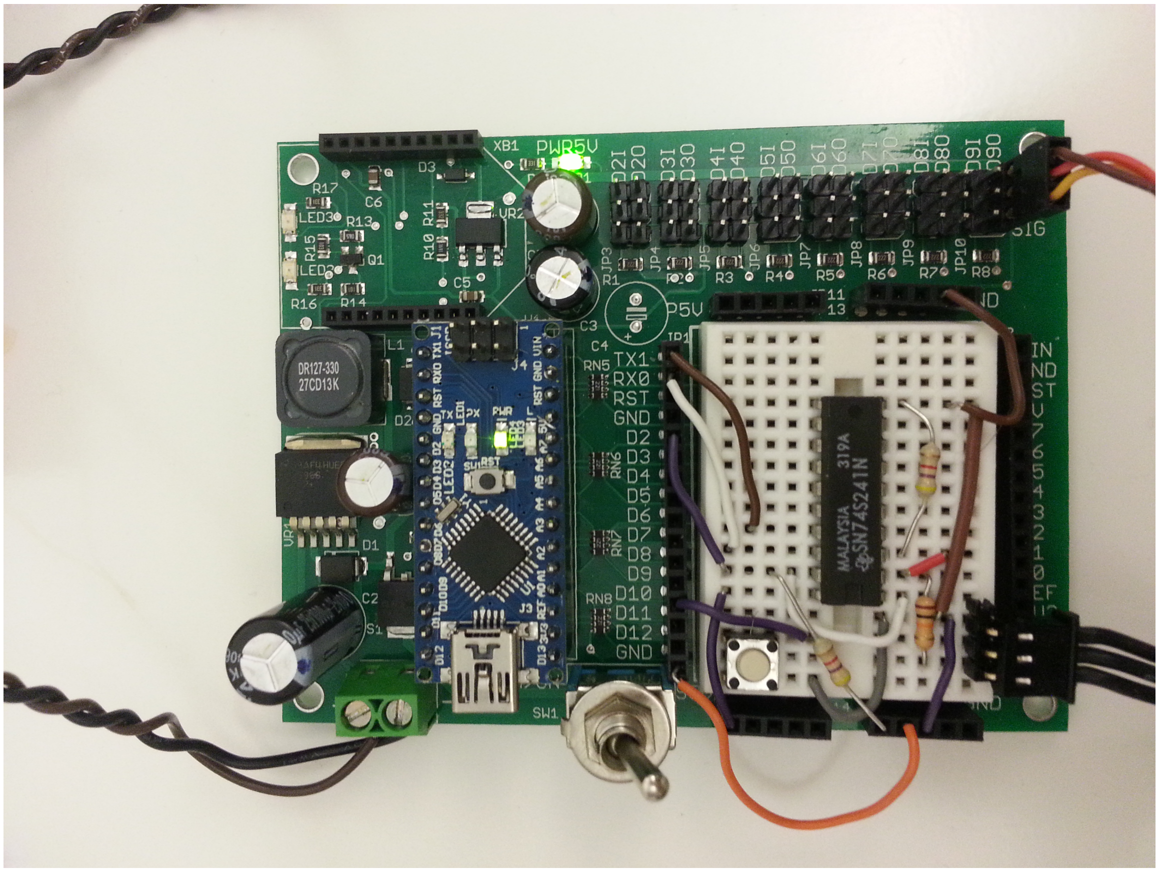


Figure 2-8: Carrier Board for the Arduino Nano and the Half- to Full-Duplex Converter circuit

A modified version of the Savage Electronics *DynamixelSerial* library[15] was used in order for the Arduino Nano to communicate with the Dynamixel MX-64. In order to convert from the half-duplex TTL communication of the Dynamixel servo and the full-duplex serial communication of the Arduino Nano, a circuit (see Figure 2-8) was built around the Texas Instruments SN74S241N Octal Buffer and Line Driver IC. The gripper uses a 13.8 Volt power supply capable of supplying up to 3 Amps. From previous experience, it is known that this is sufficient to supply the MX-64 at stall torque.

