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Design, fabrication and testing of ModBot, the biomimetic, backdrivable, modular finger robot

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Design, Fabrication and Testing of ModBot, the Biomimetic, Backdrivable, Modular Finger Robot.

A Thesis submitted in partial satisfaction of the requirement

for the degree Master of Science

in

Engineering Sciences (Mechanical Engineering)

By

Michael Scott Kelley

Committee in charge:

      Professor Raymond de Callafon, Chair
      Professor Nathan Delson
      Professor Frank Talke

2011

The Thesis of Michael Scott Kelley is approved, and it is acceptable in quality and form for publication on microfilm and electronically:

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Chair

University of California, San Diego
2011

TABLE OF CONTENTS

LIST OF TABLES AND FIGURES

LIST OF EQUATIONS

ABSTRACT OF THE THESIS

Design, Fabrication and Testing of ModBot, the Biomimetic, Backdrivable, Modular Finger Robot.

by

Michael Scott Kelley

Masters of Engineering Sciences (Mechanical Engineering)

University of California, San Diego, 2011

Professor Raymond de Callafon, Chair

The work in this thesis introduces a new type of biomimetic fully backdrivable modular robotic finger that makes use of low friction joints actuated by cable drives to achieve given tasks such as reaching, grasping fragile objects and applying force to surfaces. The ModBot finger is a 3 degree of freedom finger that has the capabilities to process force and touch sensation at and along the tip of the finger while retaining all capable movement and degrees of freedom achieved by a human finger.

Every piece of the ModBot finger has evolved many times in order to shed weight, lower inertia and achieve a backdrivable system. To achieve a true backdrivable system gears could not be used, due to the backlash, friction had to be reduced to its smallest value, weight was optimized for a high strength to weight ratio and part shapes were carefully engineered to achieve a low inertia, all of this allows for a smooth operating joint. This is all achieved with a minimal amount of parts used per finger.

The contribution of this thesis is to create a modular finger robot that is fully backdrivable, biomimetic and that does not use gears. The second contribution is to optimize the design of the robot utilizing different materials, mechanisms and sensors to achieve near frictionless movement. The final contribution is to design the robot that can be modular, so that it can placed in various positions with multiple fingers to accommodate a given situation or test setup.

1. Introduction

Ever since audiences' experienced Fritz Lang's masterpiece Metropolis in 1927, robotics have incited wonder and fascination in the public eye. Scientists and Engineers have always known the benefit of robots and have been building robots to further human's existence and better our lives since the dawn of time. Hollywood movies have taken robotics and imagination to the next frontier with futuristic movies about fully mobile robots capable of artificial intelligence, morphing robots and even human replica robots. While all of this is nice to ponder and watch on the silver screen, researchers are not too far behind, and with continued funding and research, robots will soon assist us with many facets of our already busy lives.

Researchers have known that to understand how we, as humans, function and operate we must design, create and test different biological systems that mimic our diverse musculature and intricate nervous system. By creating biomimetic robots, robots that mimic their target biology, we can better understand how we interact with the world and can also gain insight into how human bodies work and process information. Touch and sense is a major part of our nervous system and is a necessary part for humans to correctly interact with their environment. As humans our perception of the world around us is solidified by our ability to touch and sense things around us, and a researcher it was a goal to create a biomimetic finger robot to further understand the interactions that occur within our own systems when we interact with the world. Our brain has an amazing capability of adapting to a variety of situations and achieving a certain type of control objective that is specific to the situation that we are in. To further understand this complex control optimization, a robot and system that resembles our own finger needed

to be developed. It was a goal to create a modular biomimetic finger that could use by many researchers and could also be used to decode the brain's control algorithm for everyday situations.

1.1 Robotics

Robots have been around for a long time and have been designed to help or aid us in many different ways. As technology has changed so have robots, from basic linkages and gears to 7 degree of freedom robotic arms for industrial applications to complex dynamic systems that are capable of making decisions and learning [2]. Engineers keep pushing the boundary of what was once thought impossible by creating more and more intelligent and complex robots, but a robot is not just limited to a full system, many mechanical devices can be considered robots. Many components usually make up all the different parts of a functioning robot, as with our bodies there are layers of skin on top of muscle on top of bone, not to mention the miles and miles of nerve endings and blood veins; each system is a subsystem of a bigger system. Humanoid robots of today are very intricate pieces of machinery with different types of actuators, motors, linkages and gears to attempt to precisely mimic and learn from human behavior.

1.1.1 Early Robots and Robotic Appendages

Robots date back to before recorded history and were passed on through stories from one to another. One of the greatest inventors ever, Leonardo Da Vinci is credited with creating one of the first robots in human form. His knight robot was created to show people, and himself, that the human body and form could be imitated and built. Sadly his

actual knight robot has been lost in time, but has been rebuilt with the finding of some of his old documents [7]. After da Vinci many other inventors and scientists began creating robotic devices to better their standard of living.

In the late 1960's Scientists became very interested in creating human type robotic appendages, its referred to as human type because functionality of a human arm or leg was needed but the tools to create these types of robots were not available at that time to correctly make a biomimetic human appendage [2][3]. General Electric created one of the first humanoid type robots, Walking Truck, that was controlled by foot and hand movements from a human operator via pneumatic actuators and hydraulic valves. Its initial use was to carry infantry and heavy equipment over rough terrain [1]. The operator inside the robot had to consciously determine what foot control or hand control to use when encountering obstacle, it has been said that the physical job was so taxing on the operator that the person operating Walking Truck needed a break after only 15 minutes of operation. The Walking Truck robot was an amazing accomplishment for its time but was very bulky and heavy and didn't perform well in the field and thus the project was discontinued after a short time.

In the early 1980's Carnegie-Mellon began its Leg Lab with the intent to create balancing and walking leg type robots, creating running planar bipeds and quadrupeds, and a one legged machine that would hop and balance itself [5]. The Leg Lab officially moved to Massachusetts Institute of Technology, MIT, in 1987 and continued to create groundbreaking leg robots, including a robot that could hop in circles, initiate and land a flip then continue hopping [6]. These robots led the way for researchers to create a variety of different robots that not only were beginning to be complex systems of gears

and motors but also had an intricate sensorimotor control onboard. Balancing and sensing was just the beginning for these robots, these control systems would fuel the field in the future leading to tactile sensing, sensorimotor feedback, robot and machine learning, robot vision, complex optimization and a myriad of other advances.
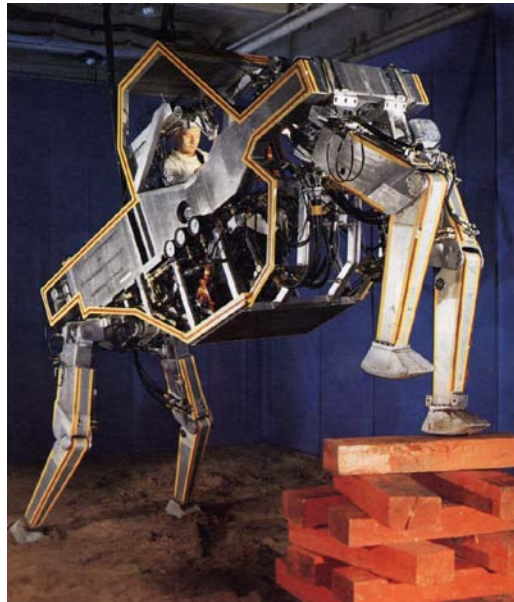
Figure 1.1: Walking Truck robot. Robot is demonstrating its ability to climb rough terrain and different obstacles, circa 1969. The operator inside had to control the robot with his hands and feet, this job was said to be mentally tough and an operator could only last about 15 minutes before needing a break.

1.1.2 New Robots and Robotic Appendages

Within the last twenty years the field of robotics has grown by leaps and bounds. We have been witness to Honda's walking humanoid Asimo robot [8], Sony's synchronized dancing robots Qrio [9][10], Kawada's HRP 2 and have seen the amazing control adaptability of Big Dog [11]. Companies and researchers haven't only focused on

full robotic systems; robotic appendages also have become diverse systems capable of performing complex optimal control algorithms under adverse conditions. These new robots resemble our anatomy and us so well that researchers are beginning to unlock many mysteries about how we interact with others and our world.

Figure 1.2: Three of the latest humanoid robots that are being used for various types of research. On the left is the Kawada HRP 2, in the middle is Honda's ASIMO, and on the right is Sony's Qrio.

Boston Dynamics, an company conceived out of the Leg Lab, has created two robots within the last 10 years that have not only rocked the robotics world but also the controls world, Big Dog [11] and Little Dog. Like Walking Truck these robots, mainly Big Dog, were created to help transport heavy gear for troops over aggressive terrain. The control system on this robot is so sophisticated that while in stride you can kick or push the robot and it will not only catch itself but will also quickly recover and continue walking [11]. Big Dog has been at the forefront of controls and robotics for almost 10 years and looks to stay in that position for a while.

Honda released its Asimo [8] robot in early 2000, to huge audiences in Japan and has gained significant momentum in the robotics field. Capable of walking, climbing up and down stairs and noticing visual cues, the Asimo robot is very human-like. Since its release many researchers have had the opportunity to use and test their own types of algorithms on the robot, a large portion of robotic papers that have been released within the last few years have been on or about Asimo.

Another popular robot used among researchers is the Phantom robot; this robot consists of cable drives that allow for a low friction low backlash research tool. The phantom robot uses encoders to track movements through six degrees of freedom [16]. A second robot, which also has the ability to have up to six degrees of freedom, and uses timing belts is the delta haptic robot [17]. This robot uses its specific geometry to create three-dimensional motions that are tracked, like the phantom robot, with encoders.

Figure 1.3: Example of a fully cable driven Phantom robot.

1.1.3 Robotic Hand Influences

Many robotic hands exist already today, many of them even resemble human fingers, or a biological form in one way or another. We wanted to make our own version of a humanoid biomimetic finger that was about the same size as a human finger but also one that was not extremely difficult to control or actuate. The ATC, (Anatomically Correct Testbed), hand for example is one of these robots. The robot is composed of ABS plastic human bones connected by pins and actuated by a number of nylon strings that act as tendons and muscles [28]. The problem with this design is that it is very difficult to control and it has a high degree of freedom.
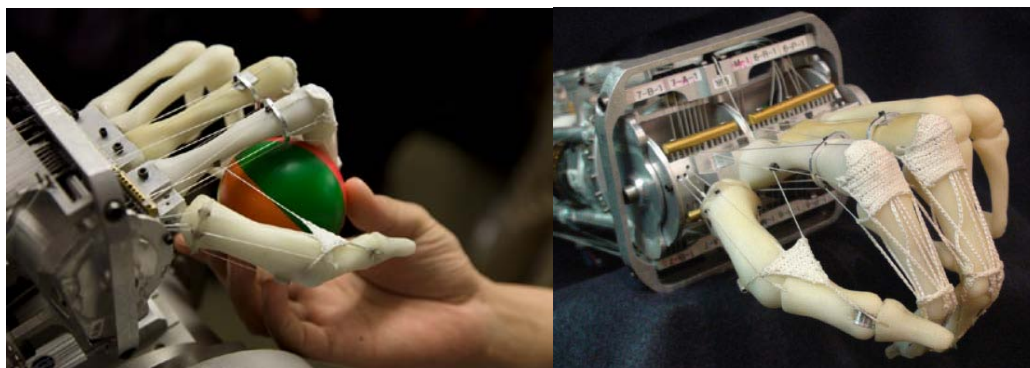
Figure 1.4: The ACT robot hand, most nylon strings, (tendons), are easily visible and lead to a singular motor.

The Shadow hand is another example of a humanoid hand that works very well but is difficult to control, very expensive and has a waiting list if one is desired for lab use. The Shadow hand itself is a very useful tool, that does a very good job of being biomimetic but due to its many actuators control is difficult and the robot is not

backdrivable. After witnessing a myriad of hand and finger robots that were almost impossible to control we wanted to create a fully biomimetic, backdrivable human finger robot that was not difficult to control and had a few parts as possible.
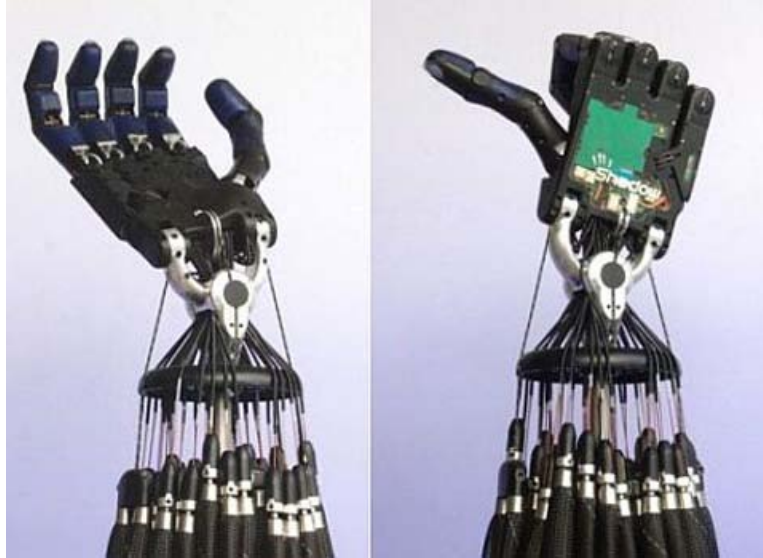
Figure 1.5: Introducing the Shadow Hand.

1.2 Definitions

Degrees of Freedom is an engineering term relating the mobility of a robot or a system; a fixed point can contain up to 6 degrees of freedom [4]. In a Cartesian coordinate system, (x, y, z), movement along each axis represents one degree of freedom, and rotation around each axis also represents one degree of freedom. Combinations of movements along or around each axis can be summed up to determine the degrees of freedom of the system. For instance the ModBot finger robot has three main degrees of

freedom; there are actually four but the joint at the tip of the finger, the distal inter-

phalangeal joint, is coupled to the middle finger joint and in this text is discounted as a

degree of freedom.
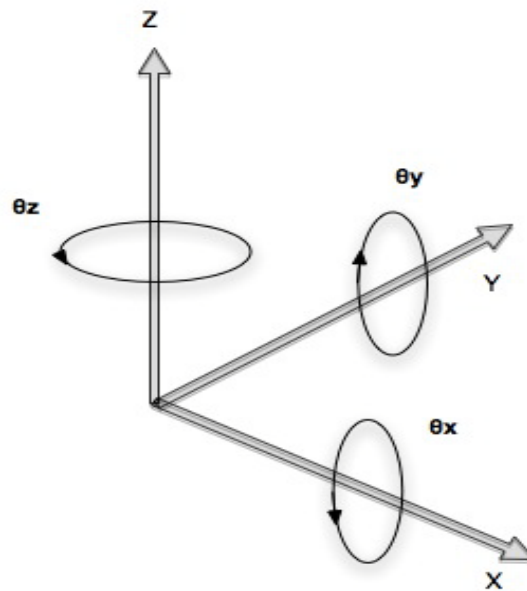
Figure 1.6: Three degrees of freedom in a Cartesian plane, notice that one point has a

maximum of six degrees of freedom.

Backdrivability is a term that describes the finger joints and how they work.

In essence humans are backdrivable and to create a biomimetic robot it has to be

backdrivable [9]. For example if a system has gears or a motor with a gearbox is not

backdrivable, when the power to this system is off you cannot move the system without

damaging or destroying it. A human hand is backdrivable, when asleep a person's hand

and fingers can be moved with little to no resistance, once let go the hand and fingers of the sleeping person return to a neutral position and nothing been damaged or broken.

Biomimetic system describes a system created to mimic some sort of biological creature or being [6]. In this case a robot has been designed to mimic a human hand, most humanoid robots are biomimetic systems but their joints are not, due to gears and geared motors.

Systems as they will be referred to in this thesis, are a combination of components that act together and perform a certain objective; a system relates inputs to outputs via a plant [13] [14]. Systems exist all throughout our world not only biologically but also industrially; a machine with controls is considered a system. A plant is a piece of equipment or a set of machine parts functioning together, with a certain purpose to obtain a goal or objective. A plant could also be any physical object to be controlled, and thus a main portion of a system.
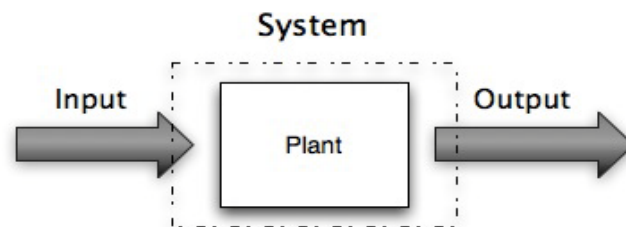
Figure 1.7: A basic block diagram of a system, it shows the relationship between input, output and the plant.

For example when you get next to or touch a hot surface you body knows, or is controlled, to move away from the heat source quickly. In this example the heat source is the input, your brain and nervous system telling your hand or body how to react is the plant, and your hand or body moving away from the heat source is the output. All together this forms a system.

1.3 Organization of Thesis

Chapter 1introduction to the filed of robotics, and early design concepts of the finger robot, basic overview of systems, and definitions of different terms.

Chapter 2 presents the changes the robot finger underwent during its creation, formulation and testing. Changes in mass, different mechanical properties of the pieces of the finger, kinematics, dynamics, different types of motors selected, design, cable drives, bearings used, joint stability and backdrivability.

Chapter 3 discuses the force sensor on the tip of the finger, how it was formulated, manufactured, and positioned. Demonstrates how it works and shows testing results, from testing a 1-degree of freedom stress sensor to testing the final finger with a 3-degree of freedom sensor.

Chapter 4 presents the modular properties of the finger, how it has been used, test set-ups and testing of different orientations of multiple fingers; preliminary test designs and future testing abilities of the finger robot.

Chapter 5 conclusions and future research.

2. Design and Evolution of Robotic Finger

Many factors were important to design into the robot as well what was wanted to get out of the robot. Many choices needed to be made before the robot could ever be fabricated including knowing the human anatomy of the hand, types of materials that were to be used, size of robot, types of motors to use, and countless others.

Having a light finger robot translates into having a light robotic hand and less work and friction acting on the motors. To make the robot light enough while strong, certain materials were going to have to be selected to create the framework of the finger.

2.1 Biology of Human Finger

Touch and sense is highly taken advantage of, since we use it every second of every day, but it takes a series of biological structures that have to work together for us to experience touch and sense. Excluding all of the bones in the wrist, the fingers are composed of metacarpal and phalangeal segments; there are 5 metacarpal bones per hand and 14 phalangeal bones, organized by proximal, middle and distal phalanx bones, where the distal phalanx bones correspond to tips of the fingers.

Each finger contains three different joints: a distal inter-phalangeal joint, a proximal inter-phalangeal joint and a metacarpal-phalangeal joint. As stated earlier the distal inter-phalangeal joint in this paper is omitted due to the fact that it is coupled to the proximal inter-phalangeal joint. The thumb contains the same type of joints as the fingers but due to the thumb not containing a middle phalanx bone, it does not contain a distal inter-phalangeal joint [18].
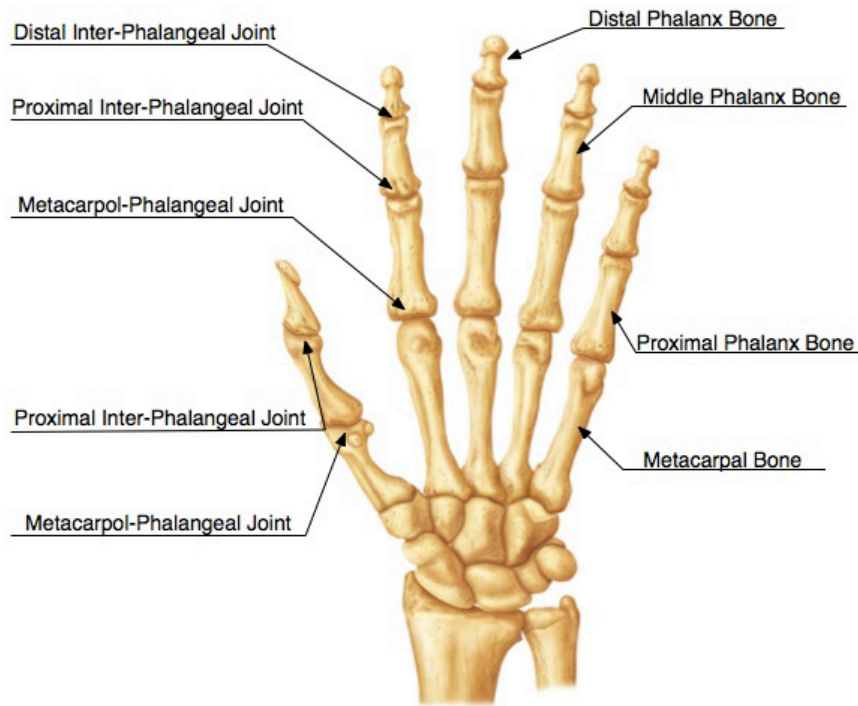
Figure 2.1: Human anatomy image of joints and bones. [18]

On top of those bones and joints are our skeletal muscles, which are connected to bones by tendons. Collateral ligaments are found on either side of every finger and thumb joint; these ligaments function to stabilize and prevent abnormal sidewise bending of each joint. Extensor tendons are located on the tops of each finger and allow each finger joint to straighten; extensor tendons flatten and create extensor hoods on the tops of each finger lowering the profile of each tendon. Myriads of tiny muscle fibers that are connected to these extensor tendons up and down the fingers aid in gripping strength and speed at which fingers can move.

