PROTOTYPE DEVELOPMENT OF AN UNDERACTUATED ROBOTIC HAND FOR OBJECT GRASPING BASED ON ANTHROPOMORPHIC TASKS

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ABSTRACT

Underactuated robotic hands are becoming more popular in the industry as they provide a solution for circumstances where there is a need to grasp objects of varying shapes and sizes. They utilize minimal actuation, and provide a lightweight and cost-effective solution for grasping a large range of objects using less complex controls.

Using a previously developed one degree of freedom multi-loop anthropometric mechanical finger, a three-finger minimally actuated robotic hand was designed based on human-like grasping tasks. The wrist component was configured so that the specially designed finger linkages would have the ability to grasp an object utilizing a spherical grasp.

Research determined the configuration of the finger linkages with respect to one another. Next, a wrist was designed using SolidWorks to better understand how each component would fit within the wrist parameters. The hand was then manufactured utilizing both 3-D printed ABS plastic parts and aluminum and Delrin milled parts.

Preliminary testing of grasp indicated the feasibility that the robotic hand would be versatile enough to grasp objects of varying shapes and sizes. Further testing would determine whether alterations would be necessary to better the design of the robotic hand.

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CHAPTER 1

GRASPING

Introduction

We use our hands for everyday tasks and tend to take their essential role in our lives for granted. They complete complex functions with ease and allow for us to eat, work and play without having to account for how we utilize them. The simplicity with which we use our hands is not easily transferable when trying to accomplish these same tasks using robotic hands. As such, studies have been conducted with hopes that, eventually, these same complex manipulations may be approached with the use of robotic counterparts.

This paper will primarily focus on grasping motion utilizing a previously designed finger linkage whose configuration was built with the use of underactuation in mind. A wrist is to be created using three of these linkages and configuring them in a way to allow for grasping to occur. Grasping, rather than object manipulation, is studied due to its simpler complexity and control modeling.

Grasping

Definition

Grasp is defined as a set of contacts on the surface of an object where the contacts are used to constrain the potential movements of the object in the case that any external disturbances are applied to the object (Leon, Morales, & Sancho-Bru, 2013); thus grasp keeps an object stable and unmoving, even when external forces are applied to said object. In this context, a contact point is defined as the joint where the finger and the object are touching. The shape and stiffness of the contacting surfaces and the frictional characteristics of the containing bodies define how the joint contacts behave (Bicchi, 1995). It is also noted that although certain grasps are better at resisting gravitational forces, those same grasps may not be best suited for resisting certain moments applied at certain directions on an object held in a grasp (Mirtich & Canny 1994). In its simplest form, grasp is holding an object so that it is stable and unmoving, no matter what forces may be applied to said object.

Human Grasping

Taxonomy. In order to find the best design for the wrist of the robotic hand, the manner in which humans naturally grasp objects has been researched. Taxonomy is a method in which the ranges of the human grasp types are organized. A range of factors are taken into account in order to organize different grasps using various parameters (Cutkosky & Howe 1990). The findings of Schlesinger, Taylor and Schwars were developed after studying medical literature and have founded much of what is used today in the taxonomy of grasp. Their studies allow for grasp to be found on a continuum of object size and power requirements and show how the task requirements for grasp, the forces and motions, and the shape of the object combine to dictate the grasp of choice (Cutkosky & Howe 1990). Their research organized and characterized human grasp to provide a benchmark that future findings in the study of human grasping could be compared to. The names for the grasps that are classified in their studies are "cylindrical, fingertip, hook, palmar, spherical and lateral" (Cutkosky & Howe 1990, p. 6).

During their research, how the human hand grasps an object became apparent. Intuitively, one would assume that an object would be grasped solely due to the size and shape of said object. Instead, it appears that human's grasp is relative to the task with which they wish to perform on an object, rather than using only the shape of the object. Therefore, we see that it is the approach to the object, rather than the shape of the object, that defines what type of grasp would be performed on an object (Cutkosky & Howe 1990). The adaptation of grasp configuration results in a change in the forces and torque applied to the object as well, those of which are dependent on the conditions to be used This behavior was first characterized by Napier who suggested that grasp should be characterized by function, rather than the appearance of the object to be grasped (Cutkosky & Howe, 1990, p. 7).

Opposition Grasp Theory. Another form to characterize grasp involves an approach in which grasping is a result of the rule of opposites; opposite forces work in opposite directions, creating the manner in which grasp is achieved (Cutkosky & Howe 1990). In this way, grasp could be characterized by the direction that force is applied and which surface of the hand the appendages are applying force to. There are three types of grasps observed with this view; they are pad opposition, palm opposition and side opposition. Pad opposition utilizes forces created between the pads of the fingers and the thumb. Palm opposition is seen when the forces are between the fingers and the palm. Finally side opposition results from when forces are applied between the thumb and the side of the index finger (Cutkosky & Howe 1990).

Power vs. Precision Grasp Theory. Precision grip utilizes the tips of the fingers in order to grasp an object, where the fingertips and the thumb are primarily used

(Landsmeer, 1962). Fingertip grasps are better suited for situations where smaller grasps are needed, similarly to how the human hand grasps a pencil, using their fingertips, and thus the source of its other name (Landsmeer ,1962). As only the ends of the fingers are used to control the motion of an object, a smaller amount of force is applied to this object. The grip is more delicate, sensitive (Cutkosky & Howe, 1990) and involves more fine-tuned control versus its power grasp counterpart.

A power grasp can be characterized by the large areas of surface contact between the fingers and palm while the fingers would have little ability to move the object. (Cutkosky & Howe 1990). Using a power grip involves treating the fingers as one end of a claw, with the palm being its opposite counterpart. The hand must be placed over the object and the fingers and thumb are positioned to be as close to the object that is of main focus. In this way, the fingers are in a position in which the power to be exerted on the object is as forceful as necessary for the action of grasping or clenching (Landsmeer, 1962). The fingers are positioned depending on the size of the object in a way where the fingers will equally position themselves to eventually fully envelope the object. The fingers are used as a jaw that jams the object towards the palm. The manner in which a power grasp envelopes an object gives it its secondary name, the enveloping grasp (Landsmeer ,1962). This type of grip is less compliant but more stable and is less likely to allow for slippage of the object in its grip when compared to a precision grip (Cutkosky & Howe 1990). The power grasp includes the cylindrical, spherical and hook grip.

Grasping Theory

Form vs. Force Closure. The theoretical basis for grasping can be followed back to form and force closure. Such types of closure are first calculated by grasping an object in two dimensions, and then is transposed to apply to a three dimensional world. Although both grasps may be clearly separate theoretically speaking, in reality, both types of closure are involved in many configurations of grasping.

First, the properties of form and force closure dictate how grasp completely or partially constrains the motions of a manipulated object. These properties are then used to apply arbitrary contact forces to the object itself. This is done without violating the friction constraints of the contact (Bicchi, 1995).

Form and force closure are developed from screw theory (MIT Encyclopedia, 2011). Both of these methodologies are found by looking at a frictionless environment that is only governed by either the geometry that the hand takes while grasping an object, or the forces exerted on the object to keep it constrained, without the dependency of geometry (MIT Encyclopedia, 2011).

Form closure focuses primarily on the geometry, or form that the hand takes, when grasping is taking place (Nanda, 2010). The geometry maintains the contacts of the joints of the fingers so that geometry is utilized to maintain a stable grasp (Prattichizzo & Trinkle 2008). Form-closure proposes that the contact points created on an object, when grasp takes place, as fixed in space. This is used to describe the capability of the hand to keep any motion from occurring on the object that is being grasped (Landsmeer, 1962). The description of form closure is developed by observing the hand while grasping an object when the joint angles of the fingers are locked in space. The palm is also fixed in space. If the configurations of the locked fingers and palm, the object held by the fingers are form-closed so long as the object cannot be moved, not even infinitesimally (Prattichizzo & Trinkle 2008). If the object is completely immobilized, the object may be considered form-closed. (Rimon & Burdick 1996) This method of calculating form-closure is done using a frictionless environment. (Park & Lynch 2012).

Force-closure, on the other hand, becomes more complicated as it attempts to describe the ability of the hand to counterbalance any external disturbances that are placed on a grasped object and maintaining stability of said object (Srinivasa, 2014). To do so, a combination of contact forces are applied that respect the abilities of the actuators and the conditions that are imposed by friction (Landsmeer, 1962). As such, this grip keeps the object stable by compensating for all of the forces and torques created by the object (Nanda, 2010). To characterize force-closure, researchers describe it using an analogy to the tooth of gear in the water mills used in the past to utilize water for energy. The weight of the wheel acted to create a "close" contact where the groove-axle came together. Since the force of the wheel causes the rotation of the wheel, the nomenclature for force-closure is used (Prattichizzo & Trinkle 2008). Force closure, when the fingertips are used for grasp, do so by generating forces so as to resist any external forces or moment applied to the object (Park & Lynch, 2012). Modeling of force-closure utilizes friction (Park & Lynch 2012)

The equilibrium with force-closure is created to prevent small object motion by using finger contacts, and not geometry, to impose constraints (MIT Encyclopedia, 2011). If we consider the robotic hand when an object that it is holding is at rest, the forces and moments that are applied by the fingers on the object must act to balance each other so that the position of the object is not disturbed. Obtaining an equilibrium grasp by the use of force closure means that the hand is capable of applying balanced forces that are both caused externally and by torque. Reauleaux found that at least four contact points are needed in order to achieve the form-closure property in a planar case, or rather in two dimensions (Bicchi, 1995). When approaching the general spatial case, three dimensions, Somov found that at least seven contact points are needed (Bicchi, 1995). While form closure grip limits the movement of any object by using the shape of the object, force closure depends on applying the necessary forces that would equate the same stability.

One of the significant differences between form and force closure lies in the manner with which the contact forces between the fixture and the object is modeled (Rimon & Burdick, 1996) When a hand holds an object at rest, the forces and moments exerted by the fingers should balance each other so as not to disturb the position of the object. This type of grasp is said to have equilibrium. If the grasp is able to balance any external force and torque, it is said to have force closure. A form closure grasp achieves the same results, but instead relies on the geometric constraints created by its finger contacts at the points of contact with the object (MIT Encyclopedia, 2011).

There is some discussion regarding whether form and force closures are interchangeable; however this is dependent on the definition used to describe both. For our purposes, force closure implies form closure, but form closure does not indicate force closure (Landsmeer, 1962).

<u>Contact Points</u> Coulomb's law is used to model the forces created by contact forces. If no sliding occurs at the contact points where forces are applied, then Coulomb's law states that tangential force (f_t) is related to normal force (f_n) by

$$|f_t| \geq \mu|f_n|;$$

where μ is the coefficient of friction which is typically between the values of 0.1 and 1 (Park & Lynch 2012, p. 365). The tangential force is the force that is tangential to the surface that the force is being applied to and is in the x-direction of the force component being applied to said surface. The normal force is the force normal to the force applied at the surface and is in the y-direction of said force. These two components will be further discussed later. When sliding occurs, the following is true

$$|f_t| \geq \mu|f_n|$$

(Park & Lynch 2012, p. 365). There exist two separate friction coefficients that may be related by relation

$$\mu_k \leq \mu_s;$$

where μ_k is the kinetic friction coefficient and μ_s is the static friction coefficient (p. 366). When the no-slip condition is in effect, the following occurs:

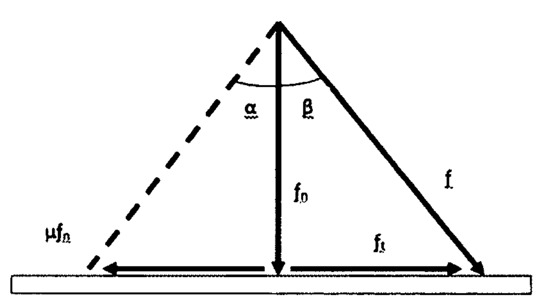

Figure 1. Diagram of applied force, Introduction To Robotics Mechanics, Planning, and Control, http://hades.mech.northwestern.edu/images/2/2a/Park-lynch.pdf (accessed September 20, 2014).

In the above diagram we can see that the applied force f is at an angle with the perpendicular to the surface that is named β. The normal force f_n is $f\cos\beta$. There is also a tangential component f_t that is parallel to the surface and is calculated by $f\sin\beta$.

There is an equal force in the opposite direction of f_t that is true as long as

$$f_t > \mu f_n,$$

a no-slip condition. This condition must also be true so that β should never exceed the value of α, resulting in the relationship of $\beta_{max} = \alpha$ (Park & Lynch, 2012, p. 367). When this condition is true, it leads to the situation where the largest area under the triangle creates a cone that is the maximum value at 2α, given by $\alpha = \tan^{-1}\mu$ (Park & Lynch, 2012, p. 367). If β were to exceed α, slipping would occur, as α would not be enough to counteract the amount of force created. This would negate the no-slip condition referenced. If there were to be frictionless points of contact, no friction would occur between the fingertip and the object being grasped. In this case, $\mu = 0$ and the only forces applied would be normal forces to the surface at the contact points (Park & Lynch 2012, p. 368).

Another representation of the contact point may be seen below, where a cone is dictated by the angle of 2α (Park & Lynch 2012, p. 368)

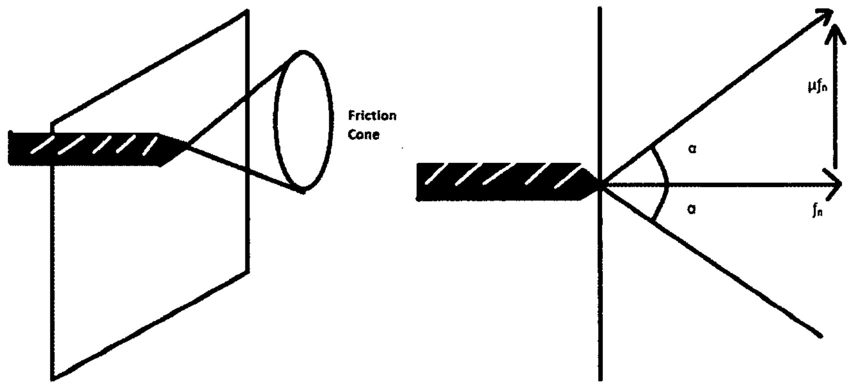

Figure 2. Diagram of cone of force created at contact point, Introduction To Robotics Mechanics, Planning, And Control, http://hades.mech.northwestern.edu/images/2/2a/Park-lynch.pdf (accessed September 20, 2014).

Using friction, any contact point that lies within the cone of friction will not cause any slippage at that point. This cone may also be characterized by the following mathematical equation

$$\{f \in \mathrm{R}^3 \mid \sqrt{f_x^2 + f_y^2} < 1 \mid \mu f_z \mid \};$$

(Park and Lynch 2012, pg 368).