Chapter 3

Prototype Manufacturing and Assembly

3.1 Manufacturing

Before any manufacturing or assembly can occur, the hardware, materials, and actuators must be ordered. The Robotis Dynamixel MX-64 servo can be ordered online from Trossen Robotics, and the EMax ES08DE digital servo can be found online from Amazon. The remaining components can be purchased from a single order from McMaster-Carr.

All of the structural components of the gripper were cut from a single 1/16-inch-thick sheet of 2024 aluminum on an Omax waterjet (see Figure 3-1). Machining was conducted at the MIT Computer Science and Artificial Intelligence Laboratory (CSAIL) machine shop and at the MIT Media Lab machine shop. If a waterjet machine is unavailable, online machining services such as Big Blue Saw (www.bigbluesaw.com) can be used for a reasonable price.

Figure 3-1 shows some gripper components immediately after a waterjet machining operation. The components are held into the aluminum sheet via tabs to avoid falling through the slats below after being cut. The parts can be easily removed from the host material, and the residual tab can be filed off by hand. Some of the components require pre-cut holes to have size 4-40 threads, which can be achieved by tapping

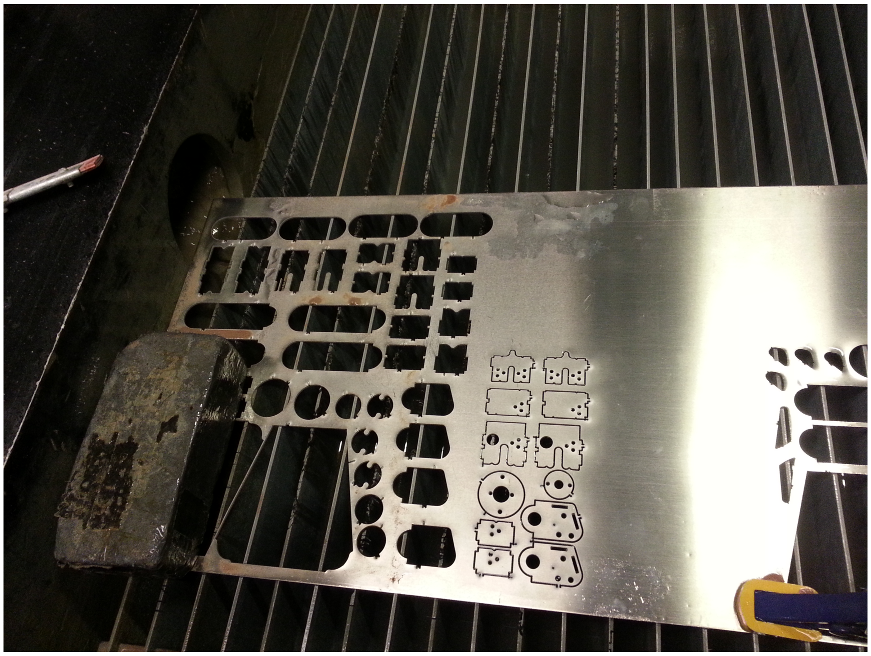


Figure 3-1: Structural Components After a Waterjet Operation

them by hand (see Figure 3-2).