On top of muscles and tendons are nerves and nerve endings, which allow touch and sense abilities, as well as pain perception. The radial nerve, median nerve and ulnar

nerves are the three main nerves that run through the wrist down the hand and to the ends of the fingers. The radial nerve allows for sensation of the thumb, pointer and middle finger on the dorsal, or back portion of the hand. The median nerve controls sensation for the volar, located on the same side as the palm, the thumb, pointer and middle finger. The ulnar nerve controls the dorsal and volar sensation for the pinky and ring fingers of the hand.

2.2 Relevant Robots and Concepts

During brainstorming for a successful robot appendage many technical aspects had to be taken into account. Strength, durability, and mobility had to be not only addressed they had to be proven viable in certain situations. To test out a couple of design ides the lab had in store for the new robot a couple of smaller acrylic robot projects were formed and built. A group of undergraduates under the tutelage of Alex Simpkins were given the task of completing these tasks while building a robot.

2.2.1 Initial Joint Design

The main idea of this project was to test if a triped robot could support itself using acrylic support material and heavy gear head motors, this served to give a high factor of safety if the project was successful. Alex Simpkins, a PhD controls student, and Emo Todorov, a Cognitive Science professor and head of the Movement Control Lab (MCL) at UC San Diego, both created the project and were very interested in biomimetic robotics. At the time the two were studying human interaction and perception having to do with touch or grasping; they were very interested in seeing how a person reacted when

holding an item, perturbing the item and noticing how the human reacted to the perturbations.

This project proved to be very difficult due to the fact that at that time there were not many triped robots used for research. Another aspect of the project was the robot had to sense where its self was in a plane, and to know where the tips of its legs were in case the surface was rough or rocky. Active sensing was also slated to be part of this robot but time constraints allowed implementation of such sensing algorithms to be very difficult.

Using rotational potentiometers, 3 8-bit PIC, Peripheral Interface Controller, microcontrollers, and a motor driver to control the three gear head motors, the triped came to life. The downfall of the design was the weight of the onboard gear head motors along with all of the gears were acrylic, after standing on its own for a couple of seconds the gears stripped themselves and months worth of work destroyed itself in mere seconds.

Figure 2.2: Triped robot concept pre-production on left, actual built triped robot post-production

2.2.2 MCL and Leg Robot

In early 2008 an idea of a leg robot fully driven by cables was thought up and planned out, the project was that of a PhD student with the goal of developing its design and completing the robot. The project consisted of a modular biomimetic leg robot that was fully compliant, but instead of using gears it was to use cable drives; the cable drives allowed the robot to be fully backdrivable, and reduced friction. With the addition of a 3 degree of freedom Computer Numerical Control (CNC) machine, unnecessary material from the leg robot was easily removed, while making an adjustable tip for different applications, touching, sensing, grasping or walking. A PhD student focused on sinusoidal commutation of the brushless AC motors and electronics while work was done on the physical design and mobility of the robot. A difficult aspect of this robot was that it was to be modular so that you can take a couple of the legs, put them in different configurations and be able to control the system, i.e. you could make a biped, triped, quadruped or any type of walking robot with multiple legs.

Once the robot was successfully created and tested, more MCL projects and robots were thought up and needed to be designed and created. One of the projects, much like the leg robot, was to formulate, create and build a modular biomimetic finger robot that has touch and sensing abilities. The project was slated to begin in mid 2008 and research was compiled during and after the robot was designed and built.

2.2.3 Desired Finger Robot Properties

There were a few aspects of the finger robot that needed to be taken account for and integrated into the design to make the robot more humanlike. These traits consisted

of it being light weight, but rigid, roughly the size of a human finger, modular, biomemitic, fully backdrivable and to be able to sense forces, for grasping or gripping. It was also decided that easy access to the cable drives, and motors to allow for easy replacement of defective parts would be a helpful attribute for the robot to have.

2.3 Mechanical Design of Robot Finger

For the robot to be fully modular much attention was focused on creating a robot that had all pertinent parts on board: motors, cable drives, motor driver PCB, and sensors. The main attribute that would set this finger robot apart from others would be that all of the hardware would be on the finger; this would make implementation of the finger/hand easy when attached to a robot arm or system. A name for the robot had also to be created to encapsulate all of the nuances of the robot while being catchy enough to stick in your mind. The name 'ModBot' finger was devised, which is short for modular robotic finger, to become the robots moniker.

Through the evolution of the ModBot finger there were many different changes that altered the shape and weight of the robot. The evolution was organized into 8 different versions; while there were many changes within a version, switching from one version to another called for substantial design and geometry changes, different motor selection or addition of degrees of freedom.
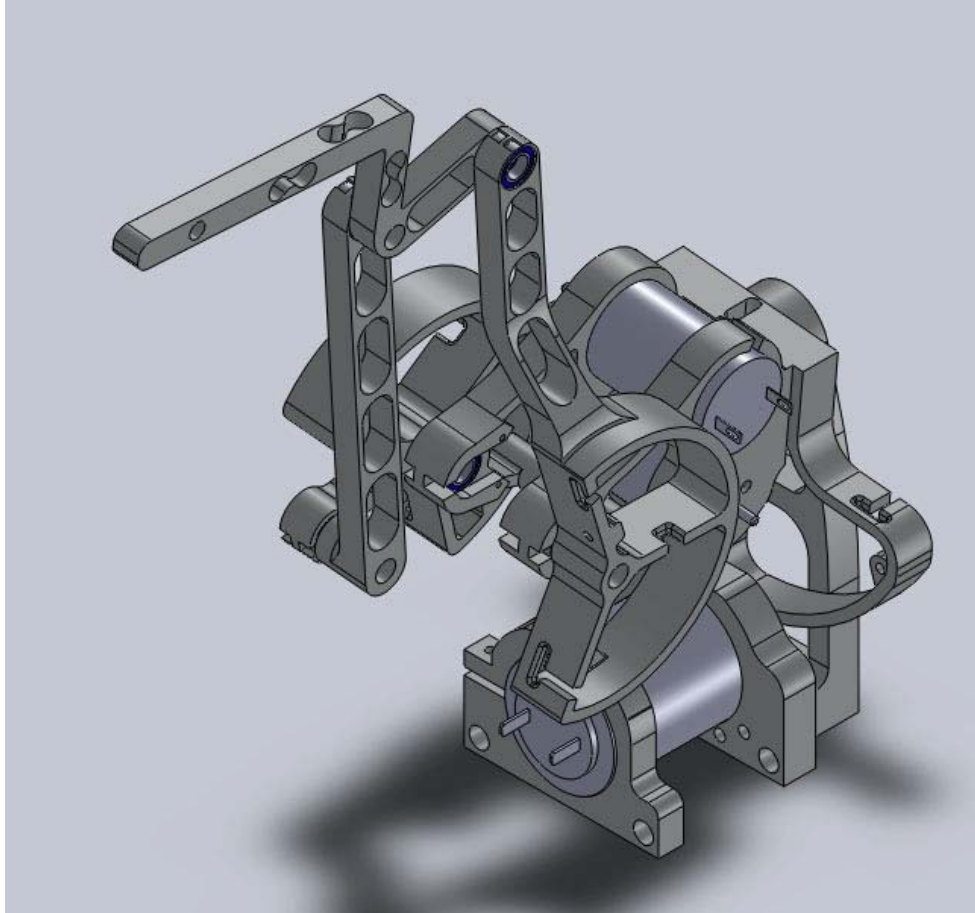
Figure 2.3: The ModBot finger after 8 evolutions.
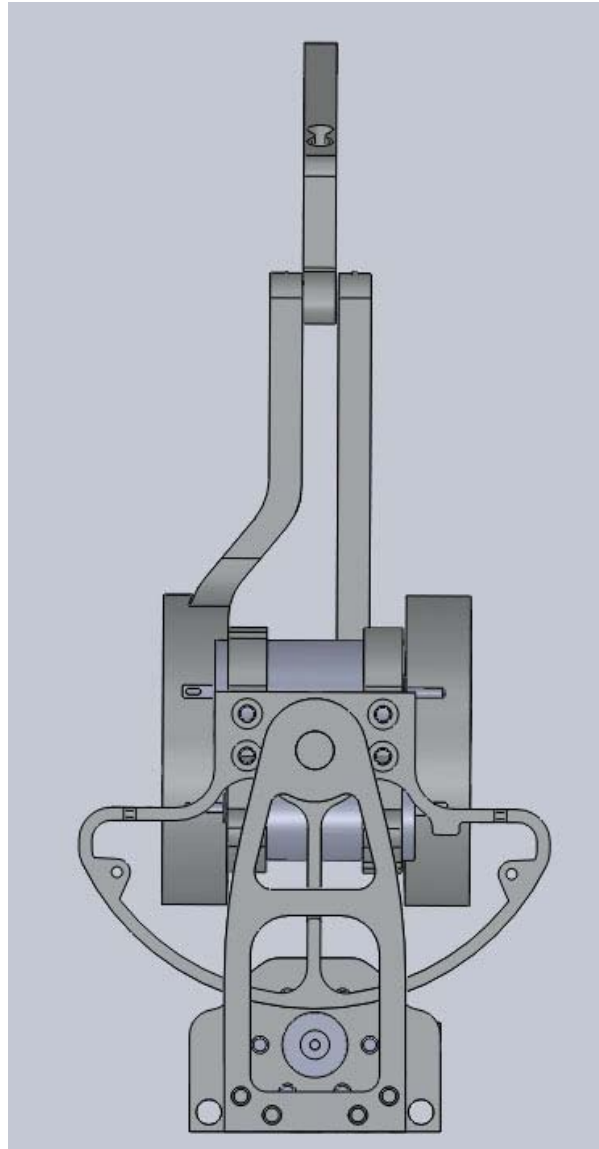
Figure 2.4: Rear view of the ModBot finger, evolution 8.

2.4 Material Selection

One of the first decisions that had to be made when building the ModBot finger was what type of material to use. This choice had many different repercussions and all options had to be weighed before a decision could be made. The main attributes that the ModBot finger needed to have was that it needed to be light weight but at the same time strong and rigid. Many different types of materials fall into these categories so the decision was not an easy one.

Acrylic was the first choice of material, it was readily available and the lab had access to a LaserCAMM, a 2-degree of freedom gantry cutting laser. Acrylics are easy to work with and have good strength but are brittle and have a tendency to chip, warp or fracture. Another problem with working in acrylic and with the LaserCAMM is that parts can only be cut out in 2 dimensions, and if a 3D part is needed the only way to achieve this is to slice the 3rd dimension of the part up in sections and build it up out of 2D parts; this layering type of building or additive process can be done but is not precise, due to the fact the layers have to be glued to each other and high tolerances cannot be held. The layering technique also takes up time since after a part is designed in 3D, it then has to be cut into layers and reduced to a series of 2D pieces.

Plastic printing was another material considered for the ModBot when choosing materials to use. Plastic printers create parts through an additive process where plastic is layered on top of itself over and over until a part is formed; it works for parts how a desktop printer works for paper. Most plastic printers use acrylonitrile butadiene styrene (ABS) as its main printing material, other high-end machines allow for the plastic to be impregnated with an adhesive or hardener. ABS is a strong material, is not as brittle as

acrylic, produces a part over night and can make any 3D part that will fit into the machine's workspace (most machines have a workspace of 203mm (8 in) x 203mm (8 in x 305mm (12 in). The problem with plastic printing is that it does not have a high enough resolution for what is needed for the ModBot finger. A Dimension Elite plastic printing machine has a resolution of 0.18mm (0.007 in), which might sound close to the 0.08mm (0.003 in) that the project calls for but the ModBot finger uses precise bearings and if they are off by more than 0.08mm (0.003 in) then there will be extra unaccounted for friction added to the robot. Another problem with plastic printing was that the lab did not have access to a printer at the time, there are companies that the lab could have sent part models to and received the printed piece in the mail but that would be costly and time consuming.

Plastic injection molding was another option when considering materials for the ModBot finger, but it was quickly decided as not a viable option. Although plastic injection creates strong 3D parts quickly, each part needs a specific mold to be created. As with any design the ModBot finger was going to have a couple of design changes, and with each change a new mold would have to be made.

After considering many other materials we looked in to metals and alloys; steel is very strong, ferro-magnetic, and pretty cheap. The lab had access to a 3 degree of freedom CNC mill that can cut steel but it is a very slow process. Steel is an extremely hard metal and thus special mills and bits are needed to cut it; not to mention it can sometimes be dangerous. When a bit or mill breaks cutting steel, metal shards and broken tools fly in all directions. Another problem with steel is that it is a heavy material; even with weight reduction if the robot was made with steel it would be too heavy.

Lastly we looked at aluminum, it is strong, light, easy to manufacture, cheap, and can be given a nice finish. Since aluminum is an alloy there were many different types of aluminum that could be used. Normally for machining there are two main choices 4041 aluminum or 6061 aluminum. The main difference between the two is that 4041 is alloyed with silicon, while 6061 is alloyed with magnesium and silicon. After some research it was decided to use 6061 aluminum due to the fact that it's easier to machine, although it is not as strong as 4041 aluminum the difference is small.

Table 2.1: Material attributes for different materials considered to use in the Modbot finger robot construction.

Materials	Density g/cc	Hardness (Rockwell)	Yield Strength MPa
Acrylic	1.15 - 1.19	45 - 101	45 - 86
ABS Plastic	1.02 - 1.17	68 - 115	22.1 - 59.3
Low Carbon Steel	7.64 - 8.08	30 - 105	140 - 2400
High Carbon Steel	4.51 - 8.26	43.0 - 100	275 - 2750
Aluminum	2.7	54 - 74	241 - 310
4041 Aluminum	2.7	63	305
6061 Aluminum	2.7	60	276

2.5 ModBot Evolution

From initial concept to final tangible robot finger, the ModBot finger went through 8 total evolutions. For an evolution to occur major changes in the structure or dimensions of a couple of parts had to be in order. After a design review of a new evolution was approved by the lab, it was then milled, put together, and tested for strength, friction, mobility and weight. Many small changes took place within each evolution that did not warrant an evolutionary step.
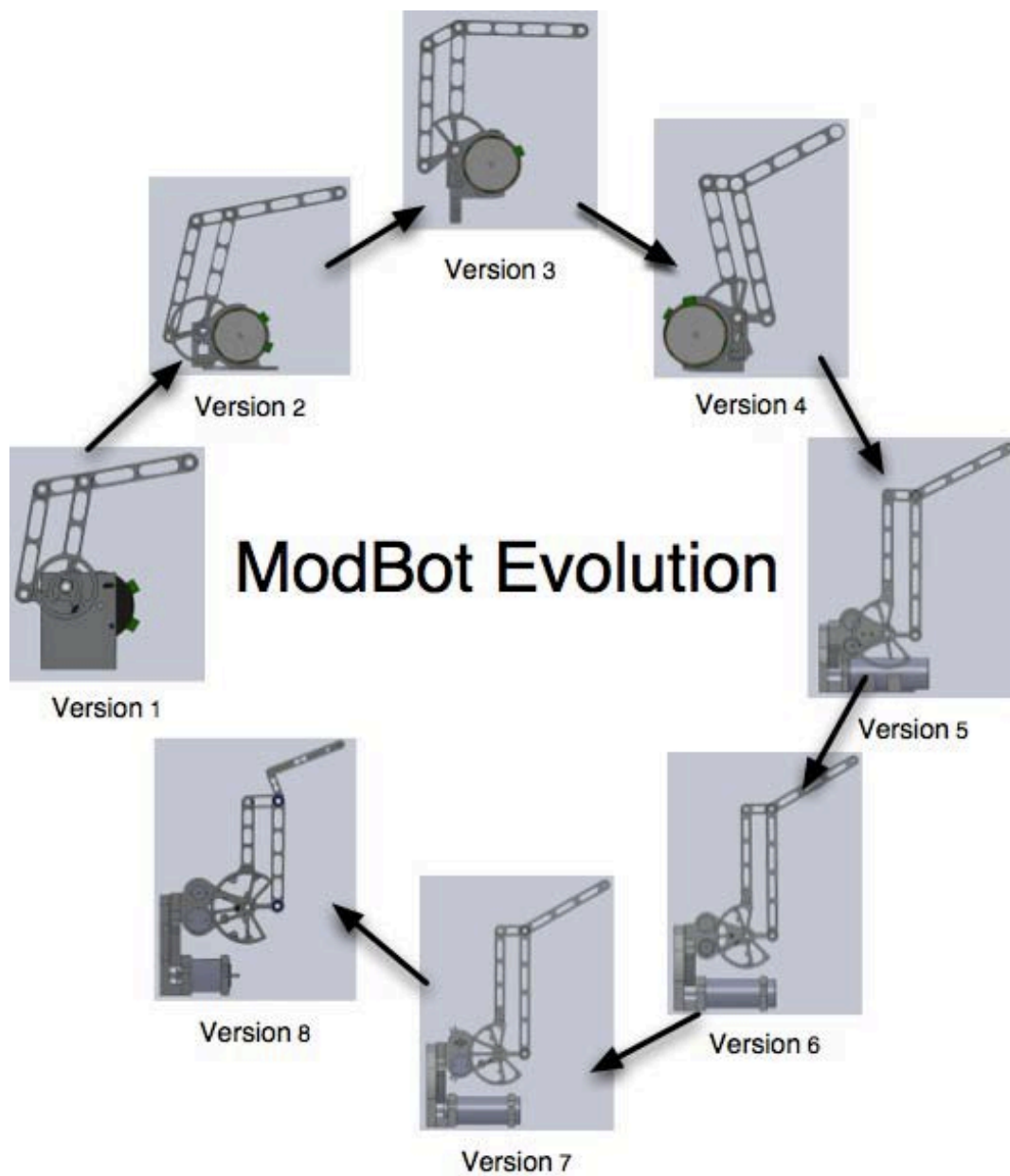
Figure 2.5: ModBot Evolutions from initial design, 1st evolution to final robot, 8th evolution

2.5.1 Evolution Changes

As the ModBot finger robot progressed through its evolution many changes occurred. Below is a list of the major changes that took place for each version of the ModBot finger:

- **Version 1:** Basic concept of the Modbot finger, used to see how the finger would be composed and the size that it would be roughly. It initially used AC brushless motors.

- **Version 2:** Massive weight reduction from version 1, the cable runners were changed from being a full circle to just the angles that the robot was going to be actuated in. Finger tip length and angle were also played with a little.

- **Version 3:** Added base cable runner so that a 3rd DOF could be achieved. More weight reduction from the side arms as well as an angle change for the finger tip was completed.

- **Version 4:** Both motors were moved behind of the linkages, where the previous versions they were in front of them. The finger tip angle was also changed for testing.

- **Version 5:** The AC brushless motors are replaced for cheaper, easier to drive brushed DC motors. A riser is added as well as a 3rd motor to control the 3rd DOF of the modbot. The Motors are also mounted close to the linkages but are close in line to the rotational axis of the 3rd DOF to lower rotational inertia.

- **Version 6:** Changed the bottom motor mount to save weight, added a rear locking motor mount, mass reduction on ever part of the robot. Created risers and locating holes for axial potentiometers for position feedback.

- **Version 7:** Added cuts to allow for cable loops to be installed and fastened, reduced mass in some parts. Introduced motor thread locks to fasten and keep the motors from moving or shifting while in use.

- **Version 8:** Changed out the base motor for a light weight DC brushed motor, reduced mass in the base motor mount, removed motor thread locks, increased channels for easier cable loop installation, removed more mass from various pieces. Redesigned the finger tip, fabricated 3 DOF force sensor finger tip to allow for force sensing.