If we assume a spatial rigid body that is completely restrained by frictionless points, whose arbitrary forces are only in the direction of the object surface normal, and these arbitrary forces are expressed as $\mathcal{F}_e = (m_e, f_e)$; m_e = 3D moment, f_e = 3D force and normal contact forces $f_1, \ldots, f_n \in R3$, then form closure exists is said to exist if

$$\left.\begin{aligned} f_e + \textstyle\sum_{i=1}^{n} f_i &= 0 \\ m_e + \textstyle\sum_{i=1}^{n} r_i x f_i &= 0 \end{aligned}\right\} \quad \mathcal{F}_e + \mathcal{F}_1 + \mathcal{F}_2 + \ldots + \mathcal{F}_n = 0$$

(Park & Lynch, 2012, p. 368). If the above is true, the object can withstand any external spatial force and is considered to be in static equilibrium (p. 370).

When constructing a planar example, two contact points with friction are considered, and can be seen as in the following two images:

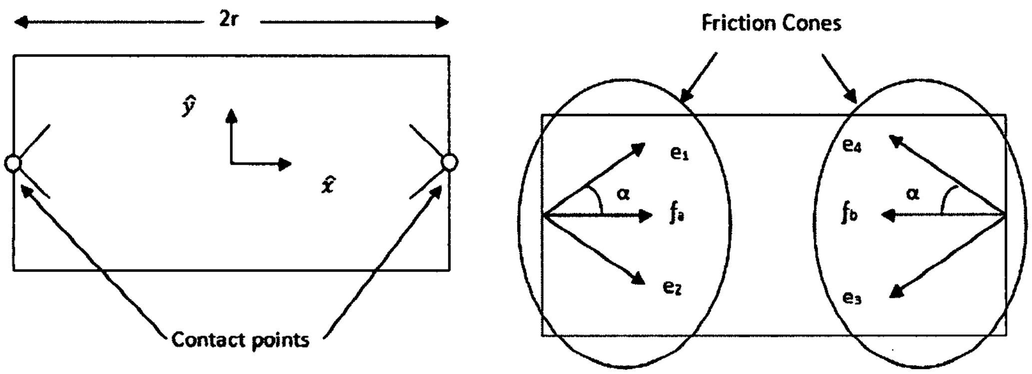

Figure 3. Geometric diagrams of forces applied at multiple contact points, Introduction To Robotics Mechanics, Planning, And Control, http://hades.mech.northwestern.edu/images/2/2a/Park-lynch.pdf (accessed September 20, 2014).

where $f_a = e_1x_1 + e_2x_2$ and $f_b = e_3x_3 + e_4x_4$ (Park & Lynch, 2012, p. 370). It can be seen that when force conditions are in effect, any arbitrary external forces and moments ($f_e \in R^2$, $m_e \in R^2$) are

$$f_a + f_b = -f_e$$

$$m_a + m_b = -m_e$$

(Park & Lynch 2012, p. 370).

The above equations are used to describe how the forces within the system interact mathematically for a planar example. Using such an example, we may apply Nguyen's theorem for planar force closure, which states that "a planar rigid body constrained by two contacts with friction is in force closure if and only if the line connecting the contact points lies inside both the cones the friction" (Park & Lynch, 2012, p. 370). Therefore, in order for force closure to take place, the force that is applied at the surface must pass through the cone of friction created by the points of contact.

For spatial force closure for rigid bodies subjected to three points of contact a similar theorem exists. Here "for a given spatial rigid body restrained by three points of contacts with friction, assume that the three contact points lie on a unique plane S, and the friction cone at each end of the contacts intersects S in a cone. The body is in force closure if and only if the plane S is in a planar force closure grasp" (Park & Lynch, 2012, p. 370). As can be seen below, an S plane exists that cuts through a point of contact.

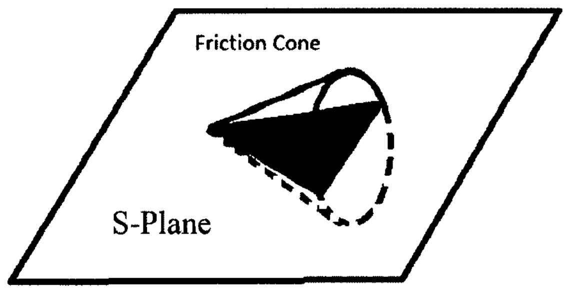

Figure 4. Friction cone for one contact point in the S-Plane, Introduction To Robotics Mechanics, Planning, And Control, http://hades.mech.northwestern.edu/images/2/2a/Park-lynch.pdf (accessed September 20, 2014).

When there are three contact points, the S-plane exists that cuts through all three contact points. It is at this point where force closure exists.

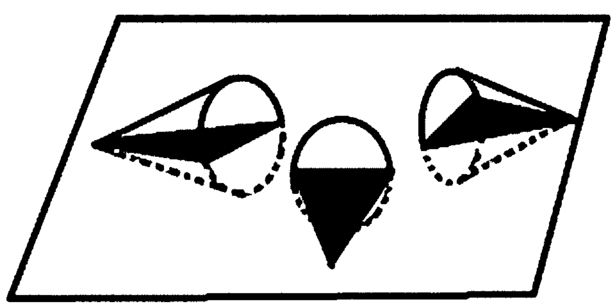

Figure 5. Friction cone for multiple points of contact that all coincide in the S-Plane, INTRODUCTION TO ROBOTICS MECHANICS, PLANNING, AND CONTROL, http://hades.mech.northwestern.edu/images/2/2a/Park-lynch.pdf (accessed September 20, 2014).

Robotic Grasping

There are many multi-fingered robotic hands, those of which have five fingers, like that of a human hand, while others are made to be more simply designed. Studies show that the minimum number of fingers needed to acquire a stable grip is three (Laliberte et al., 2002).

One study was a primary example that focused on the three particular configurations and how to transition from one type of grasp to another.

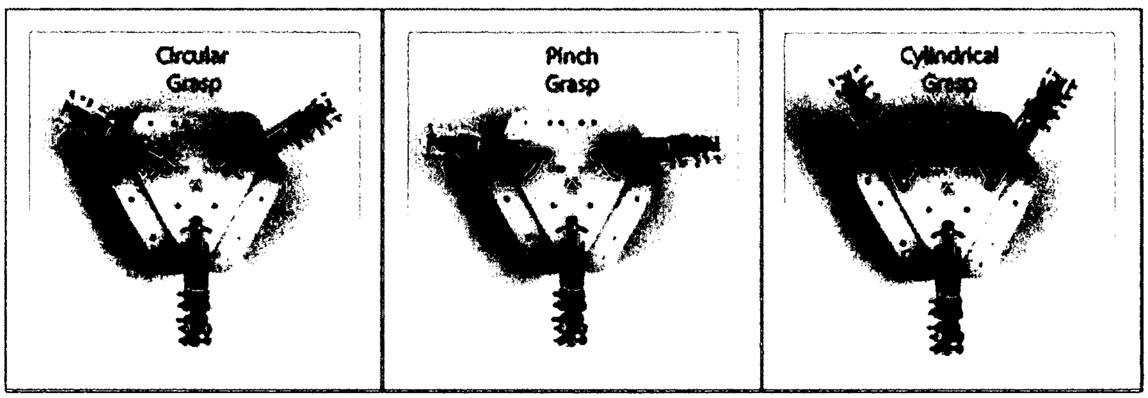

Figure 6. Different robotic hand configurations, UNDERACTUATED HAND , http://mechproto.olin.edu/sp12/final_projects/itt.html, (accessed September 14, 2014).

The study here created a robotic hand that utilizes an adjustable wrist. This wrist allowed for changes in the position of the fingers, altering grasp configurations. The grasps that are depicted above are categorized as circular grasp, pinch grasp and cylindrical grasp. These linkage fingers were based off of the three DOF underactuated finger presented by the study run by Laliberte, Birglen, and Gosselin (Bassford et al., 2012). It must be noted that where circular grip is indicated, in other texts, the same configuration was categorized as a spherical grip.

Cylindrical grasp is described as using three fingers where there are two fingers pointed in the same direction. The third finger in this configuration is pointed in the opposite direction with respect to the other two fingers. A spherical grasp, using three fingers, involve positioning the fingers in a triangle configuration, where each finger linkage is in a 120° position relative to each of the other gingers of the robotic hand. Finally, a planar grasp utilizes only two of the three fingers for this configuration. Here two of the fingers face opposite each other. This grasp gets its name from the method in which it is able to grasp a plane, where the plane is normal to both surfaces of the grasping finger linkages (Laliberte et al., 2002).

Position of the fingers is not the sole important factor involved in grasping motion. The distance left in the center between the finger linkages may be considered the palm of the robotic hand which the robotic hand may grasp properly. The farther the finger linkages are from each other, the larger the space is created to allow for larger objects. Likewise, a smaller palm allows for smaller objects to be grasped more stably With the larger palm, the fingers may be too far apart from each other to grasp the object (Laliberte et al., 2002).

Types of Robotic Grasping

There are several types of grasping achieved with robotic hands that model human grasping. The two most common and widely used are the palm (or enveloping) grasp and the pen (or fingertip) grasp. Both were previously discussed in the section regarding precision vs. power grasp. The palm, or power, grasp is achieved by completely enclosing an object within the hand, utilizing the palm as a touch point to the object. This grasp utilizes geometry of the hand to hold an object still and can be seen here:

Figure 7. Palm Grasp, Sensor Fusion: High Speed Robots, http://www.k2.t.u-tokyo.ac.jp/fusion/HighspeedHand/grasp_type/index-e.html, (accessed September 10, 2014).

The pen, or precision, grasp is much more delicate than the palm grasp. It entails the use of force, rather than geometry, to hold an object still. It is more commonly used for picking small objects and entails a more fine manipulation over the use of the fingertips. The name stems from the grasping of a pen using only the fingertips.

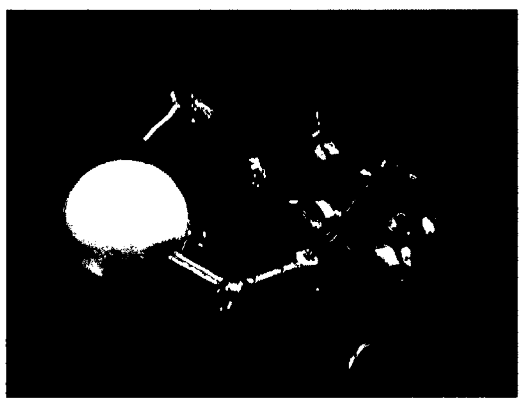

Figure 8. Pen Grasp, Sensor Fusion: High Speed Robots, http://www.k2.t.u-tokyo.ac.jp/fusion/HighspeedHand/grasp_type/index-e.html, (accessed September 10, 2014).

CHAPTER 2

UNDERACTUATED ROBOTIC HANDS

Using robot hands for grasping is both beneficial for time and production costs. There are circumstances however where using a robot would benefit humans; there are jobs where human operators are exposed to dangerous and harmful environments that may cause harm to those completing these task. These particular jobs may necessitate the use of fine manipulation or adaptability. The difficulty with using standard robotic hands stems from the number of actuators necessary to complete such tasks. The complexity of controls, as well as the price needed to manipulate various objects becomes an issue. If instead, underactuated systems are used, complex motions may be executed by robotic hand using simpler methods for control design.

Underactuation involves the use of one actuator to control one dimension of motion that results in multidimensional adaptive motion (Bassford et al., 2012). This underactuation leads to selfadaptibility, allowing a device to work with complexity of movement utilizing a simpler design that allows for easier control development (Laliberte et al., 2002). The benefit of said flexibility allows for a low cost, simple design and the potential for mass marketability, making the field of underactuation quite promising (Wang et al., 2011, 1380).

Underactuation

Robotic hands lack versatility. Robotic hands are typically designed for a particular task or type of object size and shape (Laliberte et al., 2002). Thus, they normally have one purpose and are only configured to approach a specific problem in a particular way. The robotic hand cannot adapt to any changes in environment or situation. This may cause issues where only one hand may be desired. Solutions may become more expensive, as the engineer must decide which robotic hand would be better situated to handle the variety of issues. This limiting factor of robotic hands designed to perform a particular type of grasp, with a set number of objects, is an area of interest for researchers. It has become a goal to create robotic hands that are versatile, able to handle a range of grasps, with a range of objects, while still maintaining a simplistic control structure (Laliberte et al., 2002). It is here where underactuation begins to take shape.

The goal of underactuation is to create a system that has fewer actuators in use in comparison to the number of degrees of freedom the system executes (Laliberte et al., 2002).Here we can say that the robotic hand of our system will have three degrees of freedom, but will only have one actuator at the bottom joint. Therefore this system is considered to be underactuated.

The use of underactuation stems from the complex problems that are posed when an additional actuator is included to a system. The controls needed to guide the system continue to become more complex as more variables become involved; each actuator must be taken into account with any calculation. For example, if more than one actuator is used for a robotic finger linkage, with just the extension and flexion of that linkage, there are more variables to keep account of to be able to model said behavior appropriately. This complexity only increases with the addition of two other finger linkages, resulting in a system that must not only account for the variables created by each actuator, but also increases the range of motion that would be involved in moving a robotic hand to achieve a grasping motion, fingers relative to one another. Therefore, the use of a fully-actuated robotic hand would result in controls that are arduous and hard to model (Laliberte et al., 2002).

Instead, an underactuated system can achieve the same complexity while limiting limiting the number of actuators used with simplified controls. Underactuation allows for the robotic hand to have more variability in its motions resulting from unknowns that the system does not take into consideration (Laliberte et al., 2002). This variability becomes beneficial as it allows for a robotic hand to adjust to differing circumstances, without the complex controls that would normally have to be involved in order to tackle the same situation with a fully-actuated system .We find that less programming is needed to achieve said configurations. These underactuated systems thus adapt to their environment and scenarios, resulting in the case of self-adaptability (Laliberte et al., 2002).

It is therefore seen that underactuated systems are best in use for environments where the environment and needs may change, and an adjustable system would be able to adapt to these changes without any additional complex controls added (Wang et al., 2011), such as a robotic hand adapting to different shapes and orientations of unknown objects. Ultimately, underactuated robotic hands are seen as a cheaper, more adaptable solution for ever-changing environments.

When approaching the robotic hand and its ability to become self-adaptive in various situations, it is able to adapt to the changes in shape so long as it is properly designed in a manner in which the behavior of the robotic hand will automatically adjust without the need of additional motor control for said action (Laliberte et al., 2002). The self-adaptive fingers which utilize an enveloping grasp, have the purpose of adapting to the shape and bringing the object closer to the palm of the robotic hand. With the use of the enveloping grasp, it was found that the forces applied by the finger linkages are evenly distributed amongst all of the finger linkages. In an appropriately designed underactuated system, even when one finger motion is blocked, the rest of the finger. The forces continue to be applied by the finger linkages to the object until this grasp is achieved, or the fingers make contact with the object, or the fingers make contact with the palm of the robotic hand (Laliberte et al., 2002).