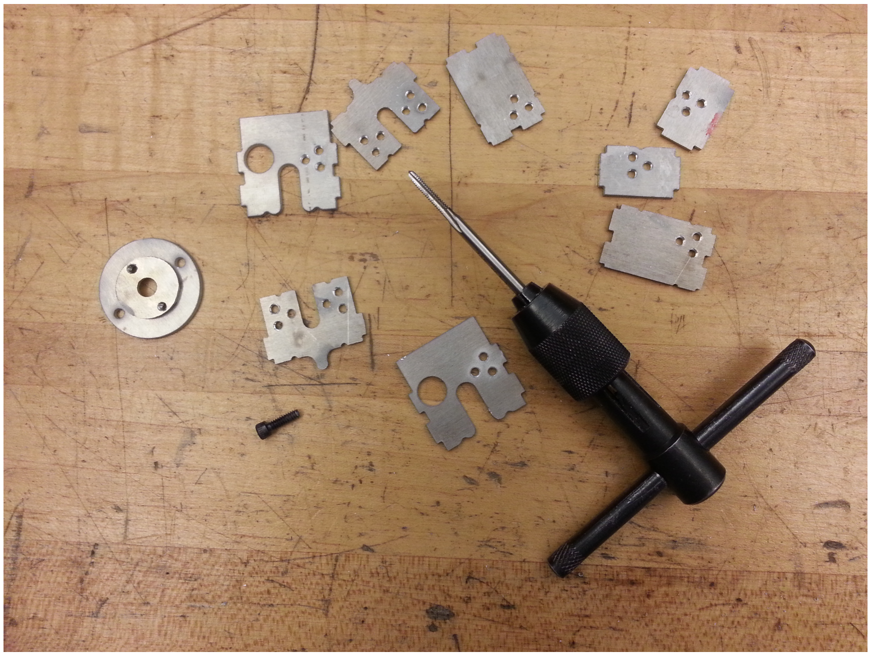


Figure 3-2: Some Components Require Holes to be Threaded with a 4-40 Tap

Next, the various steel tendons must be prepared. The Main Drive Tendons allow the Main Drive Servo to close the fingers, the Parallel Constraint Tendons keep the

Middle and Distal Links from returning to a rest position other than parallel. The Midlink Extensor Tendon, which must have an extension spring roughly in the middle, must first be cut into two parts and then joined with the extension spring in between. The 3/64-inch-diameter steel wire rope comes in 10-foot lengths, so must be cut to size with a steel cable cutter. Stop Sleeves are used to prevent the ends from fraying. The following cables must be prepared: 2x Main Drive Tendon (9.5”), 2x Parallel Constraint Tendon (5.75”), 2x MidLink Extensor Tendon A (3.25”), and 2x Midlink Extensor Tendon B (3.75”).

Finally, the grip pads must be cut and adhered to the inner faces of the fingers and palm. The grip material comes in a roll and can be cut to size with scissors. Adhesive such as Krazy Glue can then be used to attach these to the inner face plates of each link in each finger and the palm.

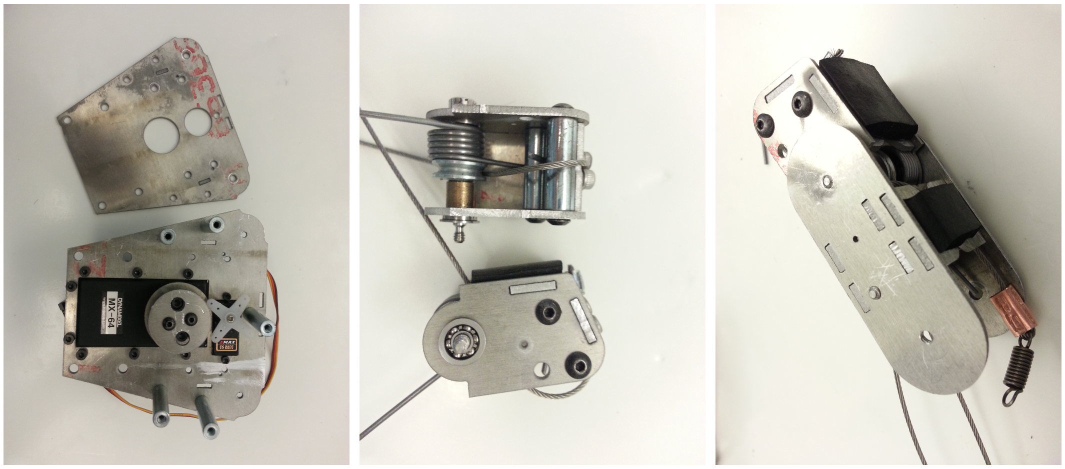
3.2 Assembly

Once all of the structural components are cut, their retaining tabs are filed down and 4-40 holes tapped, and once all steel wire rope is cut to size and their endstops crimped, the gripper can be assembled. The assembly process is straightforward (see Figure 3-3), and is aided by having the solid model as reference.

