The Development of a Brain Controlled Robotic Prosthetic Hand

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Abstract

An anthropomorphic, brain controlled, under actuated, Prosthetic hand has been designed and developed for upper extremity amputees. The hands function is based on micro servo actuation and the use of coupling links between parts of the finger. The control of a prosthetic hand is what differentiates this project from the others. It is the intent of this project to increase the sense of belonging between prosthesis and amputee by controlling the designed device by the brain of the amputee. The platform has been designed to use multiple force sensors to improve control. The project is a feasibility study and will be used to test whether a multi-functional and intuitive prosthetic hand is attainable. The control of the hand will be driven through a neural interface and controlled by a micro-board. This paper focuses on the mechanical design of the hand and the processes used to control the hand using signals emitted from the brain, to increase the sense of belonging between the amputee and prosthetic device. The hand has been developed as a foundation for future research into brain controlled prosthetics at the University of Waikato.

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Chapter One

1.1 Introduction

The aim of the project is to develop a brain controlled prosthetic hand which can perform the basic functions of a human natural hand. An integrated design approach between mechanics and electronic control, applied to an under-actuated anthropomorphic artificial hand for prosthetic applications will be presented.

Estimates suggest that ten million people on the earth at any one point in time suffer from the effects of a missing limb or body part [1]. Thirty percent of these people are arm amputees that suffer from the loss of either their whole arm or parts of it. Until recent years the development of prosthetic devices that return function and confidence to these upper limb amputees has been very limited. Over the last decade research and development in prosthetics has opened the door to a new age of prosthetics. Never before have we been able to mimic the aesthetics, function and performance of a human hand as we can today.

The mechanical design and electronic control of an artificial anthropomorphic hand requires interdisciplinary research in the fields of electrical engineering, mechanical engineering, computer science, economics and mathematics.

In New Zealand there is a serious gap in the knowledge required for the design and control of anthropomorphic robotic prosthetic hands. This knowledge will only be gained by the research, design and development of these devices in the south pacific.

1.2 Motivation

The major contribution of this research is to support the rehabilitation of amputees. A study suggest that three million people on the earth at any one point in time suffer from the loss of an arm or parts of it [1]. One of the major issues for an amputee using a prosthetic limb is the “sense of belonging”. A successful prosthetic gives amputees the feeling that it belongs to them and it becomes an intimate extension of their body. If there exists a “sense of belonging” from the amputee it is more likely that the prosthetic will be successful [2]. The pressing of buttons or performance of a specific posture to get a prosthetic to perform a task makes the amputee feel that the prosthetic hand does not belong to them. Using brain signals to control a prosthetic device will raise the sense of belonging. The research will increase the availability of neural prosthetic devices and encourage the development of functional, dextrous and useful prosthetic devices for upper extremity amputees.

1.3 Objectives

The key objectives of this project include the evaluation, design and selection of a prosthetic hand that is controlled by the brain. The research will focus on the electronic control and mechanical design of the proposed hand. To achieve these objectives chapter one introduces the thesis aims, motives and objectives. Chapter two is the literature review which has been separated into two sections based on the ideas introduced in chapter one, which are: prosthetics and robotics. In light of chapters one and two, chapter three explains the mechanical design of the hand. Chapter four discusses the control system of the hand and the development of controlling the prosthetic. Chapter five discusses the performance and aesthetics of the hand and in chapter six conclusions are drawn.

1.4 Scope

The scope of this paper is limited to off-the-shelf electrical components due to restrictions in budget, simplicity and availability. These factors justify the need for a simple, inexpensive and easy-to-program prosthetic device. This research is to act as a platform for the development of brain controlled prosthetics at the University of Waikato.

The research will use force sensors to provide simple feedback to the controller. Force sensors are included in the scope of the work because of its direct relation to function and the potential to increase the "sense of belonging" between amputee and prosthetic device.

The mechanical design of the hand will be achieved by the computer aided design program "SolidWorks". The hand will be based on the skeletal structure of the human hand.

Material choices are limited to the three dimensional printing materials available at the University of Waikato. Limitations associated with the material used for production will be addressed but no effort will be made to minimise the effects of it.

Consideration of other or all types of prosthetics would avail no useful information due to the broad range of amputees and potential pathways towards recovery. The research, analyses, the performance, aesthetics and function of the designed prosthetic hand. The hand has four fingers and an opposable thumb.

The methods used to evaluate the hand will be limited to what is already found in literature. Some of these methods include: trajectory planning, kinematics, velocity kinematics, force evaluation and workspace planning. No new testing methods will be created in the testing of the developed hand. Rather a combination of current testing methods will be employed to analyse the hand in three specific but different areas: Performance, function and aesthetics.

Chapter Two

The literature relevant to the thesis aim falls into two fields: Prosthetics and Robotics. These two fields are enormous. Therefore the scope of this review is limited to areas of research that are considered relevant to the thesis aim. In the first section the history and challenges associated with prosthetic development are reviewed. In the second section research into the development and control of robots and electromechanical hands is revised. The review is concluded by highlighting the areas of prosthetics and robotics that can be combined to produce and develop a sufficiently dexterous prosthetic hand that can be controlled by the brain.

2.1 Prosthetics

The world around us is built upon the premise that it can be manipulated and changed by the human hand. Everyday activities inevitably involve the use of hand operated tools, devices and utensils. The loss of a limb or parts of it can have a dramatic effect on the quality of life and the emotional stability of individuals.

In the field of medicine a prosthesis is a man-made device that replaces a missing body part. Other sources define prosthesis as devices that are either external or implanted, that substitutes for or supplements a missing or defective part of the body. Throughout literature there is a common theme that prosthetics are devices which aid, give function or restore function to body parts that are missing, not functional or partly functional.[3]

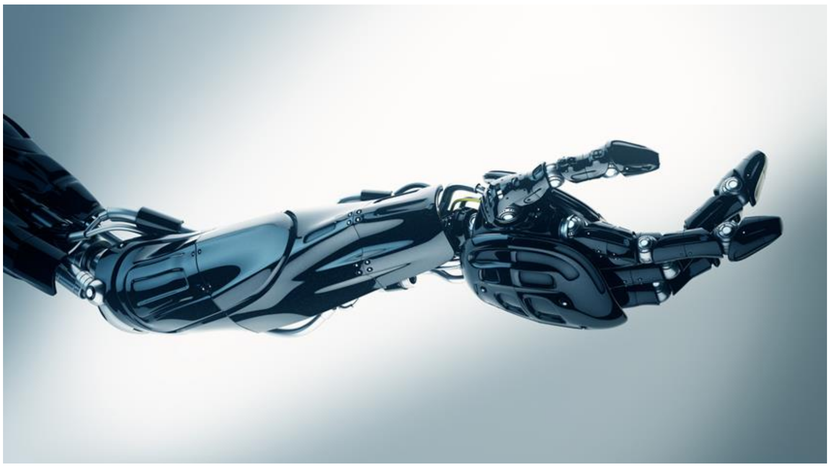

Figure 2.1: A render of a futuristic artificial arm [4]

Limb loss most commonly originates from, trauma, disease, congenital condition and injuries suffered through warfare. Prosthetic devices are designed and assembled according to the need of the amputee. Amputee needs vary widely and may be met in multiple ways according to the patients varying need for function. The future of prosthetics is bright. Advances in technology are opening doors to new and superior prosthetics. Figure 2.1 shows an artists prediction of where prosthetics are heading.

2.1.1 History of Prosthetics

Prosthetics in this day are able to mimic the function of a human natural limb more now than in any other time in history. Improvements in technology and understanding of mechanical systems and computer control have opened the door to an exciting age of human like prosthetic devices.

Artificial limbs and prosthetic devices were first realised and used in ancient Egypt where fibre was used to fill the empty cavity of missing limbs.[5] In these times the prosthetic was used purely aesthetically with the intention of making the amputee 'whole' or 'natural looking'. Figure 2.2 shows an artificial toe made from wood.

A Prosthetic device dating to around 300 B.C. was found in Italy in 1858. The device was made of bronze, iron and wood and was made for a below knee amputee. There is also an account of a Roman general in the second Punic war (around 218-210 B.C.) who had an arm amputated but returned to war using an iron hand fashioned to hold his shield.

Figure 2.2: An early prosthetic toe fashioned from wood. [6]

Little improvement or progression in the field of prosthetics was realised in the dark ages. Most prosthetics at the time were used to hide deformity. Functioning prosthetics were simple and consisted of a hook or peg leg. The use of functioning prosthetics did not progress until the early 1500's where reports of prosthetic hands claimed that mechanical spring systems were able to manipulate the grip and force exerted by the prosthetic hand.

Prosthetic devices since this time have advanced in many aspects. Prosthetics from the 1500's till now have employed lighter and stronger materials like plastic, titanium, aluminium and composite materials: each iteration being more effective. In addition to lighter and more durable devices the advent of microprocessors, computer chips and robotic systems is returning higher levels of function to amputees than ever before. Today's state-of-the-art prosthetic devices combine the latest technology in robotics with multi degree of freedom mechanical systems.

2.1.2 Types of Prosthetics

There are many types of prosthetics used for both function and appearance. Prosthetics are typically divided into four different categories: Joint Prosthetics, Arm Prosthesis, Leg Prosthesis and Cosmetic Prosthesis. An explanation of each type of prosthetic will be given in the following text.

2.1.2.1 Joint Prosthetics

Cartilage is a part of the human body that provides padding between bones. When this cartilage becomes worn the bones rub directly on to each other and limit movement. Prosthetics can be suitable replacements for these joints. The most commonly replaced joints are hips, knees and shoulders. Figure 2.3 shows a typical knee replacement.

Figure 2.3: Prosthetic replacement for lower limb amputee above the knee. [7]

2.1.2.2 Arm Prosthetics

Arm prosthetics commonly referred to as upper limb prosthetics are used to replace parts of the arm or the whole arm in some cases. The main types of arm prosthesis are Trans-radial and Trans-humeral. Trans-radial prosthetics are attached below the elbow, while Trans-humeral prosthetics attach to the upper arm (when the elbow joint is missing). Nigel Ackland (Figure 2.4) shown below has a trans-radial prosthetic attached to his arm.

Figure 2.4: Nigel Ackland demonstrating the use of his Bebionic prosthetic limb. [8]

2.1.2.3 Leg Prosthetics

There are two types of leg prosthetics (also termed lower limb prosthetics). Trans-tibial prosthetics are used to replace limb loss below the knee and Trans-femoral prosthetics are attached to the upper leg and include the knee joint. Leg prosthetics attempt to return function (ambulation) to amputees by customisation of the prosthetic to the amputees' needs, finance and health. Figure 2.5 shows a foot prosthetic.

Figure 2.5: Prosthetic foot replacement and its aesthetic covering. [9]

2.1.2.4 Cosmetic Prosthesis

These type of prosthetics do not improve function. These are only used to improve appearance. Some common cosmetic prosthetics are artificial eyes, feet, toes, fingers, hands, dentures and dental replacements. These prosthetics are often used to correct facial deformities, disease and trauma. Figure 2.6 shows an array of finger, hand and arm prosthetics that have only cosmetic applications.

Figure 2.6: A group of cosmetic prosthetics. [10]

2.1.3 Complexity versus Function

The complexity of any prosthetic device is interwoven with its ability to function well. A balance between function and prosthetic device complexity is of great importance when developing prosthetic devices. This section introduces ideas applicable to all prosthetic devices, but due to the aim of the thesis, the scope of this section will focus on the limitations associated with prosthetic hands.

"The human hand is a masterpiece of mechanical complexity"[11]. An ongoing challenge for scientists and engineers is imitating the complexity, function and aesthetics of the human hand. The human hand is a complex system [12] capable of accomplishing a wide range of movement with function covering small and precise control (grasping a pen, figure 2.7) to the wielding and grasping of heavy objects with considerable force. The wide range of possible movement the human hand is capable of is not realised in any prosthetic or mechanical device to this day. Finding a balance between complexity and function is the aim of all prosthetic and mechanical hand designers.

Figure 2.7: prosthetic hand grasping a pen in a tripod grip. [13]

2.1.4 Degrees of Freedom

Successful prosthetics are often measured according to its ability to use tools in an unmodified human environment. References [14] and [15] suggest that other predictors of prosthetic success are ease of application, function and method of control. In mechanics the degrees of freedom (DoF) of a system is "the number of independent parameters that define its configuration. It is the number of parameters that determine the state of a physical system and is important in the analysis of systems of bodies in mechanical engineering."[16]. The DoF in a mechanical hand relates directly to its functionality. An increase in DoF for a finger means that the three dimensional workspace of the finger also increases. A relationship exists between the amount of DoF and the physical limitations of the mechanical system being used. The following section describes the limitations of physical workspace with respect to the maximisation of DoF within a hand design.

Reference [17] Claims to obtain a hand that accurately represents the posture and movement of a human hand. It uses a twenty four DoF hand model to measure the required balance between complexity and realism. Figure 2.8 describes the joints of the human hand, these joints account for a single degree of freedom.

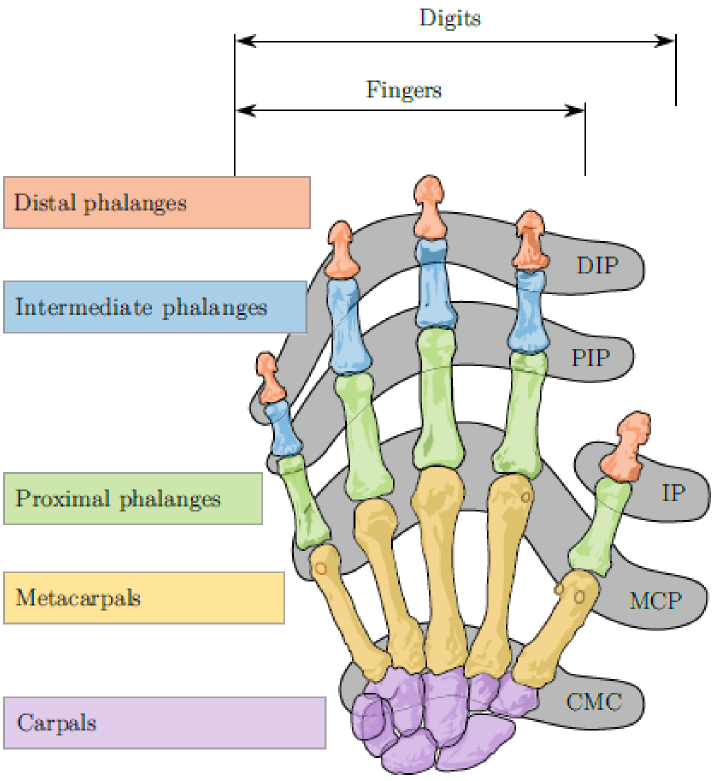

Figure 2.8: Bones of the human hand act as the basis for most prosthetic kinematic set ups.

Reference [18] Uses the human skeleton (Figure 2.8) of a hand as the basis for a twenty six DoF hand while [19] uses the same structure to model a DoF hand. Reference [14] suggests that the hand can be modelled effectively in twenty two DoF. There is a collective concern that these models cannot be represented as workable physical models due to the limitations of current technology [20]. A major limitation arises with actuator size. In order to model the above mentioned hands an actuator is required per degree of freedom. Twenty six DoF would require twenty six actuators. It is difficult to find actuators that are small and powerful enough to move the fingers and thumb of a prosthetic hand.

The models above are only feasible as computer generated simulations and are not yet representative of a real, self-contained working model of the human hand. Reference [21] explains that current prosthetic fingers have single joint actuators for independent actuation: in these cases the bulky driving mechanisms are an impractical choice for prosthetics due to space limitations. Most self-contained hands have the capacity to hold only a few actuators within the workable space of the hand. Table 1 shows the relationship between the amount of DoF with respect to under-actuation and self-containment. Self-contained in this case means the actuators are mounted within the device workspace and are not driving the fingers from an external position. Table 2.1 lists fourteen electro mechanical prosthetic hands and their respective DoF with relation to amount of actuators and under actuation. The far right column states whether the hand is self-contained or not.

Table 2.1: Comparison of current electro mechanical hands

Hand	**DOF**	**Actuators**	**Under-actuated**	**Self-contained**
I-limb	6	DC motor	yes	Yes
Bebionic	5	DC motor	yes	yes
Dextrous	6	DC motor	yes	yes
Robonaut	12	-	yes	yes
Shadow	20	Air muscle	no	no
Utah/MIT	15	pneumatic	no	no
Hitachi	12	Shape Memory Alloy	no	no
Rugters	20	Shape Memory Alloy	no	no
Belgrade	4	DC motor	yes	no
Stanford	9	DC motor	yes	no
NTU	17	Micro-motor	no	yes
DLR	16	DC motor	no	yes
Michaelangelo	2	-	yes	yes
Azzurra	11	DC motor	yes	yes

(Appendix 3 contains an evaluation of the hands presented in this table)

In 2002 reference [12] claimed that prosthetic devices in its day were very limited due to the following factors:

- Low grasping capability due to most digits on any hand being individually actuated by one motor.
- Unnatural appearance of grasping movements because of the low number of DoF.
- The lack of sensory information given to the user.
- The lack of intuitive and natural command interfaces that are non-fatiguing and practical to use over a long period of time.

Suggestions to improve in these areas are given by reference [12] and explored by references ([18],[17] and[19]). Reference [22] expresses the following as the key contributors to limitations in prosthetic devices.

- The availability of bidirectional neural interfaces.
- Light powerful actuators.

An interesting point is raised with respect to complexity versus function when considering the control of robotic prosthetic hands. Literature in general supports the notion of gaining functionality by increasing the amount of DoF in any prosthetic device; however a rise in DoF increases the complexity of controlling the device. Therefore a balance of complexity and function is required, one cannot be dominant at the expense of the other as they are both essential.

In 2006 participants at the state-of-the-science meeting in prosthetics and orthotics identified a wide range of research priority areas that would ultimately improve the success rate of prosthetic wear. Reference [15] Suggests that control inputs and product development were of the greatest importance at that time. This justifies claims from references [22],[12] and [21] that the control requirements of prosthetic devices failed to adequately meet the mechanical requirements of operation at that time. Since 2006 the control of mechanical hand devices has improved: meaning that the need for mechanical actuators that are light, small and powerful has increased.

2.1.5 Abandonment and Success

In response to the aim of this paper to support the rehabilitation of amputees it is vital to understand the reasons for prosthetic abandonment and prosthetic success. The success of prosthetic devices hinges upon the relationship between the designer and the end user. A successful prosthetic becomes an intimate extension of an amputee and as such must qualify and adhere to a high standard of function, quality and aesthetics.

In 2007 reference [23] claimed to have identified some of the factors relating to the abandonment of prosthetics. These factors included: control, age, environment of prosthetic use, cosmetic appearance, functionality, social acceptance, fitting time, lifestyle, gender and hand dominance.

A 1989 survey of upper extremity amputees and prosthetic device success rate claimed the following factors as invalid reasons for prosthetic abandonment: Age, loss of dominant hand, loss of elbow, marital status, use of rehabilitation services, use of a temporary prosthesis and training [24].

Another review of prosthetic success was conducted in 2002 by reference [25]. The review focussed on the limitations of the rehabilitation procedure with respect to electric powered prosthetic devices. The unique approach of the review revealed important factors relating to design theory. Design theory includes the following areas of prosthetic rehabilitation: Comfort, range of motion, component consideration, stabilization, anatomical contouring, cosmetics and suspension. The review concluded that the knowledge of these concepts increases the effectiveness of the rehabilitation and help selecting appropriate control systems, interfaces and componentry for every amputee.

The review of literature in this area is inconsistent. As such it is not easy to claim to have designed a prosthetic device that will be accepted by all. "It remains difficult to sketch a truly reflective picture of the general state of upper limb prosthesis use and abandonment based on the available literature". [23].