CHAPTER 3

ROBOTIC HAND DESIGN

Previously Designed Finger-Linkage

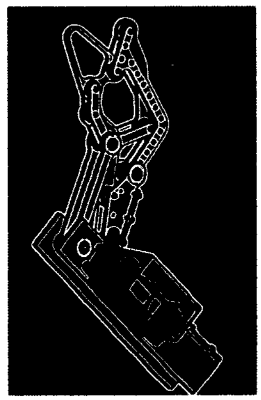

Figure 9. Previously designed finger linkage assembly

The above is a one degree of freedom multi-loop anthropometric finger linkage that has been previously designed by Robson, Allington, and Soh (2014). The design of the above finger linkage was accomplished by obtaining kinematic data of a subject performing pen grasping using both a sensor based glove and a motion capture system by Vicon (Robson et al., 2014). This data was then applied to an eight-bar linkage, chosen for its history of performing well with tracking anthropomorphic trajectories (Robson et al., 2014). Their experiments showed that this finger linkage design closely resembled the trajectory created by their subject performing the same task. The application of the finger as an exoskeleton was later presented by Robson and Soh.

The finger linkage was designed as an underactuated system, where the linkage allows for a bending motion to occur when actuation is applied at the bottom of the finger linkage. The point where actuation must be applied may be seen in the following picture:

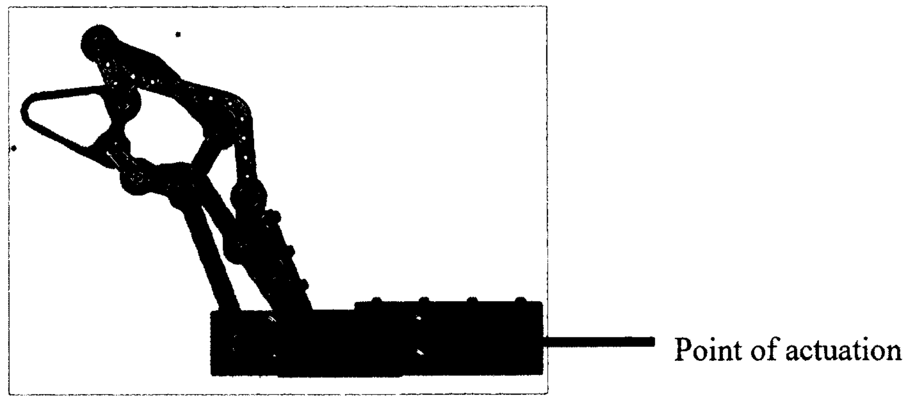

Figure 10. Finger linkage assembly with indication of point of actuation.

Rotation at this point of contact allows for the entire finger linkage to move about this point. See below for pictures of the linkage in the extended and flexed positions.

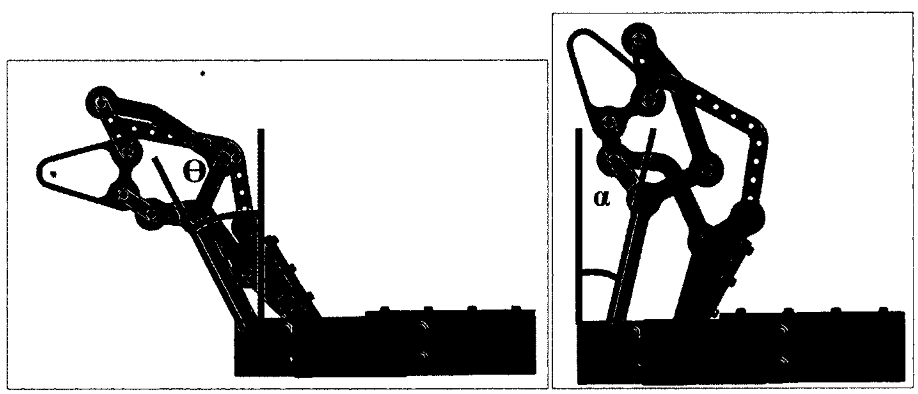

Figure 11. Angle at Extension (Θ) and Angle at Flexion (α) depicted repectively.

The angle of extension (Θ) and the angle of flexion (α) were measured as $\Theta = 25.6°$ and $\alpha = 14.8°$; resulting in a total angle of $\gamma = 40.4°$ with which the finger linkage rotates. As a result, the finger position from full extension and full flexion results in the following manner:

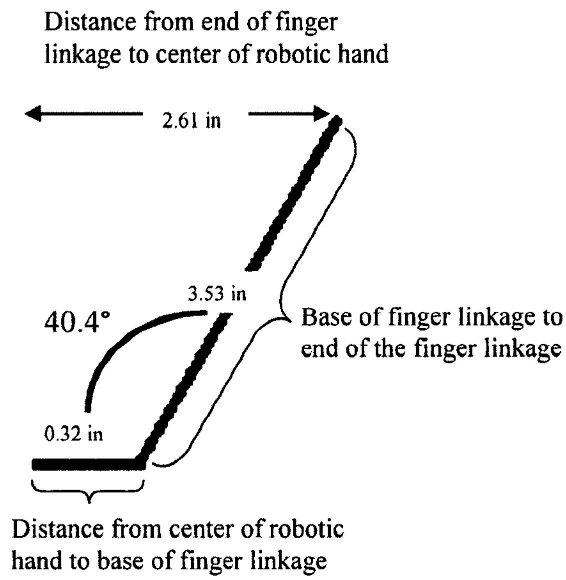

Figure 12. Diagram calculating the size of the grasp from SolidWorks modeling.

Taking the distance of 2.61 inches calculated for the radius of the fingertip to the center of the robotic hand, the largest object size that the finger linkage may grasp must be within a diameter of 5.22 inches.

The linkage is designed as its own subsystem and was tested as a single finger linkage. To counterbalance the weight and movement of the system, an extended brace was included in its design. This brace is highlighted by a green box below. Its purpose is to hold the linkage in a stable position that allows for the rotation necessary to test while still accounting for the weight of the extended linkage.

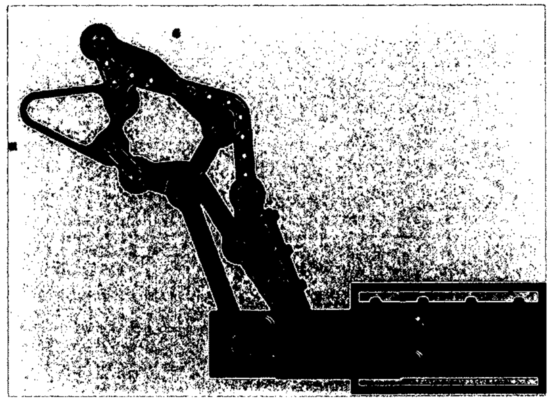

Figure 13. Finger linkage bracket with extended rear.

Design Approach

Initial Considerations

Knowing that eventually the robotic hand would be attached to a UR5 robot arm, seen below, the form of the location where the robotic hand would be attached was taken into consideration.

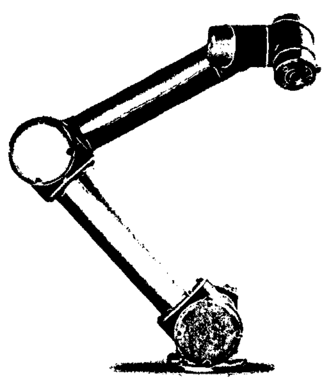

Figure 14. UR5 Robotic Arm, Universal Robots, http://www.universal-robots.com/en/, (accessed September 19, 2015).

The UR5 is a robotic arm that may be used to move objects. It has a reach radius of 33.5 inches and it can automate tasks up to 11 lbs [parallax website]. The UR5 arm is easy to use and program, making it ideal for our research purposes. The technical specifications of the end of the UR5 arm follow:

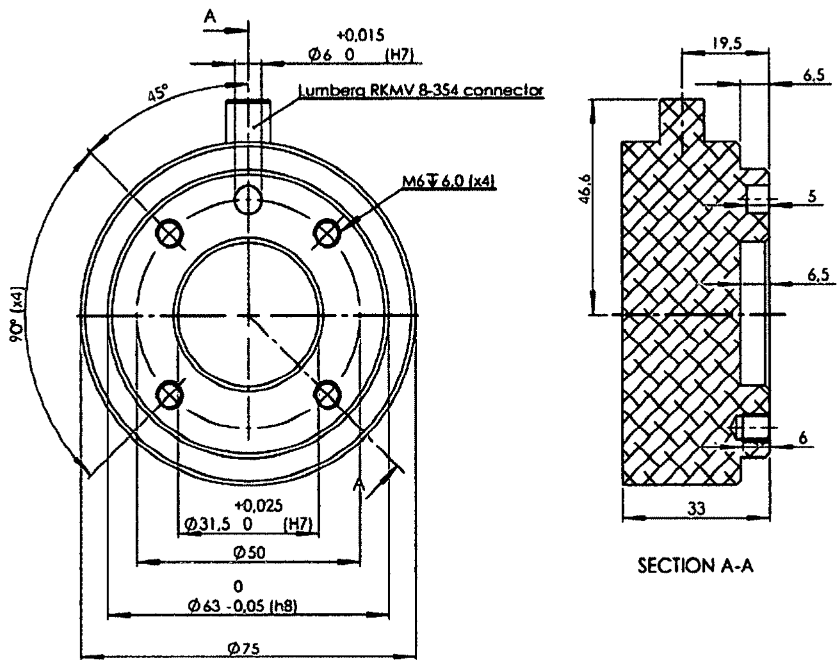

Figure 15. Technical specifications for the UR5 arm connector, Universal Robots, http://www.universal-robots.com/en/, (accessed September 19, 2015).

The location of the M6 screws was recorded as they would provide a means to attach the end effector to the arm. The diameter of the UR5 arm face was also observed as it would provide a guide for dimensioning the base of the robotic hand to be created. The thickness of the robotic hand was measured, as it provided an option to the robot hand involving extending the base of the wrist to wrap around the end, allowing a more stable hold on the end of the UR5 arm. If this last approach was taken, the Lumber KRMV 8-354 connector location would need to be considered in the design, as it is located on the side of the UR5 arm.

After the end of the UR5 arm was measured, the configuration of how the finger linkages would need to be positioned when attached to the wrist of the robotic hand had to be determined. Previously, the configuration of a cylindrical grasp had been utilized to design the single finger linkage. Although the cylindrical grasp had been the initial projected grasp to be used in this project, as the goal was to grasp a pen with the robotic hand, the research conducted pointed in the use of a grasp that may prove more stable, as the cylindrical grasp created gaps between the finger linkages when they were fully extended. Instead it appeared that perhaps a spherical grasp would prove to provide a more stable configuration and allow for smaller objects to be grasped by the robotic hand. Both configurations were used in the infant stage of designing the wrist component of the robotic hand in order to see what type of models they would both create.

Conceptualization and SolidWorks Modeling

As the different wrists of the robotic hand were being designed, the entire finger linkage used in previous testing, including the bracket that created a support system for the finger linkage was included. The position of the finger linkage when it was in its most extended position was also accounted for. The farthest that the finger linkage could move was used as the position the finger would be in to grasp the smallest of our desired objects. The angle was measured that the finger would need to sit at in order for the three of the finger linkages to be in order for the ends of the finger linkages to touch when in their most extended positions. This angle was used in the design of the bracket that the finger linkages would sit on in order to achieve the desired position.

A triangular base was the initial design for the bracket to hold each finger linkage, as it was simple and allowed for implementation of the angle the linkages would need to be positioned for to achieve the desired configuration. The triangular base may be seen here:

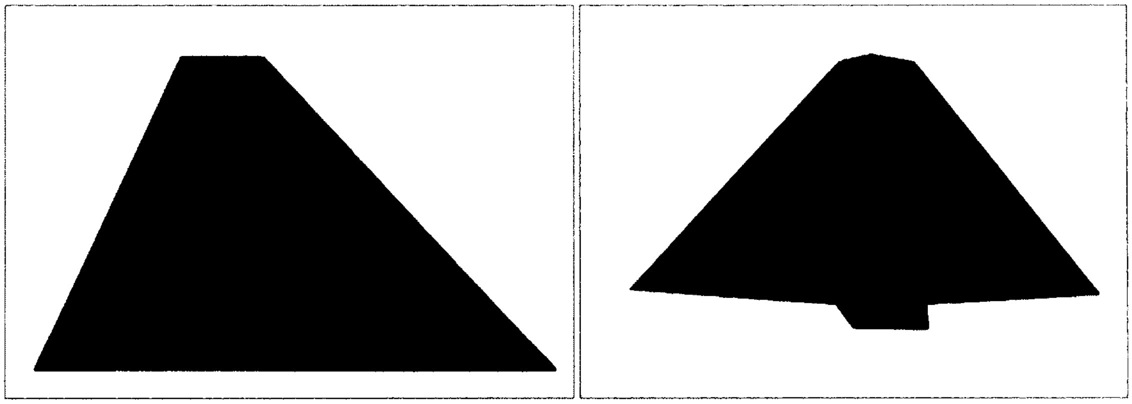

Figure 16. Triangular base in a spherical configuration.

The base was created in two separate setups, one allowed for a spherical configuration whilst the other utilized a cylindrical grasp configuration. Each finger linkage was positioned on the triangular bracket, allowing for the desired finger position relative to the base of the bracket.

Figure 17. Triangular base with attached finger linkage.

Combining the triangular bracket and the two separate configurations, the following format for the wrist configuration was formed:

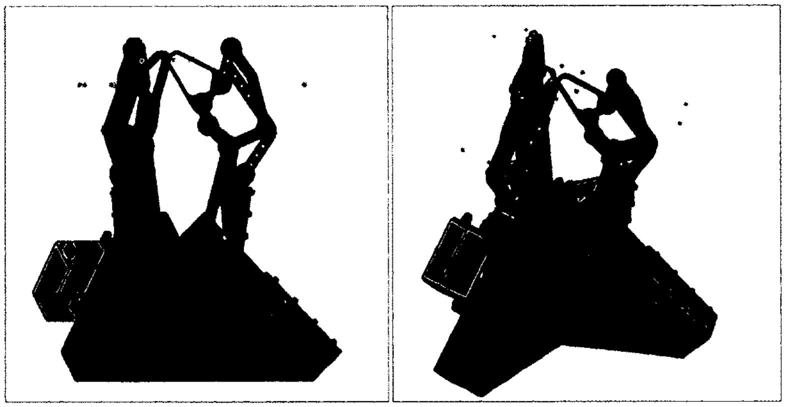

Figure 18. Spherical configuration of the triangular base with attached finger linkages.