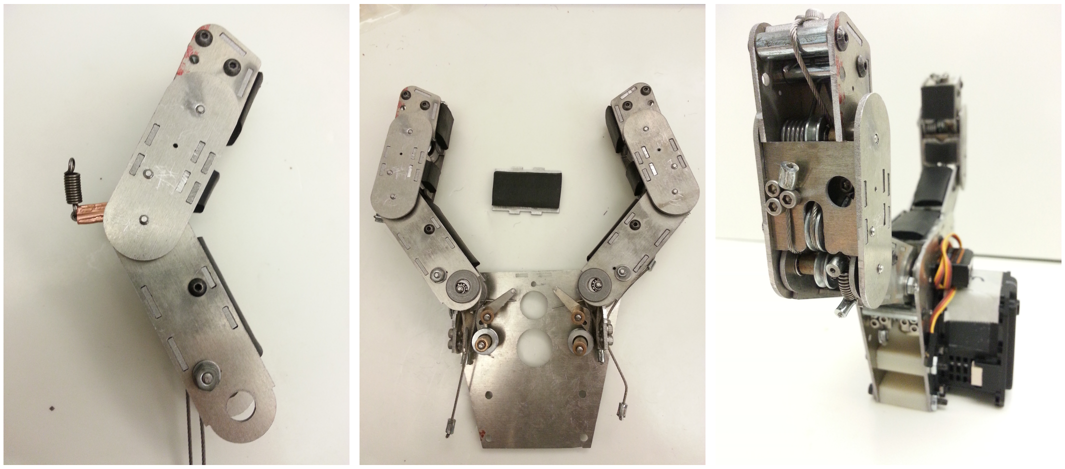
First, the Main Drive Pulley Spool should be assembled and attached to the Dynamixel MX-64 servo. Then the MX-64 and ES08DE servos and the 4-40 standoffs should be attached to the back plate of the palm, as in Figure 3-3(a).

Next, the fingers should be assembled link-by-link in order from the Distal Link in towards the palm, with each new link being built around the previous one. Once the Distal Link is built (Figure 3-3(b)), the Middle Link can be built around it and the assembly can be securely coupled with a shoulder bolt (Figure 3-3(c)). Each finger can be completed by building the Proximal link inserting it into the other end of the Middle Link (Figure 3-3(d)).

Once the fingers are assembled, the palm can come together. The Cam Locks, idler pulleys, palm inner grip pad, and other retaining walls can be inserted into the



(a) Palm is Assembled (b) Distal Links Assembled (c) Distal and Middle Link



(d) Completed Finger (e) Palm and Fingers (f) Completed Assembly

Figure 3-3: The Assembly Process

front plate, and the fingers passed through the shoulder bolts as shown in Figure 3-3(e).

The back plate can then be attached to the rest of the assembly to complete the structure of the gripper. The steel wire rope tendons must be preloaded and tightened to the Main Drive Spool and clamps located in the wrist, and the gripper is complete (see Figure 3-3(f) and Figure 3-4).