2.5.2 Mass Property Changes Over Design Evolution

Every piece of the Modbot finger robot was rendered and designed in solid modeling software; the software also allowed a metal attribute to be assigned to a part, and thus every part was given a 6061 aluminum attribute. This attribute was very important to assign each part so that the software could determine weight, dynamics, strength, centroids and moments for every piece.

When the project began the parts were to be milled in the lab with a recently built tabletop three-degree of freedom CNC mill that was purchased from the internet. After many failed attempts to make parts that held a tolerance of $\pm$ 0.08mm (0.003 in), parts were contracted out to an outside machinist. This allowed the designs to become more intricate due to the professionalism of the machinist, and allowed the design to evolve freely. Every version was carefully thought out, discussed, modeled, and then milled out of aluminum. Once all pieces were milled out they were weighed, assembled, tested and then discussed.

Referring to figure 2.6 each piece of the ModBot finger is outlined and given a part name. Notice that there are two motor mounts but only one is listed as both are in essence the same part just flipped over, a left and right motor mount. Figure 2.7a and figure 2.7b show the weight

Figure 2.6: ModBot finger parts

Figure 2.7a: Changes in mass for each part of the Modbot finger, refer to figure 2.5 for part names. From top right to bottom left: (a) refers to the main motor mount of the Modbot finger, (b) refers to the long rotating arm or s-shaped arm, c) refers to the small rotating arm of the Modbot finger robot, and (d) refers to the riser between the small arm and the finger tip of the robot.
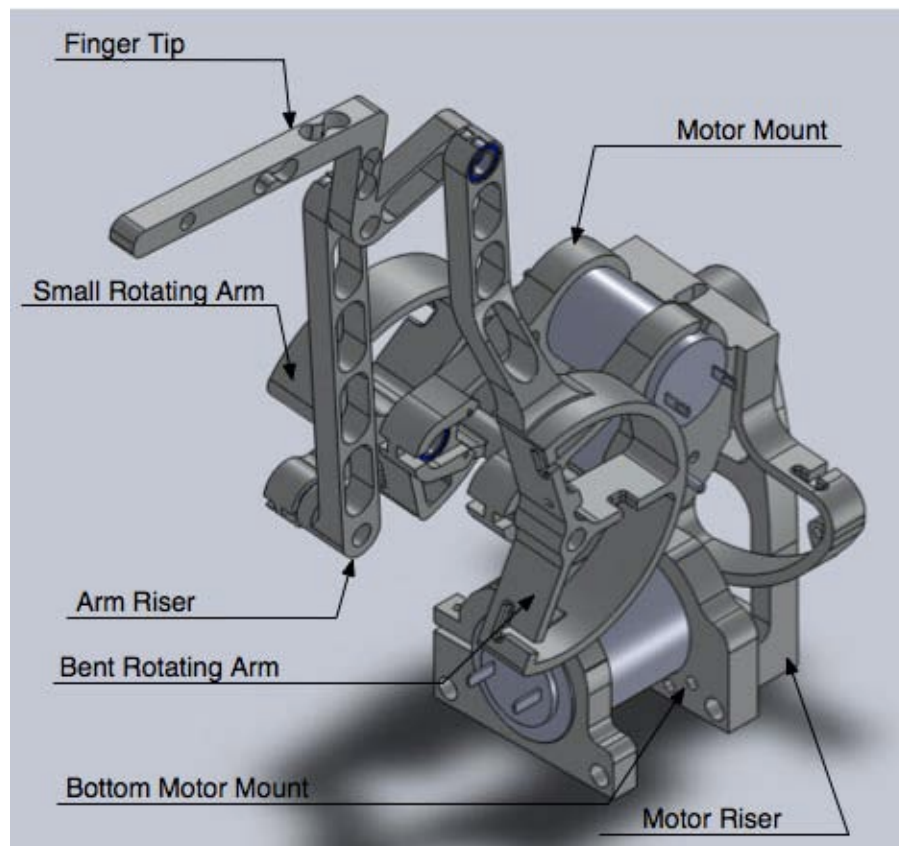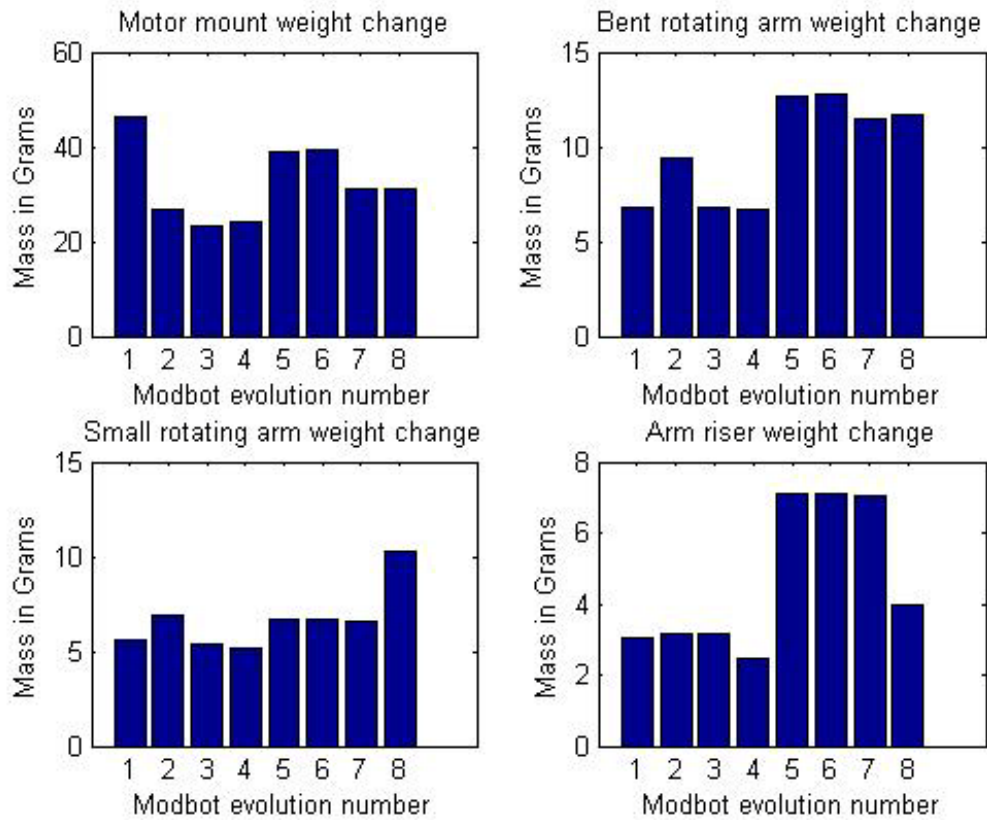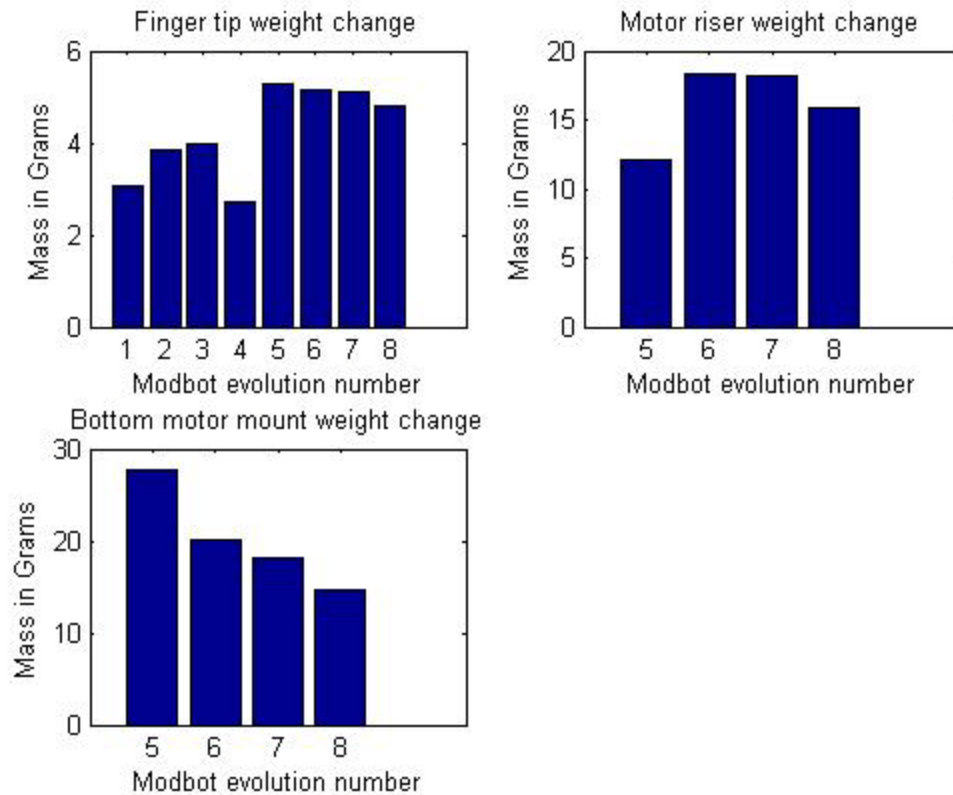
Figure 2.7b: Changes in mass for each part of ModBot finger, refer to figure 2.5 for part names. From top right to bottom right: (e) refers to fingertip piece that includes 3 axis touch sensors, (f) refers to ModBot finger riser, and (g) refers to bottom motor mount. Note that parts (f) and (g) were introduced later into the evolution of the ModBot finger.

2.5.3 Mechanical Properties of Each Piece

Before each piece of the robot was fabricated out of aluminum it was tested for durability, stress and factor of safety. Using solid modeling technology each piece was modeled using Solidworks, this allowed us to render each piece in 3D virtual space. The program was also used to test each piece for stress and deformation, using Cosmos express testing methods. Cosmos allows us to apply a fixed segment to the part then a force or pressure point is chosen on the part, along with the amount of pressure or force and lastly a material type is chosen. Once the simulation begins a solid mesh is created for the part using the finite element method calculation, then using stress tensor equations and Von Mises yield criterion deformation, stress and factor of safety are calculated and displayed. Below shows each part's simulation results. Figure 2.3 shows displacement of each piece under 50N of force, Figure 2.4 shows each pieces displacement in mm under the same 50N force. Note that the green arrows consist of fixed points on the part while purple arrows show the direction of the force applied. Although 50N of force is more than any piece of the robot will ever see, it was decided that all pieces needed to withstand a substantial amount of force.
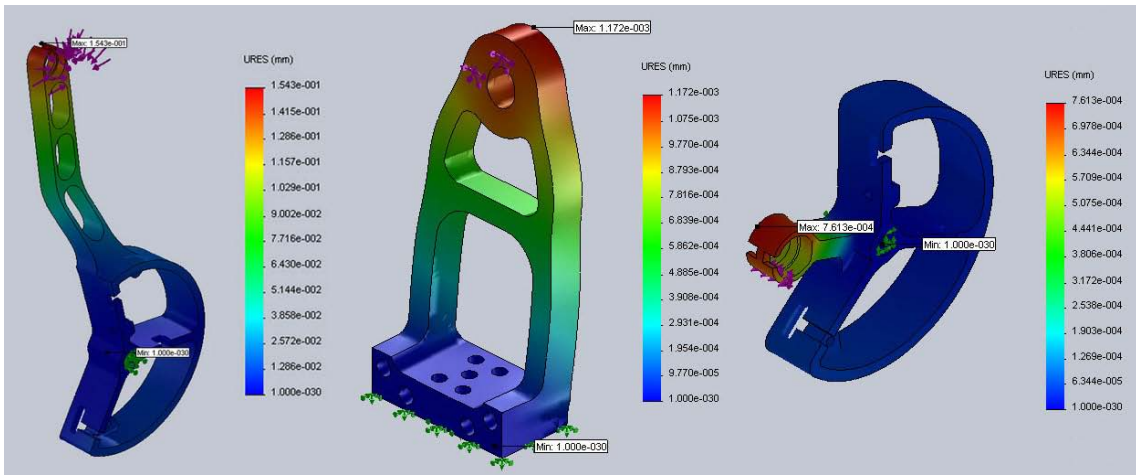
Figure 2.8a: Displacement location pictures of three parts of the ModBot finger, each part deforms differently, and so has its own displacement scale.
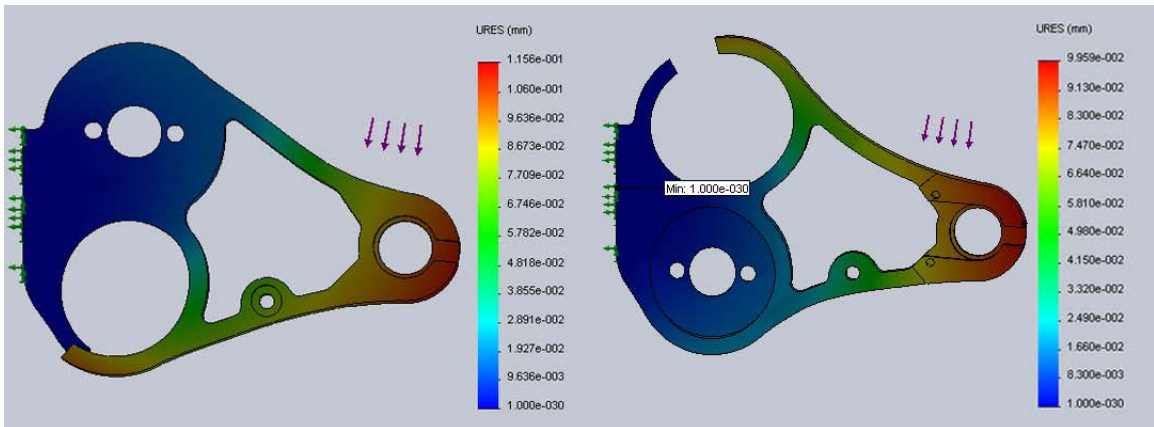
Figure 2.8b: Displacement pictures of both sidepieces of the ModBot finger.
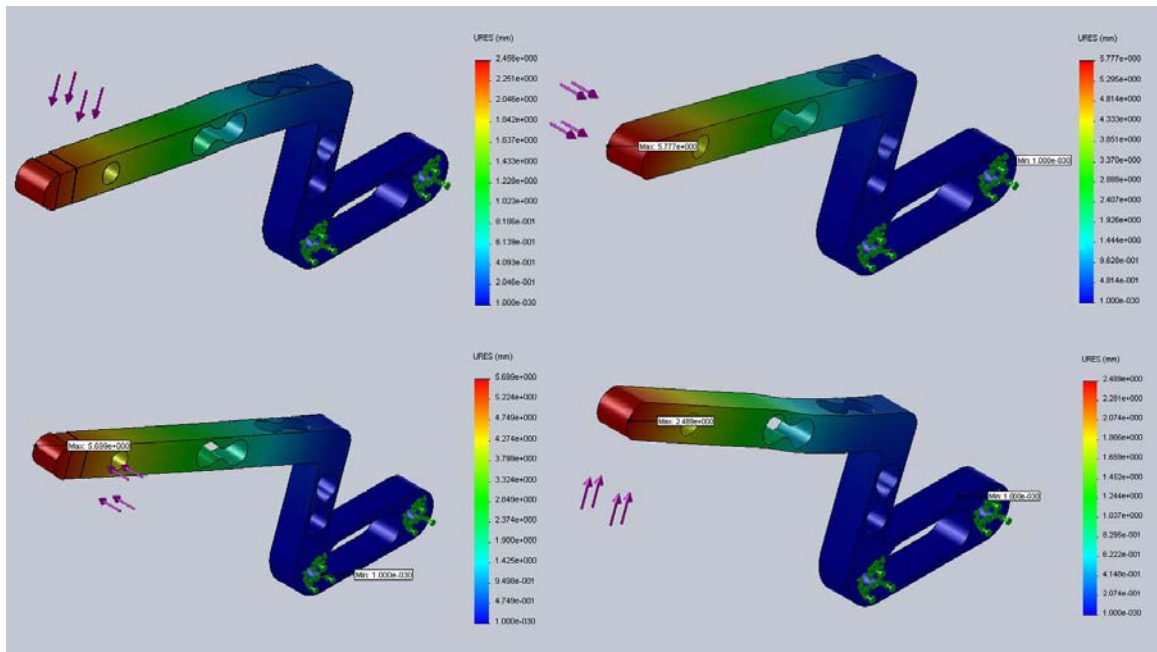
Figure 2.8c: Displacement pictures of the finger and end effector of the ModBot finger, notice the force in all directions on the tip deflects the force sensor most significantly at its bending points.
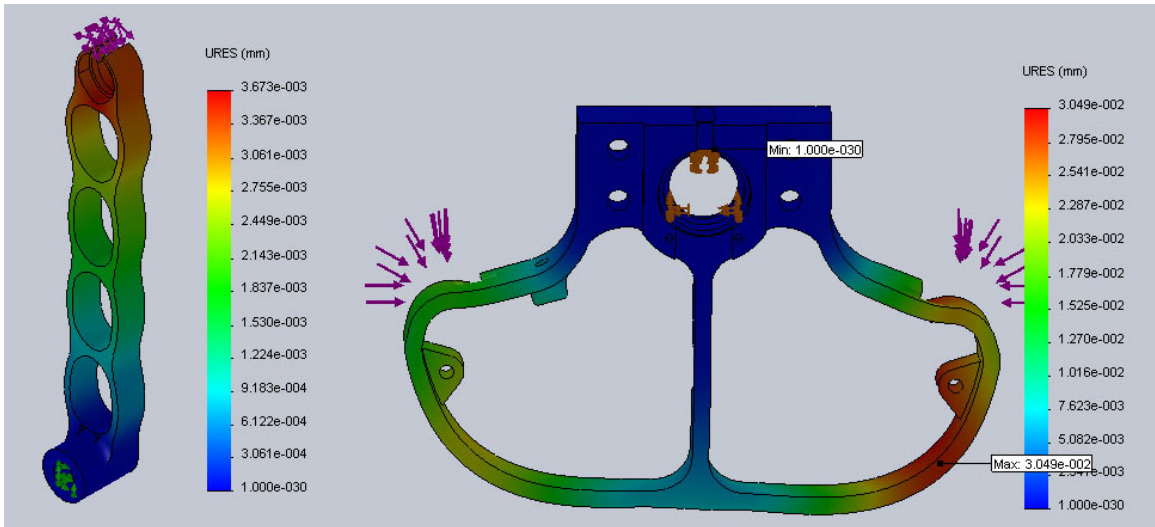
Figure 2.8d: Displacement images of the back piece, and left riser of the ModBot finger.
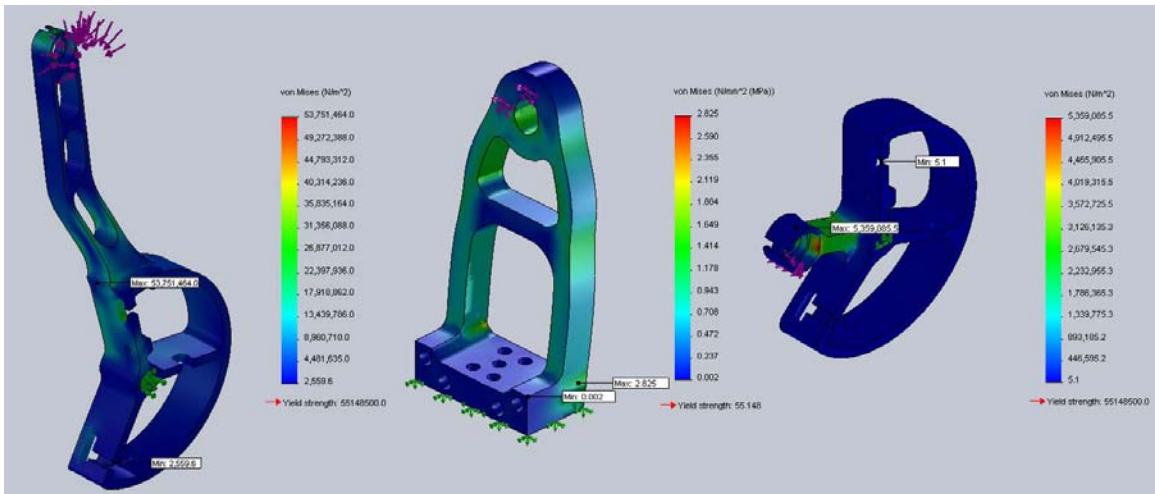
Figure 2.9a: Stress distributions of three pieces of the ModBot finger, each piece has its own stress scale according to the Von Mises yield criterion.
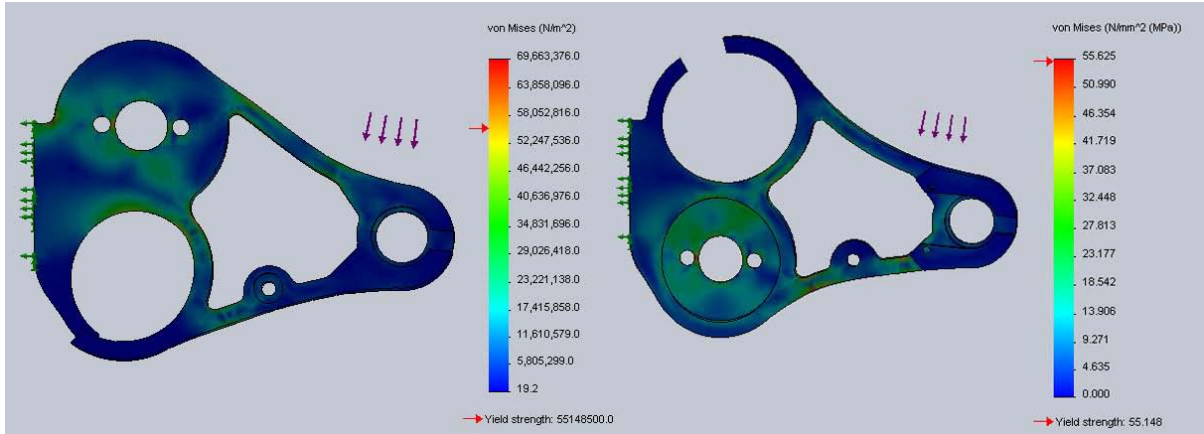
Figure 2.9b: Stress distributions of both sidepieces of the ModBot finger.
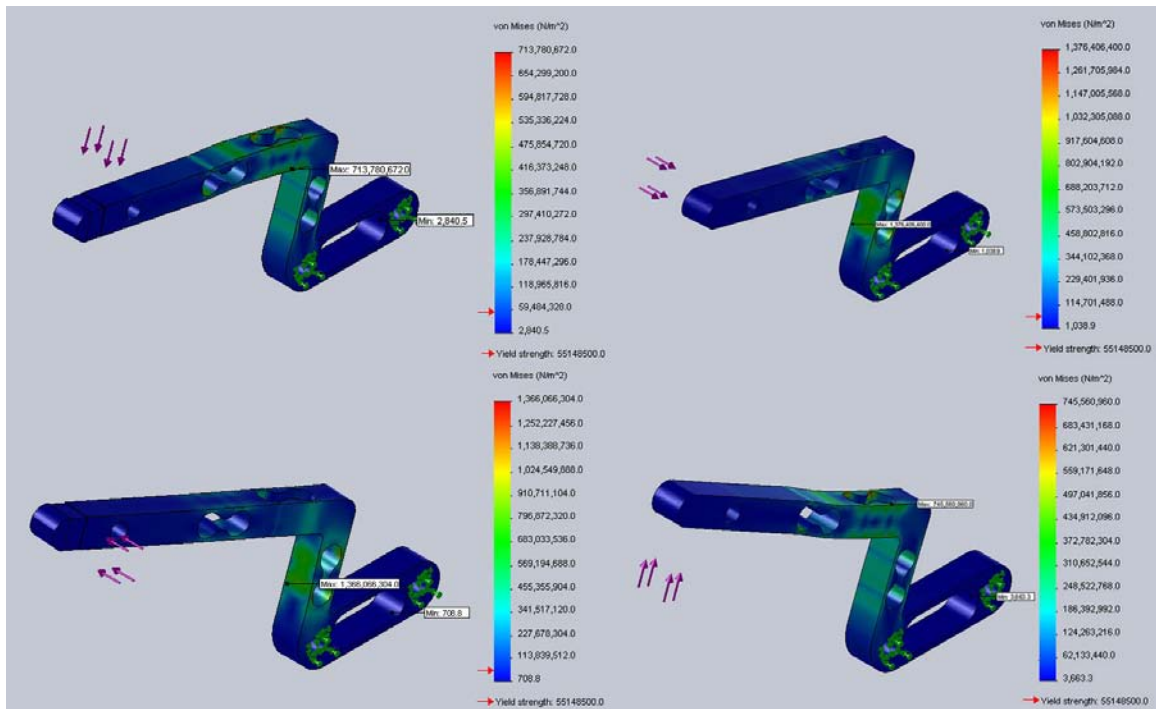
Figure 2.9c: Stress distributions for the finger and end effecter piece of the ModBot
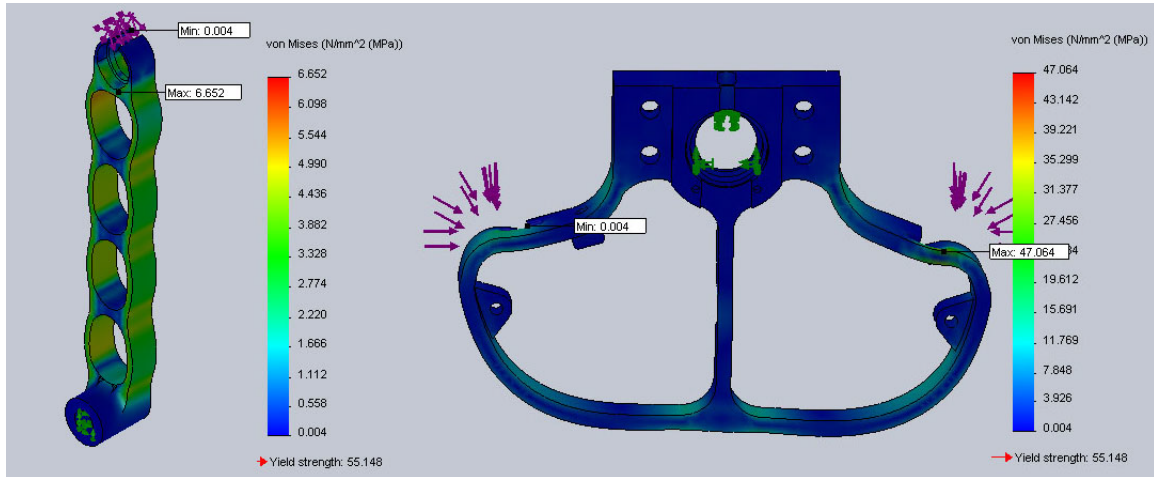
Figure 2.9d: Stress distributions for the back piece and left riser of the ModBot finger.