Here, the grasp configuration had not been decided upon as it was necessary to see what modeling each grasp would yield. As such, the several wrist configurations were developed.

The following are photographs taken from SolidWorks models created utilizing the cylindrical wrist configuration. The first is a model using the original angle that was calculated. Following this are configurations with the angle at 45° and 42.5°.

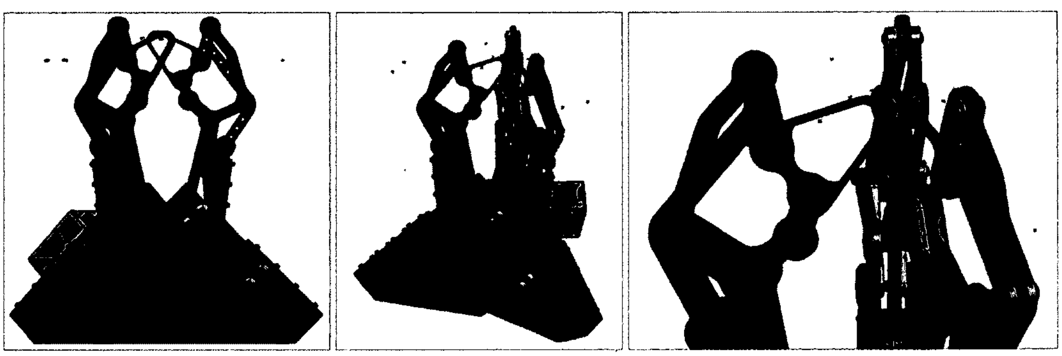

Figure 19. Cylindrical configuration with triangular base and attached finger linkages.

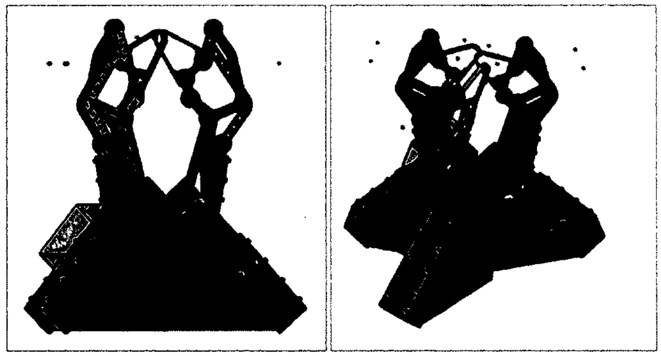

Figure 20. Cylindrical configuration with triangular base angled at 45° with attached finger linkages.

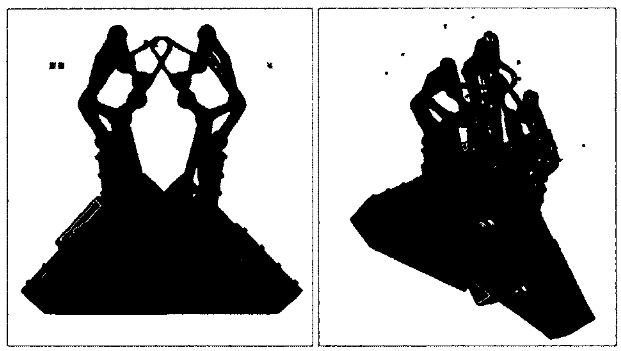

Figure 21. Cylindrical configuration with triangular base angled at 42.5° with attached finger linkages.

What can be noted is that, even when the finger tips are close to each other, large gaps are allowed, leaving the possibility of smaller objects, such as pens, to slip through these.

After attempting to model a cylindrical grasp with varying angles, the same modeling was done using SolidWorks and a spherical grasp configuration. The following are models using the angles of the original calculated angle, 45°, 44° and 42.5°.

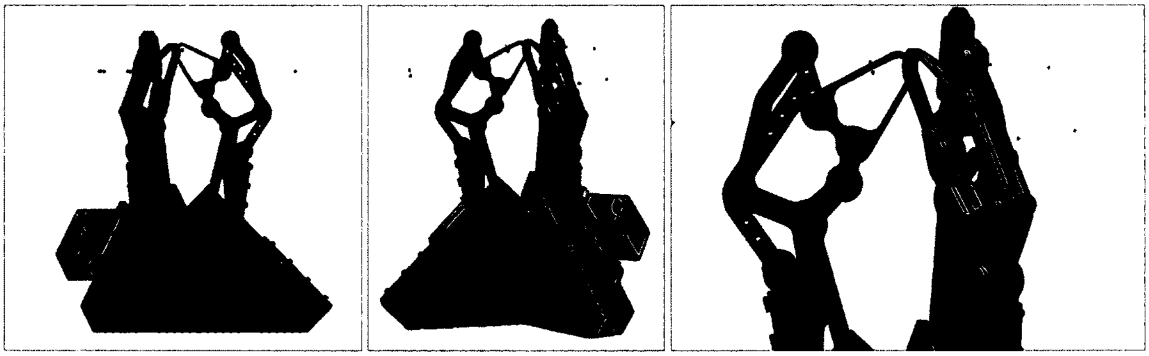

Figure 22. Spherical configuration using triangular base with attached finger linkages.

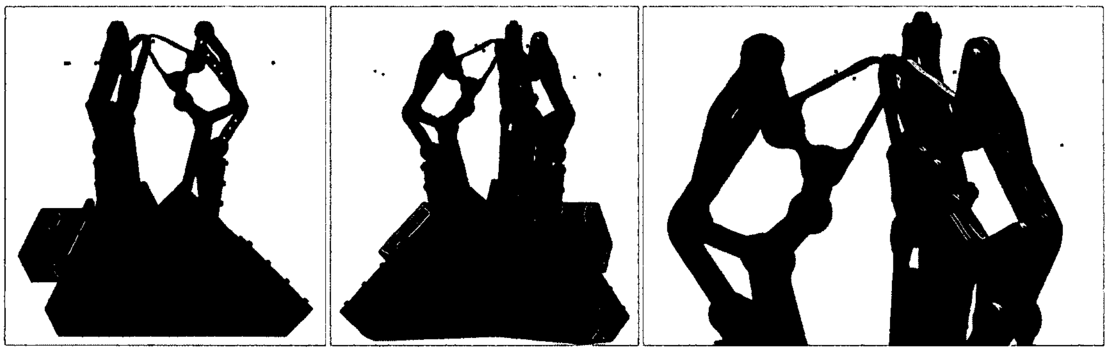

Figure 23. Spherical configuration with triangular base angled at 45° with attached finger linkages.

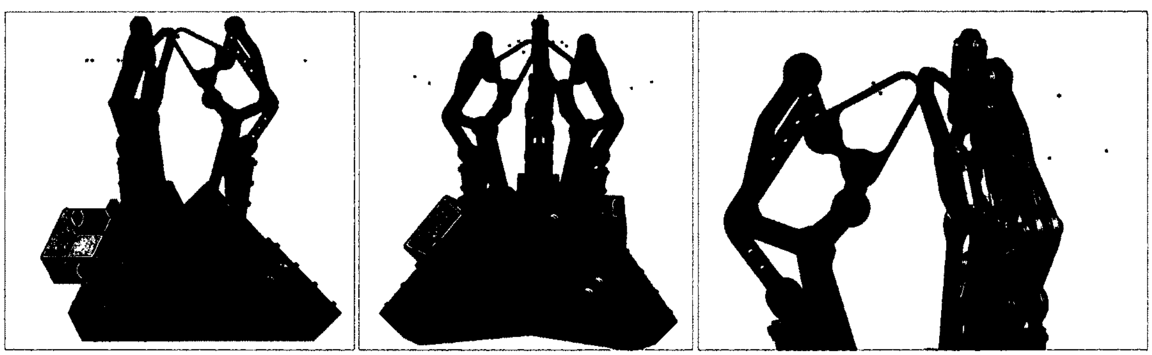

Figure 24. Spherical configuration with triangular base angled at 44° with attached finger linkages.

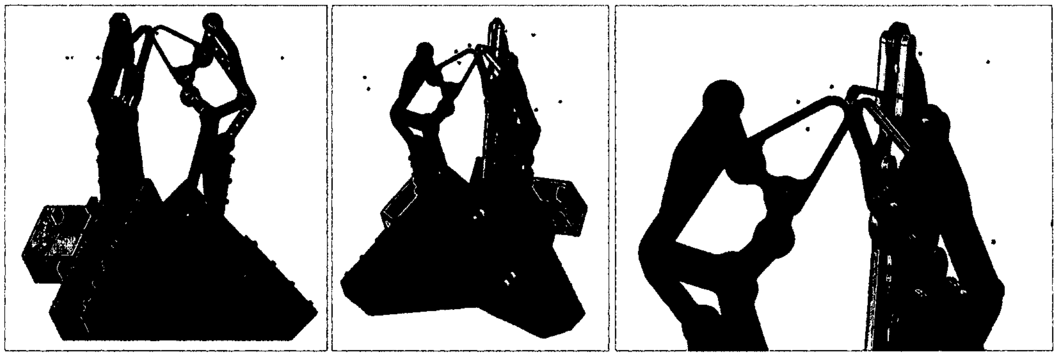

Figure 25. Spherical configuration with triangular base angled at 42.5° with attached finger linkages.

It was noted that the spherical grasp lacked the gaps seen with the cylindrical gaps. It decided at that time, that a spherical grasp would for further modeling.

Now that the grasp type and angle with which the finger linkages would be positioned at was decided, a mechanism to secure the finger linkage to the triangular base was needed. As such, several attempts were made to find the best solution for this. Initially, a rectangular box was attached to the triangular base. Threaded rods were included with the intention of including additional holes to the preexisting bracket holding each finger linkage to the triangular base, using nuts.

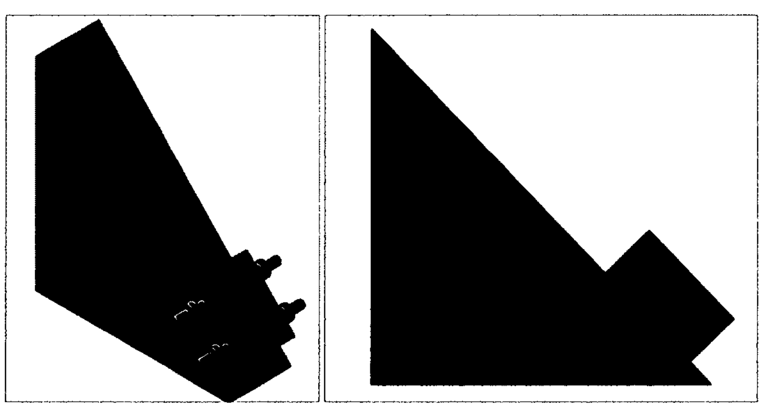

Figure 26. Concept for attaching elongated bracket to triangular base internally.

Another approach attached rectangular pieces to the top and bottom of the triangular base, again utilizing threaded rods and nuts to secure through holes added to the rectangular bracket holding the finger linkages together.

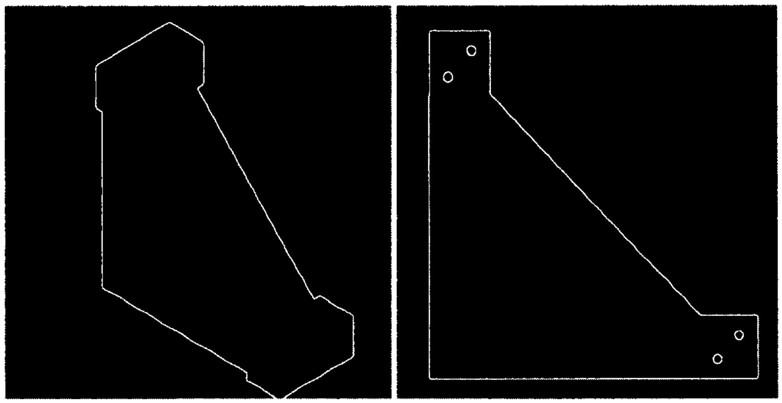

Figure 27. Concept for attaching triangular bracket using external points.

The triangular bracket was deemed to be too much material and the design changed in order to adjust the wrist to be more lightweight. The triangular shape would still be employed, as it allowed for the implementation of the necessary angle with which the linkages needed to be positioned. At this point, an additional feature was included that would allow for the base created to attach to the UR5 arm, as had been previously determined. The following approach is reminiscent of the triangular shape and includes a circular attachment for the end of the UR5 arm.

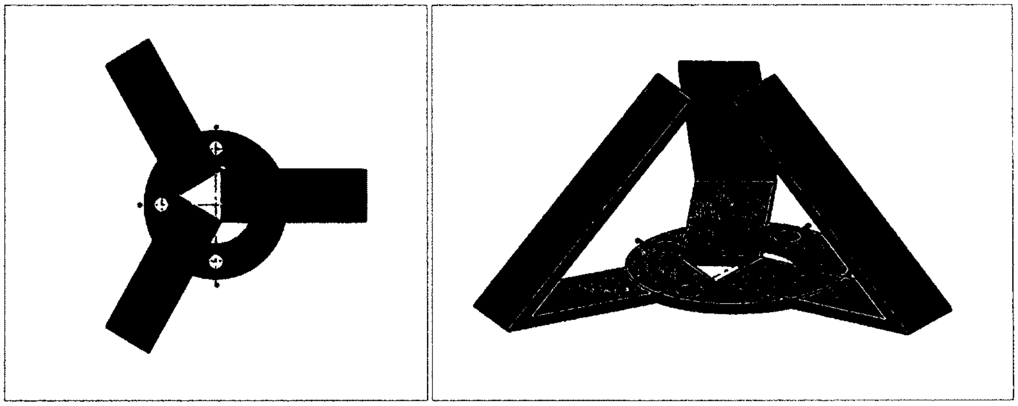

Figure 28. Concept for wrist keeping triangular base and including circular attachment for robotic arm.

The next concept utilized the triangular angle, but instead used a triangular prism central to the finger attachments as a means for stability. The base was extended to wrap around the UR5 arm, in hopes of increasing stability during robotic arm movement. It may also be seen that a notch was included to account for the connector that had been previously discussed.