2.1.6 Conclusion

This section has reviewed the current limitations, types, complexity and reasons for success of prosthetic devices. There is no simple solution that caters for all amputees. The aim of the paper suggests that a prosthetic hand that is brain controlled will increase the success of prosthetic devices. The following section will review current technology in robotics that can be used in conjunction with the ideas expressed in this section.

2.2 Robotics

The previous section has reviewed prosthetics and its relationship with the aim of this paper to develop a brain controlled prosthetic hand. The following section builds upon this knowledge and looks over robotic ideas and principles that can be related to the thesis aim. The ideas expressed in this section are used in combination with the ideas reviewed in the previous section.

“Robotics is a relatively young field in modern technology that crosses traditional Engineering boundaries. Understanding the complexity of robots and their applications requires knowledge of electrical engineering, mechanical engineering, systems and industrial engineering, computer science, economics and mathematics.”[26]

“Robotics is the branch of technology that deals with the design, construction, operation and application of robots” [27]. Robots are mechanical or virtual artificial agents that are usually an electro-mechanical machine that is controlled by a computer program or electronic circuitry. Robots have a wide range of autonomy and in some cases are given human-like characteristics to convey a sense of intelligence or use of agency as shown in figure 2.9.

Figure 2.9: Nao the programmable humanoid robot by Aldebaran robotics in France. [28]

The field of Robotics is large and includes many areas that will not be represented in this text. The material covered in this review is only a small amount of a much larger discipline.

2.2.1 History of Robotics

Robotics is a term derived from the word robot which was first used in a play written in the early 19th century by a Czech writer named Karel Capek. His play named "Rossum's Universal Robots" begins with a factory that produces artificial people. The Slavic word robota is used to describe the artificial creatures. Robota translated into English means labour. Although Capek used the word he named his brother Josef as the words originator. The word robotics was then used in text by Isaac Asimov in an original publication named "Liar!" and is generally cited as where the word originates.[29].

Milestones in the history of robotics can be found in appendix 3.

2.2.2 Structure and Classification of Robots

Robot mechanisms and manipulators are classified by different criteria. Some of these criteria include their power source, actuation of joints, geometry, kinematic structure and method of control [26]. The classification of robots is useful in determining the correct application for a specific robot. The following section describes the typical structure and classifications of the majority of robots on the market.

2.2.3 Power source

Robots are generally powered electrically, hydraulically or pneumatically. Each power source is an asset in some instances but has its limitations in other circumstances. For example a DC motor is a good fit for small, quiet and cheap applications such as a toy car, whereas a hydraulically powered system would be too loud and unclean. In the case of foundry robots the most sensible choice would be to use hydraulics because of its ability to lift heavy loads. Pneumatically powered robots are cheap but not well suited to precision applications without the help of control systems to control the energy of the system. Figure 2.9 shows an electrically powered cheetah.

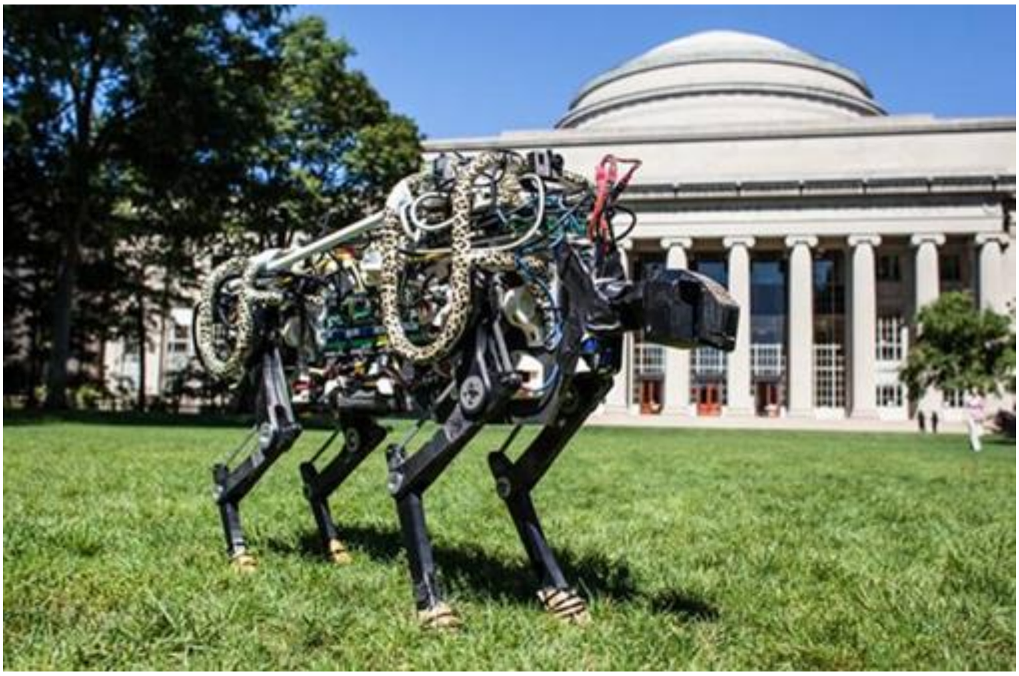

Figure 2.10: electrically powered robotic cheetah. [30].

2.2.4 Application Area

It is common to classify robots into assembly and non-assembly robots. This classification is accepted generally due to the increased need for factory and assembly robots. The area of application is dependent upon the robots power source and its intended use. Figure 2.11 gives an example of multiple assembly robot arms used to produce vehicles.

Figure 2.11: An assembly line using assembly robots to complete the welding of car chassis. [31].

2.2.5 Method of Control

Robots are generally classified as servo or non-servo robots. Non-servo robots are limited to predetermined mechanical stops while servo robots are more complex and involve controlling the method in which the end effector is manipulated in real space. The simplest servo robot in this class is called a point-to-point robot. These robots are limited to a discrete set of points. The pathway of the end effector between the taught points cannot be controlled and therefore the applications for such robots are very limited. 'Continuous path' robots control the path of the end effector from start to finish. There is however a more complex control unit needed to control a 'continuous path' robot. It is most desirable to have a continuous path robot in many instances due to the wide range of applications and the ability of the robot to be taught new tasks.

2.2.6 Geometry

Most assembly and non-assembly robots have less than six DoF. These robots can usually be defined by one of five kinematic configurations. The configurations are: Articulate (RRR), Spherical (RRP), SCARA (RRP), Cylindrical (RPP) and Cartesian (PPP).

2.2.7 Quantification of Prosthetic Hand Performance

The human hand can be used in a variety of ways to manipulate the physical world. In order to quantify the complex hand configuration and movement of a human hand there first needs to be a common definition of a human grasp. After an in depth analysis of grasp taxonomy reference [20] claims that the lack of a general definition of human hand grasp stems, from the mingling of multiple disciplines defining the human grasp as something that fits conveniently into their field of expertise. The following text explains this giving specific examples. Reference [22] defines an acceptable grasp as a hand that can exert 35 N of force upon grasping whereas reference [11] focuses on finger placement as the definition of a successful grasp. Each approach is correct in their respective fields of engineering and computation however each field lacks important elements of grasping.

In consideration of hand performance the following sources [32-36] each defined a list of human hand grasps as a reference for comparison. Prosthetic hands were rated on how well they mimicked the human hand grasps in their reference. In each article different references were used and therefore a myriad of results were produced, even for the same artificial hands. Methods of comparison also varied greatly. Reference [33] identified multiple methods of comparison when quantifying the performance of artificial hands. Some of these comparison methods are: shape matching, calculation of end effector trajectories, dimensionality reduction and control algorithms.

In the case of this paper grasping will be “every static hand posture with which an object can be held securely with one hand, irrespective of the hand orientation”[20]. This review will only consider one handed grasps and will not include gravity dependant grasps. In cases where hand orientation is limited by the contents of an object (for example a glass of water) the definition still applies.

In 2013 reference [37] set forth a detailed analysis of anthropomorphic prosthetic hands. Their report analysed the mechanical characteristics of the following hands: iLimb, iLimb Pulse, Bebionic, Bebionic v2 and the Michelangelo hand. The factors considered in the review included: finger design, kinematics, joint coupling, actuation methods, weight, size, DoF and developer differences. The review compared quantifiable factors common throughout each hand and ranked each hand according to its effectiveness in that particular area.

Throughout literature there are viable methods of quantifying individual areas of artificial hand performance but there is no standard at which to compare prosthetic hands in general. In review of [37-50] it is apparent that each hand is designed to be functional and aesthetically pleasing, however, there is no way of adequately ranking the general performance of one hand to another because of the vast differences in: developer aims/goals, intended use of hand and consumer needs. To this point in time there is no literature claiming to have found any decisive factors that fully contribute to prosthetic device success with the exception of age and the presence of additional physical limitations in amputees.

2.2.8 Analysing Methods

The methods of analysing the functionality, performance and aesthetics of prosthetic hands are wide ranging and in most cases use complex mathematic algorithms, equations and processes. A few of these methods will be described and analysed.

2.2.8.1 Kinematics

Kinematics is part of the mechanical study of motion it helps describe the motion of points, bodies and systems of bodies. Kinematics does not consider the cause of motion, rather it describes the possible motion of kinematic chains given certain parameters [51]. A kinematic chain is a series of rigid bodies connected by joints. Understanding kinematic chains are vital because a human hand can be represented as a number of separate kinematic chains supported on the palm of the hand [20]. Each finger can potentially be a single kinematic chain with the joints of the hand being the joints of the chain.

Forward kinematics is the process where kinematic equations are used to describe the position of an end effector with the knowledge of joint angles and linkage lengths. Reverse kinematics operates in the reverse order where end effector position is given to find joint angles and linkage lengths.

The Denavit-Hartenberg formalism is used to simplify the process of predicting the position of links in the kinematic chain with reference to a frame chosen to reduce the amount parameters needed to describe the chain.

2.2.8.2 Velocity Kinematics

In the previous section the kinematic equations were used to determine end effector trajectories and positions under given conditions. In this section the end effector or any part of the manipulator is related to the joint velocities. The velocity analysis of the hand will be examined by use of the Jacobian manipulator and the grasp matrix. [26] Describes the Jacobian as a matrix valued function that is involved with determining the following in robot manipulators and mechanical devices.

- Planning and executions of smooth trajectories
- Derivation of the dynamic equations of motion
- Execution of coordinated anthropomorphic motion
- Transformation of forces and torques from the end effector to the manipulator joints

2.2.8.3 Jacobian Manipulator

The Jacobian manipulator also called the Jacobian is used to relate the linear and angular velocities of the end effector of a robot manipulator to the joint velocities of the said manipulator. The forward kinematics describe a function between the space of Cartesian positions and orientations with the space of joint positions [26]. The Jacobian of this function then determines the velocity relationship between joints, positions and orientations. The Jacobian is represented by the letter J and is a matrix valued function. Comprehensive detailing of the processes involved in this method can be found in. [26]

Suppose there is m equations for end effectors and each has an n amount of degrees of freedom. We can write.

$$\begin{matrix} x_1 \\ \vdots \\ x_m \end{matrix} = \begin{matrix} x_1(\alpha_{1,\dots,}\alpha_n) \\ \vdots \\ x_1(\alpha_{1,\dots,}\alpha_n) \end{matrix} \tag{10}$$

Deriving the above equation yields.

$$\begin{matrix} \frac{dx_1}{dt} \\ \vdots \\ \frac{dx_m}{dt} \end{matrix} = \begin{matrix} \frac{\delta x_1}{d\alpha_1}\frac{d\alpha_1}{dt} + \cdots + \frac{\delta x_1}{\delta\alpha_n}\frac{d\alpha_n}{dt} \\ \vdots \\ \frac{\delta x_m}{\delta\alpha_1}\frac{d\alpha_1}{dt} + \cdots + \frac{\delta x_m}{\delta\alpha_n}\frac{d\alpha_n}{dt} \end{matrix} \tag{11}$$

Re-writing in vector form gives.

$$v = J\frac{da}{dt} \tag{12}$$

The Jacobian is now seen as

$$J = \begin{bmatrix} \frac{\delta x_1}{d\alpha_1} & \cdots & \frac{\delta x_1}{\delta\alpha_n} \\ \vdots & \ddots & \vdots \\ \frac{\delta x_m}{\delta\alpha_1} & \cdots & \frac{\delta x_m}{\delta\alpha_n} \end{bmatrix} \tag{13}$$

The Jacobian of a two link planar manipulator is shown below

Here the Jacobian is.

$$J = \begin{bmatrix} -l_1\, sin \propto_1 - \ l_2\, sin(\propto_1 + \propto_2) & -\ l_2\, sin(\propto_1 + \propto_2) \\ l_1\, cos \propto_1 + \ l_2 \cos(\propto_1 + \propto_2) & l_2 \cos(\propto_1 + \propto_2) \end{bmatrix} \tag{14}$$

(Jacobian calculations and relating theory is found in appendix 5)

2.2.8.4 Trajectory Planning/Shape Matching

In order to mimic the human hand the movement of an artificial hand must look natural and move in a way that does not draw attention to itself. Trajectory planning is an analysis method used to compare the trajectory of an artificial finger with the movement of a human finger. In order to execute trajectory planning successfully there are multiple factors that need to be considered. These factors are: joint velocity, joint acceleration, torque (in the case of revolute joints) and position. Successful trajectories match the shape and form of human hand movement and are quantified by shape overlap.

2.2.8.5 Dimensionality Reduction

Dimensionality reduction explained in reference [33] is the process in which prosthetic device performance is quantified by recording human hand movements and projecting them onto a two dimensional space (figure 2.12) using a linear reduction algorithm. The movements of an artificial hand are then projected onto the same space, the overlap is used as the basis for comparison.

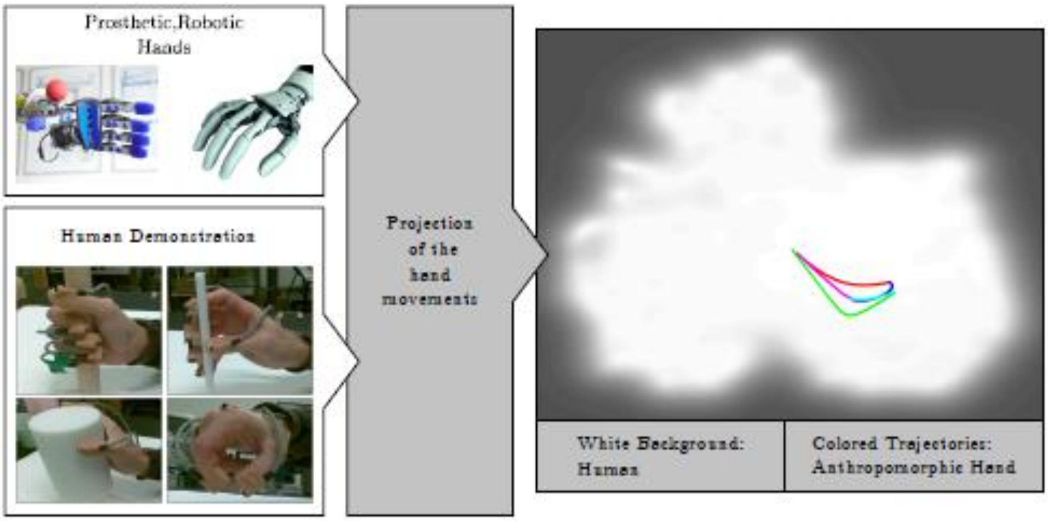

Figure 2.12: Projection of prosthetic hand workspace in comparison to a human hands natural workspace. [33]

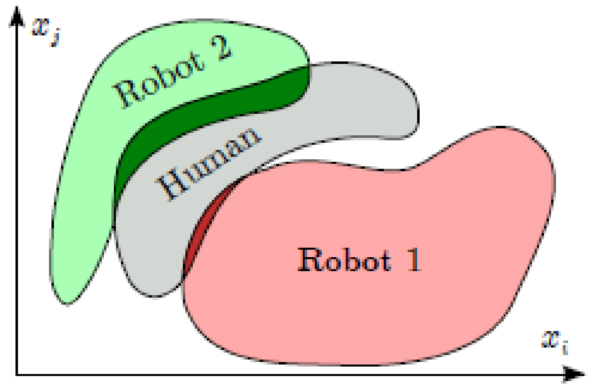

Figure 2.13: Action manifolds of a human in comparison with two robots. [33]

[20] Defines "action manifold" (Figure 2.13) as the postures a hand can reach. The action manifold can represent all the postures a hand can reach or any subset of those postures. The action manifold varies widely as the kinematic setup of the artificial hands change. Once sufficient action manifolds have been recorded and reduced to two dimensions it can be represented as a two dimensional shape with associated area. Artificial hands are then considered anthropomorphic if the two dimensional shape produced from its action manifold considerably overlaps the human action manifold. In the figure above "Robot 1" has a larger action manifold, however it is considered less anthropomorphic than "Robot 2" because its overlapped area with the "Human" action manifold is smaller. "Robot 1" could have a larger area because: it has more DoF, of a larger amount of individual actuators or a larger amount of available configurations. Each of these reasons increase dimensionality.

There are benefits to using dimensionality reduction. In each case a configuration of the human hand is used as reference, this reference configuration can be representative of the performance of the whole hand or an accurate reflection of an individual configuration. An artificial hand that is capable of fine movements may be highly anthropomorphic when referencing to an action manifold of fine human motor skills but score poorly when subjected to a reference that only considers gross motor skill. Dimensionality reduction can take into account the general performance of an artificial hand as well as the task specific orientations needed for individual tasks.

2.2.9 Latest Technology

2.2.9.1 Neural Interface

The field of biotechnology is growing at a rate where new areas of study are constantly created. One such area is neural engineering. Neural engineering combines the disciplines of neurophysiology, electronic engineering and mechanical engineering [52]. Neural engineering is the key to linking brain activity to man-made machines and devices with the intention of restoring sensory and motor function to amputees and patients with neural disorders.

A neural interface (figure 2.14) is used to record brain activity with the intention of using it to control a mechanical device or computer simulation. Brain activity produces signals which are detectable on the surface of the scalp [53]. These signals are translated into a useable signal that can be used to communicate a user intention without the use of natural communication methods such as peripheral nerves and muscular interactions.

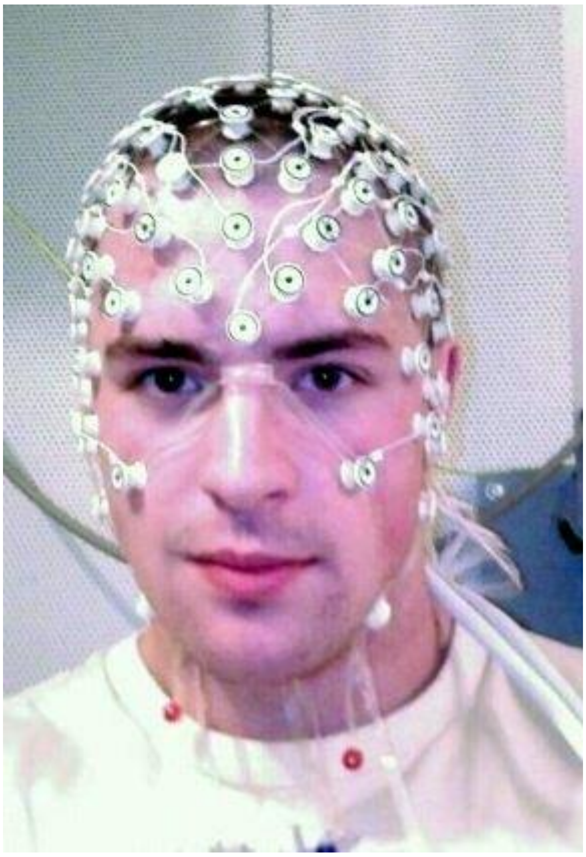

Figure 2.14: Electroencephalography patient with probes placed on head. [54]

“Brain controlled interfaces (BCI) are devices that capture brain transmissions involved in a subject’s intention to act, with potential to restore communication and movement to those who are immobilized.”[52]. Neural prosthetics are devices that are used to associate transmitted brain signals with physical movements.