2.6 Robot Finger Kinematics

The robot finger was designed to follow a four bar linkage style machine. This allows for easy kinematic equation derivation. This design also simplifies the movement of the robot and utilizes easy movement with little friction or pieces of the robot colliding with other pieces. Figure 2.10 outlines the ModBot linkages that are defined in figure 2.11 and analyzed.
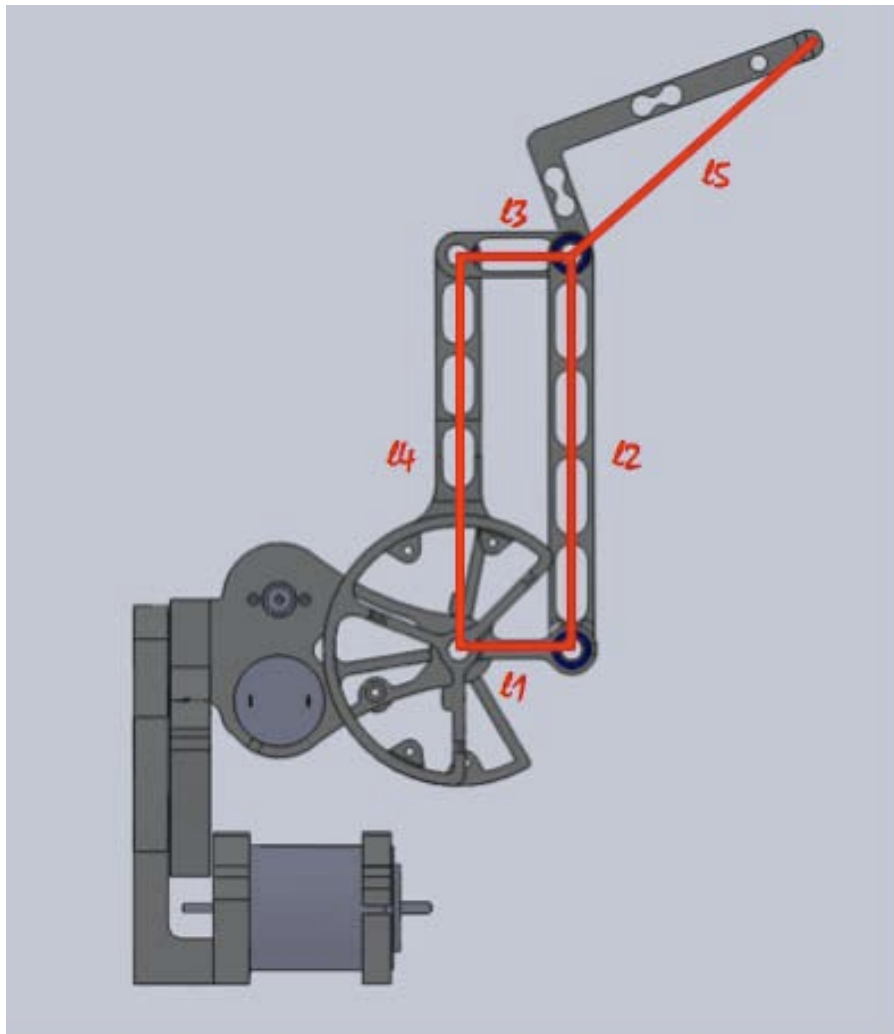
Figure 2.10: Side view of ModBot evolution 8, with 4 bar linkage overlay for kinematic analysis.
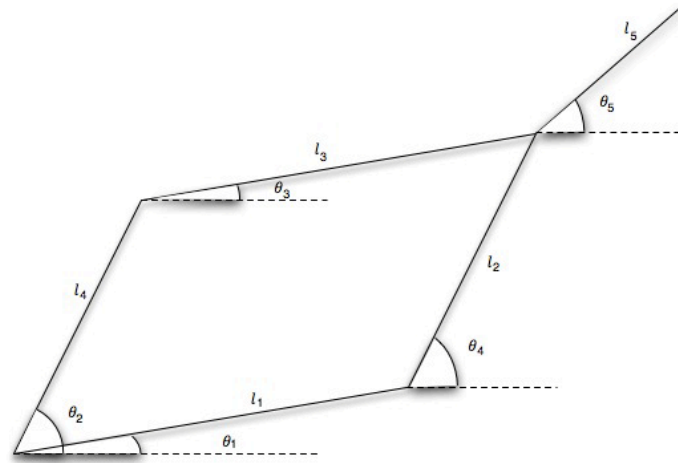
Figure 2.11: Four bar linkage representing the ModBot finger robot

$$\theta_1 = \theta_3 \tag{2.1}$$

$$\theta_2 = \theta_4 \tag{2.2}$$

$$x(\theta_1, \theta_2, \theta_5) = l_1 \cos\theta_1 + l_2 \cos\theta_2 + l_5 \cos\theta_5 \tag{2.3}$$

$$y(\theta_1, \theta_2, \theta_5) = l_1 \sin\theta_1 + l_2 \sin\theta_2 + l_5 \sin\theta_5 \tag{2.4}$$

$$dx = \frac{\partial x\,(\theta_1, \theta_2, \theta_5)}{\partial\theta_1}\,d\theta_1 + \frac{\partial x\,(\theta_1, \theta_2, \theta_5)}{\partial\theta_2}\,d\theta_2 + \frac{\partial x\,(\theta_1, \theta_2, \theta_5)}{\partial\theta_5}\,d\theta_5$$

$$\tag{2.5}$$

$$dy = \frac{\partial y\,(\theta_1, \theta_2, \theta_5)}{\partial\theta_1}\,d\theta_1 + \frac{\partial y\,(\theta_1, \theta_2, \theta_5)}{\partial\theta_2}\,d\theta_2 + \frac{\partial y\,(\theta_1, \theta_2, \theta_5)}{\partial\theta_5}\,d\theta_5$$

$$\tag{2.6}$$

Using vector form so that the above equations can be put in matrix form:

$$dx = J * d\emptyset \tag{2.7}$$

Where

$$d\emptyset = \begin{bmatrix} d\theta_1 \\ d\theta_2 \\ d\theta_5 \end{bmatrix} \tag{2.8}$$

$$J = \text{Manipulator Jacobian}$$

$$J = \begin{bmatrix} \dfrac{dx}{d\theta_1} & \dfrac{dx}{d\theta_2} & \dfrac{dx}{d\theta_5} \\ \dfrac{dy}{d\theta_1} & \dfrac{dy}{d\theta_2} & \dfrac{dy}{d\theta_3} \end{bmatrix}$$

(2.9)

$$\frac{dx}{d\theta_1} = -l_1 \sin \theta_1$$

(2.10)

$$\frac{dx}{d\theta_2} = -l_4 \sin \theta_4$$

(2.11)

$$\frac{dx}{d\theta_5} = -l_5 \sin \theta_5$$

(2.12)

$$\frac{dy}{d\theta_1} = l_1 \cos \theta_1$$

(2.13)

$$\frac{dy}{d\theta_2} = l_4 \cos \theta_4$$

(2.14)

$$\frac{dy}{d\theta_5} = l_5 \cos \theta_5$$

(2.15)

2.7 Robot Finger Kinematic Trajectories

The ModBot finger is capable of precise movements through certain angle ranges, depending on what linkage or linkages are being excited. Using the kinematic equations that govern the ModBot finger that were derived in section 2.6 a layout of the range of motions can be determined. By looping a range of angles at each of the joints of the finger then rendering the linkage layout before moving to a different linkage angle figures 2.6 a, b and c were obtained. All input angles were limited by the mobility of the ModBot finger, if the robot couldn't move past a certain angle then that value and above were not analyzed.
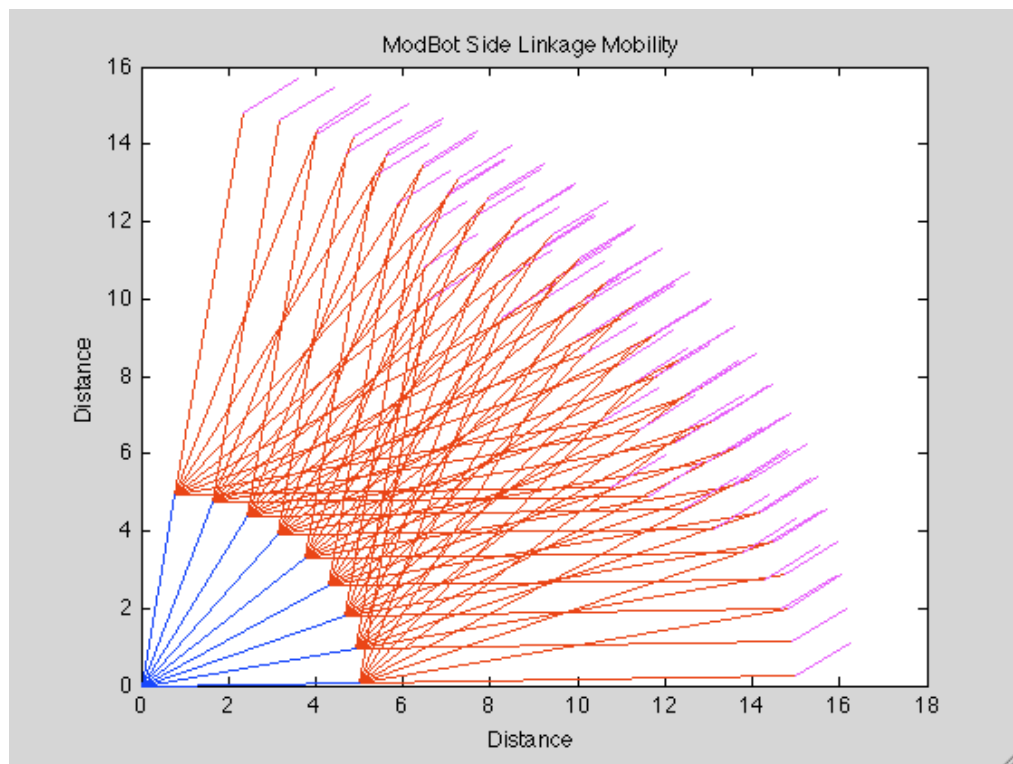
Figure 2.12a: Range of motion of ModBot finger, each color represents a different linkage of the ModBot. The blue bars represent linkages l2 and l4, the red bars represent linkages l1 and l3, and the pink linkage represents l5
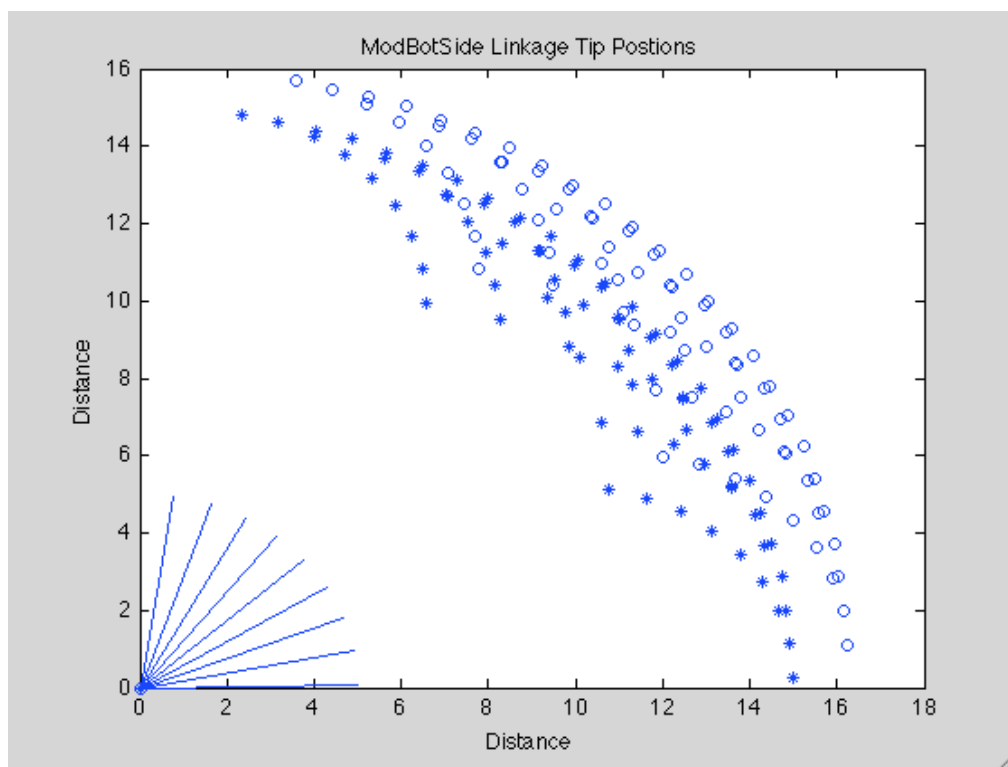
Figure 2.12b: Linkage tip locations of ModBot finger as it moves through its allowable angles. The lines represent linkages l2 and l4, while the stars represent the end of linkages l1 and l3 and the circles represent the tip placement of l5 as the robot moves through its allowable joint angles.
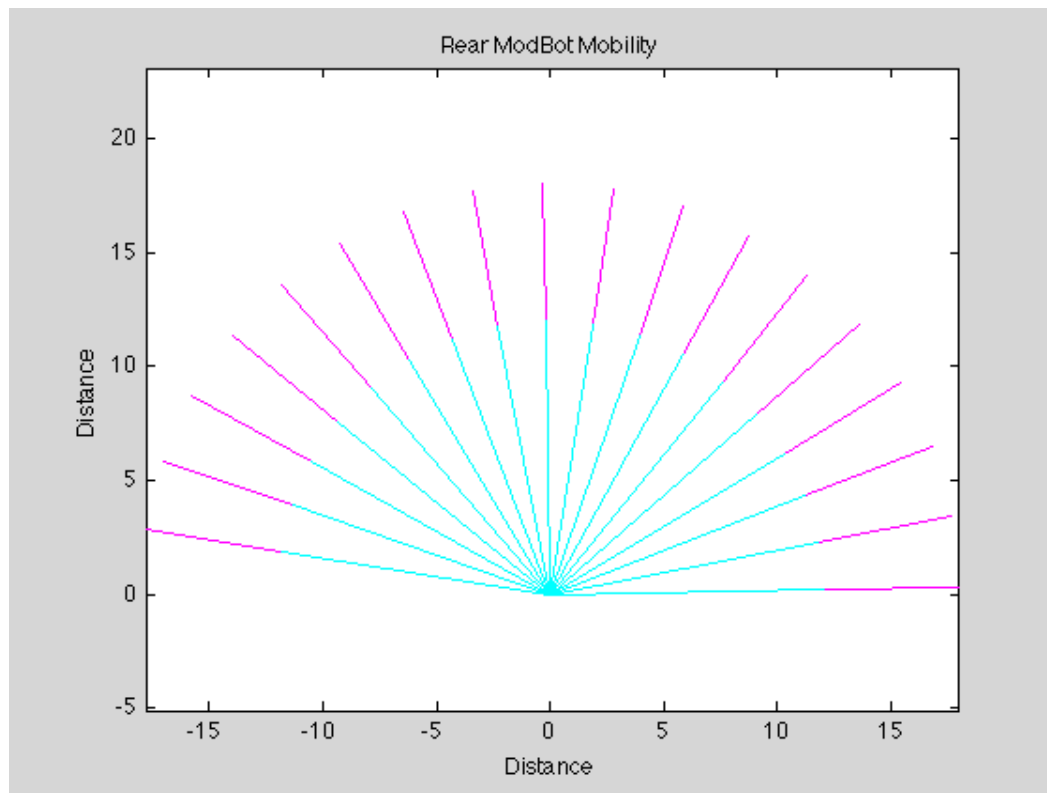
Figure 2.12c: Rear linkage mobility of the ModBot finger, as the finger runs through its allowable angles. The blue lines represent the l2 and l4 linkage and the pink lines represent the l5 linkage. In this figure the only angle that is changing is the motor mount axle, each linkage is held in a static angle to show the rear rotation of the ModBot finger.