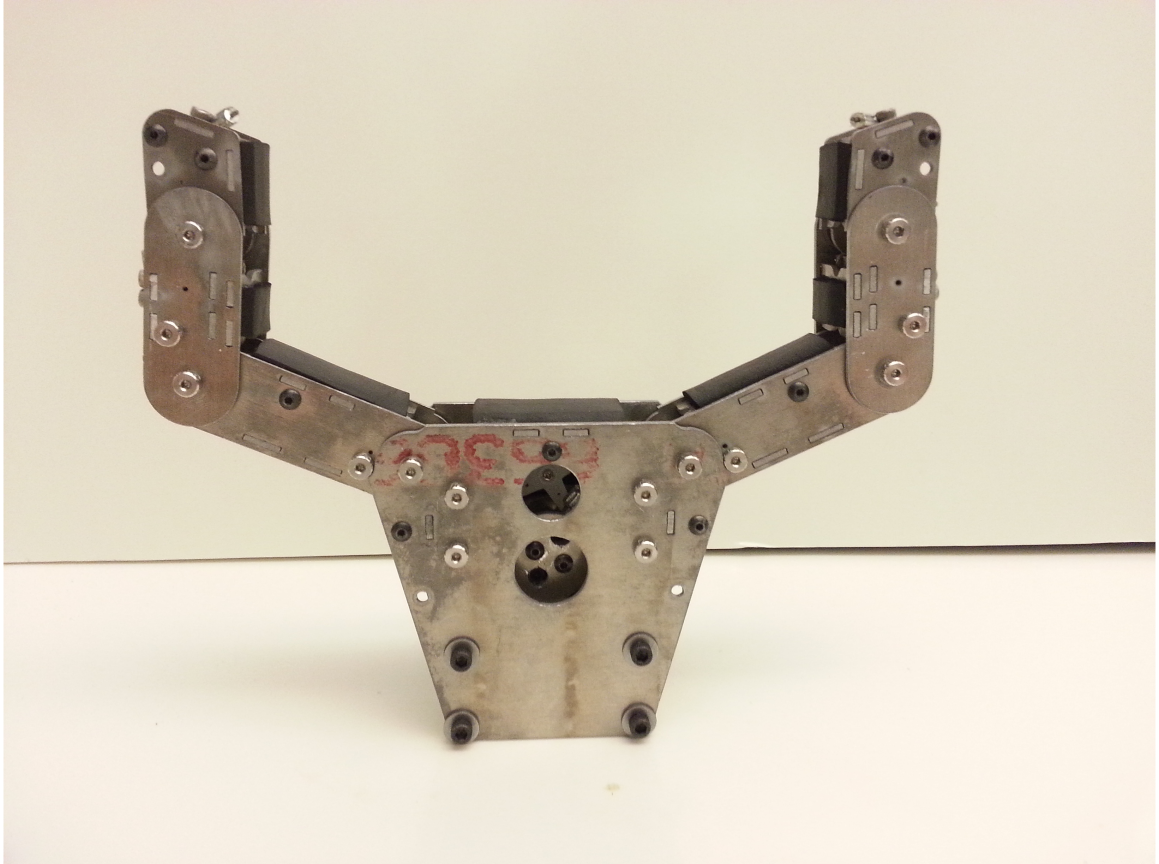


Figure 3-4: Fully Assembled Gripper

Chapter 4

Grasp Tests and Integration

Initial grasp tests were performed by hand on a variety of human-sized objects (see Figure 4-1). These objects all varied in size, weight, and shape in order to demonstrate the variety of objects the gripper could grasp, as well as test the gripper's strength.

In order to allow for custom coupling to other robots, holes for 6-32 bolts are located on the bottom of the gripper wrist faces. Two flexure-based clamps were 3D-printed in ABS plastic to couple with the 0.75-inch output shafts of the MIT Supernumerary Robotic Limbs (SRL). A steel 0.75-inch shaft was used to hold the gripper by hand during grasp tests to simulate the Supernumerary Robot Limbs. The digital input that commands grasping action was triggered by a push button.

Once the gripper was shown to be able to grasp a wide variety of objects by hand, it was integrated with the SRL Robot (see Figure 4-2). The gripper coupled to the output shaft of the SRL Robot's left arm via the ABS plastic flexure clamps. The prototyped electronic components were electrically isolated from the rest of the arm with foam padding and electrical tape. The digital input that commands grasping action was tied to a digital output of another microcontroller located on the SRL Robot. The gripper power was provided by a separate supply from the rest of the SRL Robot, though it could have drawn power from an onboard 12-Volt line.