Reference [53] suggests two main types of brain controlled interfaces: invasive and non-invasive. As the names suggests non-invasive BCI are inclusive of headsets and external devices that can pick up emitted signals from the brain. Current non-invasive BCI use electroencephalography. Invasive BCI are directly linked to the brain by implantation, surgery and other similar methods.

Reference [52] recognizes the four main types of methods used to acquire useful brain signals.

- Electroencephalography (EEG)
- Electrocorticography (ECoG)
- Local field potentials (LFPs)
- Single-Neuron action potential recordings.(single units)

Whatever method is employed the processing of brain signal remains constant. Emitted brain signals are acquired through a BCI, the signal is then translated into a useable command signal. The command signal is then used to control a mechanical device. The user then processes the information and changes input signal according to the current state of the mechanical device being controlled. The following section will briefly touch on the basic ideas involved with electroencephalography. The research only looks at this method of acquiring brain signals due to time limitations and project scope.

2.2.9.2 Electroencephalography

Electroencephalography is the recording of electrical activity non-intrusively along the scalp. The process involves monitoring an individual cell in the brain called a neuron for action potential. An action potential is an electrical impulse produced from the neuron and is what neurons use to communicate with each other. The electrical impulses represent information. Recording neuronal interaction produces signals that can be compartmentalised to represent a specific desire of the person who is subject to the recording. Figure 16 conveys how a common spike in the generated signal can be interpreted as the subjects desire to turn left. (Figure 2.15) A lack of these spikes could also be used as a signal from the user to turn right.

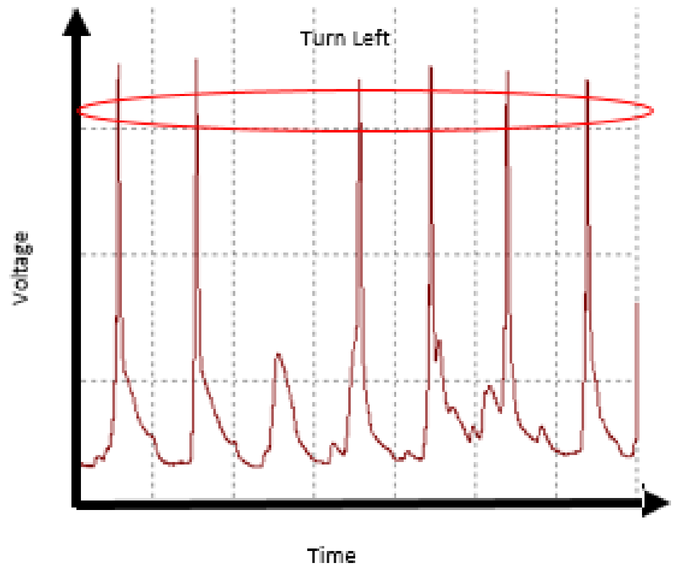

Figure 2.15: data analysis of a potential "turn left" signal [55]

Recording more neurons increases the amount of information that can be analysed and interpreted. Figure 2.16 conveys the process of acquiring and using brain signals to control mechanical devices.

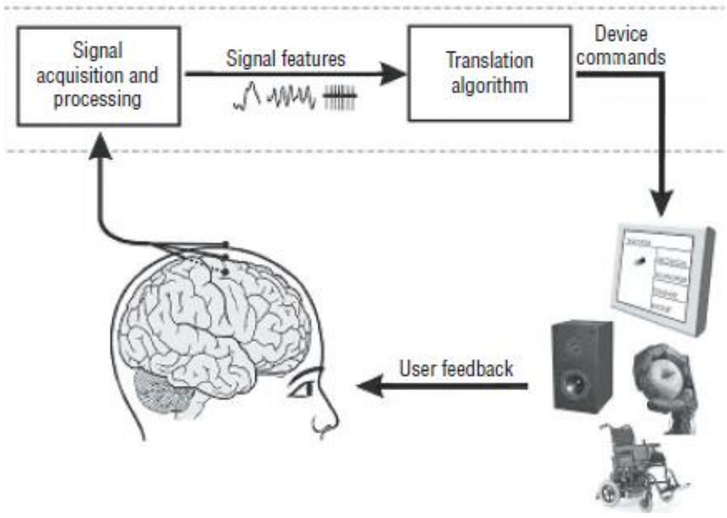

Figure 2.16: Common method of acquiring and using brain signals to control a mechanical device. [53]

Reference [53] identifies some of the limitations of invasive BCI. These limitations are substantial technical difficulties, the risks of surgery, no guarantee the device will function well for extended periods of time and brain damage. Successful non-invasive studies include the controlling of emitted brainwaves to move a robotic arm, move a computer mouse and select programs in a two dimensional frame and moving a mouse in a three dimensional frame.

2.2.9.3 Sensory Feedback

An ongoing challenge for scientists and engineers is to copy the sensory motor function of the human hand. Reference [12] claims prosthetic hands in our modern day exhibit common limitations in sensory motor functions due to mechanical, aesthetic and sensory feedback limitations. Until recently sensory feedback to amputees has been limited to visual observation and sounds emitted from prosthetic devices.

Reference [56] explains the processing of sensory information as a cyclic procedure rather than a linear sequence. “Although it is customary to think of behaviour as a linear sequence of sensing, analysing, and acting, this is not the case. When animals are in motion, they are constantly probing the environment, sensing changes and using the information to generate the next action. This is a continuous cycle rather than a linear sequence, with sensation directing output and altering sensory input.”

There are four stages of receiving sensory information (Figure 2.17) and four sensory receptors used to detect the type of energy input to the system or body. The four stages are: reception, transduction, transmission and perception. The types of sensory receptors used in receiving sensory information are: mechanoreceptors, chemoreceptors, electromagnetic receptors, thermos-receptors and pain receptors. [56]

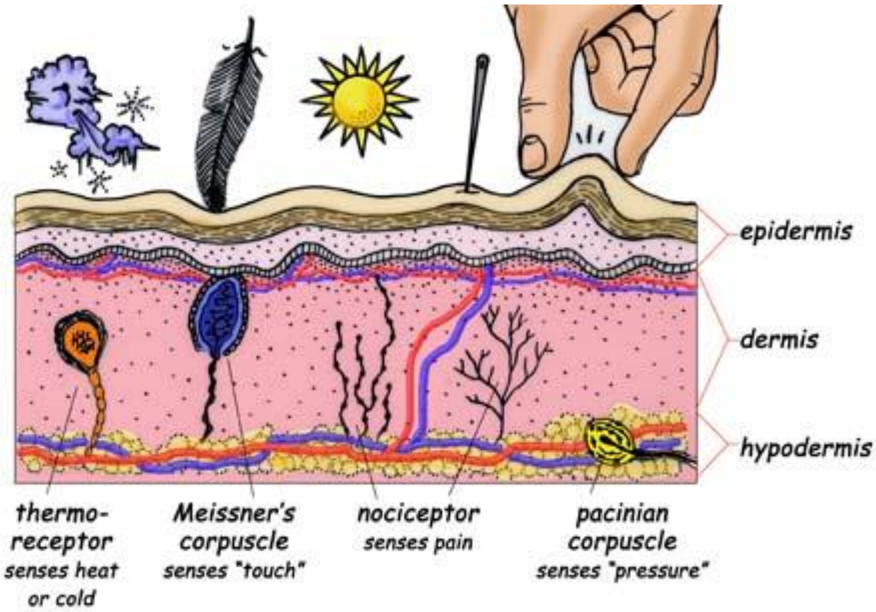

Figure 2.17: Display of the four receptors found in the human skin. [57]

The cyclic procedure of obtaining and using sensory feedback has been examined by reference [12] concluding that technological advances in recognising the perceived changes in the peripheral nervous system will open pathways of returning sensory information to the user. In 2013 reference [58] identifies two methods of providing amputees with sensory feedback: modality matched feedback and sensory substitution. Experimentation found that modality matched feedback was achievable; however they were too big, expensive and consumed a lot of power. Sensory substitution is low cost, low power and easy to integrate, it is however a substitute and the "sensation" or "feeling" created by touching is eliminated. Responsibility for these issues has been accredited to the limitation of technology in neural interfaces and the timing of the feedback. [59]

2.2.10 Conclusion

An effective and successful prosthetic hand involves the combination of prosthetic knowledge and applications with the automation and technical capabilities of robotics. This chapter has addressed important aspects of robotics that can be directly used in the world of prosthetics. The chapter has been focussed on upper extremity amputees with the intent of responding to the thesis aim of developing a brain controlled prosthetic hand. Understanding the limitations of current technology and the physical limitations of actuation methods in robotics is essential in the mechanical design of a functional prosthetic hand. A successful prosthetic must have a good balance between complexity and function. In the following chapter the mechanical design of the hand will be addressed with relation to the ideas expressed in this chapter. A functional hand is fundamental and necessary to the design of a brain controlled prosthetic hand. Sufficient time and consideration has been given to the mechanical design of the hand.

Chapter Three

The previous chapter has reviewed current theory and considered the latest knowledge in the design and development of brain controlled prosthetics. A large portion of this research has been dedicated to the development of a functional and dexterous mechanical hand. The physical design of the hand is expressed in this chapter. The hand expressed in this chapter is controlled by signals emitted from the brain. The method of control is explained in chapter four.

3.1 Mechanical Design

In light of chapter two the mechanical design of a prosthetic hand will be discussed. This chapter will explain the design method used to design a functional prosthetic hand. Important ideas that will be discussed are:

- The design simplifications
- The degree of under actuation
- The driving mechanism of the hand
- The mechanical assembly of the hand
- The kinematics and path planning of the fingers.

The hand is capable of five grasps/gestures and will be analysed on its ability to perform the grasps and gesture in a timely manner and with sufficient force.

3.2 Skeletal simplifications

Reference [19] Explains the anatomical model of the hand (including the wrist) as consisting of forty five muscles acting to engage twenty joints in the hand. The joint geometry defines a need for twenty DoF to mimic the movement of the natural human hand. Reference [20] presents the human hand to be made up of twenty seven bones as shown in figure 3.1.

Figure 3.1: Diagram naming the bones in the human hand and wrist. [60]

The natural complexity of the human hand necessitates simplification when attempting to mechanically replicate functions of the human hand.

The following simplifications will decrease complexity in design and increase the effective movement/control of the designed hand.

- The metacarpal bones (excluding the thumb metacarpal) and the entire set of carpals will be combined to make up one part in the designed hand representing the palm.
- The middle and distal phalanges on each finger will become one part representing the end of the finger.
- Proximal phalanges on each finger will be driven by individual actuators and the end of the finger will be coupled by a rigid link.
- The thumb Metacarpal will be driven by a single actuator and the remaining bones in the thumb will be actuated by another individual actuator.

Mechanical simplicity facilitates the electronic control of the hand but it can decrease the hand dexterity. Finding a balance between simplification and dexterity is of great importance and should be considered in the design of all prosthetic hands.

The mechanical replication of the human hand necessitates simplification. In this section the relationship between the designed hand and the natural human hand will be explained. The fingers, thumb and palm have been simplified.

(Additional drawings of the hand can be found in appendix 2)

3.2.1 Fingers

The human fingers consist of three bones: the proximal phalange, the intermediate phalange and the distal phalange. These bones can be seen clearly in figure 3.2 In order to simplify the finger of the human hand the middle and distal phalanges on each finger are one part representing the end of the finger. Figure 3.3 shows a picture of the index finger.

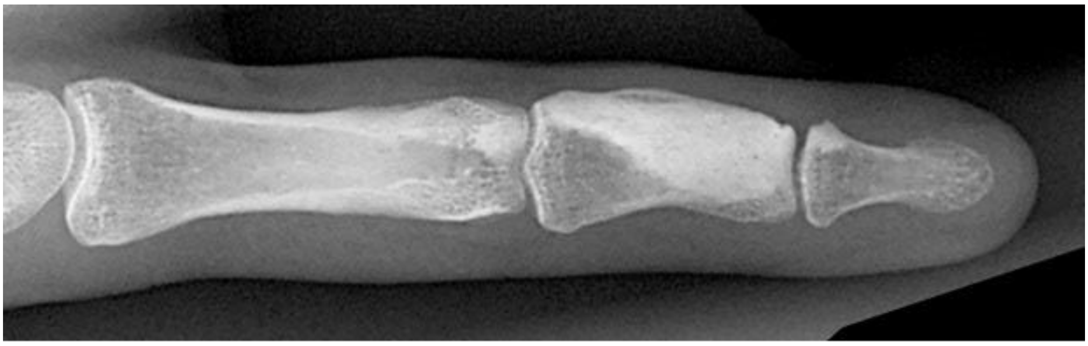

Figure 3.2: X-ray showing the three bones that make up the finger. [61]

Figure 3.3: The human index finger consisting of three main parts

As seen in figure 3.4 the proximal phalange exists as the main driver of the finger while the distal and intermediate phalanges are rigidly connected. A link between the servo motor and middle phalange drives the middle and distal phalanges while the proximal phalange is directly driven by the actuator. This coupled mechanism imitates the natural grasping motion of the human hand well.

Each finger is simplified in this manner as shown in figure 3.4. The function of the designed hand is not significantly affected by this simplification and the ability of the hand to grasp is adequate for the scope of this work.

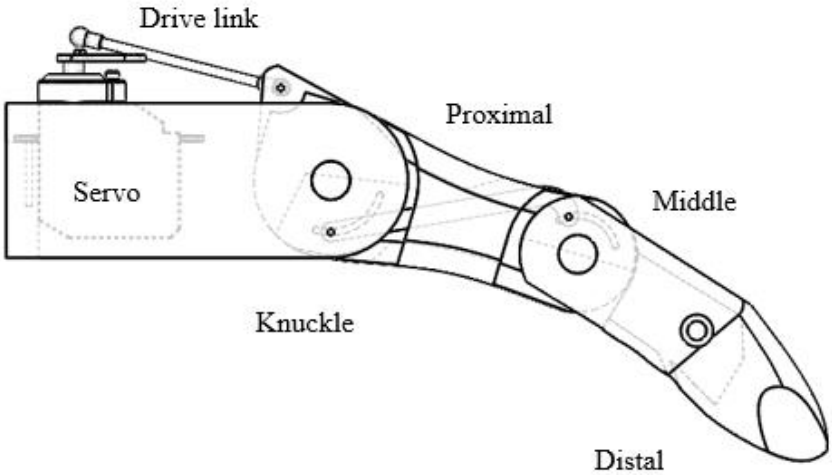

Figure 3.4: The index finger of the designed hand. Simplified having only two major parts.

3.2.2 Thumb

The thumb is an important appendage to the hand. It is capable of high levels of function including fine motor control for precision grips and gross motor control for power grips. The mechanical design of a prosthetic thumb is complex. The thumb is designed to have the most function of any part of the designed hand and as such is driven by two servo motors. The thumb is capable of flexion, extension, adduction and abduction. The thumb will be simplified by taking away its ability to radially abduct and adduct. This simplification allows space in the palm of the hand for servo motors. The thumb consists of three bones: the metacarpal, the proximal phalange and the distal phalange as shown in figure 3.5.

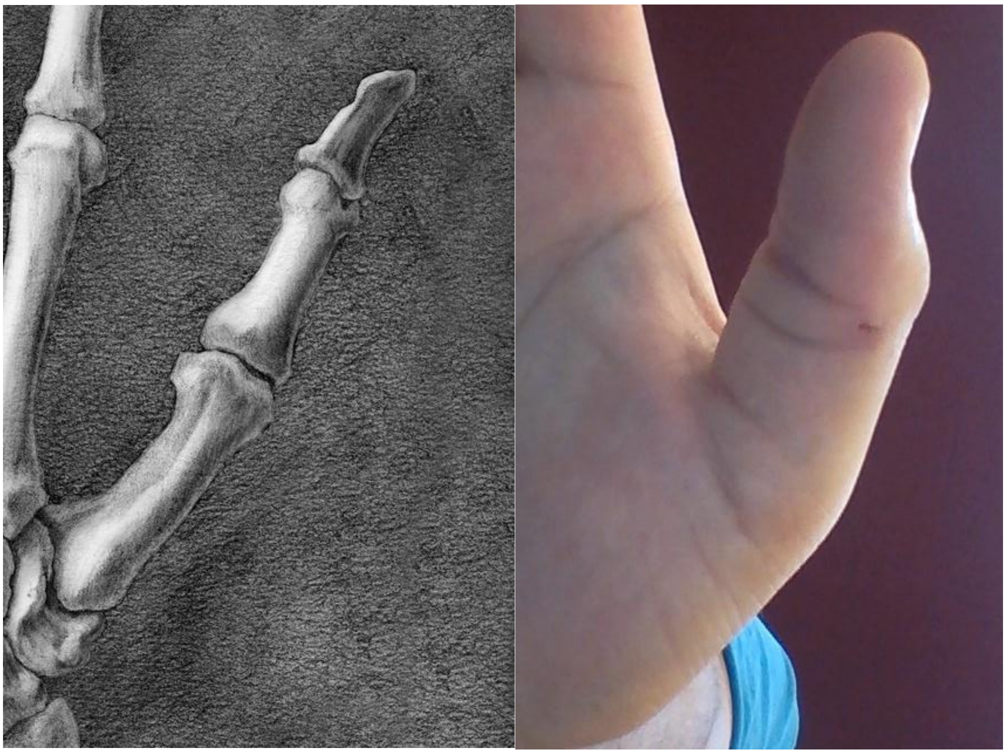

Figure 3.5: Left, skeleton of the hand. Right, thumb of the hand

From figure 3.6 it can be seen that there is a mechanical part representing each bone in the thumb. The simplification of this appendage arises from space limitations in the palm of the hand. This simplification means radial adduction and radial abduction movements are excluded from the hands motion. The thumb Metacarpal will be driven by a single actuator in the palm (not shown in figure 3.6) and the remaining bones in the thumb will be actuated by another individual actuator based in the metacarpal part of the thumb.

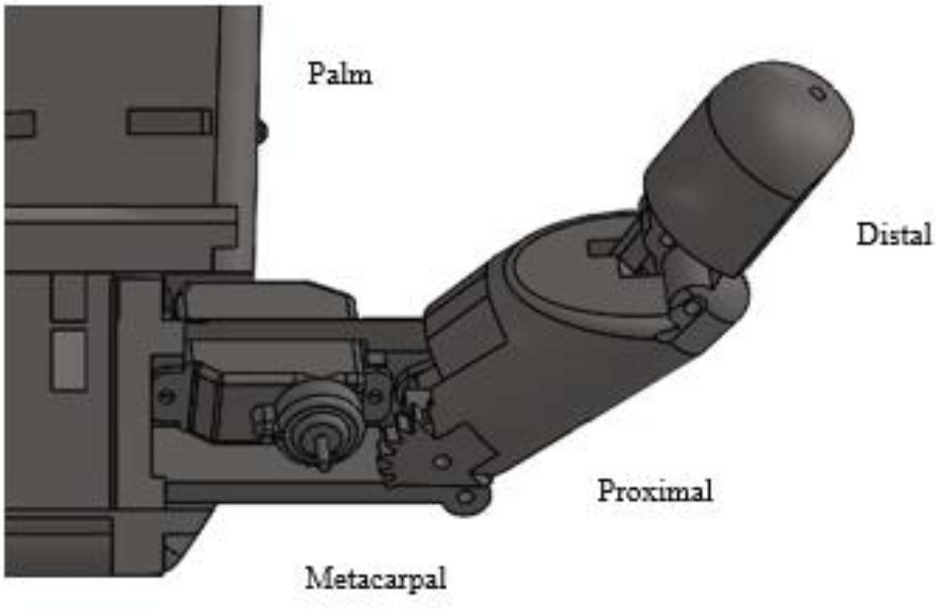

Figure 3.6: The simplified thumb

3.2.3 Palm

The palm of the human hand naturally has thirteen bones inclusive of all carpal and metacarpal bones. The palm serves as a base for the fingers and thumbs. Figure 3.5 shows an x-ray of the human hand and the palm of the human hand.