2.8 Motor Selection

Over the evolution of the robot one of the many things that was a concern was motor selection. The lab had flat pancake motors and experience using them on the leg robot, but wanted to consider different types of motors before making a decision. Some of the main points focused on were electricity type, AC or DC, ease of implementation, friction, weight, footprint, commutation, back EMF, hall sensors, and cost. With a myriad of motor companies it was easy to get lost in a sea of decisions.

2.8.1 AC Motors

Although AC motors are efficient, it is preferable to use batteries on a robot instead of a tether or leash that creates a limitation; also most small AC motors are heavy and bulky, which would be a step in the wrong direction for the design. During the initial designs of the ModBot finger robot AC motors were considered for a possible means to achieve our goal but after much discussion it was decided to use DC motors on the ModBot robot due to ease of implementation of the motors.

2.8.2 DC Motors: Brushed Versus Brushless

Once the choice was narrowed down to DC there was only one more question to ask, should brushed or brushless motors be used for the project? The outcomes of both motor types are the same, current causes a shaft to turn and thus torque is created, but the motors differ in their respective methods of current use.

Brushed motors are cheap to make and buy, are easily implemented, and have a basic structure to them. Brushed motors are composed of carbon feelers or combs,

brushes that run on the edges of a commutator, a set of electrical contacts on the rotor, much like a cam and follower. These brushes connect the commutator to the windings causing current to flow in and out of the rotor and thus turning a shaft [19][20]. Since the brushes have constant contact with the commutator the faster the motor spins the more wear and tear the brushes experience leading to grooves at the end of the brushes and causing the brushes to be replaced or a new motor must be bought. The life of a brushed motor can be increased by seating the brushes properly, as a car is broken in at low RPM's before driven, a brand new brushed motor must also be set at low RPM's to ensure longevity of the motor. Small brushed motors have some disadvantages also, they are not robust, if you put much axial pressure on them and unseat or bend a brush the motor will cease to operate, they have some internal friction due to the brush contact, they tend to be larger in size, emit a high audible noise at high speeds, commutator limits the achievable speed, and they have a limited life span once the brushes form grooves or lose tension on the commutator the motor or brushes have to be replaced.

Brushless motors have very little internal friction, can last for very long periods of time at high speeds, emit very low noise at high speeds, can withstand axial loads without damaging the motor, and they can attain a very high angular precision. Brushless motors work by having a round stator with poles that are wrapped with copper wire; the stator is magnetized having the same magnetic orientation, north pole or south pole magnetic, 180 degrees apart [19]. Inside the stator is a rotor with poles of its own, the rotor is connected to the output shaft that spins. A motor controller controls which coil poles are charged in a certain order, this causes the nearest inside poles to be pulled into alignment with the appropriate stator poles. Once the middle rotor is about aligned with the charged coil,

charge shifts to another coil, turning the internal rotor even more. This process is repeated at high frequencies to create smooth rotor torque and quiet rotation. As with brushless DC motors there are negative attributes that come with brushless AC motors; they are complex motors, brushless motors are expensive, if position control is desired, position feedback is required, and a driver is needed to operate them. Most of the time if you don't buy the company's motor driver for its respective motor, a motor driver will have to be developed from scratch which would take up time and research resources.

2.8.3 DC Motor Selection

Before the brushless or brushed motor was selected the objectives of the robot were reviewed to make selection easier. High speeds would be nice but the biggest piece of the robot only rotates 128 degrees, a motor that could reach a high speed very fast then reverse and gain high speeds in reverse would be optimal. Weight is also a concern, since modularity is important to the ModBot finger robot, weight must be considered; also in the focus of modularity, motor drivers will make the finger bulky and even weigh more. Brushed motors also need motor drivers unless they are just needed to spin up and run, but motor drivers for brushed motors are easier to code, cheaper to buy and lighter to implement.

With all of that taken into account a decision was made to use DC brushed motors, since the motors for the ModBot finger are easily accessible replacing them would not be difficult and cost versus a comparable brushless motor was a factor of 10. If this project were ever to be turned into a consumer product, cost would be a big determining factor if the ModBot finger were embraced or shunned.

Another important decision was picking the right motor company, many companies make motors but some are better than others. From personal experience the turnaround for a motor order from a couple of companies can range from a week to a couple of months. Much discussion and research was done to pick out the correct motor company that offers reliable, cost effective motors with quick shipping. Portescap was suggested by a colleague as a great motor brand and after much research it was settled to use them as the motor provider. Motors were purchased from Portescap to test various aspects and controllability of the motors before final decisions were made.

As the ModBot finger robot evolved through its design, different motor types were used. For the leg project nuvoDisc flat pancake motors were used throughout its design and evolution and in the initial designs of the ModBot finger robot it was assumed that nuvoDisc motors would also be used. The problem with this is that the nuvoDisc motors although thin have a huge footprint of 32mm (1.26 in), and they were also brushless motors which at the time of the robots conception did not include hall sensors which made motor control only possible through back EMF or hall sensors had to be applied to the outside of the motor.

The last couple of evolutions of the ModBot finger robot were outfitted with a new line of Portescap motors - the Athlonix series. The Athlonix motors fit the project amazingly, were small but sturdy and extremely cost effective. Changing from the nuvoDisc motor to the Athlonix motors not only slimmed down the robot size all together but also improved controllability of the robot going from brushless to brushed DC motors.

Table 2.2: Various comparisons of motors that were considered for the ModBot robot; notice the difference between brushed and brushless motors.

Portescap Motors	Frame Length (mm)	Frame Diameter (mm)	Voltage AC/DC	Motor Type	No Load Speed (RPM)	Max torque (mNm)	Rotor inertia (Kg^2 x10^-7)
nuvoDisc 32BF	16	32	12	Brushless	12800	9.4	N\A
B0610-024A-R00	70.6	16.5	24 DC	Brushless	58394	18.71	N\A
16N78-208E Athlonix	35.5	16	24 DC	Brushed	8200	6.3	1.18
22N78-215E Athlonix	39.5	22	24 DC	Brushed	9100	14.5	4.5

2.9 Finger Joint Design

One of the most important aspects of the ModBot finger was keeping friction between joints to a minimum. Many different techniques were used to limit friction and add to the versatility of the robot. Less stress is applied to the motors when each joint flows and moves freely, and the robots operational life is increased.

2.9.1 Bearing Selection

Bearings are classified into 5 different classes noted by ABEC numbers from 1 to 9. ABEC stands for Annular Bearing Engineers' Committee, this committee is part of the ABMA or the American Bearing Manufactures Association, which controls the ratings for all bearings that are used on anything from skateboard wheels to machines or cars [21]. ABEC numbers also refer to ISO or International Organization of Standardization numbers for international use. Bearings that fail to meet ABEC 1 standards do not receive an ABEC number and are considered non-precision bearings due to their tolerances being too large.

Table 2.3: ABEC bearing tolerance and ISO numbers table.

ABEC #	Tolerance mm x 10^-3	Tolerance In x 10^-4	ISO #
1	7.5	2.95	P0
3	5.0	1.97	P6
5	3.5	1.38	P5
7	2.5	0.98	P4
9	1.2	0.47	P2

One of the main goals of the robotic joints was to minimize friction, it is easy to just choose ABEC 9 bearings for all of the joints. The problem with this is that as bearings become smaller it is harder to achieve high ABEC ratings. Since the main goal was to create a robot finger that resembles the human finger in not only function but also in size bearing choices were limited. When choosing bearings, the smaller the size of the bearing the harder it is to hold a tight tolerance and thus achieve a high ABEC number.

After taking all choices available to us into account two different types of bearings were used but both were so small that an optimal ABEC 9 rating was not available. The main bearing used in the finger has dimensions of 7mm (0.28 in) outer diameter by 4mm (0.16 in) inner diameter and 2mm (0.08 in) thickness, and is made by only one company, Dynaroll. Each ModBot finger uses 12 of these high precision, special order bearings to be able to move around with almost no friction. The highest available rating for available bearings with the above dimensions was an ABEC 7 rating.

The second bearing used on the robot was a flange bearing and was bigger than the first bearing type used. Although bigger it was still too small to receive an ABEC 9

rating. The flange of the bearing helped in location and stability of the bearing. The flange bearing has dimensions of 10mm (0.40 in) outer diameter by 6mm (0.24 in) inner diameter and a 3mm (0.12 in) thickness. As with the first bearing the project had to settle with an ABEC 7 rating for this bearing.

Figure 2.13: Bearings used on the ModBot finger robot with a penny for size comparison.

2.9.2 Double Bearing Joint Stability

Once all bearings were selected a method of joint stability was needed to translate the almost frictionless motion of the bearings to the fingertip. Many robotic joints use one bearing and a press fit; this method works well and is very easy to implement but it does not fully constrain the joint and allows for movement in a degree of freedom, unless

needle bearings are used. This extra movement adds friction to each joint, wears the bearing prematurely and makes controlling the robot difficult.

A solution to this problem is to use double redundancy, shown in figure 2.14, to keep the shaft from twisting and creating more friction. Every joint on the ModBot finger robot has two bearings and a through shaft. Since each part is milled to a high tolerance and all the bearings also hold high tolerances, friction is minimized and fluid movements are achieved.
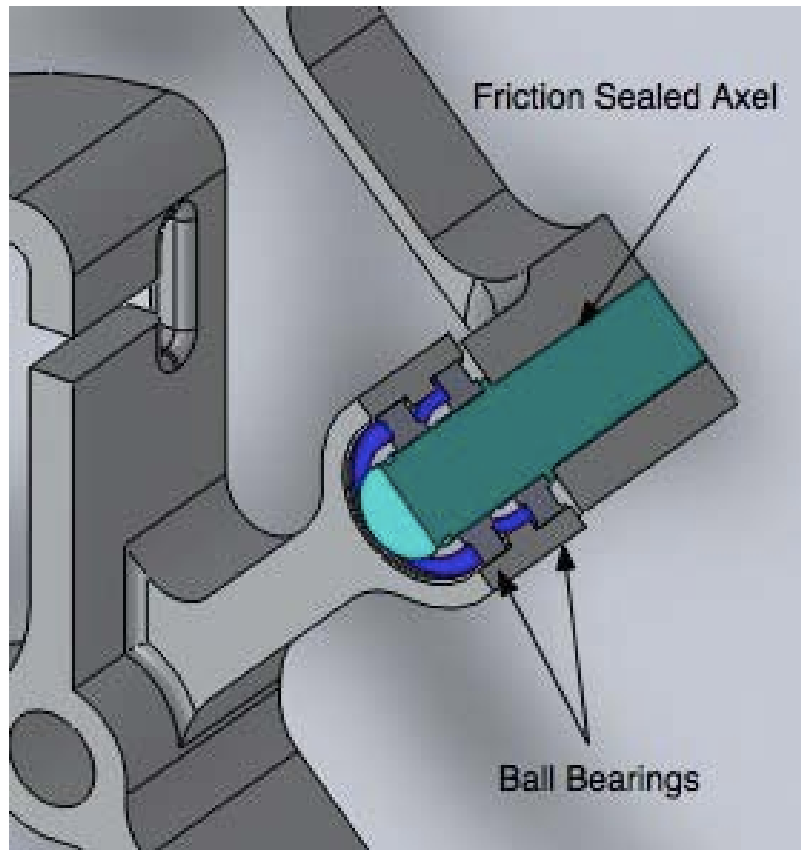
Figure 2.14: Cut away view of double ball bearing joint stability, this type of

stability occurs in every joint of the ModBot finger.

2.10 Cable Drives

The main and most innovative piece of the ModBot robot is its drive train; unlike most other robots this robot operates via cable drive. Torque is conveyed through the cable via a pulley that is attached to the shaft of a motor. Due to the flexibility of the cable and the size of the pulley, this drive train type can be considerably smaller than a typical gear set up for a given gear ratio.
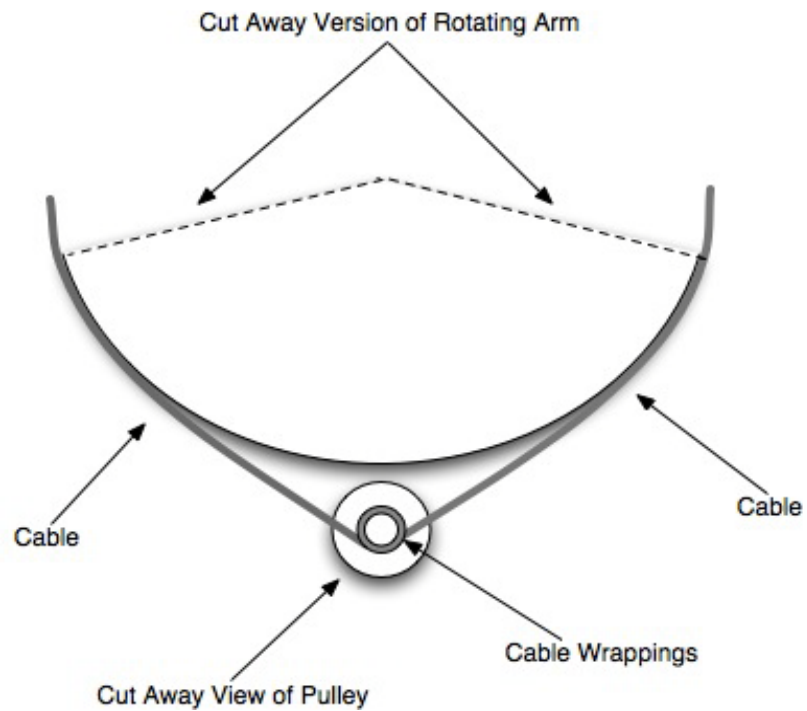
Figure 2.15: Cable drive assembly shown with attached cable and cut away pulley.

To conduct torque from the motor into the system without slipping, an appropriate number of cable wrappings are needed around the pulley shaft. As the motor turns and the cable wraps and unwraps, 'walking' or 'cable walking' occurs. Cable walking is defined as cable wrappings moving, not overlapping; in the opposite direction the motor is moving at least one diameter of cable thickness per revolution of the pulley. Since both ends of the cable escaping the pulley are in a tension walking occurs at the same speed of the motor, while minimal torque and slippage occurs due to cable walking. The mechanical advantage of the cable drive is given by:

$$n2\pi r_1 = 2\pi r_2 \qquad (2.16)$$
$$n = \frac{r_2}{r_1}$$

Equation 2.16 shows that walking versus distance rotated is related with minimal cable walking. Distance rotated versus walking distance can also be formulated by using simple geometry.

$$s = r\theta \qquad (2.17)$$

The above equation represents angular movement with an arc where s represents arc length, r is the radius of the pulley or rotating piece and θ represents the angle the piece has moved through. Since there are two arcs that control walking distance the equation forms to:

$$\alpha s_1 = s_2 \tag{2.18}$$

$$\alpha = \frac{s_2}{s_1}$$

$$\alpha = \frac{r_2 \theta}{2\pi r_1}$$

Cable Pulley

Cable

Cable wraps

Pulley Set Screw
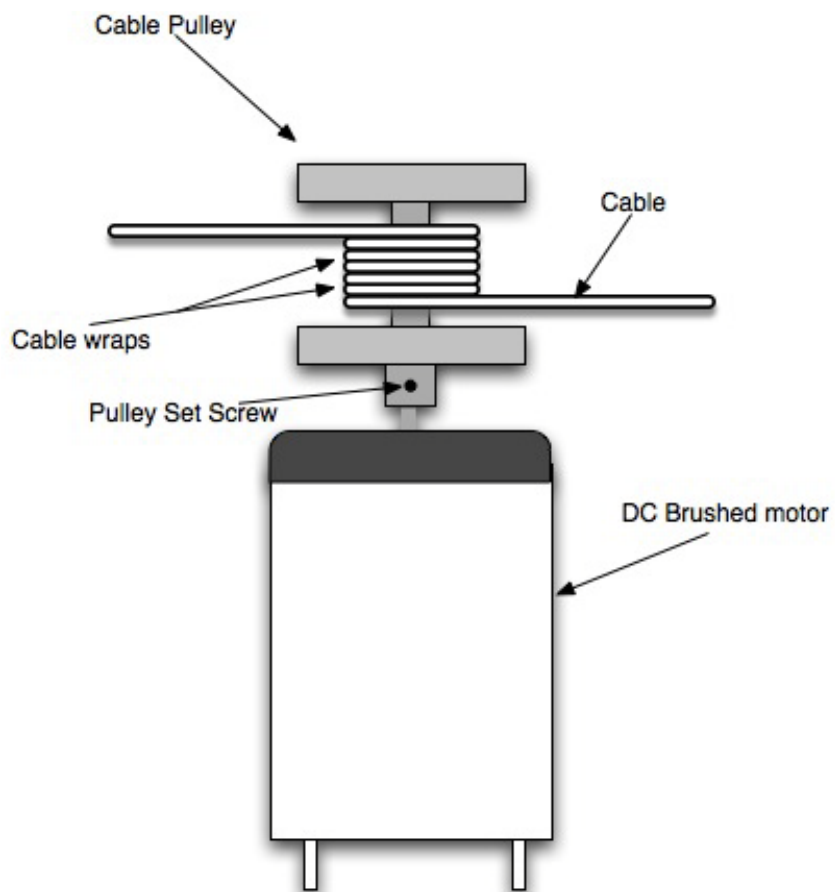
DC Brushed motor

Figure 2.16: Cable wrapping around pulley connected to DC brushed motor.

Using equation 2.18 axial walking distance can easily be calculated; this aids when trying to determine pulley shaft diameter and rotating arm diameter.

2.10.1 Cable Drives Versus Gears

In this thesis when discussing gears it is in reference to spur gears, gears that have straight teeth; this excludes beveled gears, worm gears and pinion gears. When most people thing of robots a giant mechanical beast is conjured up with many gears. Gears are easily associate with robots due to the fact the most robots make use of them. The advantage of a cable drive over gears is that cable drives are light weight, they have no backlash and are backdrivable [4]. Even with symmetric gears there is a small amount of backlash that will leach power and mobility out of each robot joint.

$$p = \frac{\pi \theta d}{360} \tag{2.19}$$

Equation 2.19 is used to determine the p, pitch circle, given θ, width of tooth in degrees. The pitch circle is the circle centered on and perpendicular to the axis, and passing through the pitch point, the point of the gear teeth where the tooth vector changes direction to make meshing with other gears easier. This pitch circle is normally equidistant from the base of a tooth to the tip of the tooth.

Gears offer more surface area when meshed with one another, as compared to a cable drive where you have n diameters of wrapped wire around a pulley giving off

friction. Used in high frequency gears teeth have a tendency to chip and loosen, crippling

the joint and rendering the robot unreliable; cables however, do not have teeth that are

bound to chip or break and stay flexible increasing their lifetime and thus increasing the

robustness and longevity of the robotic joints.