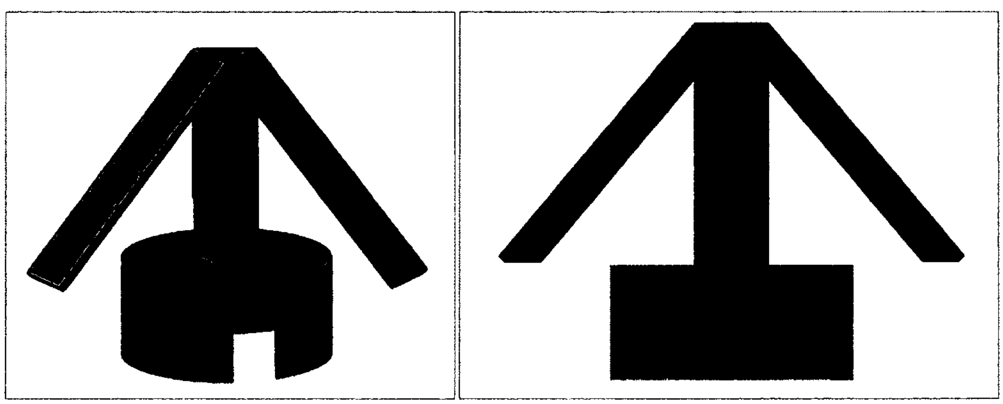

Figure 29. Concept for wrist using triangular base with central support and base that wraps around robotic arm attachment location.

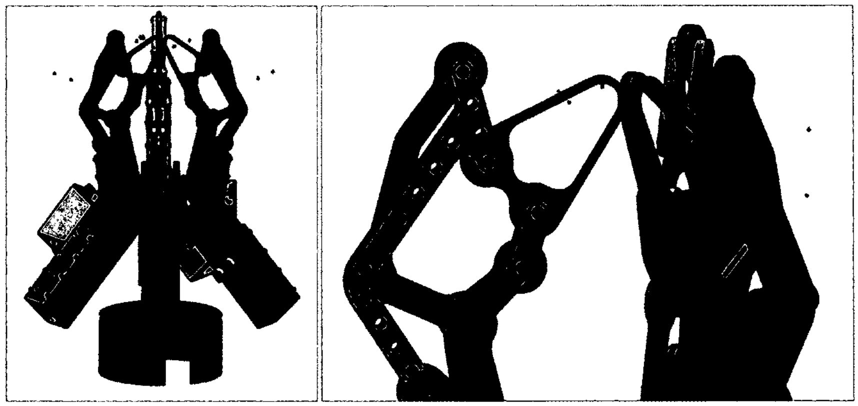

Figure 30. Concept for wrist using triangular base with central support and base that wraps around robotic arm attachment location with attached finger linkages.

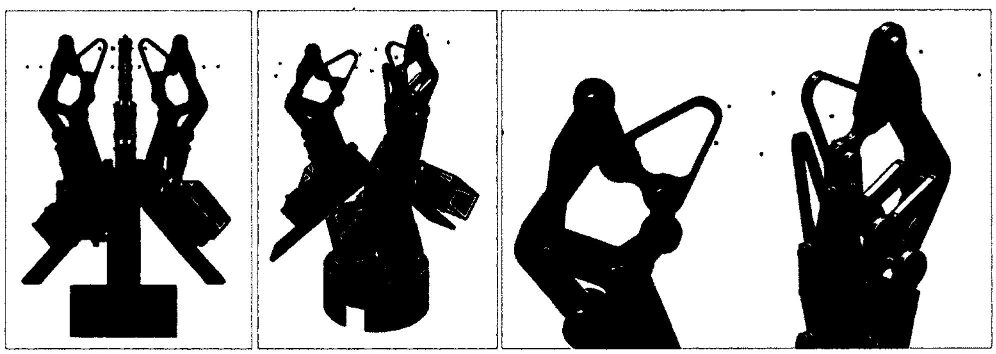

Figure 31. Concept for wrist using triangular base with central support and base that wraps around robotic arm attachment location with attached finger linkages at wider angle.

Another model made took the design previously discussed, but instead the bottom bas was not extended. This was done in hopes of limiting the weight of the end effector. It still maintained the triangular shape and triangular prism in the center of the wrist design for stability.

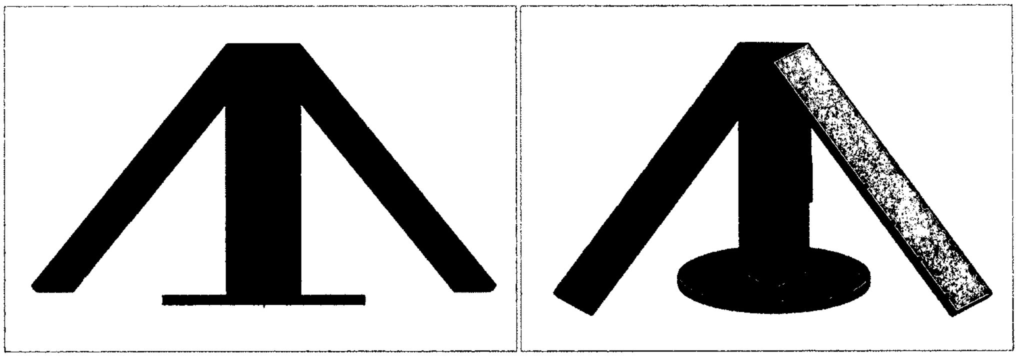

Figure 32. Concept for wrist using triangular base with central support and flat base.

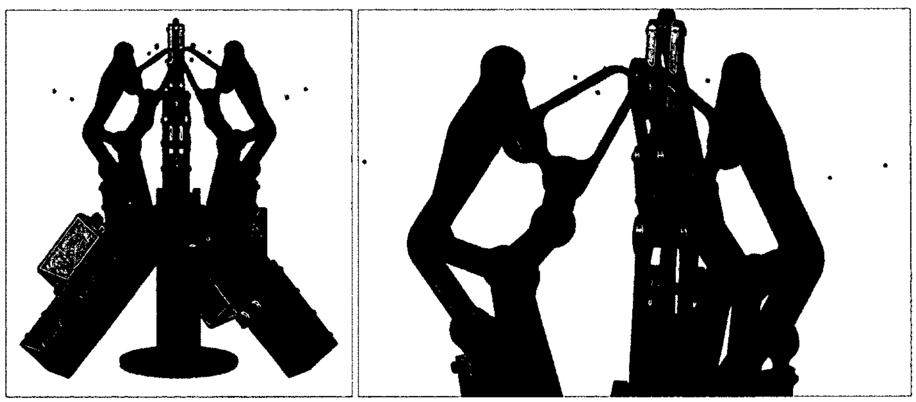

Figure 33. Concept for wrist using triangular base with central support and flat base with attached finger linkages.

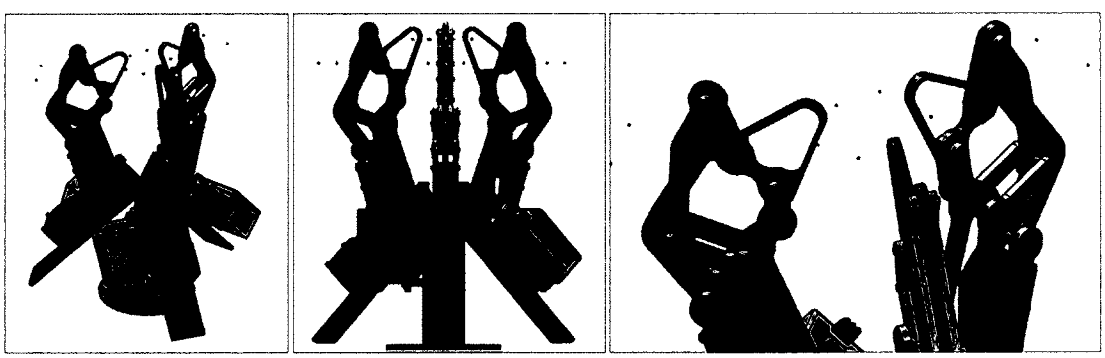

Figure 34. Concept for wrist using triangular base with central support and flat base with attached finger linkages at a wider angle.

A change in location of where support is provided in the model may be seen here. Instead of having support on the central axis of the robotic hand, the wrist uses rectangular supports on the outer edges of the design. Two separate lengths were used for these rectangular pieces, and two separate angles were tested.

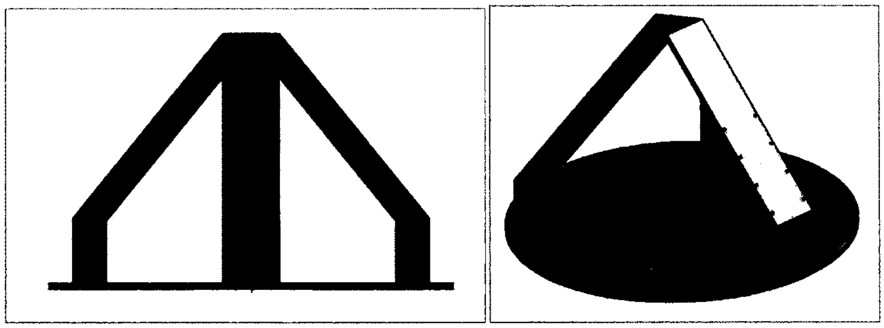

Figure 35. Concept for wrist with exterior support.

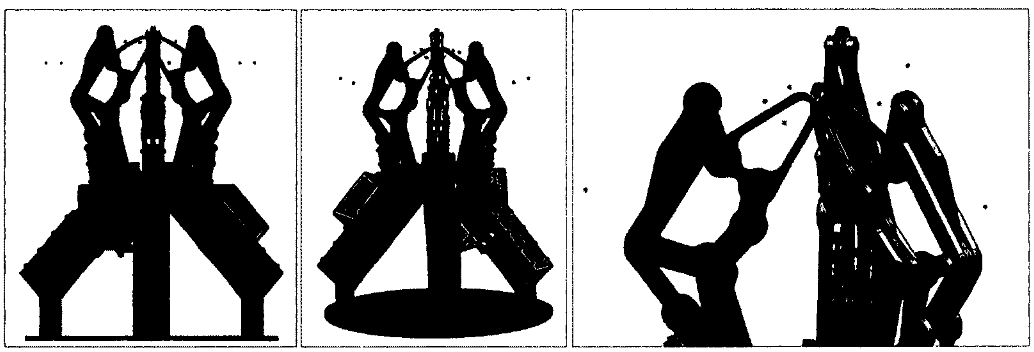

Figure 36. Concept for wrist with exterior support with attached finger linkages.

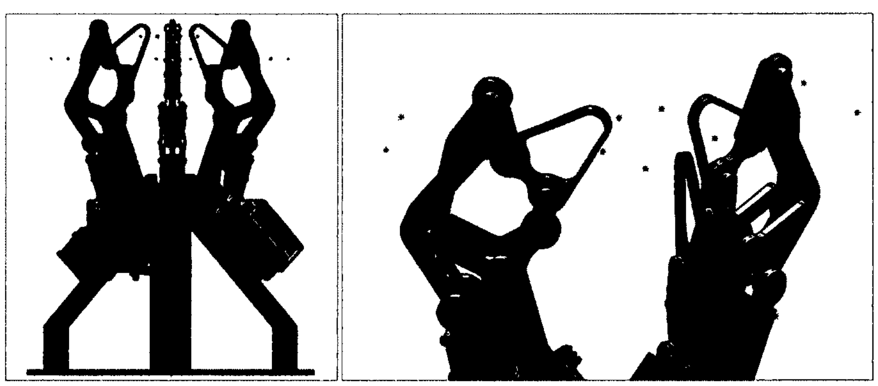

Figure 37. Concept for wrist with exterior support with attached finger linkages at a wider angle.

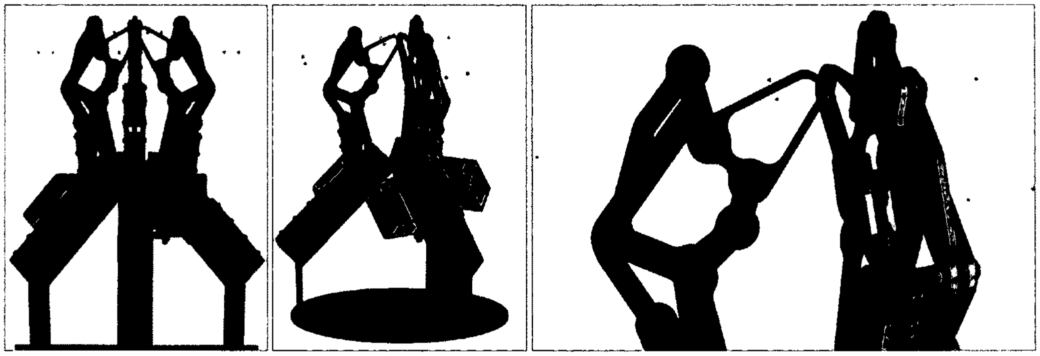

Figure 38. Concept for wrist with exterior support with attached finger linkages and longer rectangular supports.

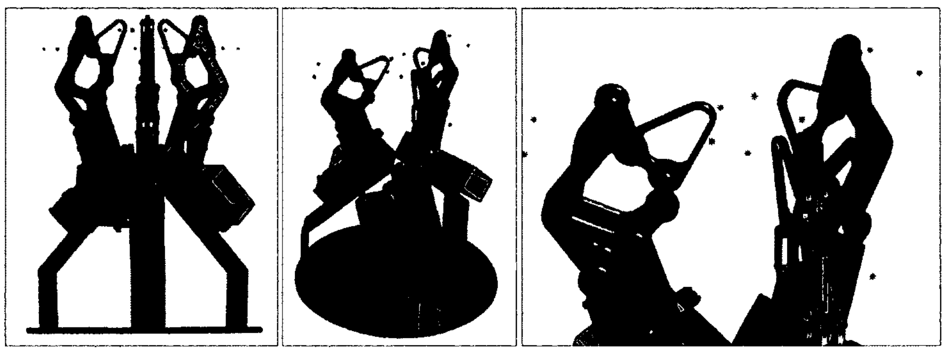

Figure 39. Concept for wrist with exterior support and longer rectangular supports with attached finger linkages at a wider angle.

The final concept in this stage of modeling shortened the distance from the base of the wrist, where the end effector would be attached to the UR5 arm, from the ends of the finger linkages when they were fully extended. To do this the central triangular prism was shortened so that the brackets would be angled off the side where the base of the wrist would attach to the UR5 arm and hang off to the side, with the intention that this would not inhibit grasping.