Figure 3.7: Left: The skeleton of the human hand [62]. Right: the palm of the human hand

The metacarpal bones (excluding the thumb metacarpal) and the entire set of carpals will be combined to make up one part in the designed hand representing the palm. The palm is designed as a rigid base to support the fingers and thumb.

On the top of the palm four recesses (figure 3.6) are used to mount the servo motors used to actuate each finger. The bottom of the palm is designed to hold the fifth servo motor and the wires from all the motors. The sixth motor is mounted to the corresponding metacarpal part. A cover protecting the bottom of the palm has been designed. Servo motors on the top of the hand are unprotected and visible.

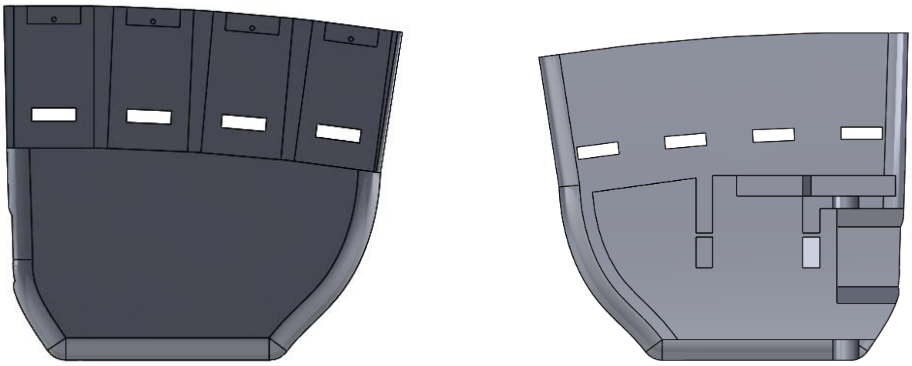

Figure 3.8: The palm of the designed hand. Left: top of the palm. Right: bottom of the palm.

3.3 Under actuation

Under actuation in mechanical devices is a circumstance where the number of actuators in the mechanism is less than the number of total DoF [63]. In the case of robotic anthropomorphic hands the likelihood of being under actuated is very high. From the research of twelve robotic hands [37-50] only four had an equal amount of actuators as DoF. In these cases space for mounting actuators became a challenge and some actuators have to be external to the hand meaning the device was no longer self-contained. In the eight remaining cases each hand varied in degree of under actuation. Under actuation simplifies control and maximises the use of available space.

3.4 Grasping

The tasks of grasping, gripping and holding are studied by many. From one hundred and forty seven sources [32] suggests that human grasps can only be simplified to seventeen different grasp types. Each of the seventeen grasps can be further separated into two different classes relating to two thumb positions: adducted and abducted. [35] Considers five main prehensile grasp types: cylindrical, fingertip, palmar, spherical and lateral where each grip is named relative to the type of object being grasped. Other sources [32-34, 36] approach grasp classification in alternate manners. Figure 3.7 shows some examples of common grasps.

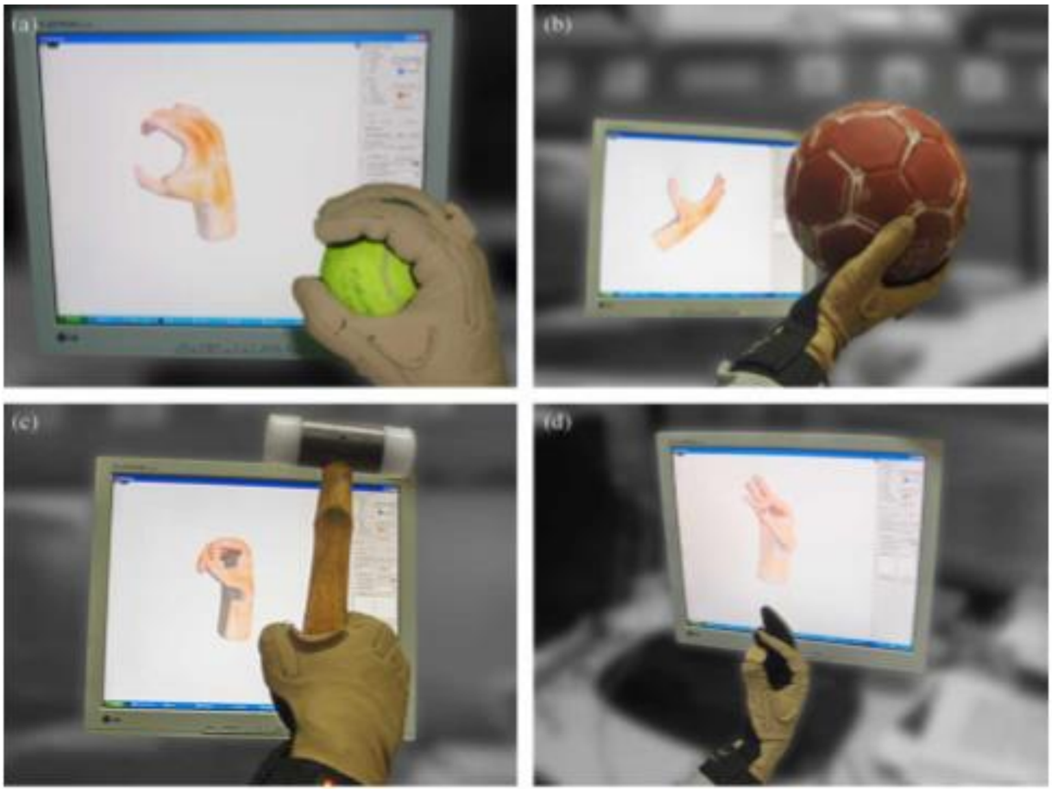

Figure 3.9: Some common grasps used.[17]

This project will study five grasps/gestures. These grasps are: key grip, power grasp, pinch, ball grip and index point. These five grasps/gestures only represent a small amount of the possible grasps types but are sufficient to test the designed hands feasibility of being a successful prosthetic.

Material choice is limited to a material named "Vero White" which can be described as a rigid opaque photopolymer. The material properties can be found in reference [64]. This choice of material is based upon project costs, available 3D printed materials and time constraints.

3.5 Driving Mechanism

A simple driving mechanism will be employed to actuate the fingers and thumb of the hand. Reference [65] tests the feasibility of using shape memory alloys as an actuator for a prosthetic hand. After study the shape memory alloys proved successful however the process is highly dependent on temperature and a specially designed power amplifier had to be designed to ensure proper actuation. Project time restraints did not accommodate further investigation of this actuation method. Other actuators considered include: Piezoelectric actuators[66], pneumatic actuators [67] and DC motors.

Servo motors were selected as the actuator for the designed hand. The Futaba S3114 micro servo provides the torque required for the hand to operate. Useable force is transferred through to the fingertip by rigid links. The driving mechanism converts linear motion to rotational motion through a series of couplings.

3.6 Assembly

The hand consists of twenty six 3D printed parts and various electronic components. This section describes the assembly of the fingers, thumb, palm, knuckles, electronics and hand in its entirety. Each of the mechanical 3D printed parts require water-blasting, cleaning and removal of excess support material before assembly.

3.6.1 Fingers

Each finger of the hand is based on the design of the index finger. The directions for the assembly of the index finger will be displayed here. The remaining fingers can be assembled in the same manner.

The fingers consist of four mechanical 3D printed parts, two link pins and one M3 bolt and one M3 nut. Figure 3.8 shows the assembly of the fingers.

- The base of the proximal phalange is inserted into the knuckle by “snap” fit.
- The index link is placed inside the proximal phalange and one link pin is placed through the knuckle, proximal phalange and base of the link.

- The inter-distal phalange is separated and placed on each side of the top end of the proximal phalange.
- The other link pin is inserted through the inter-distal phalange, proximal phalange and the top end of the link.
- The assembly is completed by the bolting together of the inter-distal phalange through the bolt hole situated where the distal interphalangeal joint would be.

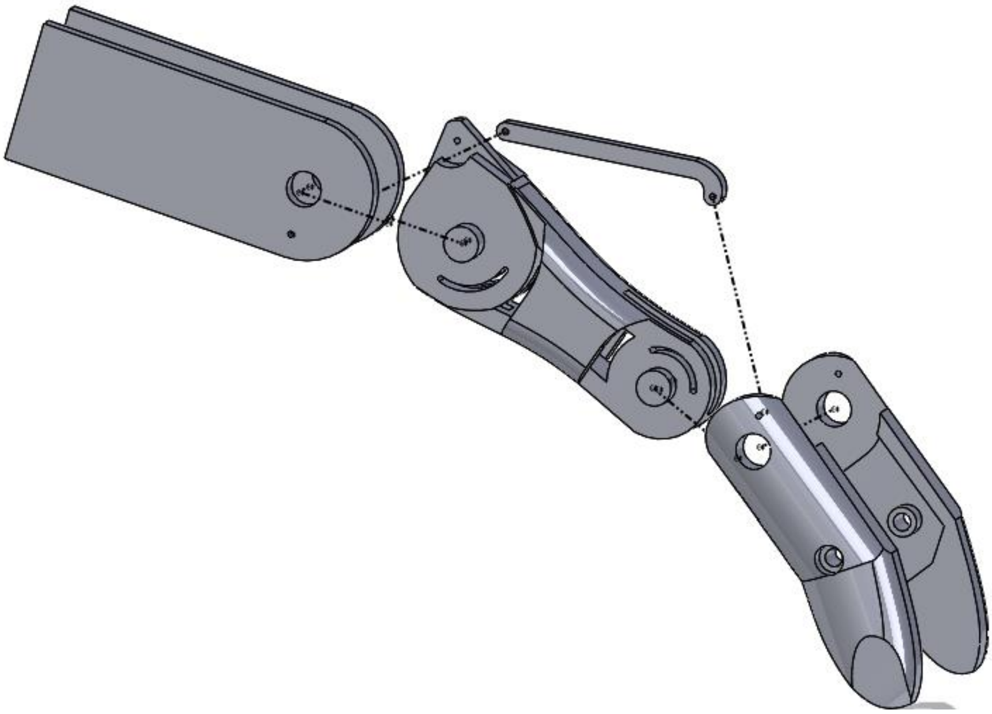

Figure 3.10: Assembly of the designed hands fingers

3.6.2 Thumb

The thumb is made up of four 3D printed parts and four M2 bolts and nuts. Figure 3.9 shows the assembly of the thumb.

- The metacarpal part serves as a base for the thumb.
- The base of the proximal phalange is mounted to the metacarpal part through the provided bolt holes and tightened.
- The thumb link is placed through the proximal phalange and fixed to the back of the metacarpal part by another bolt and nut.

- The distal phalange is bolted to the top of the proximal phalange and the top of the thumb link through two different bolt holes and tightened.

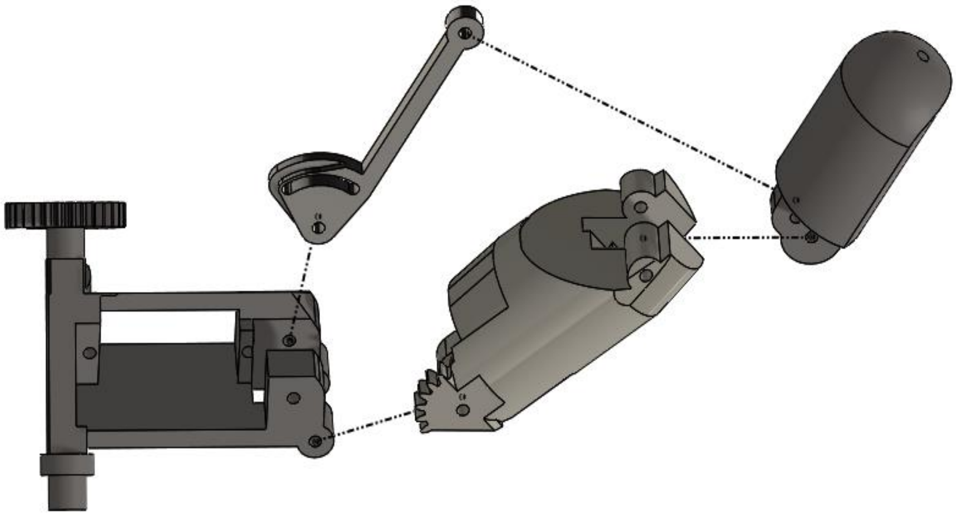

Figure 3.11: Assembly of the designed hands thumb

3.6.3 Palm and knuckles

The palm of the hand is designed as a base for the fingers and thumb. On the top side of the palm are four identical areas designed to fit the finger assembly. As shown in figure 3.12 the full assembly of the fingers fit into the areas provided leaving room for the mounting of the servo motors. Figure 3.13 shows the assembly of the drive link assembly.

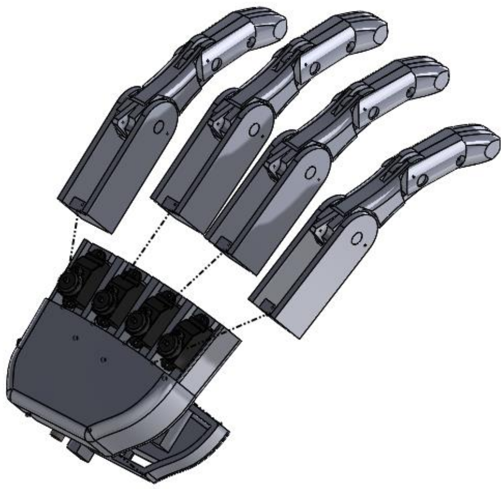

Figure 3.12: Assembly of the palm and knuckles of the hand.

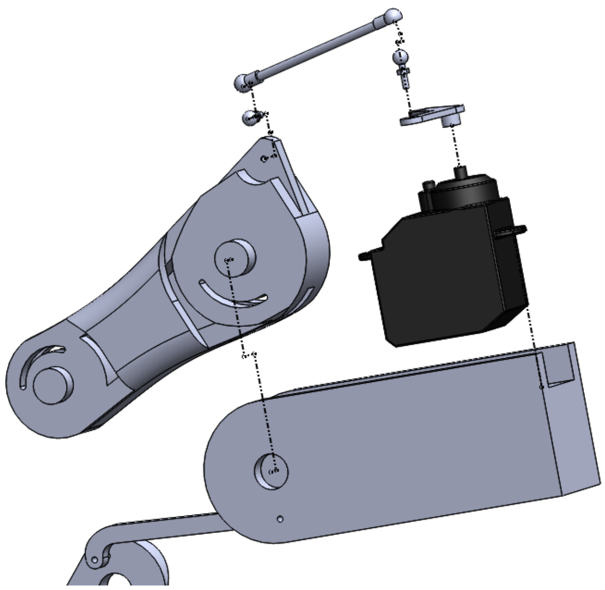

Figure 3.13: Drive link assembly

3.6.4 Thumb and palm

Once the thumb is assembled it can be mounted to the bottom of the palm. Figure 3.14 shows the assembly of the thumb and palm.

- The top of the metacarpal part of the thumb is placed in the recess in the palm where the gear can fit just below the knuckle of the index finger.
- The bottom of the metacarpal part is placed in the semi-circular recess where the wrist bones would connect to the palm.
- The palm cover is placed over the bottom of the palm and fitted firmly into place.

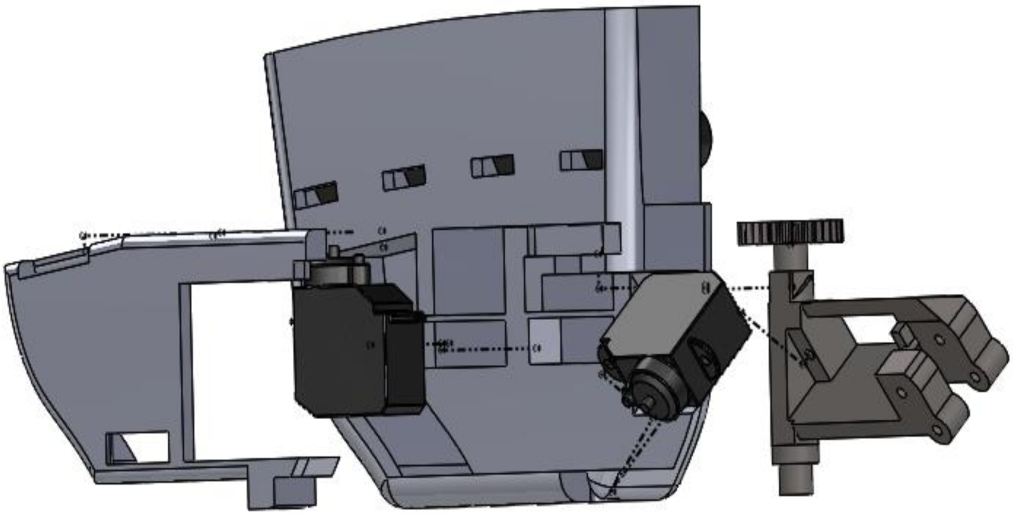

Figure 3.14: Assembly of the thumb and palm of the hand.

3.6.5 Electronic Assembly

The assembly of the electronics is completed in two parts: assembly of the finger servo motors and assembly of the thumb servo motors. This section will only convey the assembly of the servo motors used to actuate the fingers and thumb of the hand. Figure 3.15 shows the electronic assembly.

When the palm and knuckle are assembled there are small compartments designed for the mounting of servo motors in the top of the palm. The assembly of the finger servo motors is simple.

- The motors are placed in the compartments provided and bolted down with the servo horn end placed farthest from the fingers.
- Wires are placed through the bottom of the hand by the holes opening directly through the palm.

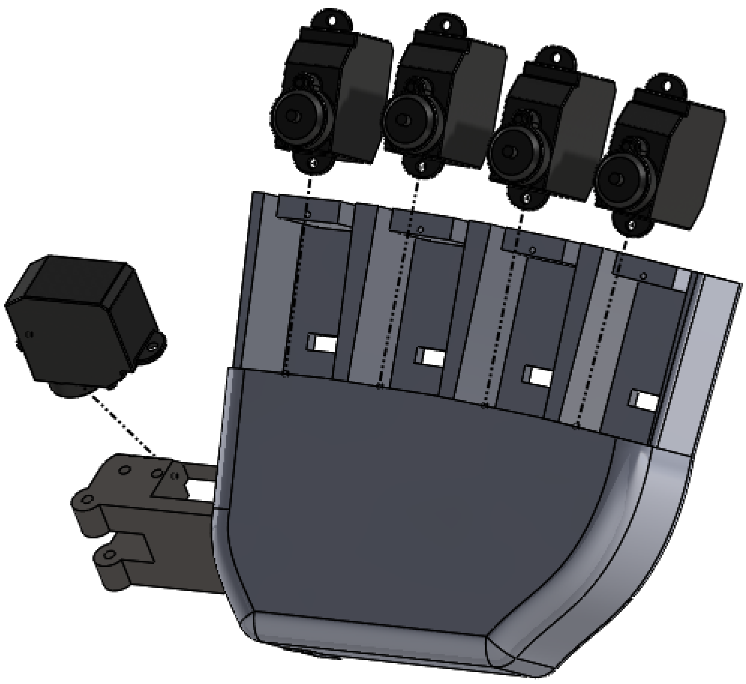

Figure 3.15: Assembly of the servo motors on the top of the palm.

(Micro-servo motor specifications are presented in appendix 1)

3.6.6 Thumb Servo Motors

The thumb requires two servo motors to be functional. The first motor is responsible for the adduction and abduction movement of the thumb, the second motor is used to put the thumb in extension and flexion. Figure 3.16 shows the assembly of the thumb servo motors.