Gears and cable drives follow the same torque and speed ratios, and in these

aspects cable drives and gears can be compared by the same equations.

$$\frac{\omega_a}{\omega_b} = \frac{N_a}{N_b} \quad (2.20)$$

$$\omega_a = \frac{N_a \omega_b}{N_b}$$

$$\frac{\tau_a}{\tau_b} = \frac{N_a}{N_b} \quad (2.21)$$

$$\tau_a = \frac{\tau_b N_a}{N_b}$$

The above equations, 2.20 and 2.21, can be used to find the speed ratio, ω, and

the torque ratio, τ, with the a and b subscripts referring to subsequent gears or radii; the

difference in the equations between cable drives and gears is that N for gears stands for

number of teeth and for cable drives it stands for the numerical radii of each rotating piece. Once motor torque is known, then applied torque using equation 2.21 can be calculated and honed to required values.

2.10.2 Cable Material and Selection

Selection of the type of material for the cable used on the ModBot finger was small. Since the cable had to have a small diameter and bend radius materials for the cable were very limited at stainless steel and urethane. Right away urethane was crossed off the list due to the fact that it can stretch.

There were many different types of small diameter stainless steel wire that had been considered but the many different attributes included in the selection process helped narrow down the decision. Attributes included having a very small bend radius, non-stretch cable, high tensile strength and ease to work with. Using thin high tension wire is very difficult to work with and has a tendency to cut through skin so consideration was given when selecting wire to make sure that the wire had enough surface area when wound to apply a substantial surface force to the pulley and to not be dangerous to work with by hand.

After searching for wire that fit our needs, the Sava Industries Inc. company was discovered which had the required types of wire available. Wires range from a nominal diameter of 0.53mm (0.021 in) to 1.6mm (0.06 in) in the precision miniature cable category. All of their precision miniature wire is classified as low stretch high fatigue wire, and can be purchased with or without a nylon coating. Since we wanted to have a small flexible wire with a low bend radius but need surface tension between the wire and

pulley it was decided to use the 0.53mm (0.021 in) nominal diameter wire with the nylon

coating. When the nylon coating is applied it changes the nominal diameter from0.53mm

(0 .021 in) to 0.69mm (0.027 in). According to Sava Industries data the 0.69mm (0.027

in) nominal diameter nylon coated wire has a minimum breaking strength of 50 lbs. or

22.7 kg, which far exceeded the amount of force the cable would be exposed to on the

ModBot finger robot.

2.10.3 Cable Drive Loops

One major drawback to cable drive trains is that they need a tensioner, normally a

spring, that allows constant tension to be applied to the cable allowing no slip. Many

cutting edge cable driven robots such as phantom robots [16], use this method to apply

tension to the cable. The problem with this method is that over a high frequency of uses

springs break down non-linearly, and perhaps more importantly deform under load (the

train loses stiffness at that point). Although a spring has a certain k value this value will

break down and slowly introduce slip into the system. We wanted to use cable drives but

we needed to find a way to bypass using a spring; this thought was twofold, first off

replacing the cable and spring takes time, some robots are very complex and getting to

the drive alone might be difficult and cost a lab much needed time or cost a company

significant money for their robots being down. Secondly a highly tuned robot must stay

tuned, with a spring slipping, data can become compromised or erroneous. Without

knowing that slippage is occurring the robot can be outputting bad data, and corrupting

experiments.

A solution we came up with was to make cable loops that could be tightened with a screw. If a cable loop breaks all the user has to do is back off the tension screw, remove the broken cable, insert a new cable loop and then tighten the tension screw. This greatly simplifies the whole cable drive system and makes it user friendly. If a gear were to break or chip a tooth replacement would not as easy. This also uses the entire cable as a highly stiff spring, effectively creating the entire spring component without any additional parts other than a screw.

Cable loops work in a simple way, a pre-measured cable is folded into an end to end loop, a washer is then inserted onto the cable, for tensioning purposes, and then the wire ends are clamped together using a cable clamp. On the ModBot finger robot each cable drive piece has receivers for the cable at three locations, the cable runs along the contoured radius, up and over the edge of the piece, then through the cable receiver around the inside of the radius, and finally out on the opposite of the of the piece, closing the loop. The washer is then looped around a screw shaft that runs through the inside of the part and two bolts are attached to the screw shaft, these bolts allow tension to be applied to the wire via the washer. If there is a chance that the cable stretches then more tension can be applied by tightening the bolts on the screw shaft.

Applying this method the ModBot finger can now be used at very high frequencies and if a cable break does occur, a new loop can be easily installed in little time without disassembling the joint or closing the cable ends after snaking it through a complex pattern of holes and slots.

3. Fingertip Force Sensor

For touch and sensing purposes the ModBot finger needed to be equipped with a method to allow the it to know when it is touching or pressing against a surface or object. There are many methods to aid in sensing but we decided that the best options available were either not small enough for the finger or were not sensitive enough. Many robots have custom-made sensors for special applications, [23] [24], and it was decided that this would be the best option for the ModBot finger robot; some robots use dielectric fields as sensors and other use precise drilled holes, (to strategically weaken the structure at certain points to enhance bending) and strain gauges.

3.1 ModBot System

To be able to safely grasp items or apply forces to objects different type of sensors, and force meters are needed. For this evolution of the ModBot finger a basic system was implemented with future plans to incorporate a complete feedback system.
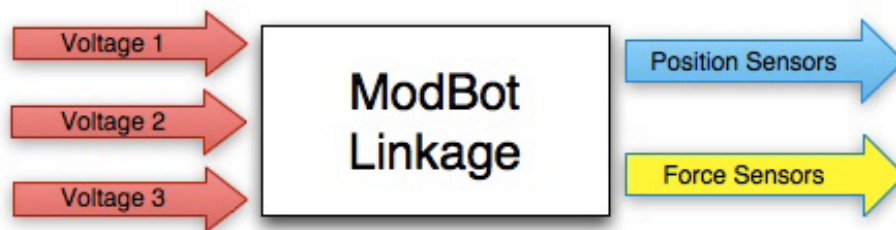

Figure 3.1: ModBot evolution 8 system, the three voltage inputs are for the DC motors and the two outputs are position sensors, potentiometers, and force sensors.

3.2 Potentiometers

Controlling the ModBot finger requires a few inputs that need to be configured correctly to know where the robot is in 3D space at all times. Along with the force sensors in the tip or end effecter of the robot, the joint angles of the robot had to be known at all times so that movement could be controlled. We derived a way to keep track of all joint angles by easily placing a rotary potentiometer at three joints; this allows the computer or controller to be aware of all joint angles at a high frequency.

We chose to use Alps thin profile rotary potentiometers that measure accurately up to 330 degrees of rotation. These potentiometers when tested have a 10 mV noise floor and have even lower noise (higher resolution possible) when shielded. Each potentiometer has two locator pins that have been incorporated into the design of the ModBot finger to insure perfect alignment. The axle is friction sealed on one end, travels through the second stage of the joint, the pivot joint, via two bearings and ends in a half circle shape that mates up with the potentiometer. When the friction-sealed end of the robot rotates, the potentiometer keeps track of the movement and follows the rotation via axle.
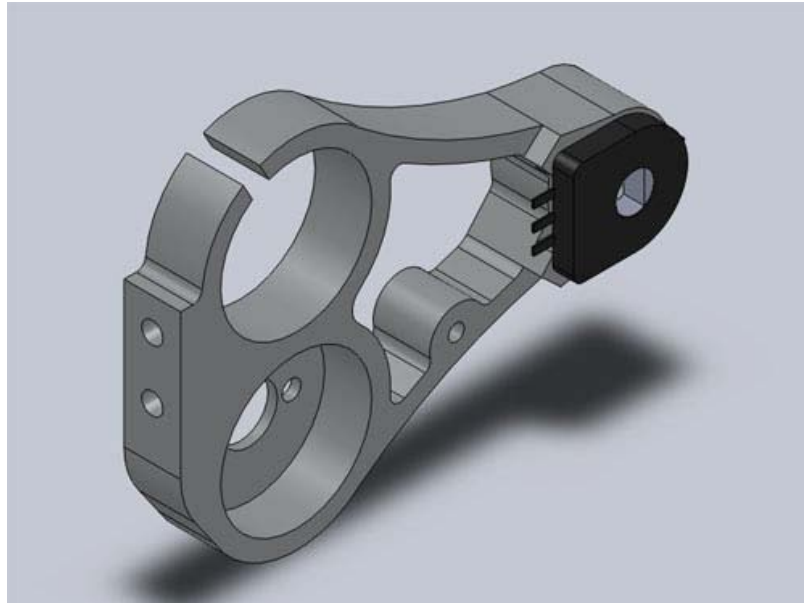
Figure 3.2: Example of potentiometer fixed onto a motor mount of the ModBot

finger, the ModBot finger has three potentiometers per finger, providing a position

measure for each degree of freedom. Each ModBot finger has two of these pieces that

each have a potentiometer affixed on the end as shown.
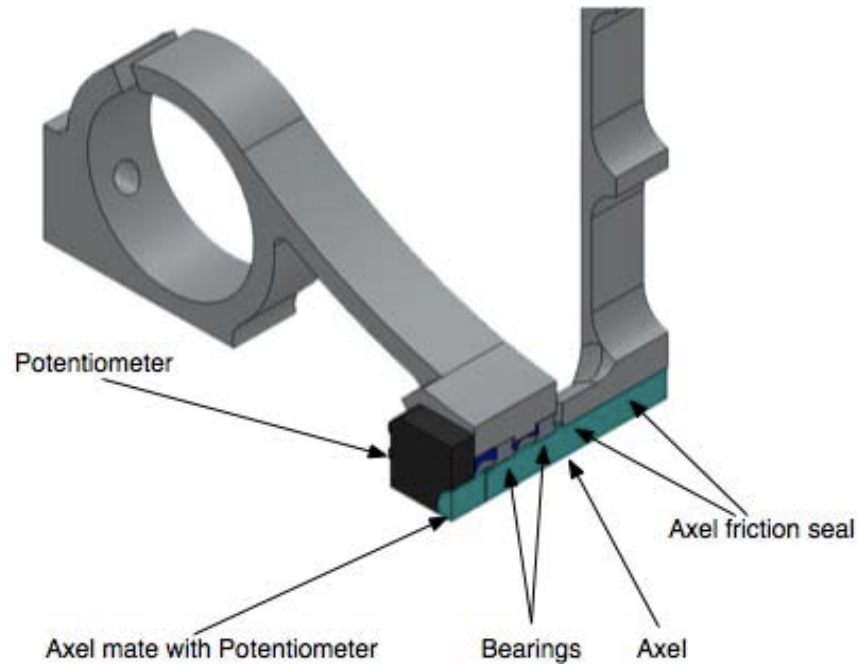
Figure 3.3: Double cut away picture of potentiometer, bearing and axel assembly, each piece has been colored to show interactions between pieces. The blue axle that travels through both parts is press fit into the riser then is friction sealed to both bearings and has a D cut in the end to engage the potentiometer. As the riser rotates the axle turns the potentiometer.

3.3 Force Sensor Fabrication

One of the main goals of the ModBot robot was to keep it as close to the size of a human finger as possible, this alone removed the chance of using a dielectric field emitter. At the time of fabrication most dielectric emitters were larger than the 5mm (0.20 in) x 5mm (0.20 in) cross section of the finger, and exiting wires needed to be at a minimum due to the fact that once a finger is placed into a matrix of 5, in the form of a human hand, all wires coming out of each finger are now multiplied by five, which can lead to electrical interference, wire tangles or robot hindrance due to force applied by exiting wires.

Omega, a company that produces a vast variety of strain gauges and sensors, made a strain sensor that fit our robot perfectly. It was decided that a precision cut would be made in the finger that resembled a figure eight in order to facilitate independent sensing of forces in each axis. Above and below the precision cut a 11mm (0.43 in) x 5mm (0.20 in) 350 ohm half-bridge is then glued into place. The s shape of the fingertip wasn't an aesthetic design but a functional design allowing measurement in three axes. This shape also allowed room for three precision force sensor cuts and the half-bridges that are located above and below the cuts. Using readings from the upper and lower strain gauges force direction and quantity can be calculated. If a strain gauge is in flexion then the resistance will drop, if it is in tension then it will rise; using this logic it is very easy to calibrate a micro processor (such as a PIC) to determine where the force is coming from and how much of it there is [25].
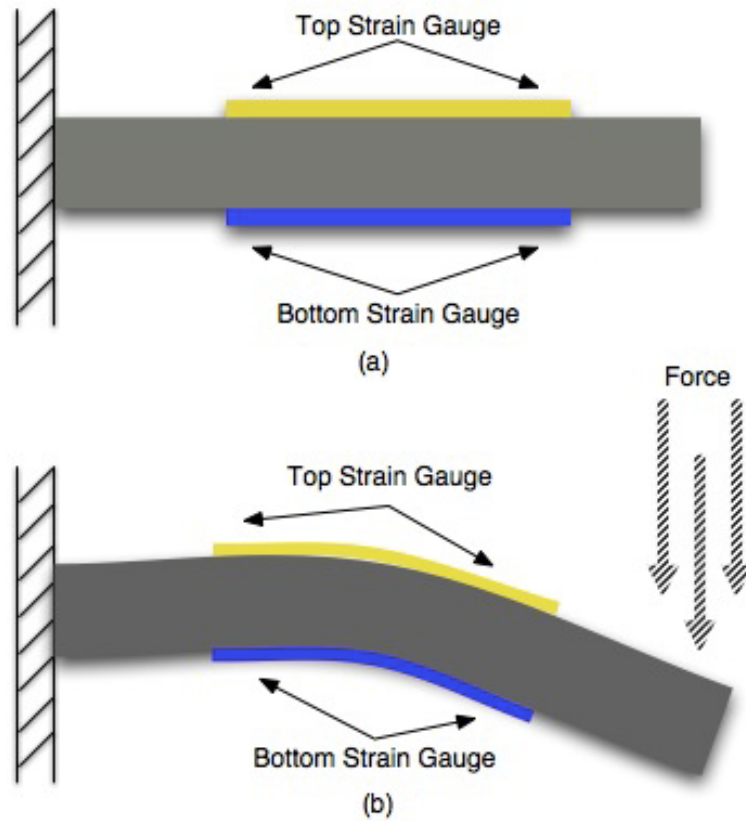
Figure 3.4a-b: figure 3.4a shows strain gauges above and below a fixed piece of aluminum (arranged as a cantilever beam). Figure 3.4b shows strain gauges reaction when a force is applied to the tip of aluminum. The force sensor will react accordingly on the ModBot fingertip.

3.3.1 Force Sensors on Robotic Fingertip

A concern with this method was that the fingertip would deform differently under forces than the strain gauge foils, since both have a different elastic modulus. Since the

strain gauge foil will deform before the aluminum it was a simple question of how to affix the stain gauges. Many books and websites suggested using a super glue type of adhesive to attach gauges to the appropriate surfaces. The problem with super glue or cyanoacrylate glues is that they are very hard when dry so may be too brittle for the required bending. Other problems with cyanoacrylate are that they becomes soft in the presence of solvents such as acetone, and it also has a tendency to become brittle at low temperatures. Since the potential uses for the ModBot finger in a myriad of lab test situations is high, all precautions for the durability of the ModBot finger were be taken in to account, and for those reasons it was decided to not use cyanoacrylate.

After an exhaustive search of different types of adhesives for electronic parts was completed we went in the direction of an epoxy. Loctite makes many different types of epoxy for every application, even for printed circuit board, (PCB), coating and electrical enclosures. Hysol, Loctite's line of epoxy based electronic coatings has a high strength bond but flexes and isn't susceptible to solvents [27]. Hysol like all epoxy has to be mixed with a hardener then applied quickly before the epoxy bonds and becomes hard, since Hysol is formulated to work specifically with PCB's and electrical components it applies as a thin coating that made application easier. When we tested the epoxy it was generously applied with a Q-Tip to make sure all exposed wires were covered and that no short circuits would occur. After the epoxy dried we tested the finger tip to make sure that all gauges still worked, no short circuits were occurring and that we were receiving clear, precise signals from all of the half bridges. Not only did the epoxy hold but it flexed well allowing the finger tip to deform in its designed fashion, moving the half

bridges with it, but it also kept wires from coming in contact with each other, which would result in a short circuit and faulty data.

Each half bridge has three wires that protrude from the strain gauge, and each designed deformation location has a strain gauge above and below it, with three of these locations per finger. Each fingertip alone has 18 wires coming out of the back of it. This alone creates a bundle of wires for just sensing purposing, not to mention that there are still power wires, and potentiometer wires. Due to space limitations a ground rail was used to link all of the ground wires coming out of the finger tip, this allowed more room for other wires and gave more freedom of movement due to less resistance from wires.
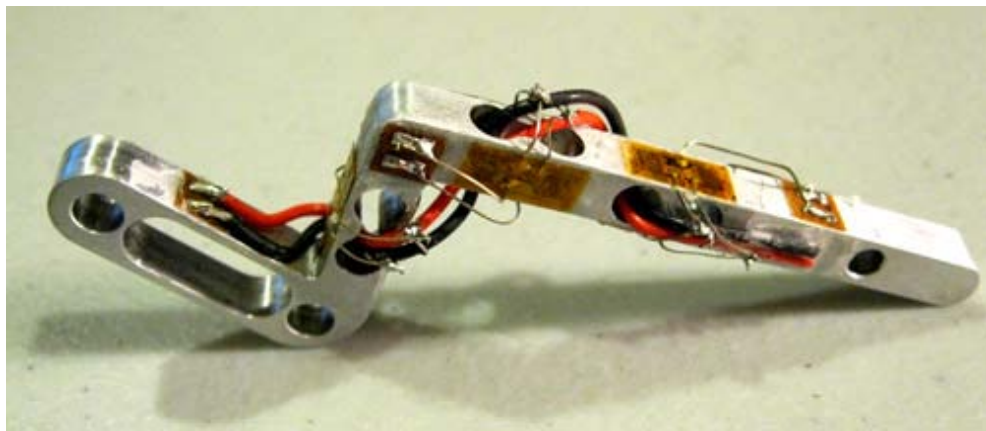
Figure 3.5: ModBot fingertip with force sensors, force sensor stress relief pads and wires installed. Each ModBot fingertip has wire routing as shown in the figure to minimize space used for wires. Exposed wires are covered in an epoxy resin to keep from shorting out.