The SRL Robot, along with the gripper, was tested by simulating a drilling operation on a mockup aircraft frame (see Figure 4-3). This task was chosen because it requires the SRL Robot to brace the operator against the wall to provide the re-

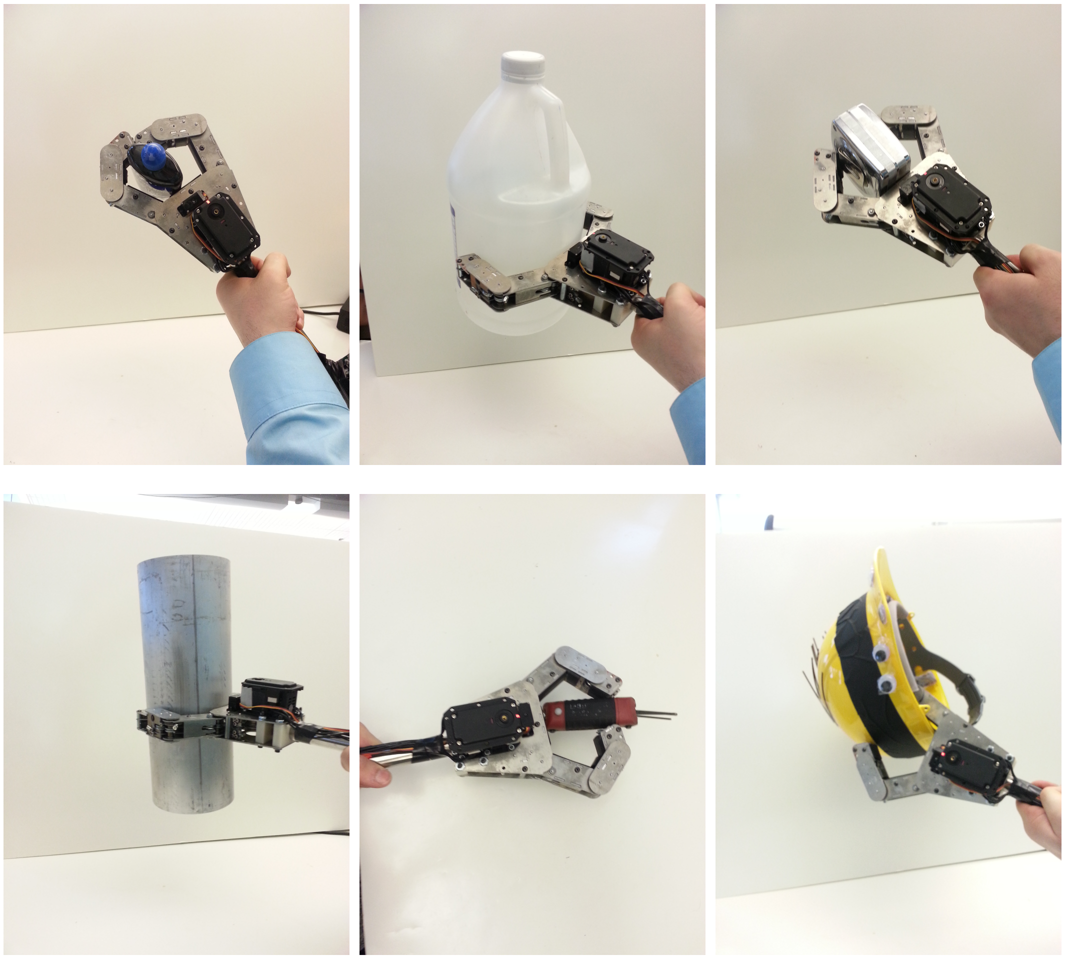


Figure 4-1: Demonstration of Various Grasps

quired reaction force. The resulting force loop runs from the drillbit, through the drill, through the operator's hand and arm and to the SRL robot attached to the operator's shoulders, back, waist, and thighs. The force then runs through the SRL Robot's left arm, through the underactuated gripper that is clamping against the workpiece (the aircraft wall).