- The first motor is place in the bottom side of the palm with the bolt arms of the servo fitting into the purpose built recess below the middle finger.
- The second motor is mounted to the metacarpal part of the thumb and bolted directly to the part.

(bolting of this second motor must be done before the thumb assembly is mounted to the palm.)

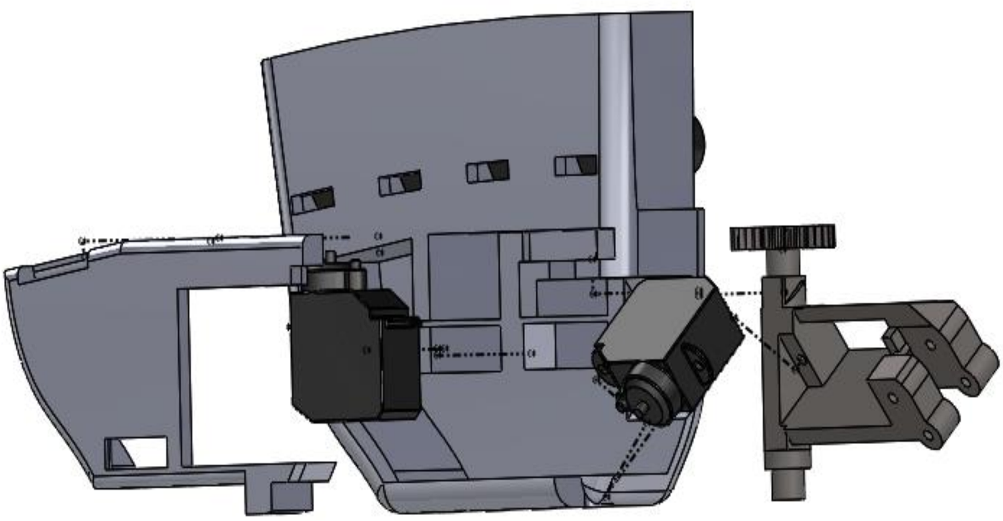

Figure 3.16: Assembly of the servo motors on the bottom of the palm.

The wiring from each of the servo motors are gathered and placed in the cavity produced between the palm cover and the palm underneath the little finger. Wires from the finger servo motors are pushed through to the bottom side of the palm through the holes provided. They are gathered and placed through the top hole of the palm cover and hidden from view. The thumb servo motor wires are already hidden but are directed towards the other wires.

3.6.7 Complete Assembly

The complete assembly of the hand is conveyed in this section. It is important to note that the Micro-board, Bluetooth unit and Neurosky headset have not been included in this section because they relate more directly to the control system and will be discussed in chapter four. Figures 3.17 and 3.18 show three different views of the complete assembly for the designed hand. All mechanical components except bolts and screws have been included for clarity in the figures. Figures 3.17 and 3.18 are diagrams expressing the complete assembly of the hand.

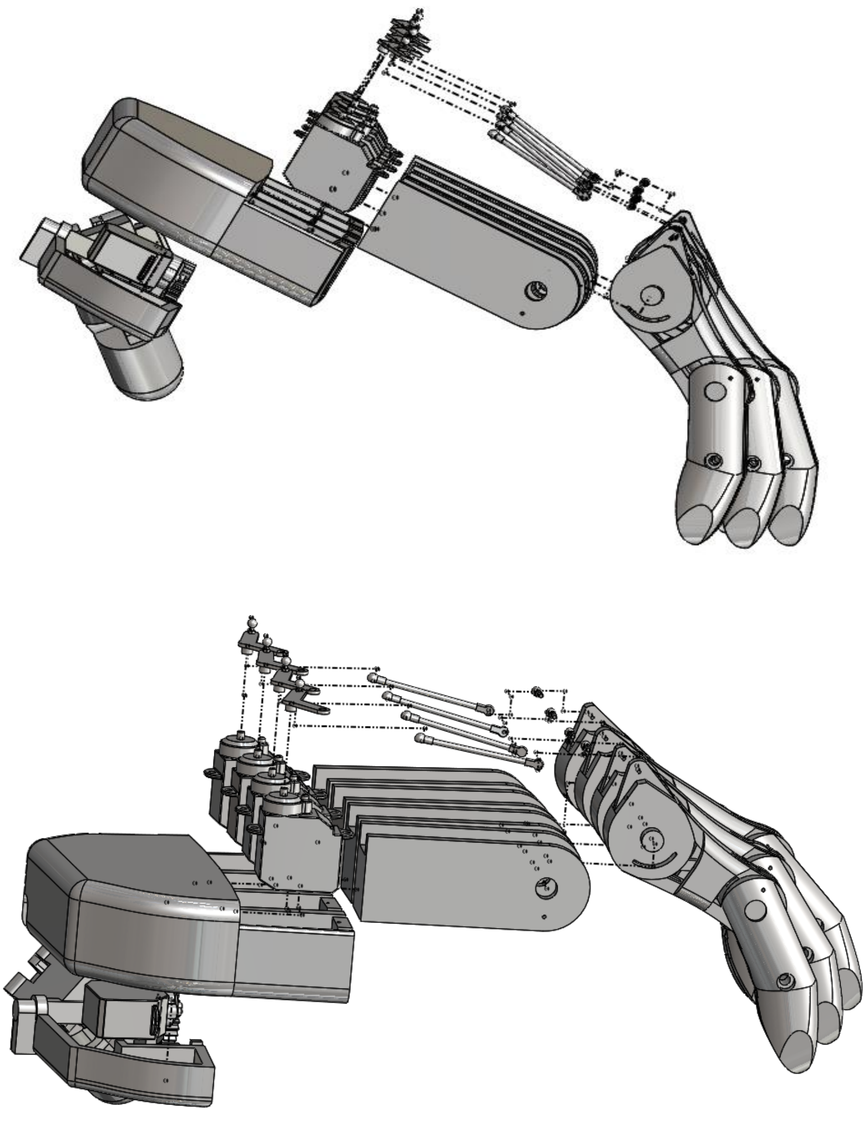

Figure 3.17: Complete assembly of the hand.

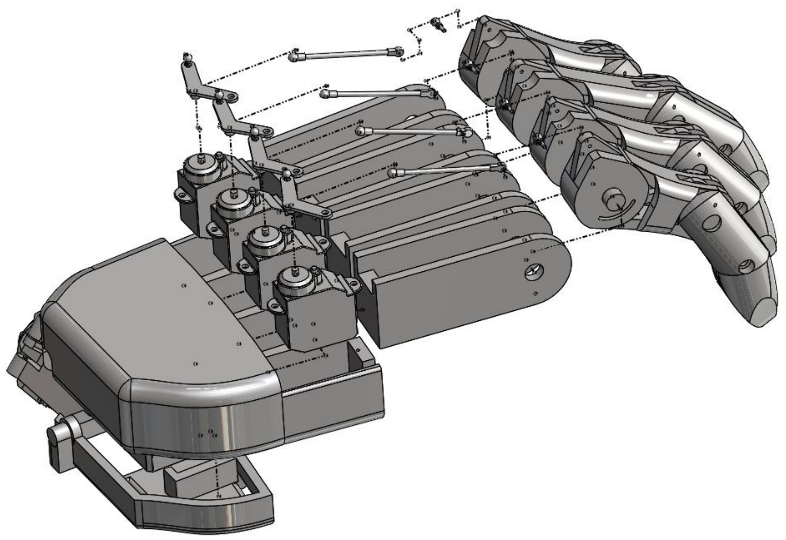

Figure 3.18: Complete assembly of the hand. Top view.

(Information about the micro-ball links is presented in appendix 1)

3.7 Denavit-Hartenberg Formalism

The Denavit-Hartenberg formalism also called the D-H convention is a method used to describe a kinematic chain using four parameters per link/joint. [20]. The convention includes prismatic joints as well as revolute joints but this study only considers revolute joints as they directly relate to the joints used on the designed hand.

This section will be used to describe the mechanical movements of the hand. By assigning the hand to a coordinate geometry system the finger workspace can be visualised by plotting the fingertip position. Using an arbitrarily chosen origin the fingertip trajectories are plotted to show the individual finger workspace. The path travelled by each finger is similar but varies because of geometry and orientation with respect to the origin.

The number of parameters needed to describe the relationship between two links is reduced from six to four by introducing special conventions. The method allows quick calculation of the transformation matrices that change the base coordinate system to the end effector frame. Calculating the end effector position given joint angles and arm length is called kinematics.

The four D-H parameters are:

$a_1 = distance\ along\ x_i\ from\ o_i\ to\ the\ intersection\ of\ the\ x_i\ and\ z_{i-1}\ axes.$

$d_1 = distance\ along\ z_{i-1}\ from\ o_{i-1}\ to\ the\ intersection\ of\ x_i\ and\ z_{i-1}\ axes.$

$\alpha_1 = the\ angle\ between\ z_{i-1}\ and\ z_i\ measured\ about\ x_i$

$\theta_1 = the\ angle\ between\ x_{i-1}\ and\ x_i\ measured\ about\ z_{i-1.}\ \theta_1 is\ variable.$

The assignment of coordinate frames for the D-H convention are illustrated below in figure 3.19.

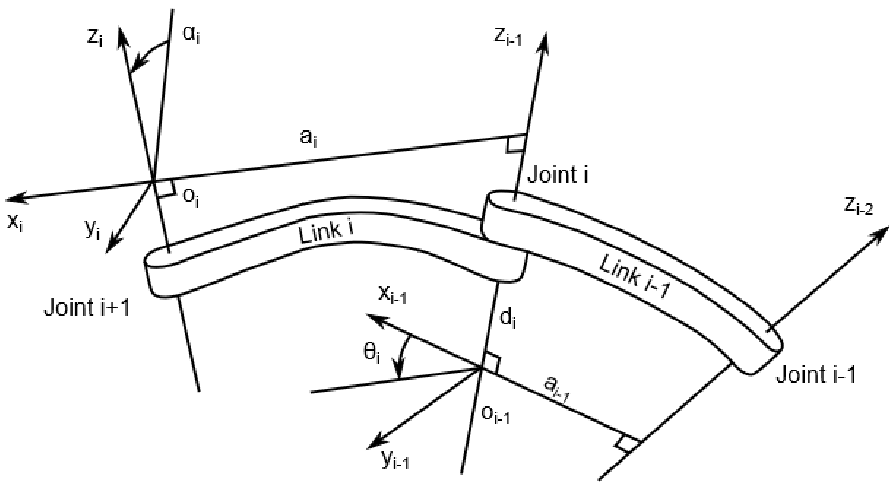

Figure 3.19: Diagram assigning reference frames for the D-H convention. [20]

The following equation describes the transformation matrix T_i using the four D-H parameters.

$$T_i = Rot_{z,\theta_i} Trans_{z,d_i} Trans_{x,a_i} Rot_{x,\alpha_i} \quad (1)$$

Where,

$T_i is\ the\ transformation\ matrix$

$Rot_{z,\theta_i}\ is\ the\ rotational\ component\ \theta_i$

$Rot_{x,\alpha_i}\ is\ the\ rotational\ component\ \alpha_i$

$Trans_{z,d_i}\ is\ the\ length\ of\ the\ link\ i-1.$

$Trans_{x,\alpha_i}$ $is\ the\ length\ of\ the\ link\ i.$

$$T_i = \begin{bmatrix} cos\theta_i & -sin\theta_i cos\alpha_i & sin\theta_i sin\alpha_i & a_i cos\theta_i \\ sin\theta_i & cos\theta_i cos\alpha_i & -cos\theta_i sin\alpha_i & a_i sin\theta_i \\ 0 & sin\alpha_i & cos\alpha_i & d_i \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (2)$$

Finally the full transformation of the base frame to the end effector frame is given by multiplying the transformation matrices matching the amount of links in the mechanical device. The full homogeneous transformation is given by.

$$H = T_1(l_1) * \ldots * T_n(l_n) \quad (3)$$

Where,

$H\ is\ the\ homogeneous\ transforamation$

$T_1\ to\ T_n\ are\ the\ transformation\ matrices\ relating\ to\ each\ mechanical\ link$

$l_1\ to\ l_n\ are\ the\ links\ of\ the\ mechanical\ device\ from\ 1\ to\ n.$

The ideas expressed above can be related to the fingers of the designed hand by treating the finger as a two link planar manipulator (shown in Figure 3.20). Note that the $(x_0\, y_0)$, $(x_1 y_1)$ and $(x_2 y_2)$ frames correspond to the base frame (axis represented on graph), the first joint frame (where the orange arrows meet) and the end effector frames respectively of figure 3.20.

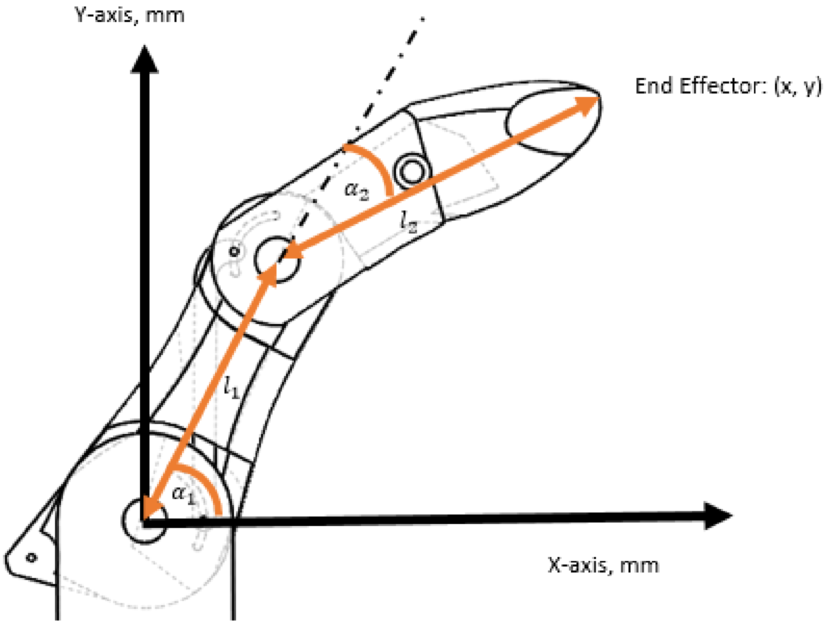

Figure 3.20: Two link planar manipulator of the designed hand.

Where,

l_1 *is the length of the first link*

l_2 *is the length of the second link*

$\propto_1$ *is the angle between the* x_0 *and* x_1 *axis*

$\propto_2$ *is the angle between the* x_1 *and* x_2 *axis*

The four parameter are given physical values as defined in Table 3.1. The range of motion for α_1 and α_2 of each finger is zero to ninety degrees. The range of motion for α_1 and α_2 of the thumb is zero to forty five degrees. The terms l_1 and l_2 are physical distances that are set by the length of the two parts in the finger. Figure 3.20 graphically shows the four parameters shown in Table 3.1.

Table 3.1: D-H parameters of the designed hand

Parameter	Index	Middle	Ring	Little	Thumb
α_1(degrees)	0-90	0-90	0-90	0-90	0-45
α_2(degrees)	0-90	0-90	0-90	0-90	0-45
l_1(mm)	44	47	44	35	35
l_2(mm)	45	44	45	35	35

Note: α_2 is a relative angle that depends upon the position of the proximal phalange.

Using figure 4.1.1 the following matrices can be derived graphically.

$$T_1 = \begin{bmatrix} cos \propto_1 & -sin \propto_1 & 0 & l_1 cos \propto_1 \\ sin \propto_1 & cos \propto_1 & 0 & l_1 sin \propto_1 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (5)$$

$$T_2 = \begin{bmatrix} cos \propto_2 & -sin \propto_2 & 0 & l_2 cos \propto_2 \\ sin \propto_2 & cos \propto_2 & 0 & l_2 sin \propto_2 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (6)$$

Multiplying T_1 and T_2 yield

$$T = \begin{bmatrix} cos(\propto_1 + \propto_2) & -sin(\propto_1 + \propto_2) & 0 & l_1 cos \propto_1 + l cos(\propto_1 + \propto_2) \\ sin(\propto_1 + \propto_2) & cos(\propto_1 + \propto_2) & 0 & l_1 sin \propto_1 + l_2 sin(\propto_1 + \propto_2) \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (7)$$

The first two terms in the last column of the matrix T are respectively the x and y components with respect to the base frame of the manipulator

The coordinates (x, y) of the end effector can be found using equations (8) and (9)

$$x = x_2 = l_1 \, cos \propto_1 + l_2 \, cos(\propto_1 + \propto_2) \quad (8)$$

$$y = y_2 = l_1 \, sin \propto_1 + l_2 \sin(\propto_1 + \propto_2) \quad (9)$$

The term $l_1 \, cos \propto_1$ expressed in equation (8) represents the distance in the x direction from the base of the robot manipulator that the first arm of the manipulator has travelled in relation to the angle between the first arm and the x-axis. The second term $l_2\, cos(\propto_1 + \propto_2)$ expressed in equation (8) represents the distance travelled by the second arm of the manipulator in the x direction in relation to the angles between the x-axis and the first and second arms of the manipulator. Equation (9) is simply a repeat of equation (8) however it is expressed in distance travelled in the y direction.

This method of analysis is used to mathematically describe the path of the end effector. Figure 3.21 shows the fingertip trajectory of the designed hand. Figure 3.22 shows the trajectories on a three dimensional plot.

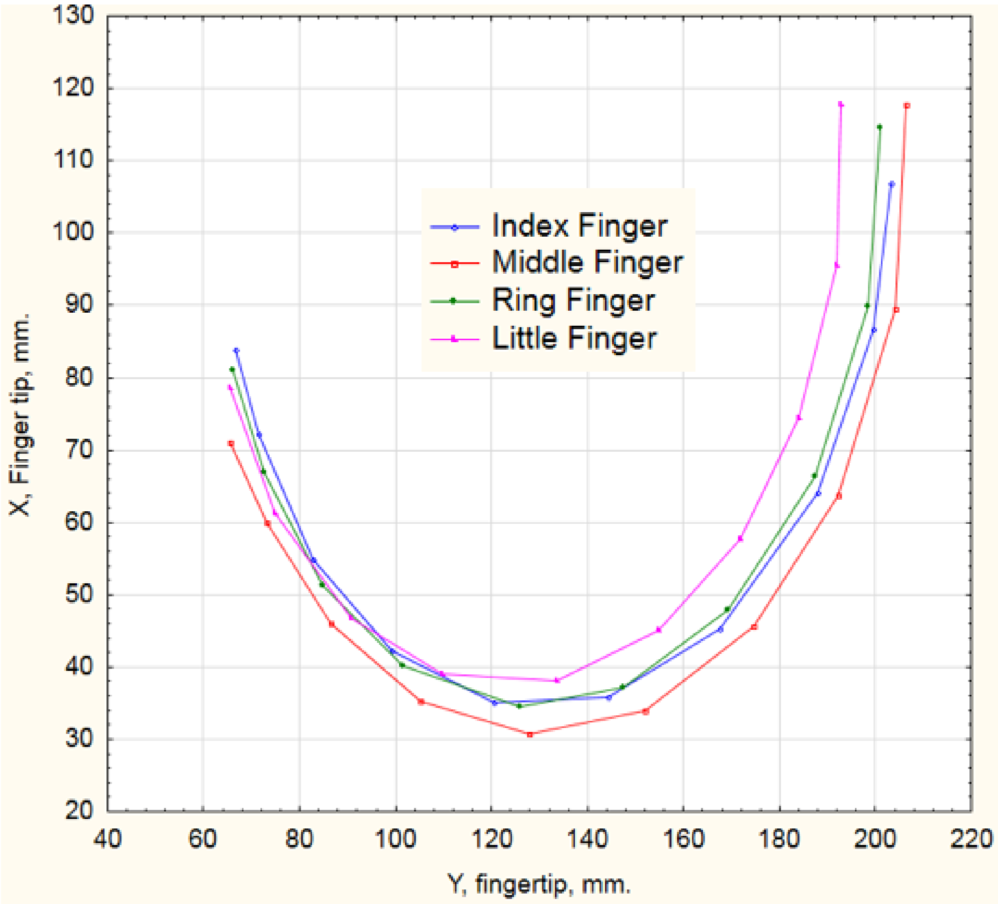

Figure 3.21: Fingertip trajectories in the y-z plane. With the palm being perpendicular to the page and facing towards the bottom of the page.