3.3.2 Force Sensor Printed Cover

Since so many wires were coming off of the fingertip, and the strain gauge foils were fragile it was decided that a protective cover would be placed over the gauges and wire. The cover had to be designed to not hinder the performance of any of the strain gauges, and to not absorb any forces that could be used as sensing forces. The way this was accomplished was by using a Dimension ABS plastic printer to print two halves of the protective cover, and that they would snap together creating a friction seal on only the tip of the finger piece, allowing a transmission of forces with little dampening and allowing for an accurate force reading. There is a through hole that a screw attaches to make sure on hard detonations that the finger cover does not come apart but that to is before any strain gauges and when tight allows for no force dampening. To help with all the wires a slot was designed on one side of the protective cover allows a small PCB to be slid into place and can accept all the wire connections. This removable PCB also allows for the strain gauges to have some slack in their wire leads, this helps in the longevity of the robot and sensors, if all the wires were tight and a hard collision occurred a lead might snap or break, causing researchers to use valuable time repairing a wire lead and losing valuable data and time.
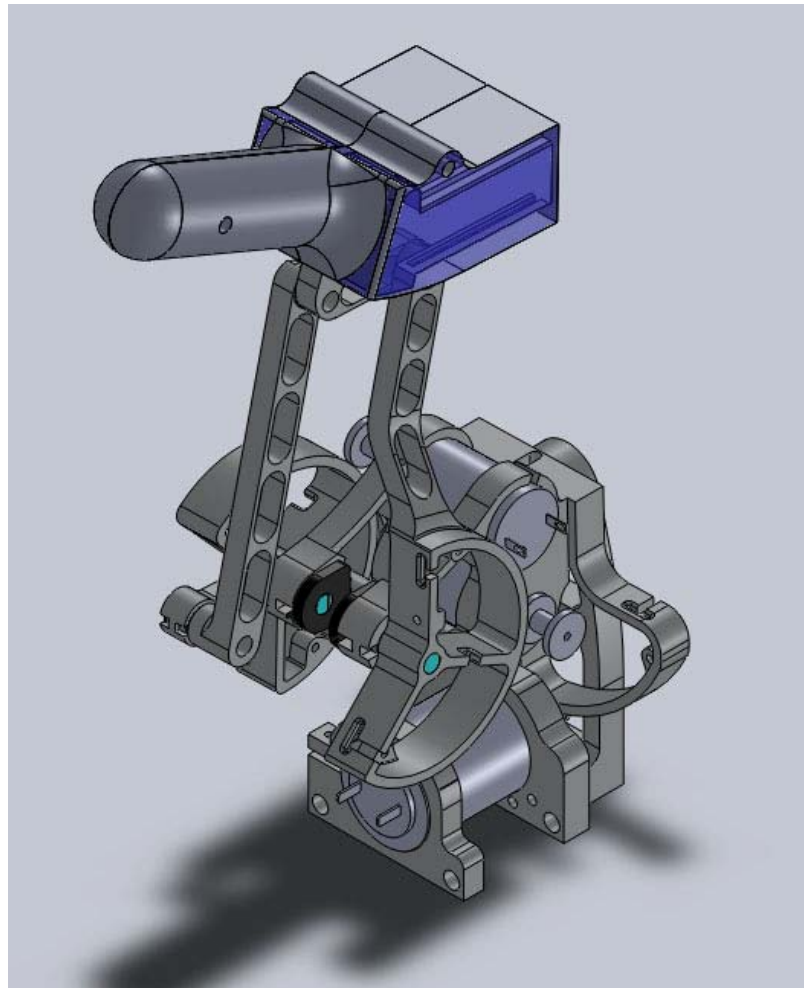
Figure 3.6: ModBot finger ISO view, with plastic printed fingertip cover.
Notice that part if the finger cover is a clear blue, this is to show the channel
inside the finger cover that allows a small PCB to be slid in side which
attaches the wires from the finger tip sensors to a small PIC. This slot PCB
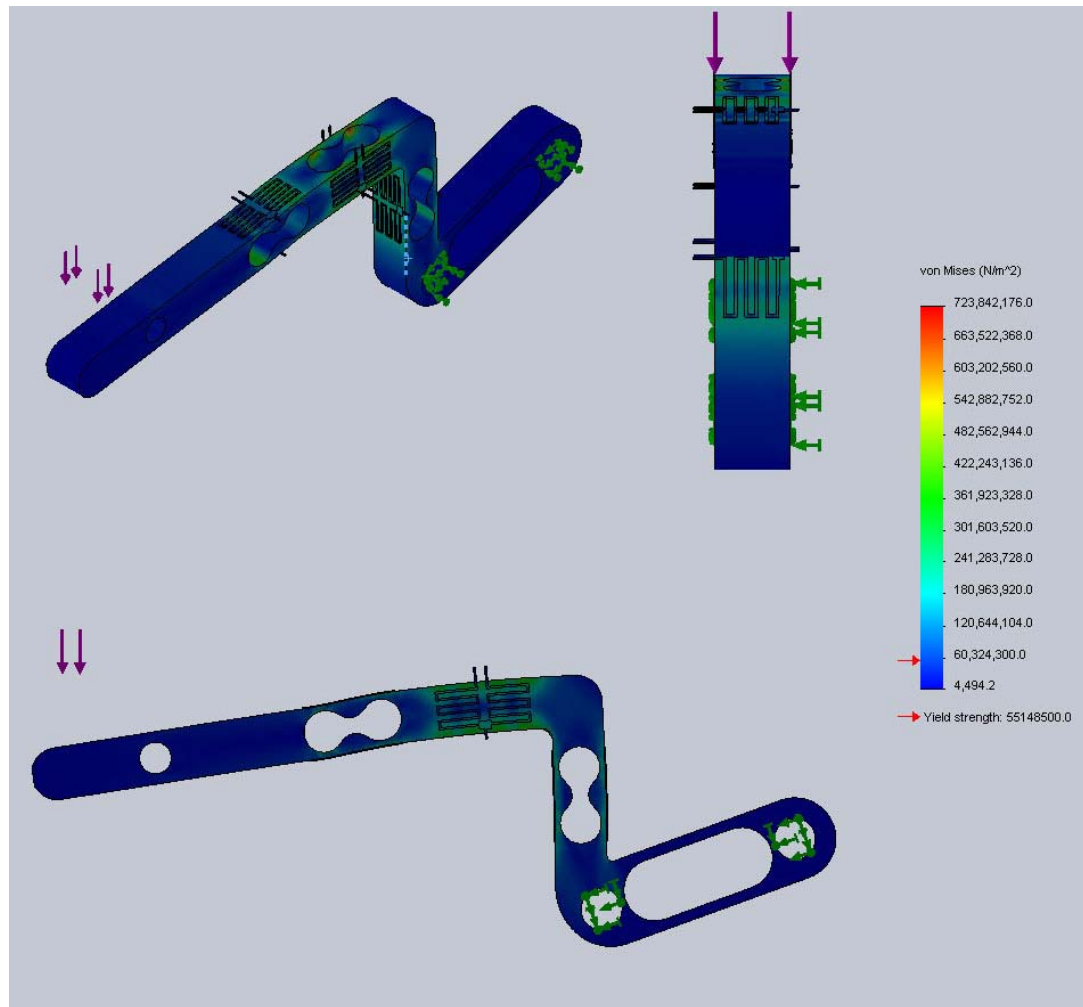idea is slated to be implemented in future evolutions of the ModBot finger.

Figure 3.7a: Fingertip deflection with attached half bridges, the above picture has 50N of force

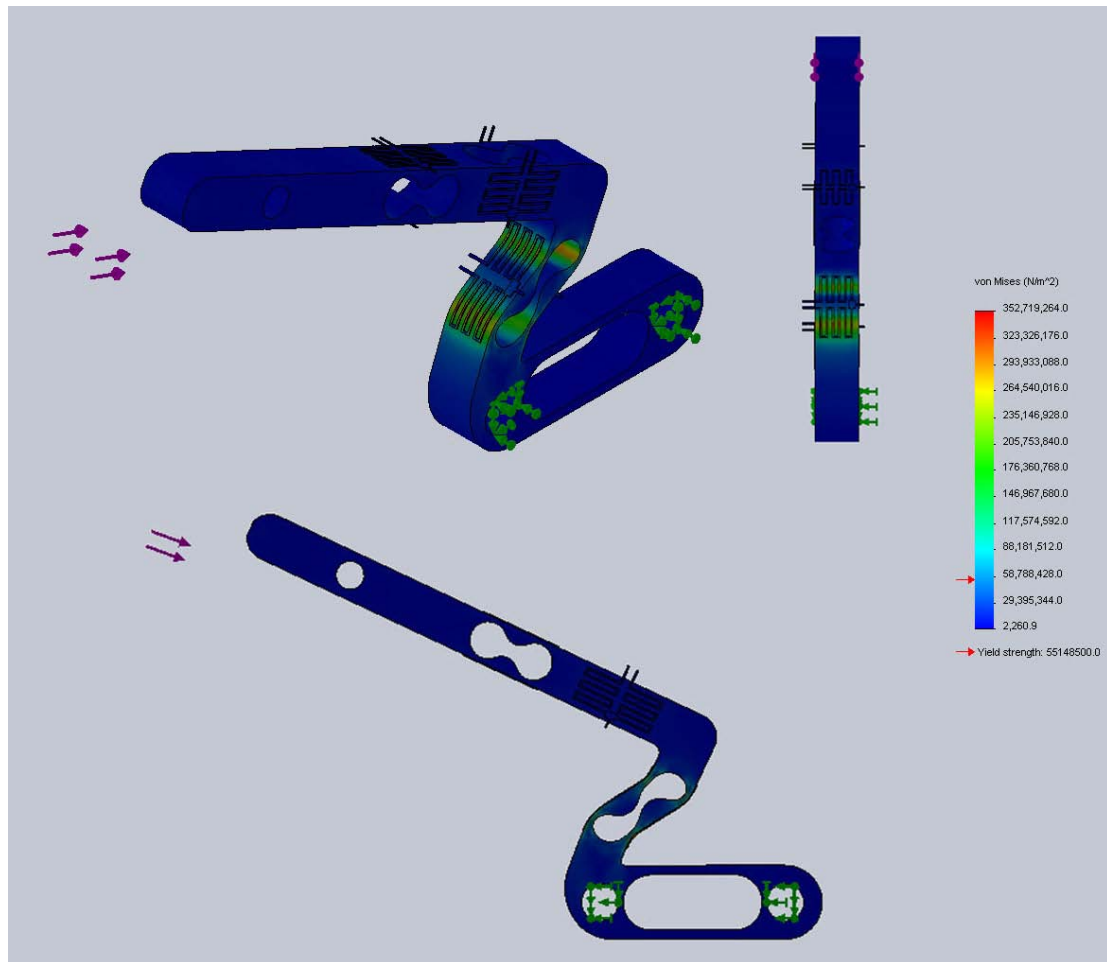pressing down on the tip of the finger, denoted by the purple arrows.

Figure 3.7b: Fingertip deflection with attached half bridges, the above picture has 50N of force pressing axially inward through the tip of the finger, denoted by the purple arrows.
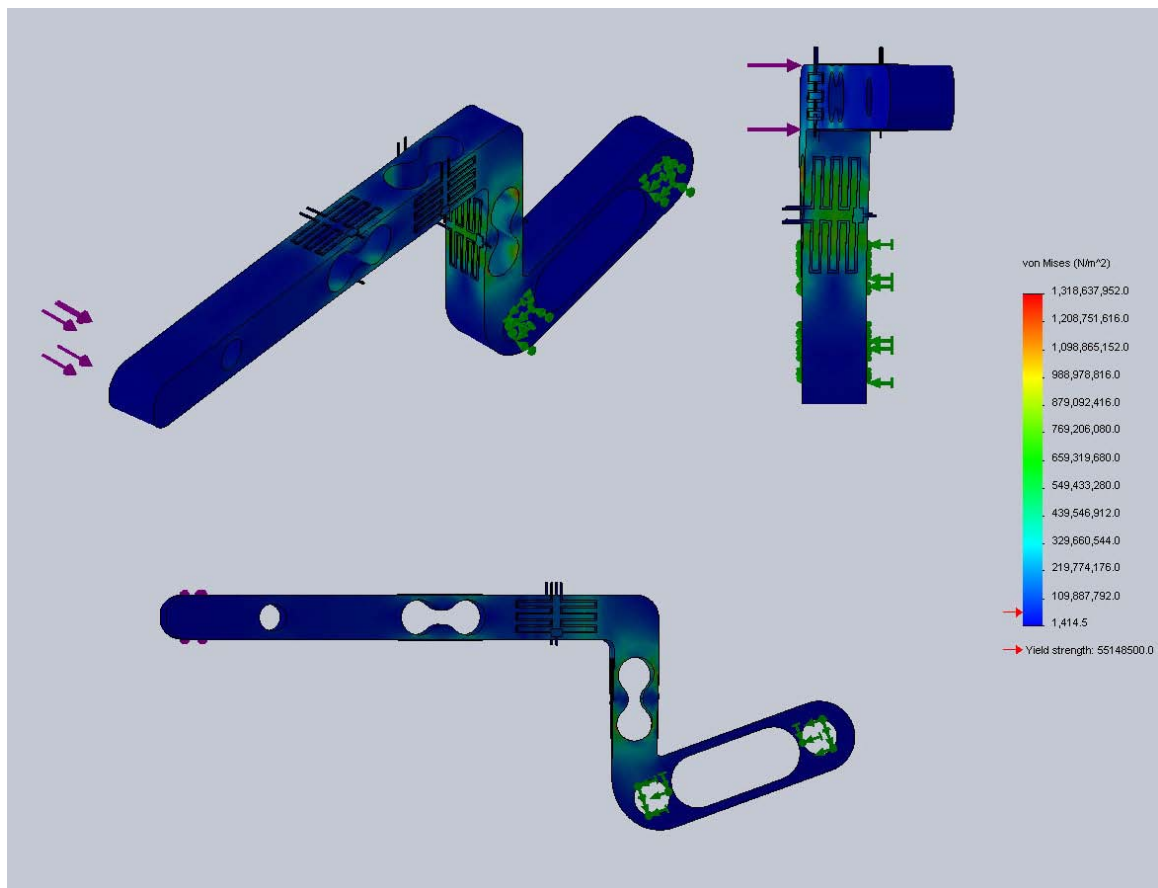
Figure 3.7c: Fingertip defection with attached half bridges, the above picture has 50N of force pressing towards the left on the tip of the finger, denoted by the purple arrows.
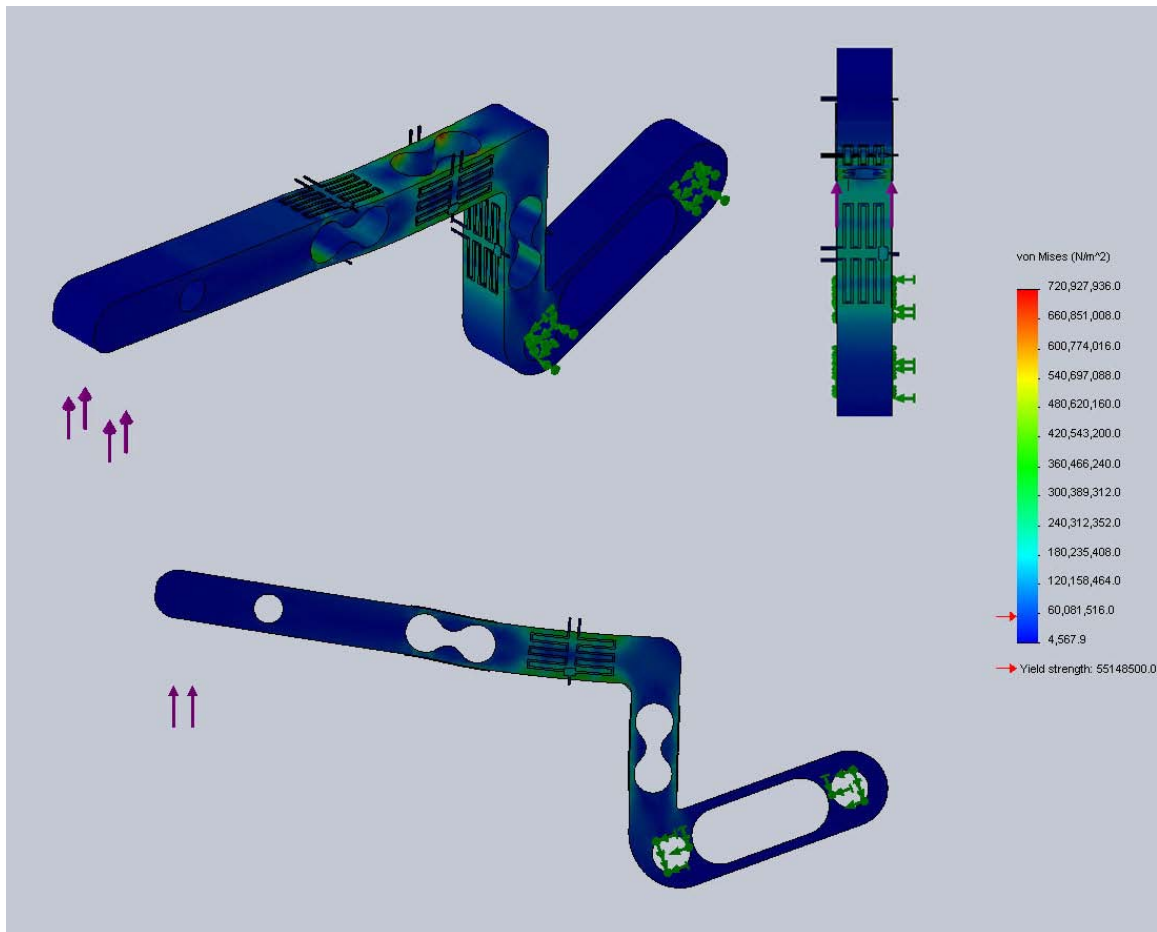
Figure 3.7d: Finger tip deflection with attached half bridges, the above picture has

50N of force pressing up on the tip of the finger, denoted by the purple arrows.

3.4 Electronic Properties of Force Sensors

The strain gauges used on the ModBot finger follow the principle of a Wheatstone bridge. This type of electrical circuit was invented in 1833 and was popularized in 1843 by Sir Charles Wheatstone, thus it has since been known as a Wheatstone bridge [26]. A Wheatstone bridge is essentially a voltage source, connected to four resistors, in the shape of a diamond, where a voltage is measured between the connections of the top two resistors and the two bottom resistors. Kirchhoff's current law can also be used in a Wheatstone bridge to find current at junctions or even voltages on different legs of the circuit. Using this setup with strain gauges allows us to sense stress in certain locations and directions with the ModBot finger.
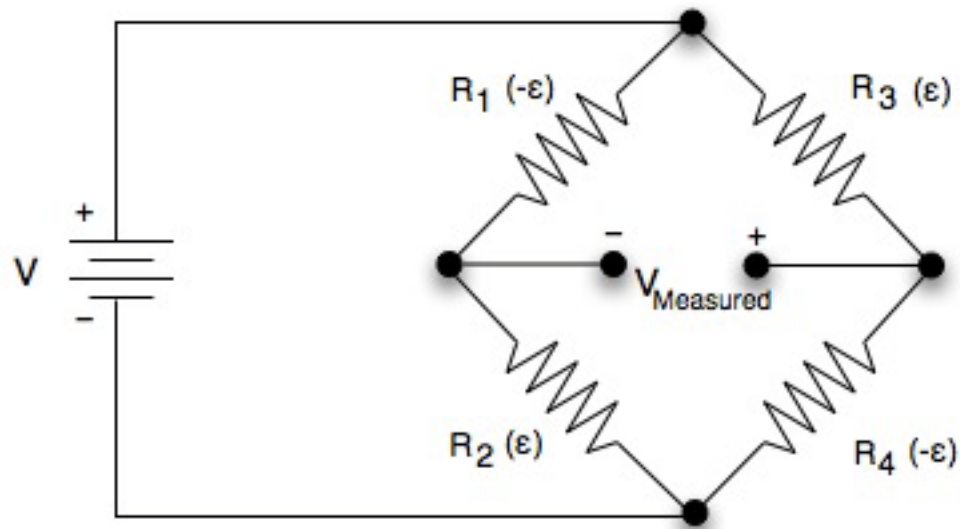

Figure 3.8: Schematic of a Wheatstone bridge set up; ε is a placeholder for resistor or strain gauge strain.

$$\vartheta = \frac{-R_g}{4R_g + 2R_g} \tag{3.1}$$

$$V_r = \left(\frac{V\,(strained) - V\,(unstrained)}{V_{Measured}} \right) \tag{3.2}$$

$$\varepsilon = \frac{-V_r}{GF} \tag{3.3}$$

Where all variables are set as:

- ϑ is the ratio of expected signal voltage to excitation voltage.

- R_g is the nominal strain gauge resistance, the gauges used on the ModBot finger have a nominal resistance of 350 Ohms.

- V_r is the voltage ratio that is used in the voltage to strain conversion equation 3.2

- ε is strain value obtained during finger deflection, this is also used to convert voltage readings to strain units

- GF is gauge factor; this value is determined by the manufacture, which for the ModBot finger is Omega.

Using equations 3.1 through 3.3 we are able to use strain gauges on the ModBot fingertip to sense touch and forces pushing against the finger robot.

3.5 Finger Force Sensor Calibration

To make sure the sensor design and implementation was not only feasible but worked correctly a force sensor test was formulated and ran. To complete the test a stand was built to hold the finger in three positions that would directly affect each of the sensor positions, front, middle and rear sensor positions, the front force sensor is closest to the finger tip. Voltage readings were taken from each sensor as weights were applied to the end of the finger tip. Figures 3.9a-c explain what happened when static weights were applied at different positions, while readings were also pulled from the other two force sensors to show exactly how coupled each force sensor is. The below plots not only show how well the force sensors work but how linear the received data was.

Figure 3.9a: Force sensor readings from the finger orientated so that the front sensor was used. Data was taken as weights were added to the end of the finger tip; a linear fit was applied to the final data. Readings were also pulled from the middle and rear force sensor.