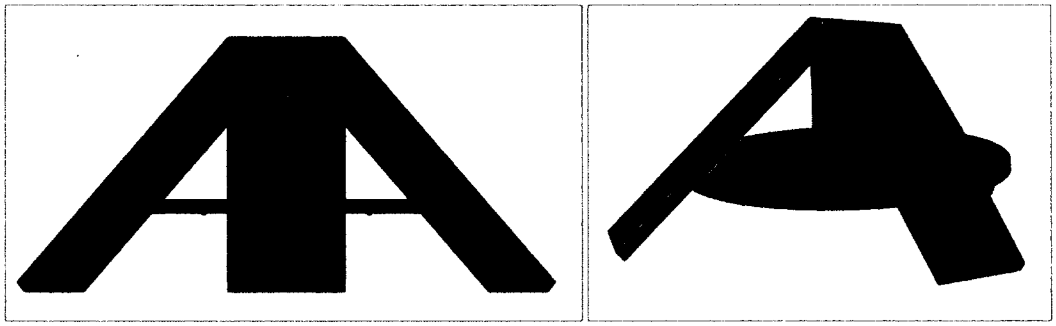

Figure 40. Concept for wrist with shorter central support.

Here there is a change in the approach to designing new concepts for the wrist configuration. Support structures were used at both the central axis and at the outer edges of the robotic wrist design. For the most part the bottom circular base diameter size was altered as experimentation for how large it should be. The length of the inner support structure was also altered in an attempt to finding the best wrist configuration.

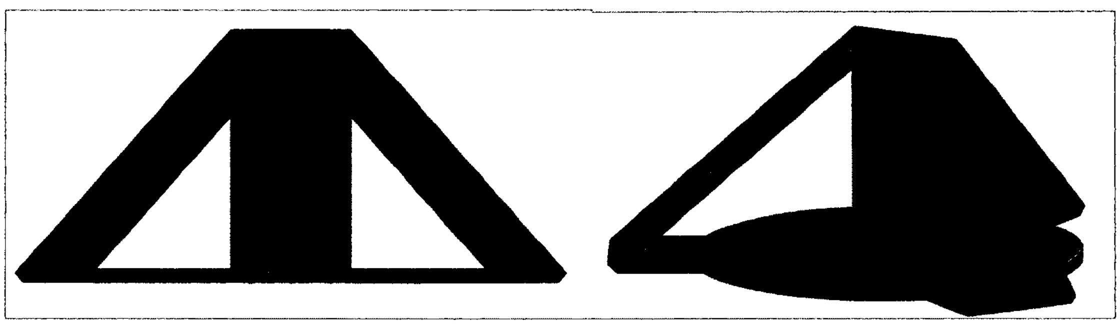

Figure 41. Concept for wrist with triangular flange attached to circular base.

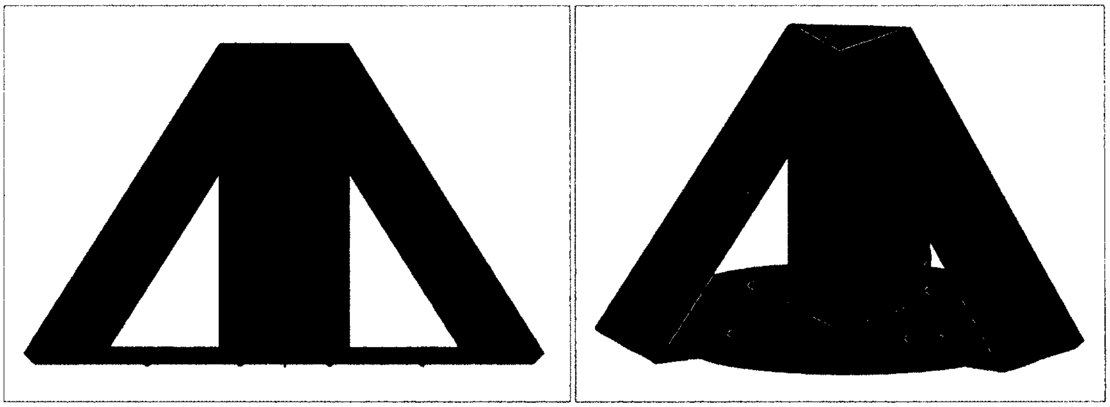

Figure 42. Concept for wrist with triangular flange attached to circular base and longer central support.

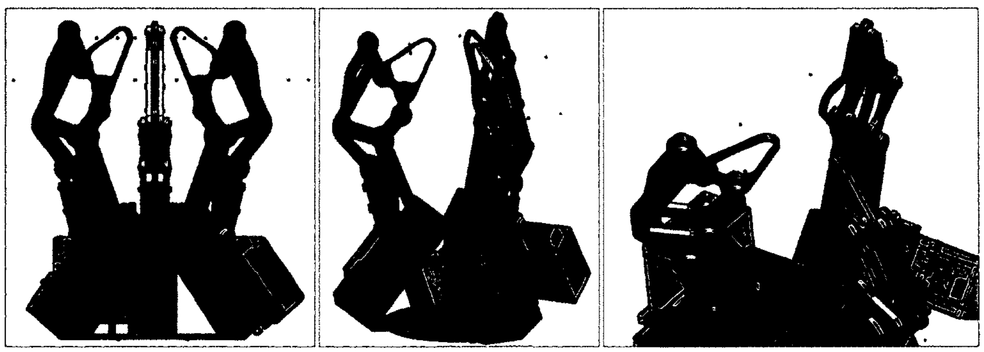

Figure 43. Concept for wrist with triangular flange attached to circular base and longer central support with attached finger linkages.

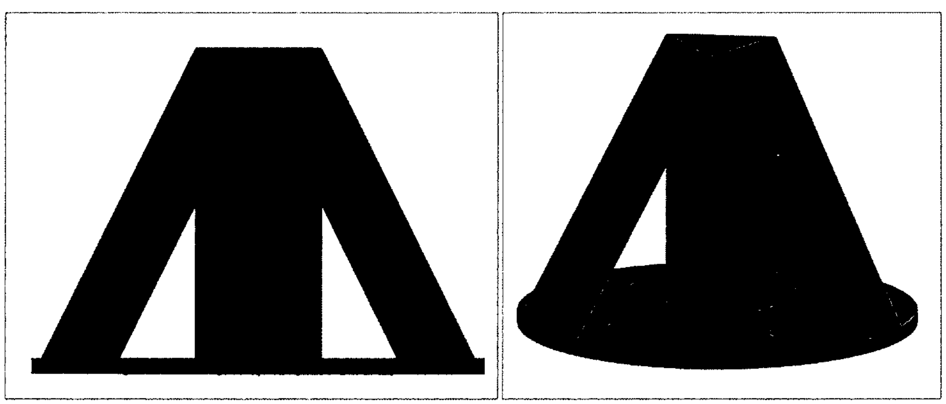

Figure 44. Concept for wrist with triangular flange attached to circular base and even longer central support.

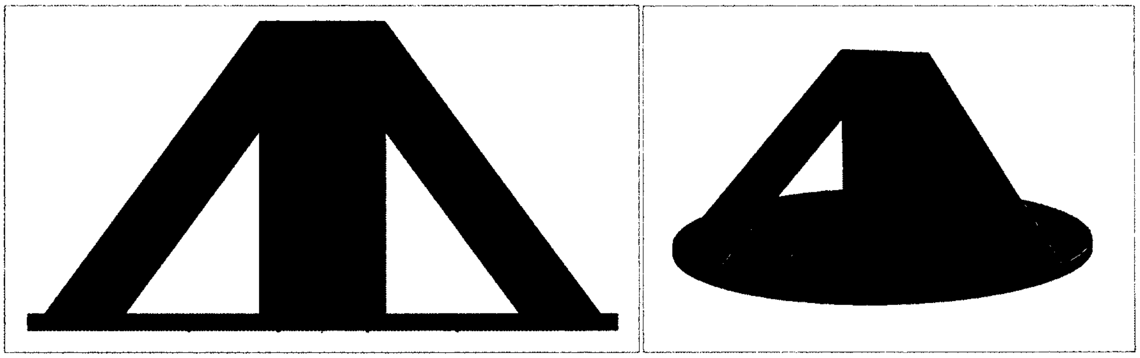

Figure 45. Concept for wrist with triangular flange attached to circular base and extended circular base.

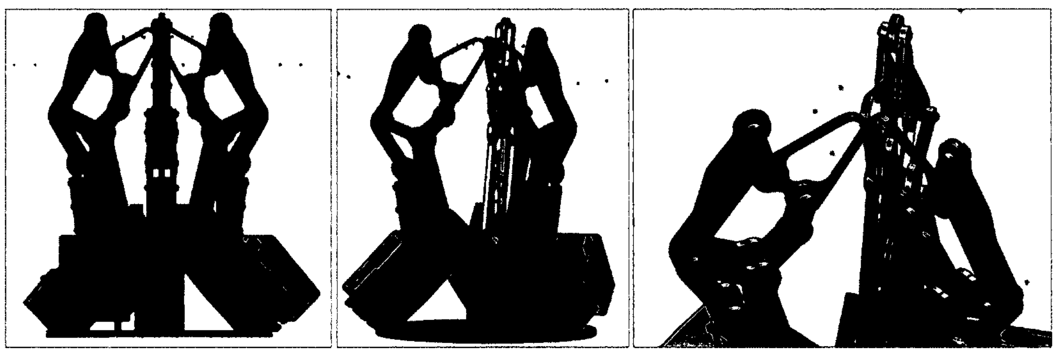

Figure 46. Concept for wrist with triangular flange attached to circular base and extended circular base and attached finger linkages.

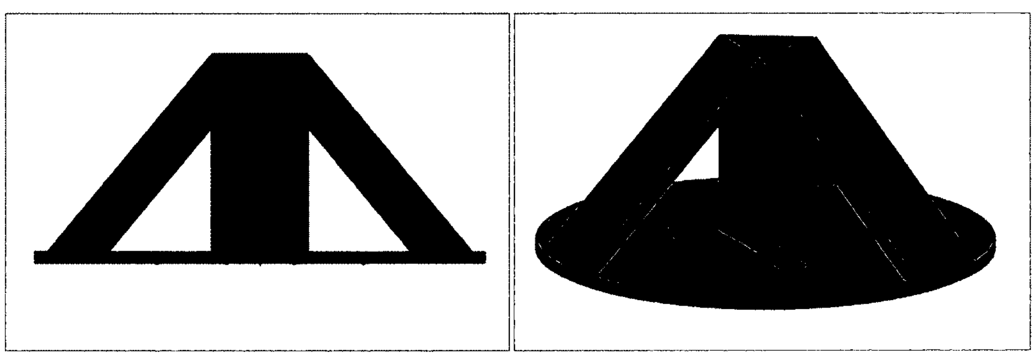

Figure 47. Concept for wrist with triangular flange at wider angle attached to circular base and extended circular base.

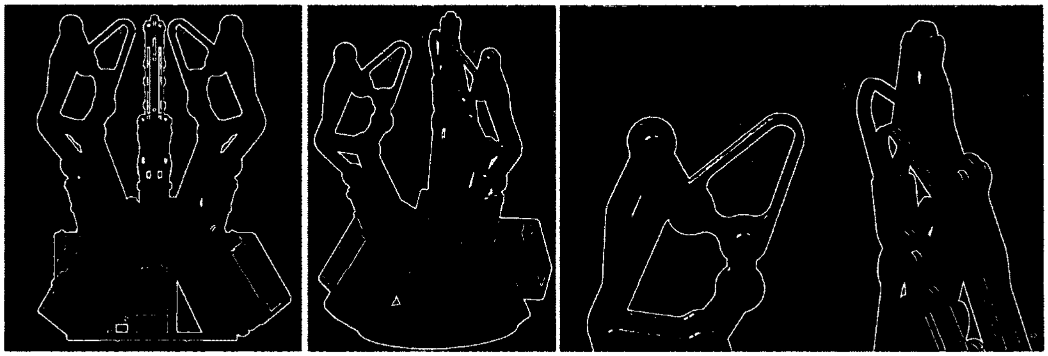

Figure 48. Concept for wrist with triangular flange at wider angle attached to circular base and extended circular base with attached finger linkages.

In the final approach at designing the wrist component of the robotic hand, the rectangular bracket that held the finger linkages was removed. This was done to remove additional components that were not necessary to the function of the finger linkages, allowing for a more compact design that would be easier to build and more lightweight. As this component was now removed, a new bracket was needed in order to hold the finger linkages together.

Here, different designs were needed for the bracket that would hold the finger linkages to the wrist, while at the same time, maintaining the angle with which the fingers needed to be positioned at. Since the design of the finger linkage would now be in a vertical position, although not decided upon just yet, the wrist was designed as simply as possible. The resulting wrist component would resemble the following structure:

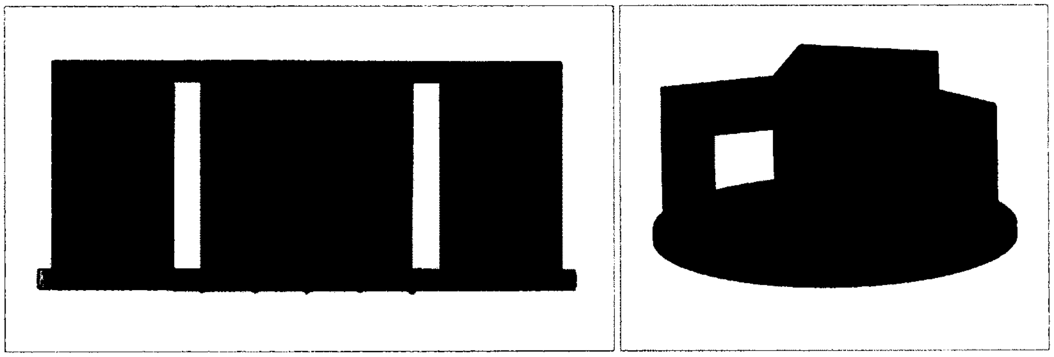

Figure 49. Simplified wrist with flat base at bottom and top

A breakdown of the components of the wrist was at then done in order to facilitate manufacturing. The top surface was made to be flat. A triangular piece was designed so that the finger linkages would maintain a spherical configuration. This piece is seen here:

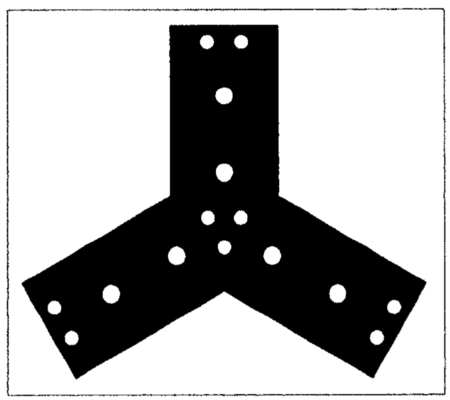

Figure 50. Top base for securing finger linkages to robotic wrist.

A triangular prism was added to provide support to the central axis of the wrist, as had been modeled in previous concepts.

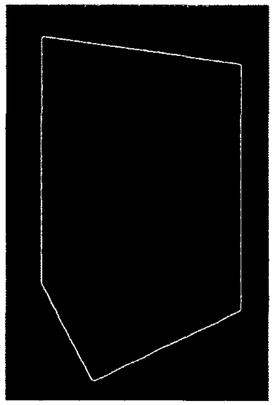

Figure 51. Central support structure for wrist attaching top and bottom bases.