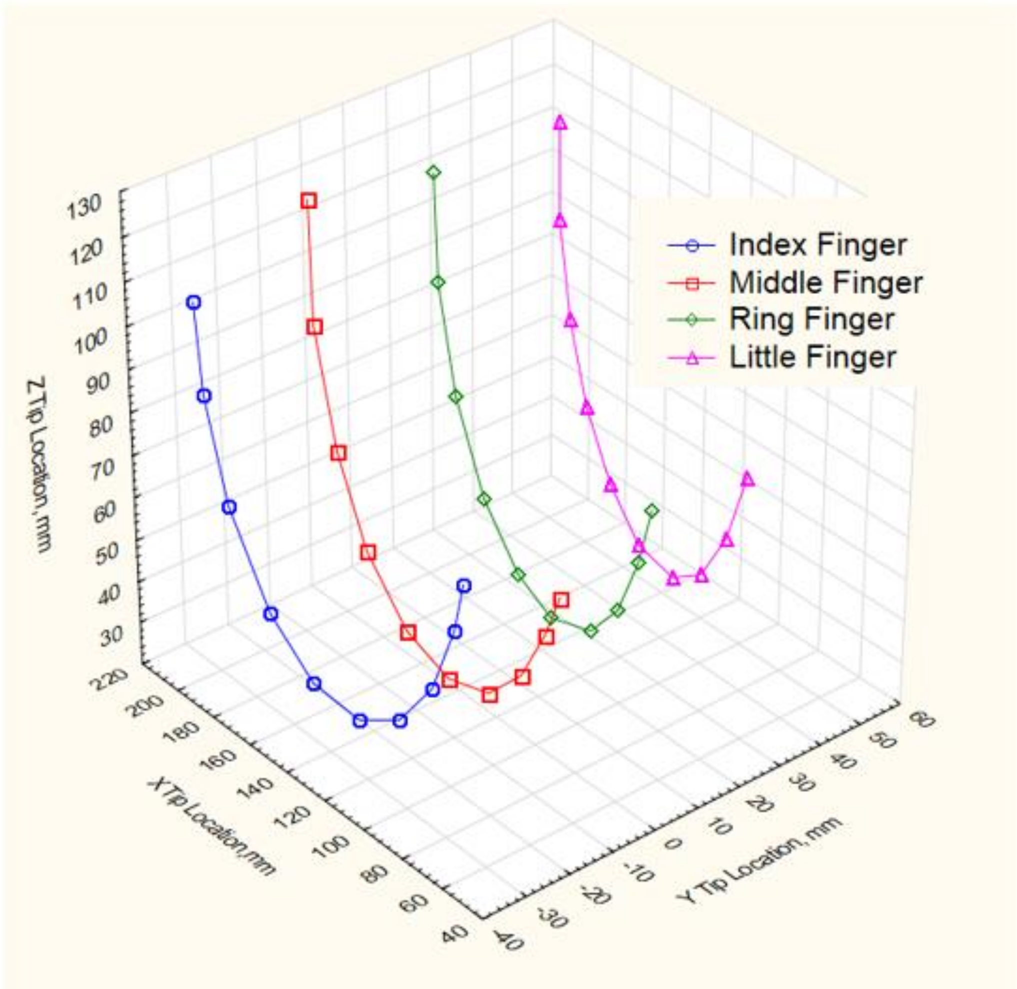

Figure 3.22: Fingertip trajectories and the overlapping of the thumb trajectory.

In figure 3.23 (below) the lines intersecting the black loop are areas where the fingers and thumb can interact. Although the graph suggests that the little finger cannot interact with the thumb in reality it can. The little finger has a width of 15mm while the thumb has a width of 20mm.These widths easily allow interaction between the two fingers.

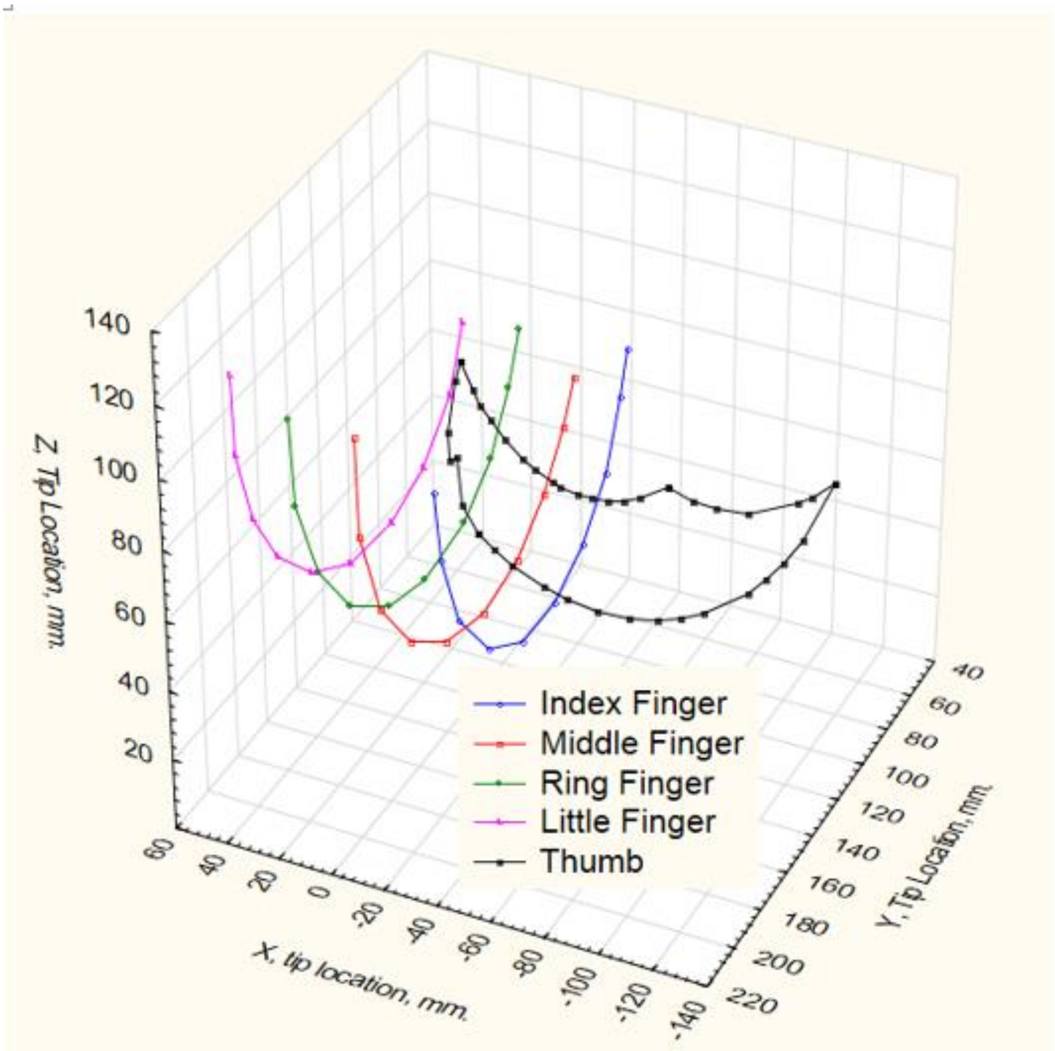

Figure 3.23: 3D plot showing the trajectories of the thumb and fingertips

The fingers and thumb overlap and interact at different kinematic orientations. It is noticeable that each finger of the designed hand interacts with the workspace of the thumb. This is important because it increases anthropomorphism and suggests this hand is designed well and capable of useful grasping positions. By adding the thumb trajectory to the finger trajectories the interaction between the thumb and fingers can be seen.

3.8 Conclusion

An effective and successful prosthetic hand requires a strong mechanical base with sound principles driving its physical operation. This chapter has carefully considered the mechanical design of a prosthetic hand. The hand will act as the platform for a brain controlled prosthetic. The following chapter will discuss the electronic control of the hand. The control will be based upon the mechanical structure of the hand. A significant amount of time and consideration has been given to the electronic design and control of the hand.

Chapter Four

4.1 Control System

The control of the hand is what differentiates this project from the others. It is the intent of this project to increase the sense of belonging between prosthetic device and amputee by controlling the designed device by the brain of the amputee. The mechanical design of the hand initially allows five different grasps/gestures in total to be performed by the hand. Four grips and one gesture will be programmed and uploaded to a micro-board when needed. The control of the hand will be driven through a neural interface and controlled by a micro-board. This chapter will discuss the method used to control the prosthetic hand.

4.1.1 Neurosky Mindwave

Neuroscience research in the last century has enlarged the knowledge base of electrical signals emitted by neurons firing in the brain. These electrical signals can be monitored using sensors applied to the head. NeuroSky ThinkGear technology proposes an algorithm to measure the analogue electrical signals produced from the brain and convert them to digital signals. Those digital signals are then made available to use in games and applications.

Table 4.1: six frequencies Neurosky monitor from the scalp by the mindwave mobile [73]

Brainwave	Frequency (Hz)	Mental state
Delta	0.1-3	Deep, dreamless sleep, unconscious.
Theta	4-7	Intuitive, creative, imaginary, dream.
Alpha	8-12	Relaxed, tranquil, conscious.
Low Beta	12-15	Relaxed yet focused.
Midrange beta	16-20	Thinking, aware of self and surroundings
High Beta	21-30	Alertness, agitated.

The NeuroSky Mindwave headset monitors eight frequencies emitted from the brain and correlates the data into useable information. Six of the eight frequencies are listed in table 4.1. Each frequency relates to a mental state or condition of the brain at a specific time. Using algorithms the headset is able to deduce the levels of concentration and meditation of an individual using the different frequencies. Intentionally blinking can also be recorded. Concentration and meditation are measured on a scale from zero to one hundred. The output digital signal will be used to control the prosthetic hand. Table 4.2 defines the parameters for elevated or reduced attention or meditation levels.

Table 4.2: Levels of a specific mental state from 1-100.

Mental state	Lowered 1-20	Reduced 20-40	Baseline 40-60	increased 60-80	Elevated 80-100
Attention	Distracted	Distracted	-	Heightened attention	Focused attentive
Meditation	Strongly agitated	Agitated	-	Calm	Mental relaxation

The Mindwave mobile core program presents the output of the Mindwave mobile as a series of eight frequencies producing a wave that corresponds to a mental state. Figures 4.1 and 4.2 represent each of the eight recorded frequencies using a multi coloured bar graph (top right). A white line is used to represent the wave produced from the combination of the recorded frequencies. Dials in the bottom right of the program window express the mental state of the user values from one to one hundred. These numbers relate directly to the levels expressed in Table 4.2. Figure 4.1 expresses an elevated attention state while figure 4.2 shows an elevated state of -meditation.

Figure 4.1: Screenshot of the Mindwave mobile core program showing an elevated reading of attention.

Figure 4.2: Screenshot showing an elevated state of meditation.

The Mindwave mobile is worn on the head with a probe placed above the eye and a clip on the earlobe as shown in figure 4.3.

Figure 4.3: The Neurosky headset being worn. [68]

The outgoing data from the Mindwave will be used to trigger a command on the Arduino Uno micro-board. The command will control the prosthetic to perform a specific task depending on the mental state of the user. For instance an elevated level of attention higher than eighty five percent will close the hand while an attention state lower then eighty five percent will open the hand. Once a grip has been completed the hand will return to a relaxed position awaiting the signal to open or remain closed. Mindwave mobile specifications are presented in appendix 1.

After three hours of training with the Mindwave mobile it took on average 9.8 seconds to produce a command signal for the hand to close. In the fastest instance the hand was triggered to move in only 1.9 seconds. These results are good. It can be expected that upon further training with the headset the average time taken to perform a command signal can be reduced significantly.

Figure 4.4 shows the role of the Mindwave mobile with respect to the control of the designed prosthetic hand. Brain waves are acquired through the Mindwave mobile and the waves are processed into useable signals. The signals are transmitted wirelessly to the Arduino Uno micro-board using Bluetooth. The prosthetic hand is then controlled through a combination of servo motors and force sensors.

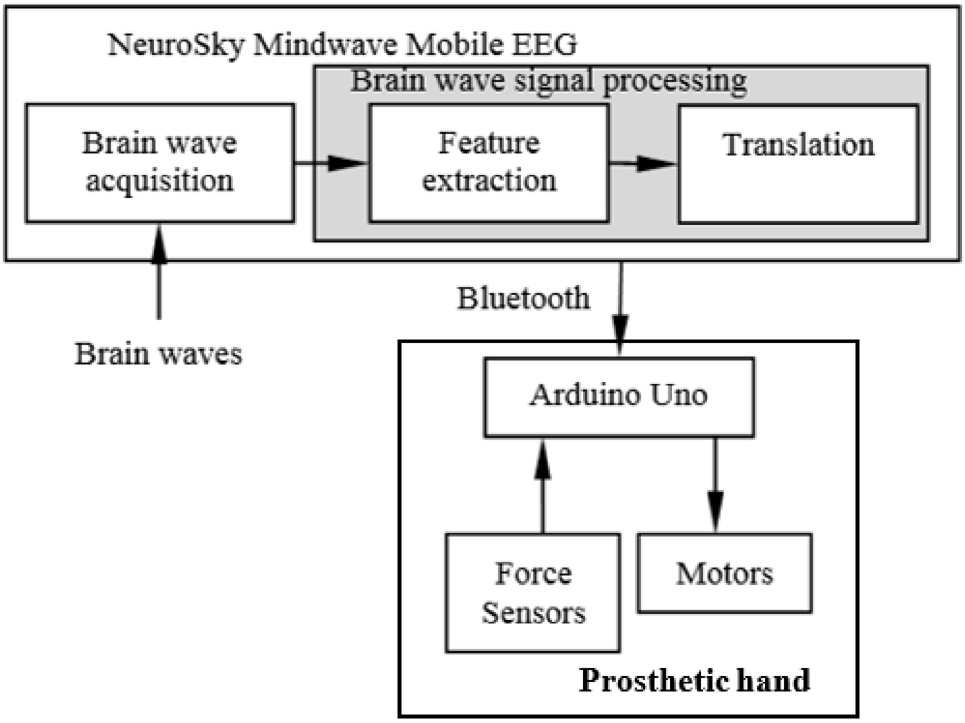

Figure 4.4: The role of the Mindwave mobile in prosthesis control

4.1.2 Electronic Control

The “Arduino Uno” (presented in appendix 1) is used to control the hand, it is an open-source electronics platform. The Uno is a microcontroller board based on the ATmega328. It has fourteen digital input/output pins, six analogue inputs, a sixteen MHz ceramic resonator, a USB connection, a power jack, an ICSP header and reset button. The board can be powered by USB or external power supply. There are a number of facilities for communicating with computers, other Arduino boards and microcontrollers. The Arduino software includes a serial monitor which allows data to be sent to and from the Arduino board. The Uno is intended for anyone making interactive projects.

4.1.3 Wireless communication

Wireless communication between the mindwave and the prosthetic hand will be accomplished through the use of the DF-BluetoothV3 Bluetooth module (presented in appendix 1). The module is designed to have two DC power inputs, a wide range of operating voltages and simple LED display of operating conditions. The module has two switches: one turns the Led on and off, the other allows the module to enter AT command mode which modifies the baud rate and the master and slave mode. Further information and instructions on using this device can be found on [69].

Figure 4.5 explains the physical set up of the hand and the control units. After acquiring brainwaves the mindwave mobile extracts relevant features from the data gathered and translates it into useable information. The information is sent via Bluetooth to the Arduino Uno. The Arduino processes the information and controls the prosthetic hand accordingly. The Arduino can be linked to a computer and serial monitor for debugging purposes.

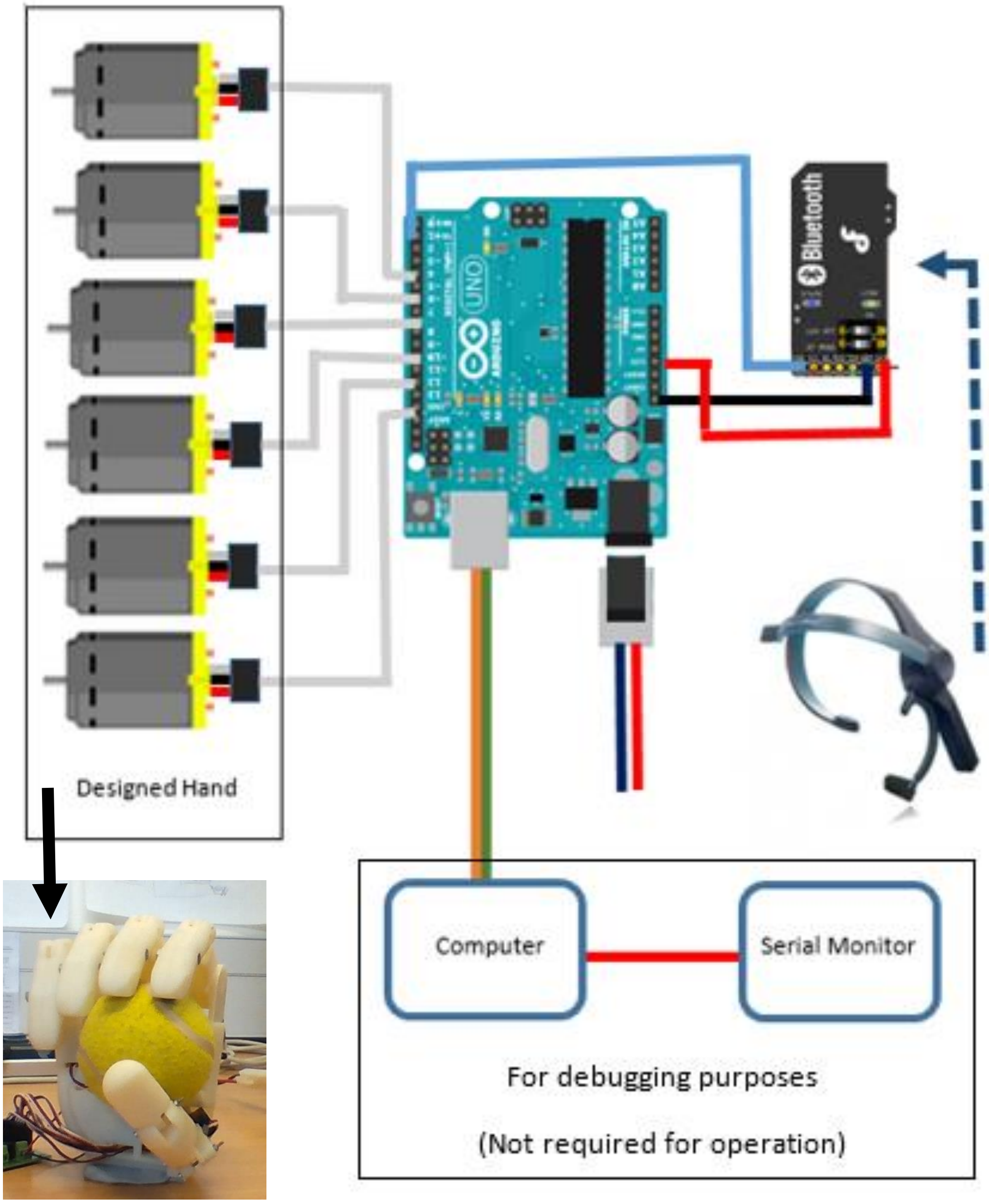

Figure 4.5: Simple circuit diagram schematic of the physical set up

(Additional information of the electronic components can be found in appendix 1)

4.2 Fingertip Sensors

Force sensors have been placed in the tips of the fingers with the intention of making the grips the hand is executing more compliant. The sensors work as a two state device. As the fingers encounter opposition from an object the force sensors switch the actuators off. Non-zero readings from the force sensor indicates obstruction to the finger. Figure 4.6 conveys the process of gripping an object.