Figure 3.9b: Force sensor readings from the finger orientated so that the middle sensor was used. Data was taken as weights were added to the end of the finger tip; a linear fit was applied to the final data. Readings were also pulled from the front and rear force sensor.
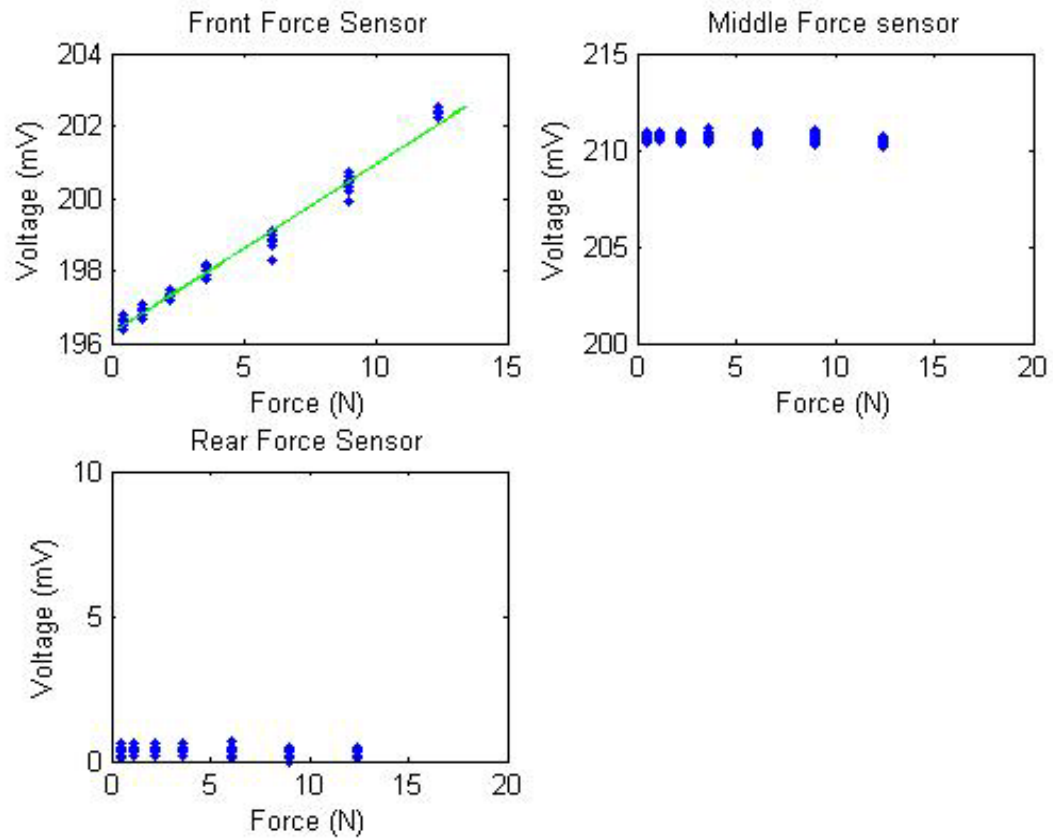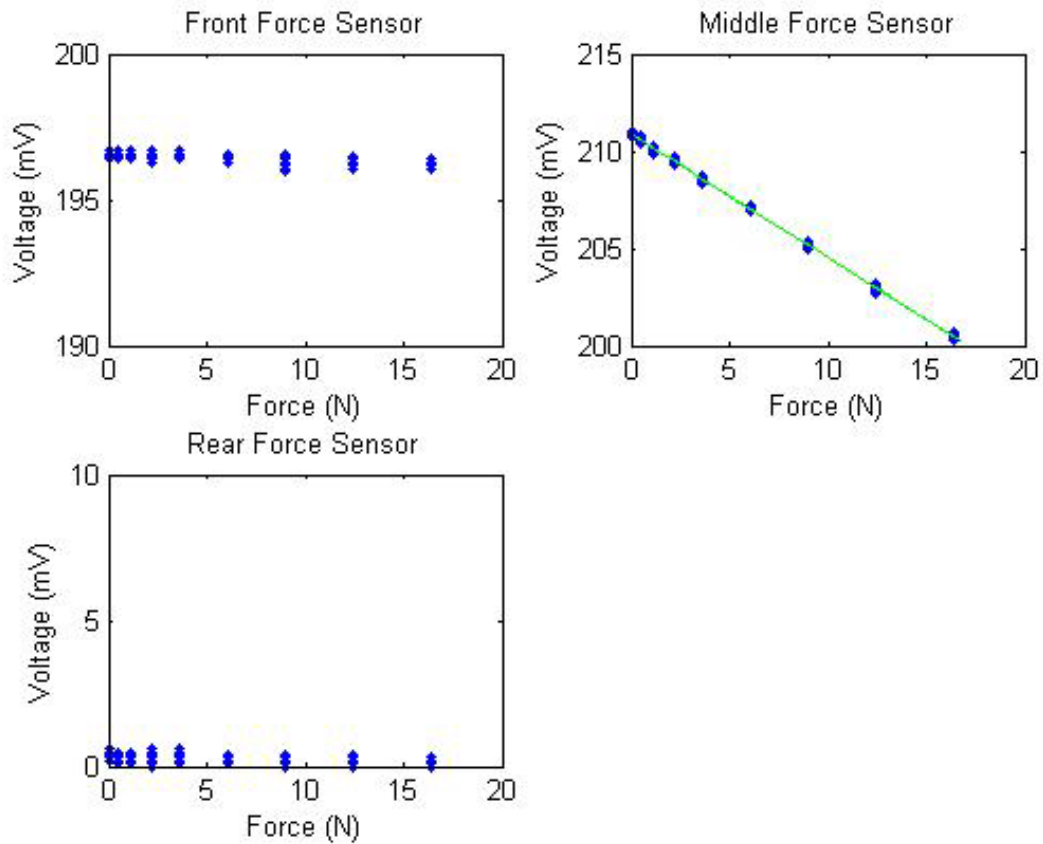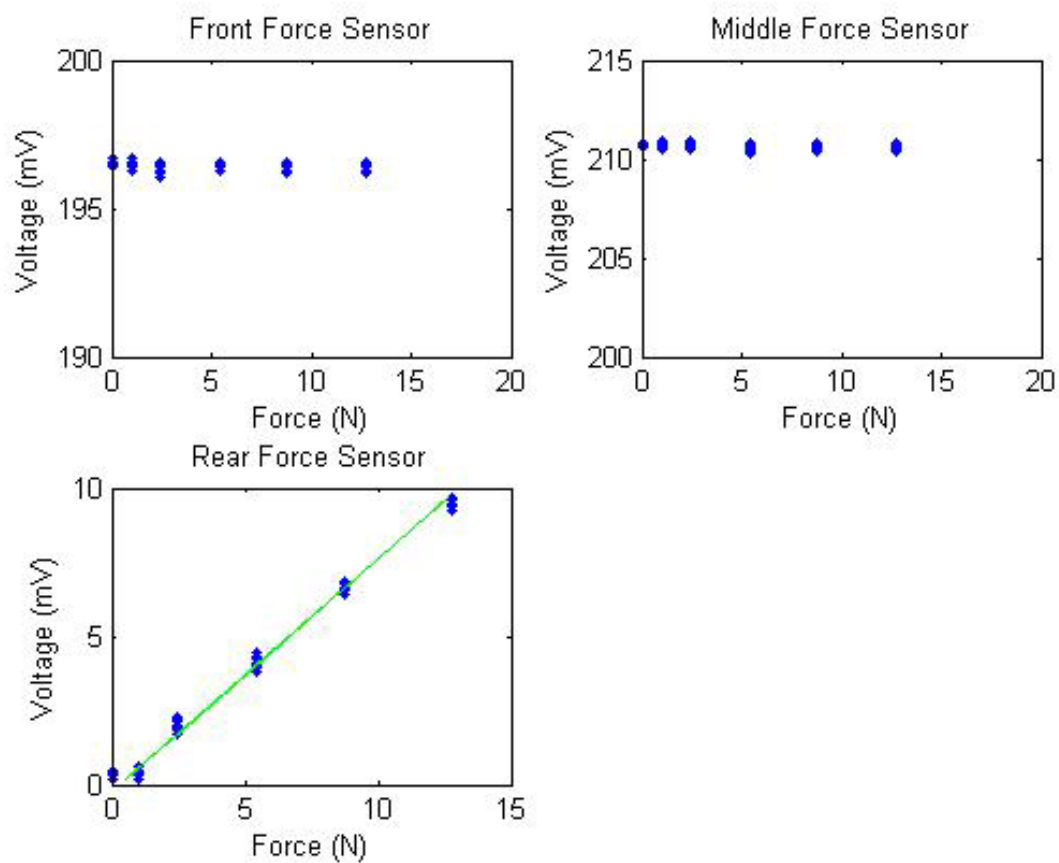
Figure 3.9c: Force sensor readings from the finger orientated so that the rear sensor

was used. Data was taken as weights were added to the end of the finger tip; a linear

fit was applied to the final data. Readings were also pulled from the front and middle

force sensor.

4. Modular Properties of Finger Robot

Another amazing design aspect of the ModBot finger robot is that it can be used and arranged in many different set-ups with little effort on the part of the experimenter. Since the finger was created without the distal phalangeal joint all fingers operate exactly the same, the human thumb does not contain a distal phalangeal joint and once that joint is discarded all fingers operate the same and differ only in length, mounting location, and coupling. A secondary goal of the ModBot finger was that it would be fully modular, would be able to accommodate researchers, and be set in many different orientation arrays to aid in a myriad of different test situations the finger will be used in once it is available for researchers. Plates and mounting brackets have been made to accommodate the ModBot finger, each mount puts fingers in many different orientations for testing, from one to a full hand of fingers have been designed.

The problem with most hand/finger robots are that they are not backdrivable, are not modular, and are not biomimetic. When brainstorming and design began on the ModBot finger it was clear that our finger robot had to do all three of those things, since we envisioned many labs all over the world would be using this robot for a variety of testing and researching. These three aspects in particular separate the ModBot finger from any other hand/finger robot that is available at the date of this thesis's publishing.

4.1 Three and Four Finger Tester Plate

After initial tests were completed on one of the ModBot finger robots, it was decided that multiple fingers needed to be tested at the same time. Putting a few fingers

facing each other allowed for gripping certain objects such as cell phones and Ping-Pong balls. It was determined that if the fingers could be controlled to delicately grasp an object, many different labs and researchers would be intrigued to purchase and use the ModBot fingers in various lab settings.

The first plate that was formulated for multiple finger robot testing was a four-finger plate that separated each finger 90 degrees. This plate allowed only three fingers if desired but was primarily designed for four. Denominations on either side of the plate, one side American units and the opposite side S.I. units, allows each finger to be placed at a certain distance from each other to allow that finger collision doesn't occur and to allow some distance between the fingers if the object is big or oddly shaped. The base motor mounts of each finger allows for three cap head screws to attach a finger to countersunk channels that allows each finger to move towards the center or parameter of the plate.
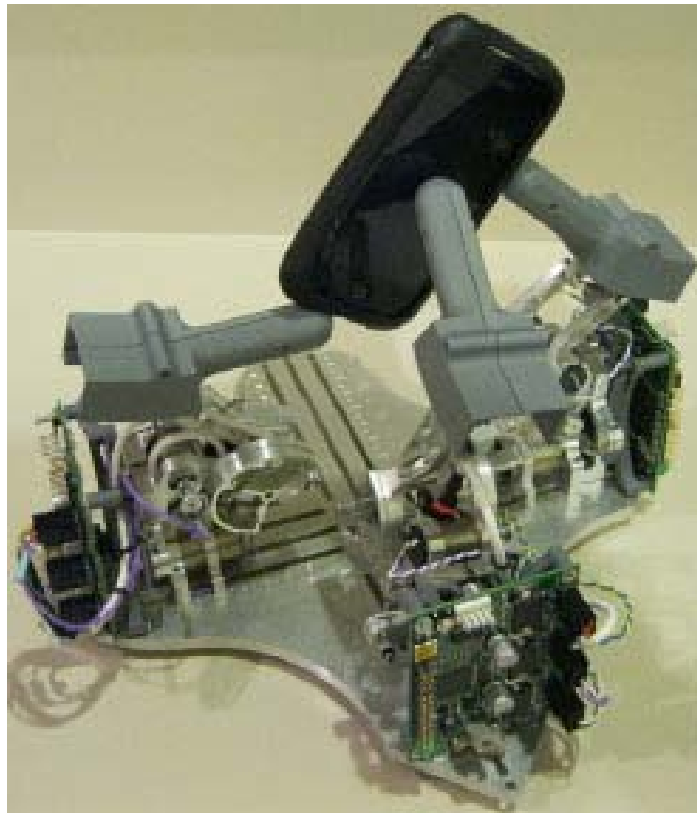
Figure 4.1: Picture of three or four fingerplate with attached fingers holding a cell phone; fingers are placed around the center of the plate and are equal distance from the center of the plate. Picture was used with permission from Charles Alex Simpkins, co-creator of the ModBot finger.

4.2 Full Hand Plate

At the time of publishing a hand plate for the ModBot finger robot had been solid modeled but had not been built or tested. At this point most testing of the finger robot has been with the plate outlined in section 4.1; to fully test out the robot and compare it to a real human hand a plate had to be developed and simulated. We have strived to create a robot that is biomimetic and thus needs to be set up as so, taking measurements from a male's palm the full hand plate was created. This reason for creating this plate was to test the reliability of the ModBot finger and also to compare it to a real human hand.
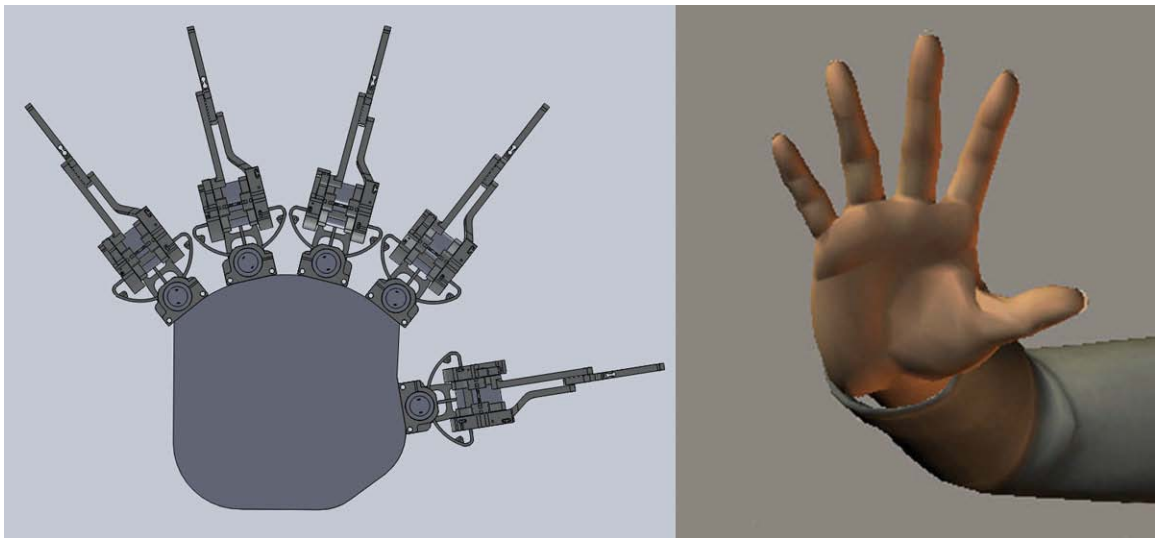

Figure 4.2: Full hand plate on the left with five attached ModBot fingers compared to a real human hand on the right. The Full hand plate was fashioned after a male's hand, and the virtual hand on the right is that of a male.
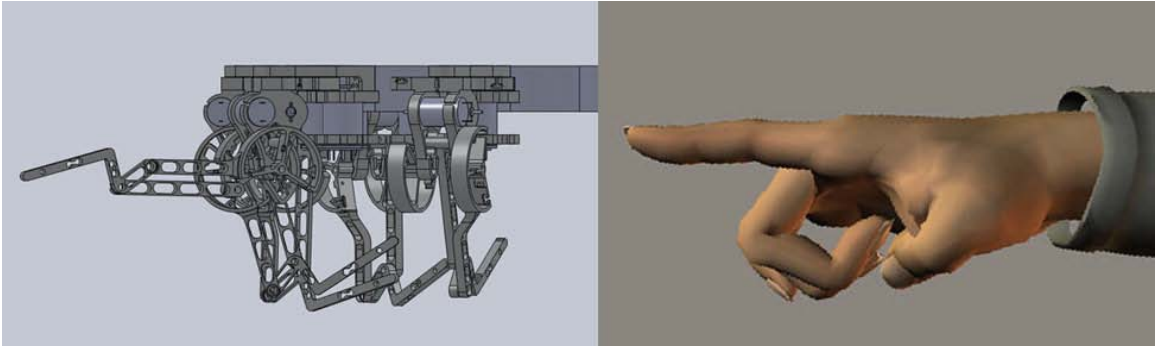
Figure 4.3: Full hand plate and human hand side view while pointing with pointing finger

Figures 4.2 and 4.3 show the ModBot finger compared to a virtual hand in the same position. Due to the modular properties of the ModBot finger a plate that could host more than five fingers could be a reality but as of the date of this publishing the full hand plate is the biggest plate that has been designed for ModBot implementation.

4.3 ModBot Finger Future

As of today the ModBot finger is under review to receive a US patent to protect the intellectual property of the inventors and the labs used to create the robot. We want to begin producing many of the fingers and have labs use them for multiple applications while at the same time honing the design and usability of the robot. We believe that the robot has the potential to be used as human aid to help those with a disability.

5. Conclusions and Future Research

This thesis has emphasized different methods and factors when creating a humanoid robotic joint for the purpose of testing. Utilizing a verity of techniques and drives the ModBot finger came to fruition not only meeting but surpassing expectations.

5.1 Contributions of this Thesis

This thesis set out to design, create and optimize a modular, biomimetic, fully backdriveable humanoid finger. The main contributions of this thesis can be summarized as the following:

- Design a state of the art humanoid finger robot using solid modeling software

- Optimized every aspect of the finger robot to minimize friction and weight. Careful selection of material type, motors, and bearings, were paramount in this process.

- Minimized mass in every piece of the finger robot to reduce overall weight, while evolving the design to increase the finger robots efficiency while reducing friction.

- Kinematic analysis of the final evolution of the finger robot to provide trajectory data and mobility plots.

- Deployment of potentiometers at rotating joints of the finger robot to keep track of joint angles. Creation of 3 DOF force sensing finger tip using strategically placed quarter bridge force sensors over cuts in the material allowing plastic deformation and force readings.

- Utilize cable drives for each joint of the finger robot instead of gears to reduce backlash and create backdrivable joints. Allowing easy access to each cable drive in the instance that a cable has to be replaced due to wear.

- Each finger can become modular, inserted into a myriad of configurations with other finger robots to accommodate the needs of the user.

5.2 Future Research

- Implementing a controller into the system to give the finger robot feedback, allowing for better measurements and more awareness of where the robot is in 3D space.
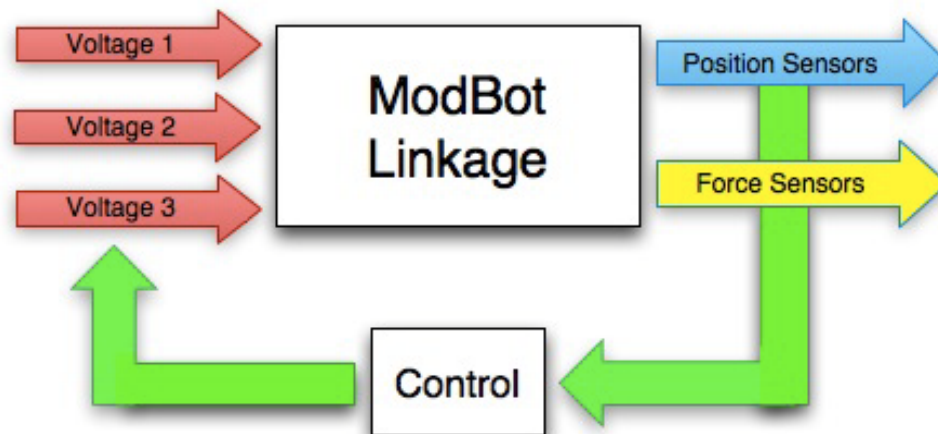

Figure 5.1: Example of feedback system that could be applied to the ModBot finger to increase precision and awareness of the robots location in 3D space.

- Fabricate the full hand prototype and test five robot fingers in a human hand matrix to get data. The prototype can be connected to a cyber glove to receive and copy movements from a real hand. This would show the resemblance of the ModBot finger robot to a human hand as well as the mobility and modularity of 5 finger robots.

- Test a finger using a simple PID (Proportional, Integrator, Differentiator), controller to see how the finger reacts. If favorable then a simple adjustment of the K gain values is needed. If not favorable then application of a optimal control algorithm is needed.

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