On the outer edge of the base holding the finger linkagès, rectangular supports were used.

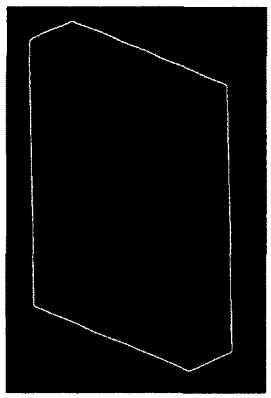

Figure 52. Outer rectangular support structure for wrist attaching outer edges of top and bottom bases.

A bottom base was designed so that the central and rectangular support structures had an attachment provided that could easily be added to the UR5 arm.

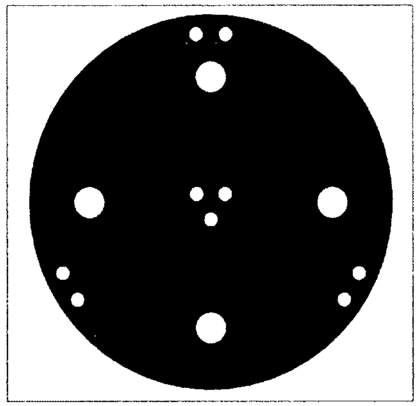

Figure 53. Bottom base of wrist used to attach wrist to robotic arm.

Each separate component would be fully attached using 4-40 machine and flathead screws.

The bracket that held the finger linkages together still had to be designed. Initially, the rectangular nature of the first bracket was maintained and can be seen here. The direction with which the finger linkage sat on the bracket was altered however so that the rectangular bracket would fit horizontally on the new wrist design and maintain the appropriate angle of the finger linkages.

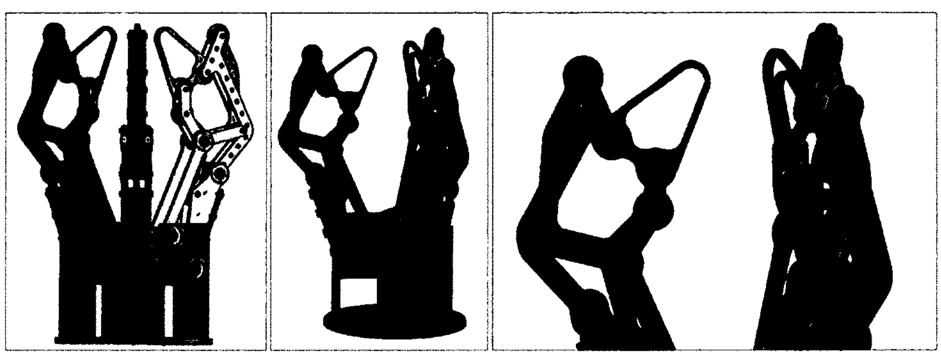

Figure 54. Rectangular bracket attached to wrist with attached finger linkages.

A triangular shape to the bracket was then tested in hopes of minimizing the use of material for the bracket. The angle was maintained from what was used in the rectangular bracket above.

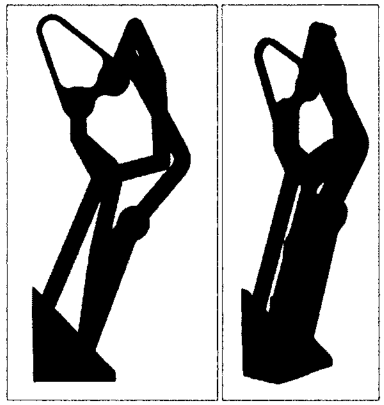

Figure 55. Smaller triangular bracket holding finger linkage together.

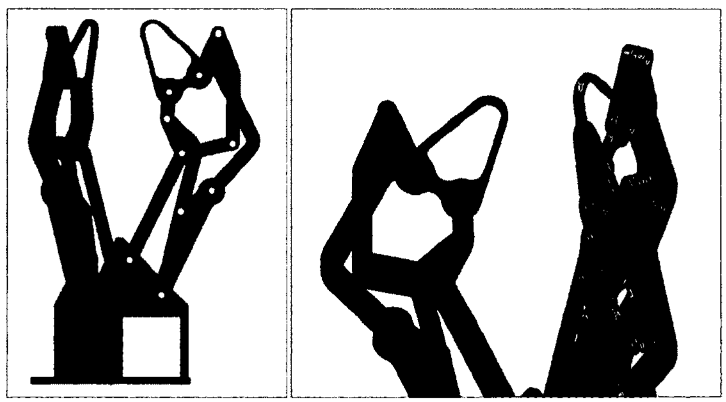

Figure 56. Smaller triangular bracket mounted to wrist with attached finger linkages.

The triangular bracket was then separated into parts that would be easier to manufacture. These separate parts can be seen here:

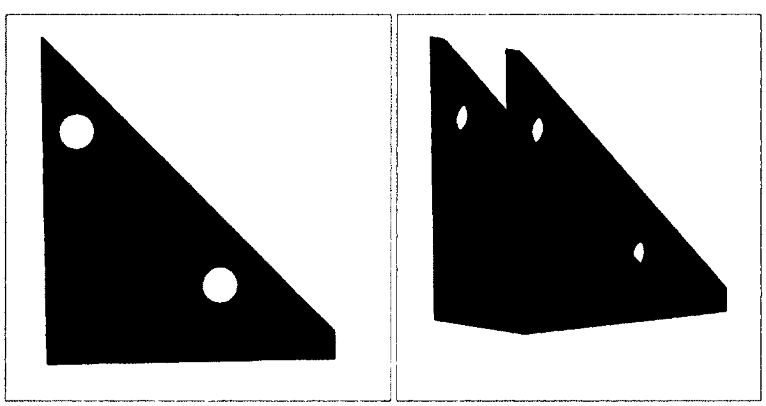

Figure 57. Smaller triangular bracket, deconstructed into three pieces.

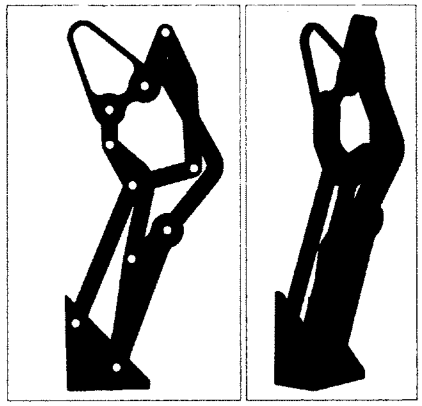

Figure 58. Deconstructed triangular bracket with attached finger linkage.

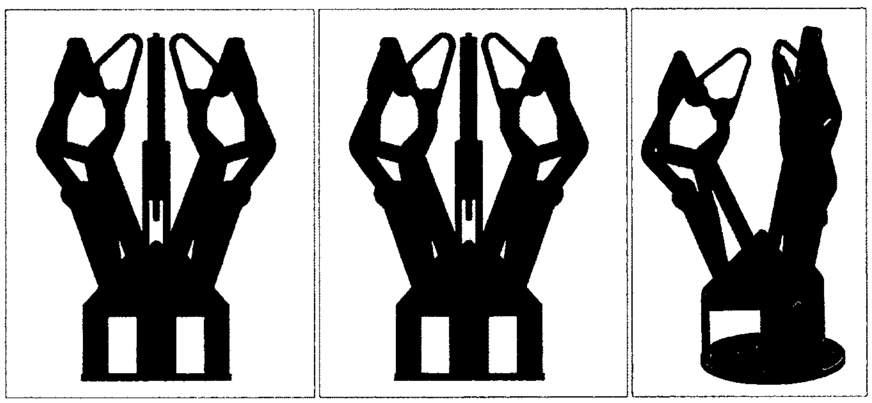

Figure 59. Deconstructed triangular bracket mounted to wrist with attached finger linkages.

When building this triangular base, it became apparent that the holes needed to be adjusted for the hardware that would be needed to join the parts of this bracket together. Space would also need to be accounted for to accommodate the bearings that would be needed in this design as well. Manipulation of the model also indicated that, for the range of motion that was desired, additional space in the bracket would need to be included so as not to hinder the finger linkage motion during actuation.

The resulting bracket provides a flat base for attachment to the wrist component of the robotic hand. The angle was maintained so that the finger linkages would touch at the tips when fully extended. The bracket is composed of three separate parts, two of the triangular topped shaped pieces, and a rectangular piece to hold these two parts together.

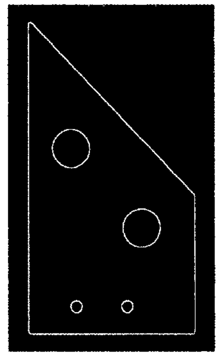

Figure 60. Triangular sides of bracket for holding finger linkages.

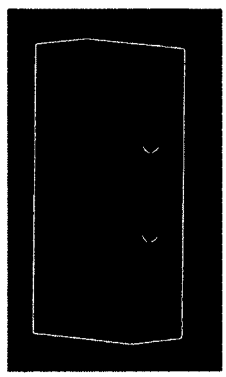

Figure 61. Rectangular bottom to bracket for finger linkages.

The rectangular base of this bracket is then designed to attach to the top portion of the wrist design.

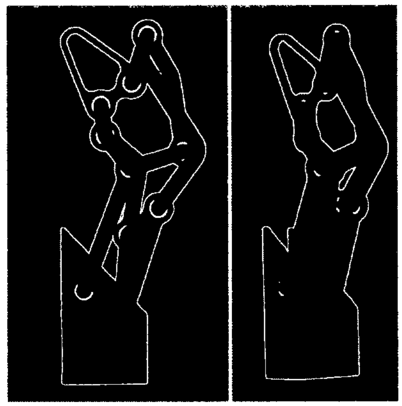

Figure 62. Final angular bracket with attached finger linkage.

Thus the resulting bracket was exchanged to save space and limit weight of the end effector while maintaining the appropriate positioning each finger linkage necessitated. The wrist component was also altered to provide as compact as a design as possible and allow for easy manufacturability. The resulting design can be seen here:

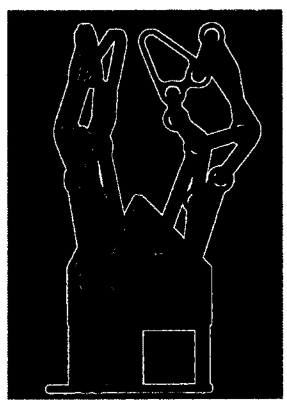

Figure 63. Final angular bracket mounted to wrist.

CHAPTER 4

MANUFACTURING

Process Selection

Discussion with the machinist provided several options that were available for the creation of the robotic hand. The first process was what was initially done; milling all of the parts from aluminum. Next, an option was available to 3D print all of the parts, resulting in a robotic hand made of ABS plastic. A third option available would be to make a hand that was made of a combination of said parts.

An initial decision was made to make the robotic hand using solely 3D printed parts. 3D printing would allow for cheaper materials to be used and a faster turnaround time. If issues were found in the design of the components of the robotic hand, changes could easily be made before the robotic hand was made of aluminum. This was seen as a chance to fully vet the design and find any flaws that could impede the functionality of the robotic hand.

Part Manufacturing

After the robotic hand parts were made, the bearings used as connections between the parts of the finger linkages were press fit into their counterpart holes within each part. This proved problematic as the ABS plastic warped substantially around each bearing. Although most bearings held within the plastic parts, any manipulation of said parts resulting in the individual components breaking. It was therefore found that the ABS plastic would not provide a feasible material to be used for components with which bearings would need to be added. As a result, all of the finger linkages would need to be made out of aluminum by using a CNC machine.

Another discovery when making the robotic hand was that the ABS plastic was too soft to hold any threads added to parts, due to the size of the screws selected for securing the pieces together Discussion with the machinist determined that it would be best to use a secondary, stronger plastic that would maintain the lightweight design desired, while allowing for the addition of threads to these particular parts. This plastic material would thus be used for any parts of the robotic linkage that would need to be threaded.

Building the Prototype

The resulting design was then to consist of three separate materials. Three of the parts would still be used from the 3D printed, ABS plastic. These would be the top and bottom bases of the wrist component and the portion used as a bracket for holding the finger linkage together and allowing for its attachment to the robotic wrist. All parts of the original finger linkage design would be made of aluminum to allow for a sturdy structure for holding the bearings needed in place without any warping occurring within the material. All threaded parts, the triangular and rectangular support structures of the wrist and the rectangular block used in the finger linkage bracket, were made of the secondary plastic material.

Additional hardware was needed, including 4-40 ¼" machine screws were used to hold the bases of the wrist together to the vertical components. 4-40 ¼" flat head screws were used on the bottom so as to create a flush surface that would easily fit onto the UR5 arm. Bearings, dowel pins and shims are also necessary in order to secure the components of the robotic hand together.

An attempt was made to put the pieces of the robotic hand together. The bearings were press fit, first into the bracket that held the finger linkages together, and then each individual part that composed of the entire finger linkage. The bracket had been specially drilled so as to make just enough of a fit to allow for the bearing to be press fit without deformation of the part. The following photograph is of one of the parts with the bearings used to allow for easier motion of the finger linkages at their joints.

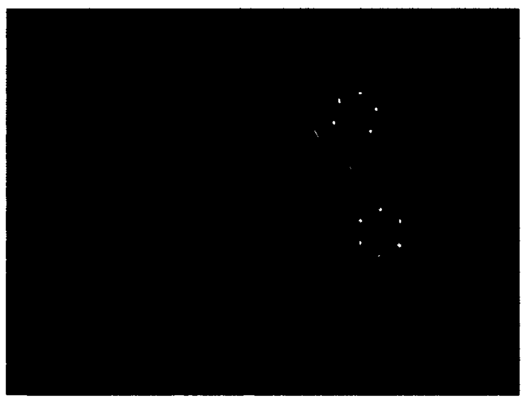

Figure 64. Finger linkage part with press fit bearing in place.

The wrist component was put together next. As can be seen the flat head screws allowed for the flush surface at the bottom of the wrist.