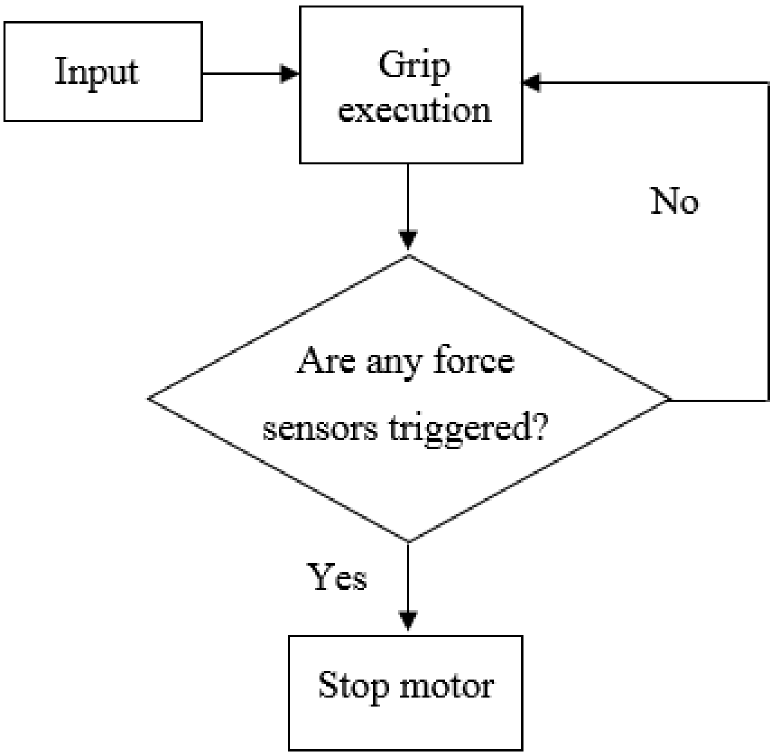

Figure 4.6: The process of gripping an object

The force sensors are placed at the fingertip and are mounted by a small opening in the distal phalange. The body of the sensor is hidden within the intermediate phalange and are connected directly to the Arduino Uno. Figure 4.7 shows the sensors on the tip of the middle, ring and index fingers.

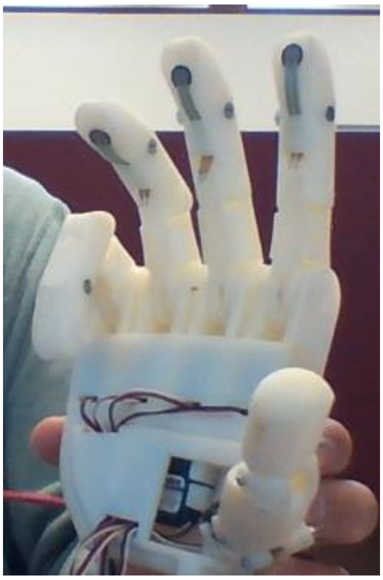

Figure 4.7: Force sensors on the designed hand

Grip/grasp strength is controlled by the use of force sensing resistors in the fingertips. Once a reading on the force sensor is reached the servo motor corresponding to the finger in motion will be stopped. The user of the hand does not need to produce a signal for the hand to stop closing. The hand will stop moving when an object is encountered. All that is required for a successful grasp is an activation signal from the user.

4.3 Programming

The Uno is programmed with Arduino software and comes pre-burned with a boot loader allowing new code to be uploaded to it without the use of an external hardware programmer. The Arduino language is a set of C/C++ functions that can be called from the code. Arduino programs can be divided into three main parts: structure, values and functions. All coding is passed directly to a C/C++ compiler. Standard C and C++ constructs should work in Arduino.

(Computer coding for the hand is presented in appendix 4)

4.4 Control Matrix

This section will describe the state of under actuation the designed hand is expected to operate under. There are six servo motors controlling eleven DoF. Each of the five servo motors embedded in the palm control two DoF while the sixth servo motor is responsible for the control of the remaining DoF. Table 4.3 shows the relationship between the servo motors and the DoF they are controlling. Observing the top row explains that "Servo one" controls the "2nd Metacarpophalangeal" and the "2nd proximal interphalangeal" bones. Figure 4.8 can be used in reference to using this table.

Table 4.3: Control table relating servo motors to finger bones

Servo one Index	2nd Metacarpophalangeal	2nd Proximal Interphalangeal
Servo two Middle	3rd Metacarpophalangeal	3rd Proximal Interphalangeal
Servo three Ring	4th Metacarpophalangeal	4th Proximal Interphalangeal
Servo four Little	5th Metacarpophalangeal	5th Proximal Interphalangeal
Servo five Thumb	1st Metacarpophalangeal	1st Proximal Interphalangeal
Servo six Palm	1st Carpometacarpal	------------------------------------

(Note: The distal interphalangeal joints do not exist in the designed hand and have therefore not been included in this table.)

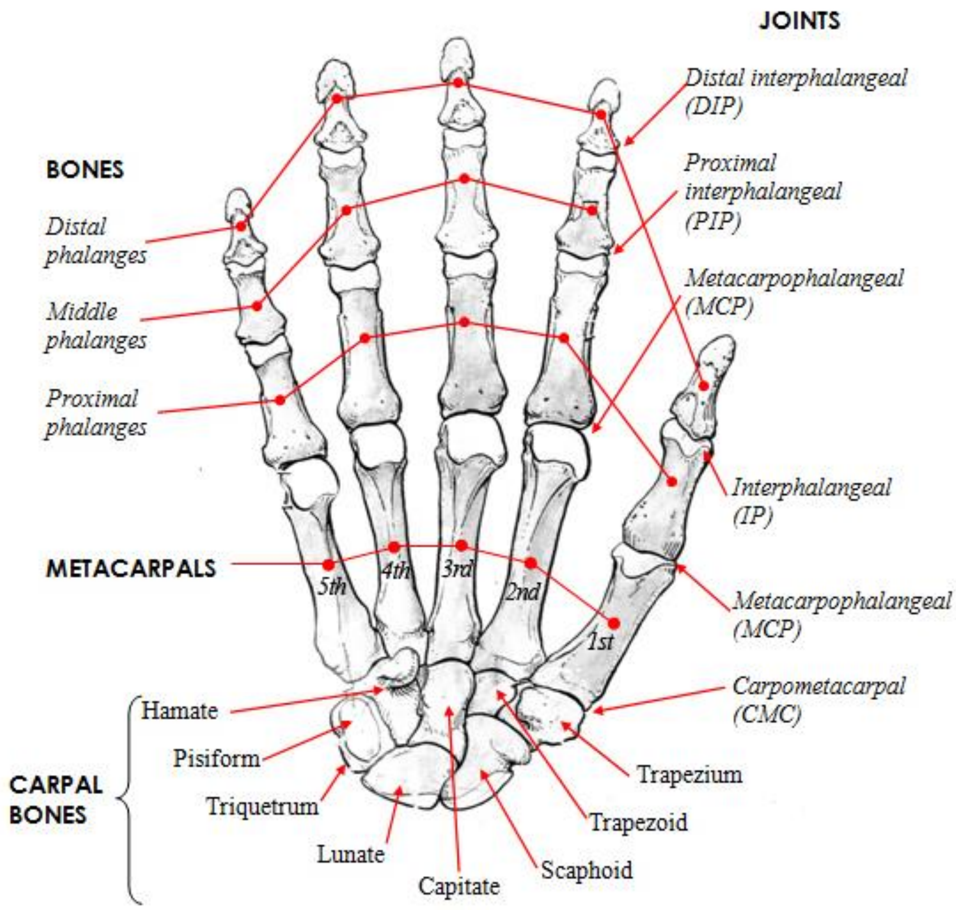

Figure 4.8: Diagram labelling the bones and joints of the human hand. [70]

The control matrix of the designed hand uses simple combining relationships with Pythagoras theorem to relate the servo motor angle to the joint angles of the finger. This section does not consider velocities of the finger mechanism. Angular displacements between joints are used in the evaluation of the control matrix.

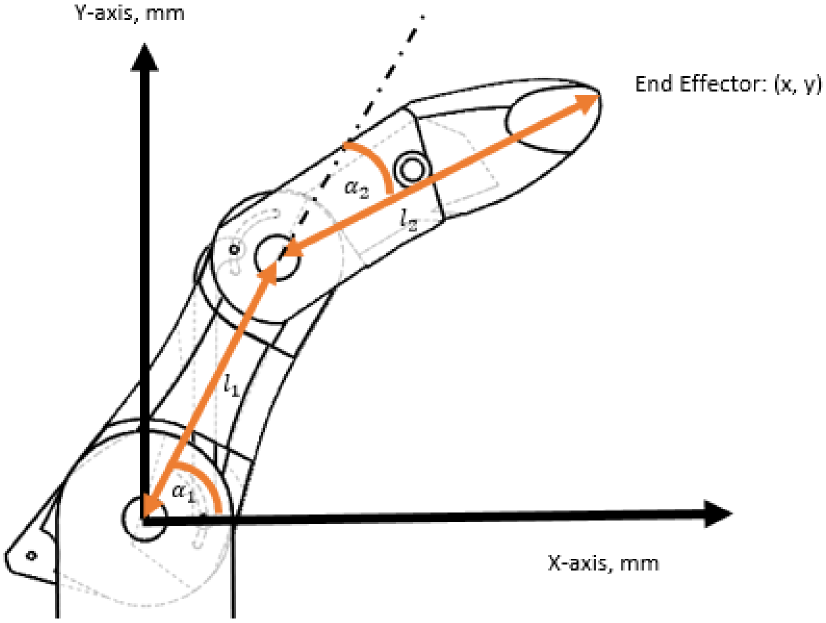

Figure 4.9: Index finger as a two link planar manipulator

Consider the index finger as a two link planar manipulator (Figure 4.9) with each joint having a zero to ninety degree range of motion. This can be shown mathematically by the following.

$$0^0 < \alpha_1 < 90^0 \quad (18)$$

$$0^0 < \alpha_2 < 90^0 \quad (19)$$

Where α_1 is the angle between the proximal phalange and the X axis and α_2 is the relative angle of the distal phalange with respect to the position of the proximal phalange.

Servo motor operating angles are limited to the following range of motion

$$0^0 < \theta_i < 180^0 \quad (20)$$

Equating the effect of θ_i on α_1 we get

$$\theta_i = 2\alpha_1 \quad (21)$$

Where θ_i is the servo motor angle.

The relationship between α_1 and α_2 can be written as

$$\alpha_1 = \alpha_2 + 90 \tag{22}$$

We can now write θ_i in terms of both joint angles using a single joint angle.

$$\theta_i = 2(\alpha_2 + 90) \tag{23}$$

This method can be applied to the other fingers of the hand and written in matrix form.

$$\begin{bmatrix} \theta_i \\ \theta_m \\ \theta_r \\ \theta_l \\ \theta_p \\ \theta_t \end{bmatrix} = \begin{bmatrix} 2 \\ 2 \\ 2 \\ 2 \\ 2 \\ 2 \end{bmatrix} * \begin{bmatrix} \alpha_{2i} + 90 \\ \alpha_{2m} + 90 \\ \alpha_{2r} + 90 \\ \alpha_{2l} + 90 \\ \alpha_1 \\ \alpha_{2t} + 90 \end{bmatrix} \tag{24}$$

Where

$\theta_i, \theta_m, \theta_r, \theta_l, \theta_p$ and θ_t Represent servo motor angle and

$\alpha_{2i}, \alpha_{2m}, \alpha_{2r}, \alpha_{2l}$ and α_{2t} are the joint angles of the second joint in each finger

In the case of θ_p there is no second link therefore the angle $\alpha_1$is directly related to $\theta_p$by the relationship.

$$\theta_i = 2\alpha_1 \tag{25}$$

Equation 24 successfully expresses the designed hand as a six variable unit controlling eleven joints.

4.5 Function

This section will relate the hands performance to its function. Function in the context of this section will refer to how closely the designed hand complies with the widely accepted definitions of the following grasps or gestures: Ball Grip, Index Point, Power Grasp, Thumb/Index Pinch and Key Grip. It is important to note that non prehensile grips or configurations will not be considered in this paper.

In the case of a human hand each finger has three segments or phalanges connected by joints. Muscles in the hand and arm actuate the joints and cause movement. The designed hand is simplified to have two phalanges connected by two joints. The finger is actuated by a single servo motor connected to the first joint which then actuates the second joint. The simplification of the finger creates a two link planar manipulator which can be replicated for each finger. Each finger is evaluated by the kinematic equation using the Denavit-Hartenberg representation expressed in chapter three.

4.5.1 Ball Grip

A good ball grip depends on the hands ability to securely grasp a ball. The grip involves the support of the thumb in either the adducted or abducted position with any number of the fingers clamping down on the top and sides of the ball.

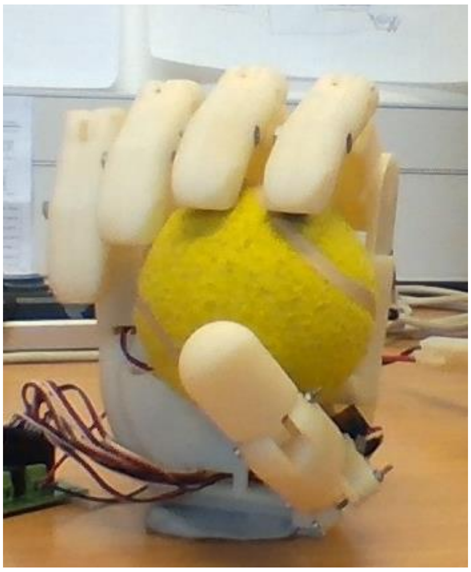

Figure 4.10: Execution of ball grip by designed hand.

The hand successfully gripped the tennis ball in its first attempt (Figure 4.10). The tennis ball fits into the hand well and there are plenty of contact points to ensure a compliant and stable grasp. The fingertips extended well beyond the objects centre of mass allowing palmar opposition in the grip. The index and middle fingers can reach around the ball cleanly and pull the ball into the palm. The thumb provides upward support through the metacarpal piece and pulls the ball inward through movement in the distal phalange.

4.5.2 Index Point

The index point (Figure 4.11) is a gesture commonly used in human interaction and has many uses. This gesture is very simple however the range of movement for the index finger had to be adjusted. Initial attempts produced a bent index finger, which was eventually resolved by the shortening of the driving rod and more accurate programming of the servo motor. The gesture functions as intended and is useful for typing, pointing and other similar applications

Figure 4.11: Execution of index point by designed hand.

4.5.3 Thumb and Index Pinch

The grip more commonly known as a “pinch” involves the pinching of a small object between the thumb (abducted position) and index finger.

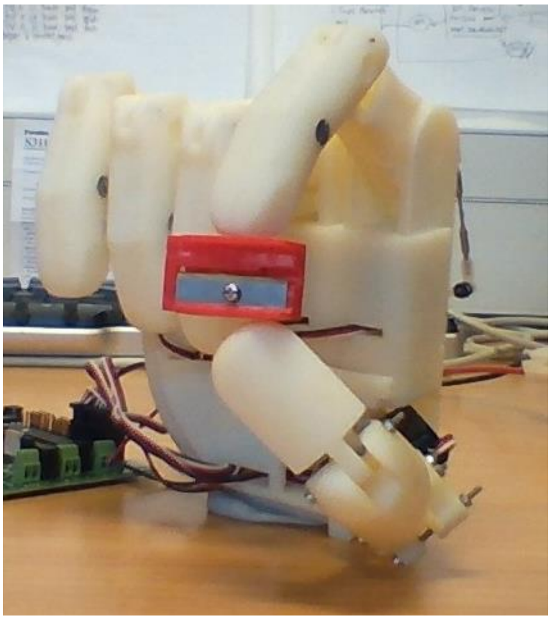

Figure 4.12: Execution of pinch by designed hand.

As shown in Figure 4.12 the hand successfully replicated the pinch grip. The pencil sharpener was gripped both along its length and width with good results. The grip is not completely stable due to the lack of force exerted at the index fingertip and thumb. Multiple attempts to obtain a secure grip on the object are often required. An obvious limitation is that the grasp is orientation dependant. In an upright position the grasp is stable but a change in orientation in any direction leads to grip failure. The solution to this can be found in an increase in force produced at the fingertips. A decrease in friction in the joints in the hand will increase stability and servo motors with greater torque will eliminate instability.

4.5.4 Power Grasp

A power grasp (Figure 4.13) involves palmar opposition to the four fingers. In this case the thumb can be positioned in either the adducted or abducted position.

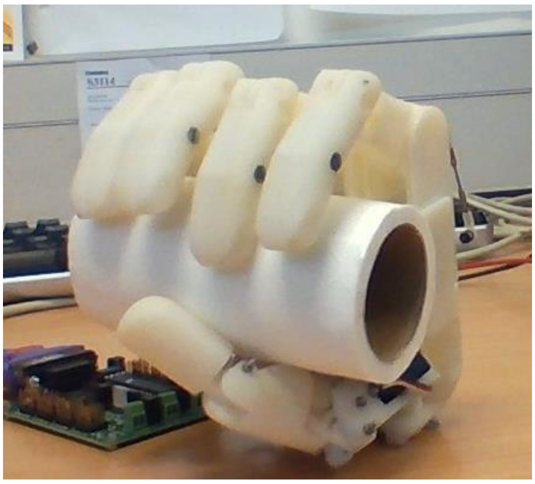

Figure 4.13: Execution of power grip by designed hand.

The power grasp closes all fingers (with the thumb in the abducted position) until the force sensors encounter a resistance which in this case is the object. The grip is stable and performed as expected. The fingers and thumb are able to wrap around the cylinder and provide the grip with palmar opposition to the fingers and thumb. There was not enough force exerted by the actuators to clamp down on the cylinder, so a similar solution as that explained in the "thumb and index pinch" section should be considered.

4.5.5 Key Grip

The key grip involves the index finger and thumb in the adducted position. As shown in figure 4.14 the object is gripped between the distal phalange of the index finger and the thumb. This grip proved the most difficult to execute. The grip involved movement at the thumbs maximum range and in some attempts the key was not gripped at all. Another sensor should be mounted on the side of the distal phalange of the index finger to sense the object being gripped. Increasing the length of the thumbs distal phalange will increase the grip stability.

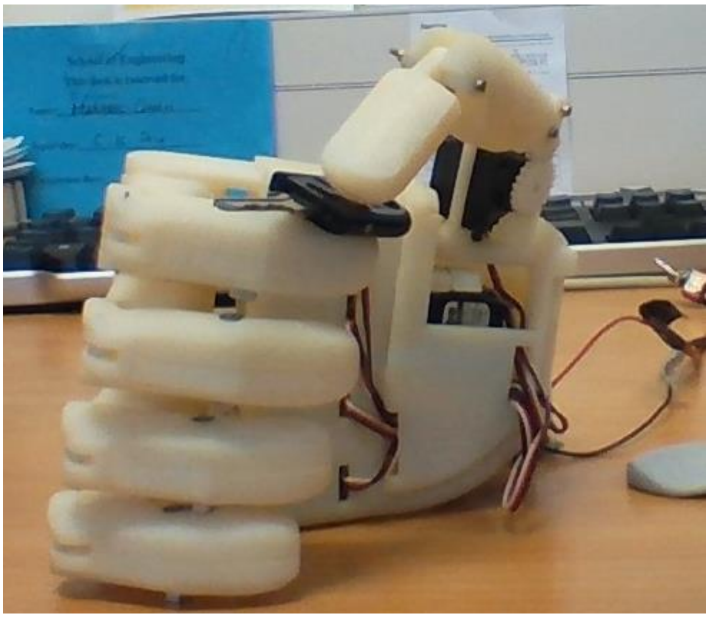

Figure 4.14: Execution of key grip by designed hand.