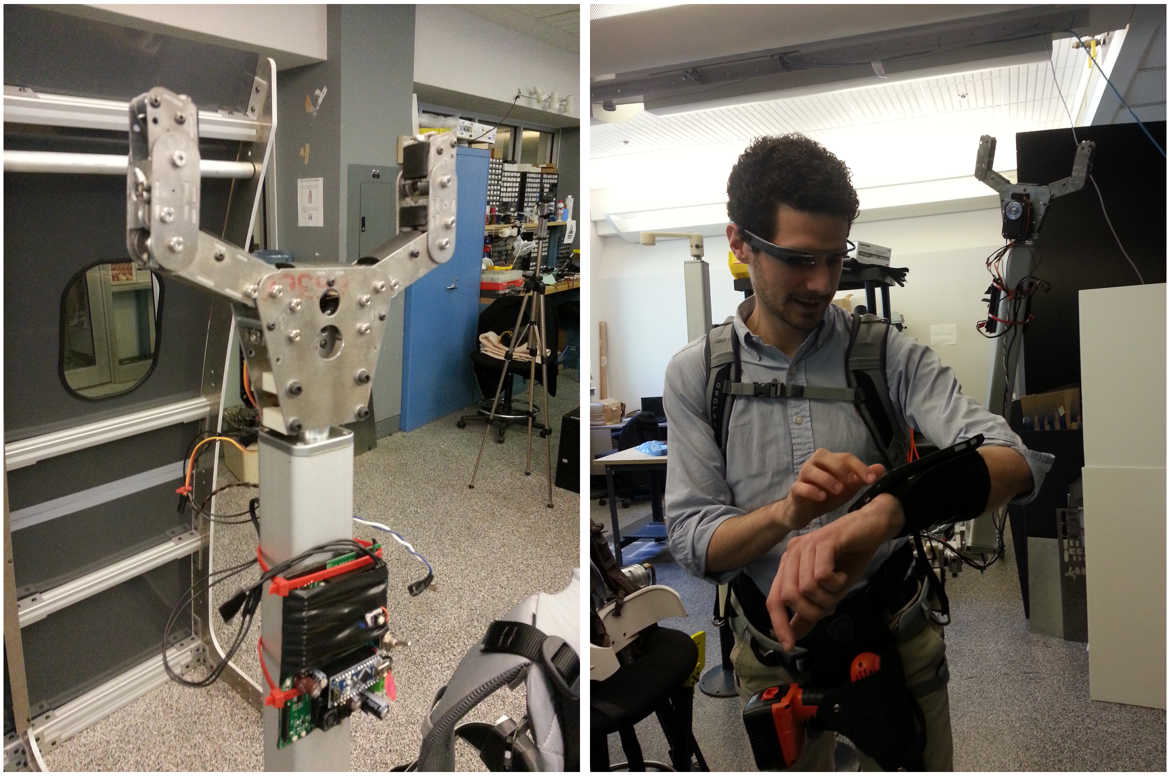


Figure 4-2: Integration with the MIT Supernumerary Robotic Limbs

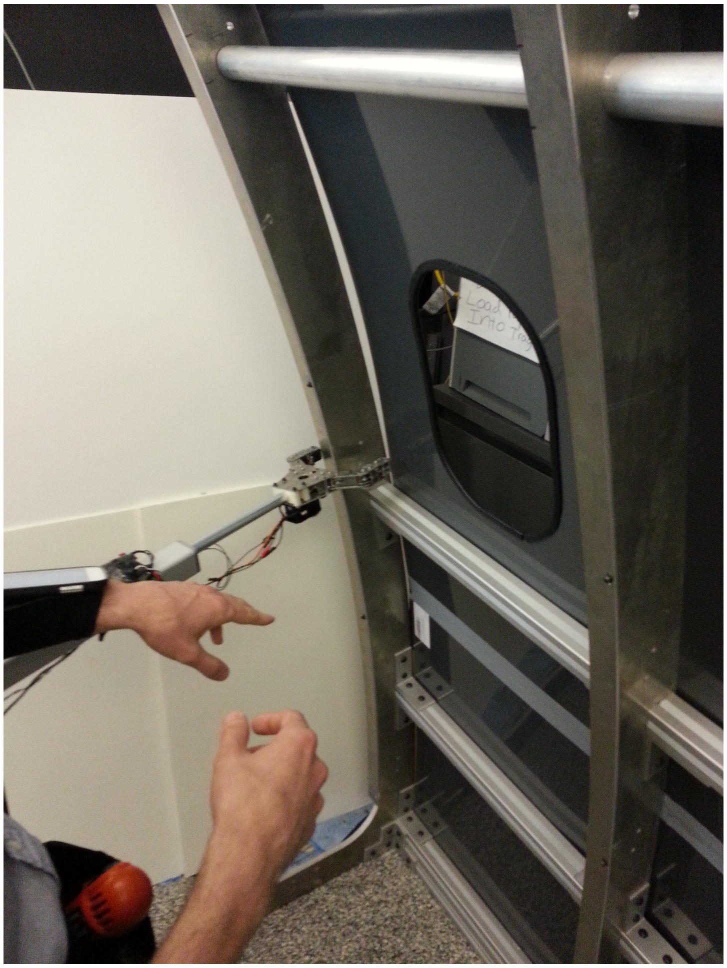


Figure 4-3: Demonstration of Grasping a Wall to Brace the Operator

Chapter 5

Future Improvements and Steps

This work aimed to design a strong, inexpensive, underactuated robot gripper that is easy to manufacture and whose design files could be released as Open-Source. All of the functional requirements were met, but the gripper can be improved upon in terms of cost, reliability, sensing capability, and ease of manufacturing and assembly.

First, the total cost of the gripper can be cut down by investigating less costly actuators and hardware. The most expensive component of the gripper, the Robotis Dynamixel MX-64 smart servo (which costs $300.00 USD: half the cost of the entire gripper), can be replaced by a far cheaper geared brushed DC motor with an integrated optical encoder. A separate motor driver and encoder decoder will be necessary to maintain the same functionality, but the cost of these new components combined will be less than the cost of one Dynamixel MX-64.

In order to further decrease the cost of the gripper, the number of shoulder bolts should be decreased and alternatives such as pins should be investigated. The 0.125-inch ID flanged roller bearings about which the shoulder bolts rotate can be replaced with less expensive bushings, and the idler pulleys themselves can be eliminated by either waterjetting custom idlers or integrating static self-lubricating material into the structure to rout the steel tendons.

The Cam Brake requires improvements in order to improve its reliability. During testing, the cam lock required careful timing in order to catch the steel wire rope. This unreliability can be addressed by modifying the geometry or by using a different material with a higher coefficient of friction against steel.

The Cam Brake can also simply be eliminated altogether, and a non-backdrivable drive such as a worm gear can be used to achieve high grasp forces without requiring a motor to continuously draw current. Non-backdrivable drive eliminated the ability to estimate output torque by sensing the motor current, however. Force estimation can be retained by integrating pressure sensing such as the Open-Source TakkTile sensors developed at Harvard can allow for closed-loop control of grasp forces so as not to crush some objects, the detection of stable grasps, and detect slipping objects by sensing vibrations.

Finally, the next revision of the gripper must be designed, packaged, and documented for successful release to the Open-Source robotics community. Before release, an accurate final Bill of Materials should be generated and the entire manufacturing and assembly process should be streamlined, simplified, and thoroughly documented. The gripper should be stress tested to identify any failure modes, and a final design revision should address them. Taking these steps will ensure the gripper is a safe, useful, and well-received addition to the Open-Source robotics community.

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