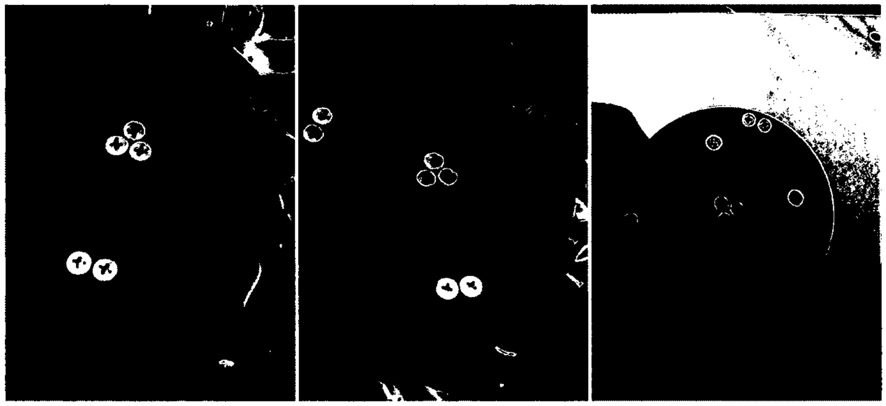

Figure 65. Building wrist component.

These flat head screws secured the base of the plate that would be flush with the UR5 arm to three rectangular prisms on the edges and a triangular prism support structure in the center axis. These would act as support for the second base that is seen on its own below:

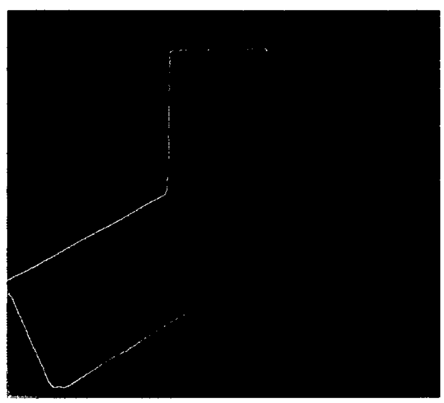

Figure 66. Direct support base for finger linkages.

Finally three thicker rectangular prisms were added to allow for the finger linkages to be attached. The resulting wrist can be seen here:

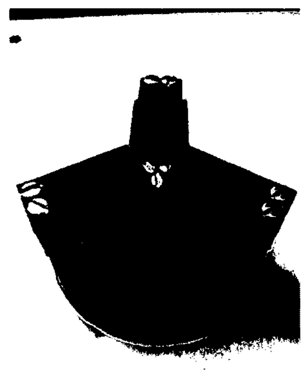

Figure 67. Final wrist component, fully built.

The last sets of parts to be put together were the finger linkages. They can be seen below:

Figure 68. Finger linkage parts, waiting for assembly.

This proved to be difficult as the finger linkage parts fit together in differing levels, resulting in parts that did not fully sit in the appropriate place they needed to without some brace. A plan was then formed to pre-wire the parts together so that, when assembling using the dowel pins by press fitting the parts together, the parts were already in the appropriate configuration and the number of shims needed would be recorded.

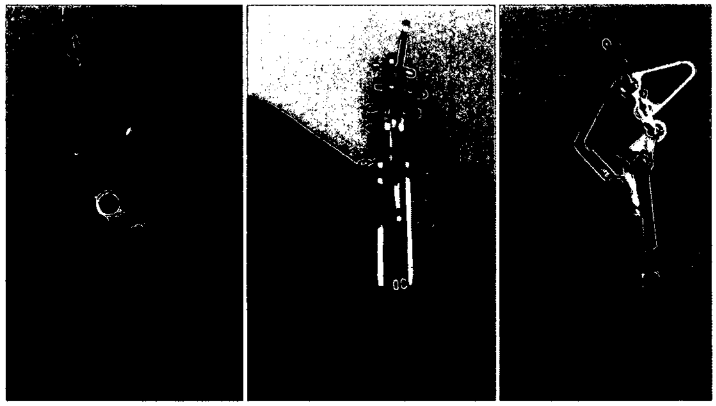

Figure 69. Prewired finger linkage, waiting for assembly.

The next step in building each finger linkage was to press fit each piece together using dowel pins. The method that needed to be followed was to build the finger linkage in layers. The next photograph is during the process of press fitting, demonstrating this method of building the finger in layers. It was necessary to consider which parts lay in the same plane, as well as whether any additional distance was needed between each part.

Figure 70. Building the finger linkages.

This was done so that the parts would be able to be added in a manner that would allow for accurate placement of each piece. For accuracy, shims were used during press fitting to ensure the distance between parts. Once each finger linkage was finished, it was attached to the wrist component. Adjustments were made to the finger linkages depending on how their movement felt when the finger was extended and flexed whilst on the wrist component of the robotic hand.

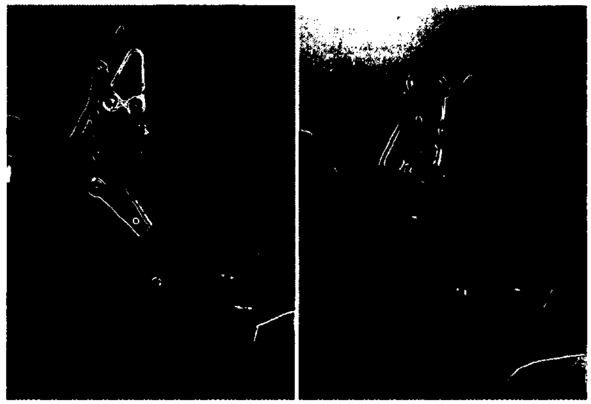

Figure 71. Building one finger at a time.

Once the final finger linkage had been properly built, it was attached with the other two to the wrist assembly. This resulted in the configuration shown below.

Figure 72. Finger linkages fully assembled.

During the pre-wiring stage, it was found that there were structural issues with the manner in which the motor would attach to the finger linkage itself. A bracket was designed and manufactured to hold the motor at an appropriate location so that the motor flange would be attached to the finger linkage, allowing for the motor to drive the rotation of the robotic finger linkage that it is attached to. The additional bracket designed can be seen in the following photograph.

Figure 73. Motor bracket to allow for motor to be attached to finger linkages.

It is composed of two pieces; a rectangular plate that is attached to the bracket that holds each finger linkage together and a block that is attached to the plate. It allows for the motors to be attached at the other end.

Figure 74. Wire attached to motor arm to rotate finger linkage.

A wire is threaded through the motor and attaches to the bottom part at the back of the finger linkage. When the motor turns it moves the back part relative to its own movements. The final configuration of the robotic hand may be seen here. It is depicted with the finger linkages both fully extended and flexed.

Figure 75. Robotic hand with extended finger linkages.

Figure 76. Robotic hand with flexed finger linkages.

To test the design of the wrist, the robotic hand was then attached the UR5 arm as can be seen here:

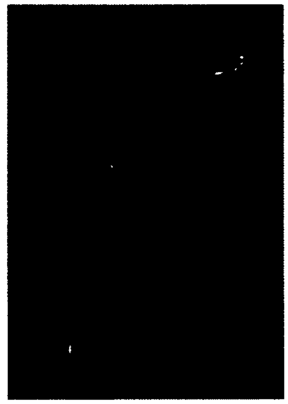

Figure 77. Robotic hand attached to robotic arm.

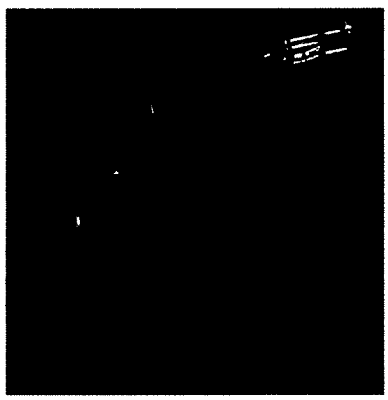

Figure 78. Robotic hand attached to robotic arm - close-up.

CHAPTER 5

ROBOTIC HAND APPLICATION

Control System

While waiting on the manufacturing of the robotic hand, components for actuation were selected. A controller had originally come with the single finger linkage that was used to manipulate its movements. Unfortunately, said controller was only usable on a Windows XP computer. It was decided that because Windows XP was no longer supported, it would be best to use a different controller for the actuation of the robotic hand. An Arduino Uno was selected as the best option for our applications. The controller would be able to handle the number of motors we would need to control. Arduino controllers are also widely used, allowing for a large network of information to pull from when it was time to design a program to control actuation. The following is a photograph of an Arduino Uno:

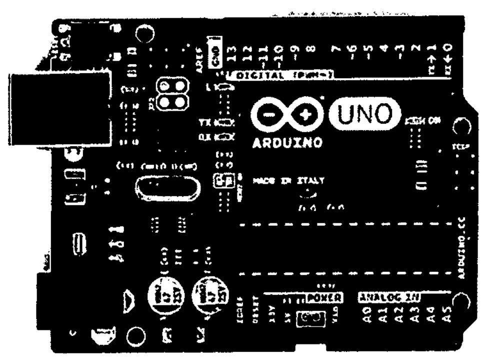

Figure 79. Arduino Uno, ArduinoBoardUno, http://arduino.cc/en/main/arduino BoardUno, (accessed December 12, 2014).

A motor was also selected for actuating the finger linkages. A motor would be needed at the point of rotation for each finger linkage, with a total of three motors. The motor model that was selected was the Parallax 900-00008 continuation rotation servo. It is compatible with the Arduino Uno, allowing for ease of use with the controller. The motor can be seen here:

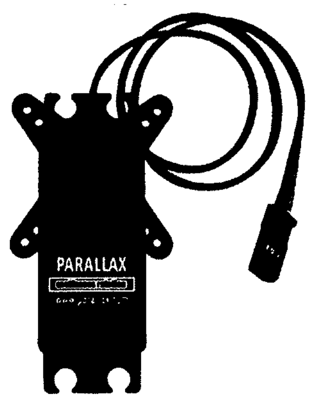

Figure 80. Parallax Continuous Rotation Servo, Parallax Continuous Rotation Servo | 900 - 00008 | Parallax Inc, https://www.parallax.com/product/ 900-00008, (accessed December 12, 2014).

The dimensions of the motor were taken into account when the motor attachment was designed. The schematic for this motor follows:

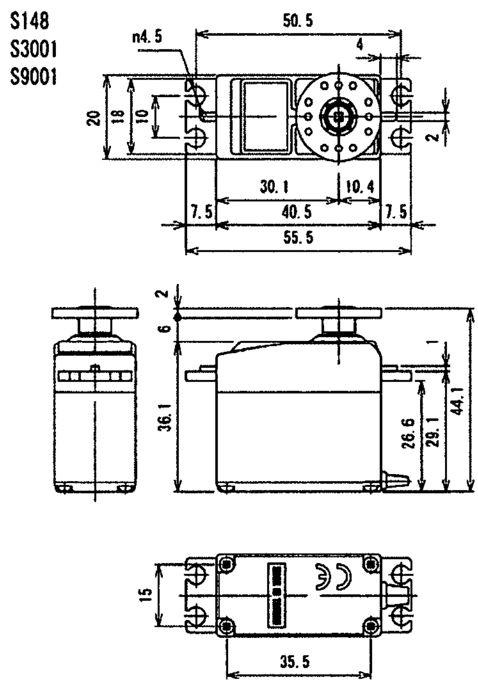

Figure 81. Servo Dimensions, Parallax Continuous Rotation Servo | 900 - 00008 | Parallax Inc, https://www.parallax.com/product/900-00008, (accessed December 12, 2014).

Preliminary Testing of Robotic Hand Grasp

Manufacturing of the finger linkages accounted for more time than was originally estimated. As such, the controls for the robotic hand were not designed. This will take place at a later date. In order to view the robustness of the design, preliminary testing of the grasp of the robotic hand was run. To do so, several household objects were used. Photographs of this preliminary testing may be seen in fig. 82, which shows that the robotic hand is capable of holding objects of varying shapes and sizes.

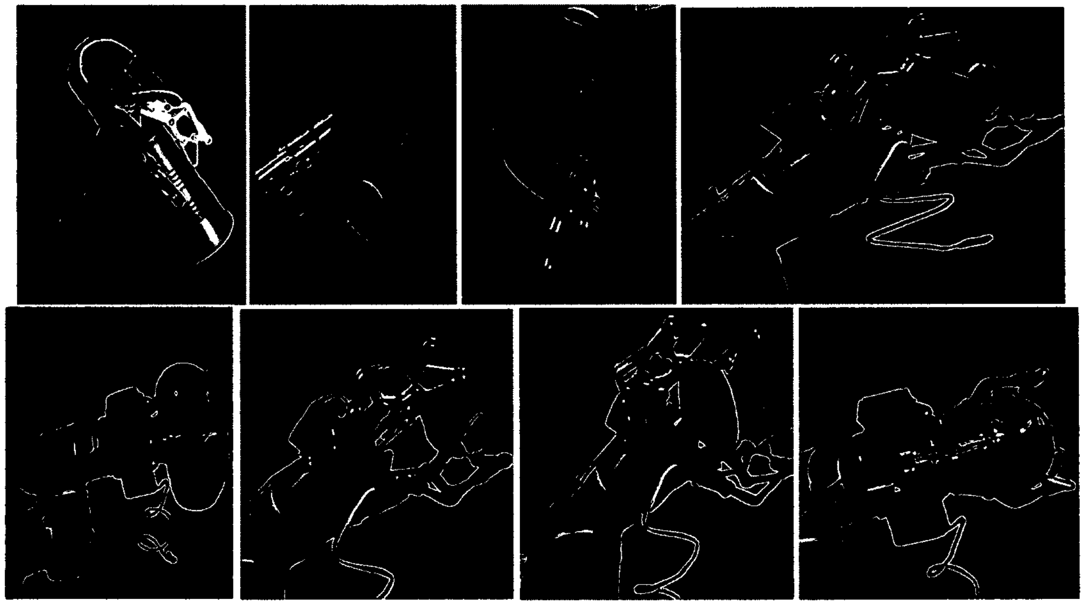

Figure 82. Grasping plastic cup

CHAPTER 6

CONCLUSION AND FUTURE DIRECTIONS

Future design modifications will take into account the distance between the fingertips. Although the hand had been modeled so that the finger linkages touched at the center when fully extended, this was not the case in the actual prototype. Either a new bracket will need to be designed or extensions may be added to the fingertips to allow for full closure of the robotic hand.

The support structures of the robotic hand may also need to be extended as they were made to be as compact as possible, resulting in a design that is difficult to attach to the UR5 arm. An additional half of an inch of height would most likely be the maximum distance needed to create a more ergonomic design.

Additionally, modifications may also be made at the motor attachment to allow for a more stable configuration. As of now, the motor is not directly attached to the bearing location where the point of rotation is located. As such, the axis that the motor rotates differs from the axis that the point of rotation occurs. The bracket will also need to be altered should the type of motor used be changed.

As can be seen, I was able to apply the research found regarding robotic hand configurations for grasping to create a robotic hand that utilizes underactuated finger linkages. The robotic hand is capable of attaching to the UR5 arm. Although time ran out for actuating the finger linkages, the parts have been chosen in order to accomplish this task. Even though I was unable to test grasping using this robotic hand, I was able to show that it is capable of grasping objects of varying sizes and shapes with preliminary tests.

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