Tables 4.4 and 4.5 define the opening and closing servo angles for each of the grips and gestures the hand is able to perform. The far right column in each table expresses the opening and closing conditions needed for the grip to execute and open. These values represent the difference between slightly elevated and highly elevated attention values produced from the user.

Table 4.4: Open positions for servo motors with respect to called grip/gesture

Grip/Gesture	θ_i	θ_m	θ_r	θ_l	θ_p	θ_t	Closing Value
Pinch Grip	170°	10°	10°	10°	90°	90°	Above 80
Key Grip	10°	10°	10°	10°	90°	90°	Above 80
Power Grip	170°	170°	170°	170°	10°	170°	Above 70
Ball Grip	170°	170°	170°	10°	90°	90°	Above 80
Index Point	170°	10°	10°	10°	90°	90°	No Actuation

Table 4.5: Closed positions for servo motors with respect to called grip/gesture

Grip/Gesture	θ_i	θ_m	θ_r	θ_l	θ_p	θ_t	Opening Value
Pinch Grip	10°	10°	10°	10°	90°	90°	Below 80
Key Grip	10°	10°	10°	10°	90°	90°	Below 80
Power Grip	10°	10°	10°	10°	10°	10°	Below 70
Ball Grip	10°	10°	10°	10°	90°	90°	Below 80
Index Point	170°	10°	10°	10°	90°	90°	No Actuation

4.6 Conclusion

This chapter has been focussed on the way the hand is controlled and is very important because it relates directly to the aim of the thesis to create a brain controlled prosthetic hand. The hand is responsive to signals emitted from the brain. There is now a closer bond between the designed hand and user like never before. The sense of belonging has increased and the prosthetic devices is more likely to be successful. The following chapter will discuss the aesthetics and performance of the hand with the intention of completing the analysis of the effectiveness of the designed hand.

Chapter Five

As intended an anthropomorphic under-actuated brain controlled robotic prosthetic hand has been designed to increase the knowledge surrounding brain controlled prosthetic devices. The design allows for a wide range of movement of the fingers and thumb. The control of a prosthetic hand using brain signals has been accomplished. This chapter will discuss the performance and aesthetics relating to the designed hand.

5.1 Discussion

The scale of the hand fits well to the average male adult hand and the weight of the hand is acceptable (310g without electronic components). The hand dimensions fit six servo-motors working to engage eleven joints. The palm of the hand can be modified to fit more actuators.

The electronic design is based around a central computer used to program the Arduino Uno. Frequencies emitted from the brain are channelled through the NeuroSky Mindwave headset and sent to the computer via Bluetooth. In addition to the functioning control system, force sensing resistors sense when objects have been gripped and are used to stop the actuators when a sufficient force has been placed on the object being grasped.

The hand is currently programmed to execute four grasps and one gesture. Upon completion of the grasp or gesture the hand will return to a relaxed position. Some of the areas this chapter will discuss are.

- Size and Appearance
- Motion
- Velocity
- Force

5.1.1 Aesthetics

The design and development of a successful prosthetic hand cannot be quantified by function and performance only. The motion of the hand and how closely it resembles the natural motion, size and configuration of a human hand must also be addressed. It is vital that the aesthetics be evaluated as a part of a comprehensive assessment of the hand. For simplicity this section has been entitled “Aesthetics” and will include the following sub sections: Size and Appearance, Skeletal Similarity and motion.

5.1.1.1 Size and Appearance

The size and appearance of the hand is an important part of the design process and end user satisfaction. The designed hand is based on the size of an average adult male hand.(Figure 5.1). Without a covering the hand is not natural looking. The driving mechanisms are mounted within the palm. The majority of electronic components are visible giving the hand a “robotic” or “futuristic” look. Uncovered the hand will draw a lot of attention in a classic everyday environment. The fingertips are tapered and the palm has rounded edges to imitate the curvature of a natural hand. As the material ages through use and wear it transforms from a clean white colour to a creamy yellow. The hand weighs 310 grams excluding the control unit and batteries. Part configurations, angles and lengths are based on the skeletal structure of the average male adult human hand. The hand is printed from a material named “Vero white”.

(Additional drawings of the hand can be found in appendix 2)

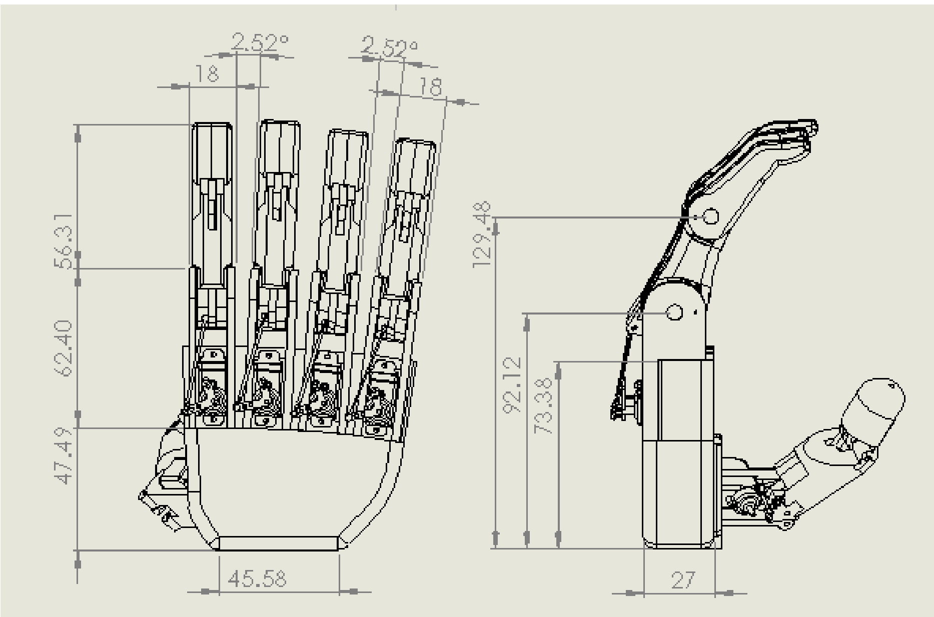

Figure 5.1: 3D model of designed hand and dimensions

5.1.1.2 Skeletal similarity

The human hand (excluding the wrist) has 27 bones. These bones contribute to the incredible dexterity the human hand possesses. Simplifications to the skeletal structure (Figures 5.2 and 5.3) have been implemented to reduce the complexity in design and control.

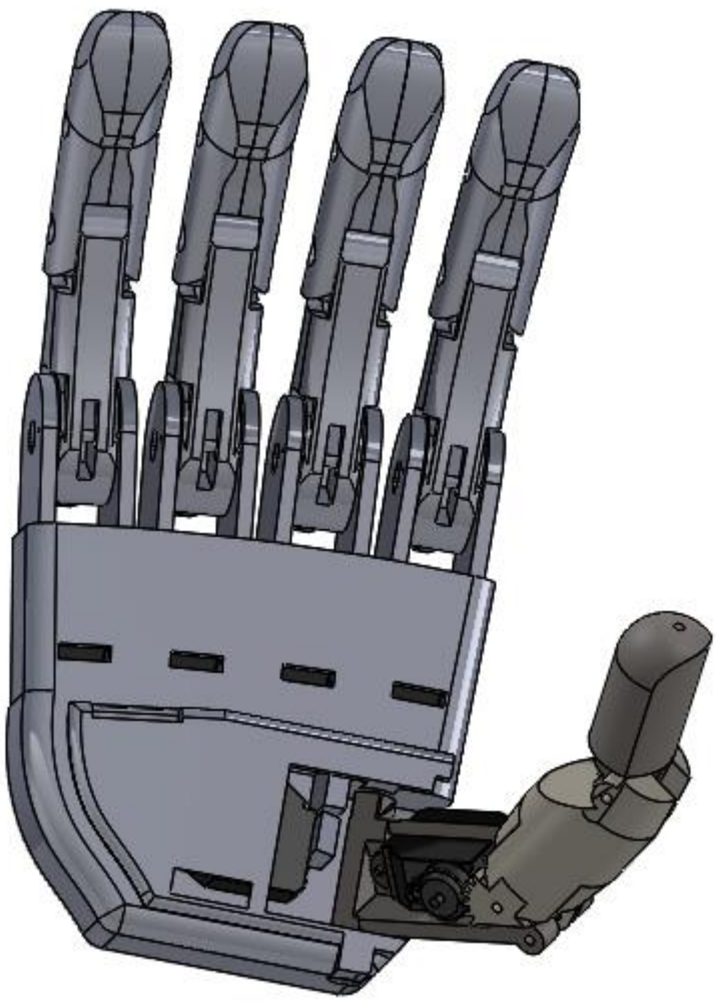

Figure 5.2: simplified hand, Palmer view

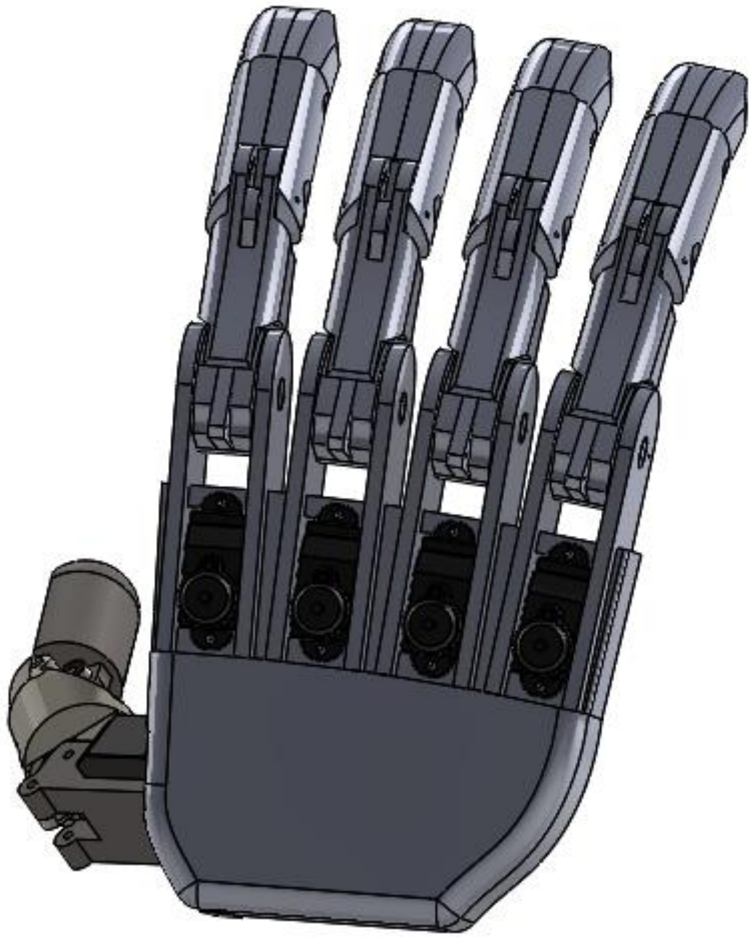

Figure 5.3: Simplified hand, top view

5.1.1.3 Motion

The motion of the fingertips on the designed hand correspond well to the theoretical end effector kinematics calculated. Although end effector trajectories are good the minimum and maximum coordinate values are not reached by the designed hand. After a range of movement measurements the fingers moved about seventy percent of the theoretical value of movement which is acceptable. The thirty percent loss in movement is due to:

- The friction increase over the joints decrease the total movement of the fingers.
- After programming, the micro servos no longer perform throughout the full rated range of motion. In some cases ten-fifteen degrees of rotation was lost.
- Servo horns tend to bend/flex throughout operation not allowing the full range of motion.
- There is an inaccuracy in the testing method due to human limitations.

The motion of the fingers are natural looking and adequately smooth. The thumb movement is smooth and full. Without a covering the thumb motion is “robotic” looking. The fingers can be made to have a smoother motion by incorporating springs in the driving mechanism, allowing the springs to dampen the sudden movements produced from the micro servos. The thumb can be improved by covering the visible micro servo in the thumb metacarpal and altering the angle at which the thumb sweeps to the opposable position. The linear sweeping trajectory the hand currently exhibits contributes to the robotic looking movements.

The hand reflects the motion of a natural human hand well, there are no obvious flaws with the motion or trajectory of the fingers or thumb. The hand moves as expected. The loss of range of finger movement was not anticipated but will not significantly affect the hands function and performance.

5.1.2 Performance

The previous section has described and evaluated the aesthetics of the designed hand. The purpose of this section is to look at the performance of the hand. The capability of the hand is quantified by evaluation of the following areas: Driving mechanism, Velocity, Force and Stress Analysis. Each area contributes to the overall performance of the hand and act as integral components to a larger system.

5.1.2.1 Driving Mechanism

The driving mechanism is driven by the Futaba S3114 micro servo capable of producing 1.5 kg.cm of torque at a speed of 0.1sec/60 degrees with the supply voltage at 4.5 volts. Increasing the supplied voltage to 6 volts increases the torque to 1.7kg.cm and the speed to 0.09sec/60 degrees.

When operating at 4.5 volts the base of the proximal phalange on each finger should experience a torque of around 0.147N.m. The transfer of torque is directed through a “DU-BRO” micro ball link and pushrod. After testing the torque at the fingertip was only twelve percent of the expected 0.047N.m.

The driving mechanism (Figure 5.4) provided sufficient torque and force to have an operational hand, however the servos are not capable of providing the hand with the force and grip strength to be useful as a prosthetic. The servo although lightweight and compact does not provide the required strength to grip objects firmly even at higher ratings including the losses due to friction.

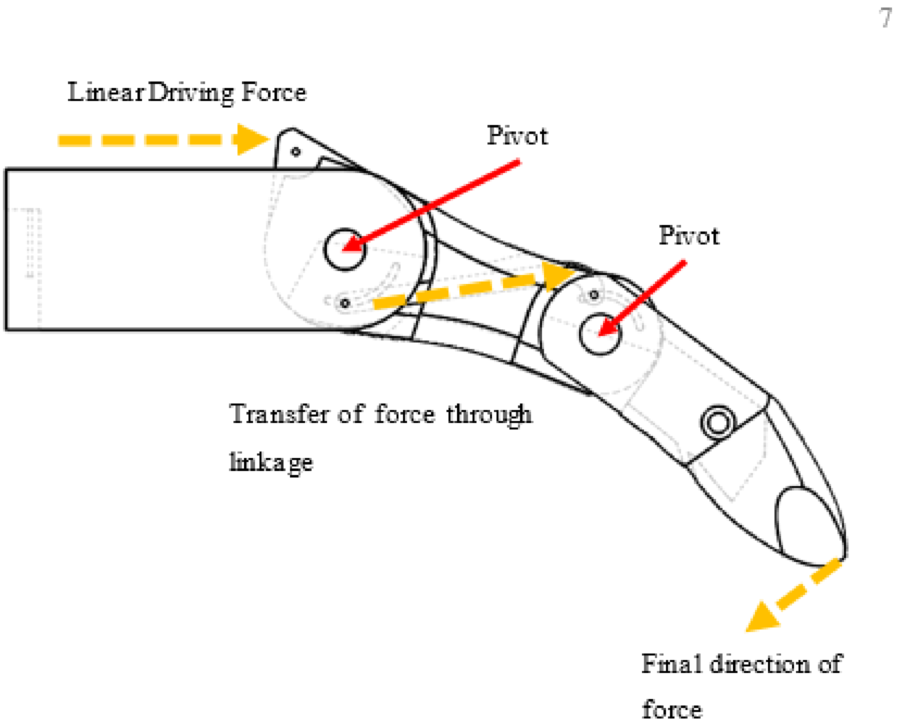

Figure 5.4: Joints and force transferral throughout the finger

The micro servo is capable of driving the fingers and providing a small amount of gripping force but are not suitable for a prosthetic hand. The current driving mechanism setup is functional for the purpose of this research and will not be developed any further here. Further development and research is required in this area.

5.1.2.2 Velocity

The velocity analysis of the designed hand employed the Jacobian transformation (defined in chapter two) to calculate the fingertip velocities in the X and Y directions as well as the overall angular velocity. The actual fingertip velocity did not perform as well as expected. Forty six percent of the theoretical speed was realised in the X direction, while only seven percent of the expected value for velocity in the Y direction was observed. One sixth of the expected angular velocity at the fingertip was recorded. Table 5.1 conveys the finger opening and closing times.

Table 5.1: Opening and closing grip times

	Little Finger (s)	Ring Finger (s)	Middle Finger (s)	Index Finger(s)	Palm (s)	Thumb (s)
Opening time						
Trial 1	1.473	1.52	1.577	1.334	1.844	0.929
Trial 2	1.632	1.647	1.464	1.232	1.74	0.834
Trial 3	1.683	1.5	1.416	1.567	1.659	1.124
Trial 4	1.857	1.293	1.572	0.954	1.711	1.369
Trial 5	1.888	1.54	1.568	1.624	1.813	0.921
Average	1.7066	1.5	1.5194	1.3422	1.7534	1.0354
Closing Time						
Trial 1	1.56	1.166	0.832	0.792	1.784	1.436
Trial 2	1.672	1.344	1.48	0.933	1.771	0.789
Trial 3	1.729	1.14	1.18	0.752	1.868	0.813
Trial 4	1.719	1.511	1.376	0.77	1.797	0.924
Trial 5	1.636	1.384	1.91	1.224	1.835	1.236
Average	1.6632	1.309	1.3556	0.8942	1.811	1.0396

On average the hand would take 1.48sec to open from a completely closed position and would take 1.35sec to close from a completely open position. These times are representative of the time it takes a natural hand to open and close. The hand is adequately responsive to obtain a desired grip/grasp within an acceptable time.

The kinematic equations and changing of variables throughout the calculating phase did not account for considerable friction increases over the finger joints, differences in micro servos and differences induced by methods of power transfer throughout the hand. There is a noticeable time delay between the command signal and finger movement which slows the finger considerably. This movement manifests itself as a “jerking” motion at the beginning of a grasp/grip. It can be smoothed by the use of a spring to dampen the force being suddenly applied to the first joint of the hand. Other improvements to be made include:

- Decreasing joint friction, by decreasing joint size and changing joint material. Lubrication or a small bearing will be adequate.
- Improving power transfer through rigid links. Link mounts need better fitting and would operate better if they were made from a smooth metal.

- Decreasing flexion of the driving mechanism. The servo horns and rigid links are too flexible and do not serve the hand well. A change of material or geometry will improve hand speed.

5.1.2.3 Force

Upon execution of the grasps and gestures it was obvious that the hand was not producing the force expected from theory. Objects weighing up to 300 grams could be gripped however anything passed this weight became difficult. A force of 0.1N was recorded at the index fingertip. This amount of force is not useful and denies the hand important function. After examination it was found that this value could not be true. At the recorded force value a 10 gram object would be the maximum weight of an object to be gripped however the hand is able to grip above that weight.

The force sensor used to measure the force at the fingertip is only good as a two state device. The sensor will function but not as a device that can be used to alter grip strength during grip execution.

Another limitation seen throughout testing is caused by the small sensing area of the force sensor. The sensing area is about one fifth the size of the fingertip and limited to the centre of the fingertip. The hand can be improved by using more accurate force sensors with a larger sensing area.

5.1.2.4 Stress Analysis

The following section conveys the stress analysis relating to the parts in each finger that are directly involved with the transferal of force throughout the finger system. The proximal phalange of each finger will be represented by a model of the middle proximal phalange (Figure 5.5). The analysis also tests the thumb metacarpal and the rigid links used to transfer power. It is important to note that the software used in the stress analysis did not contain the material properties of the material used to construct the hand. Results are subject to the difference between the 3D printed material and the closest material within the software's database.

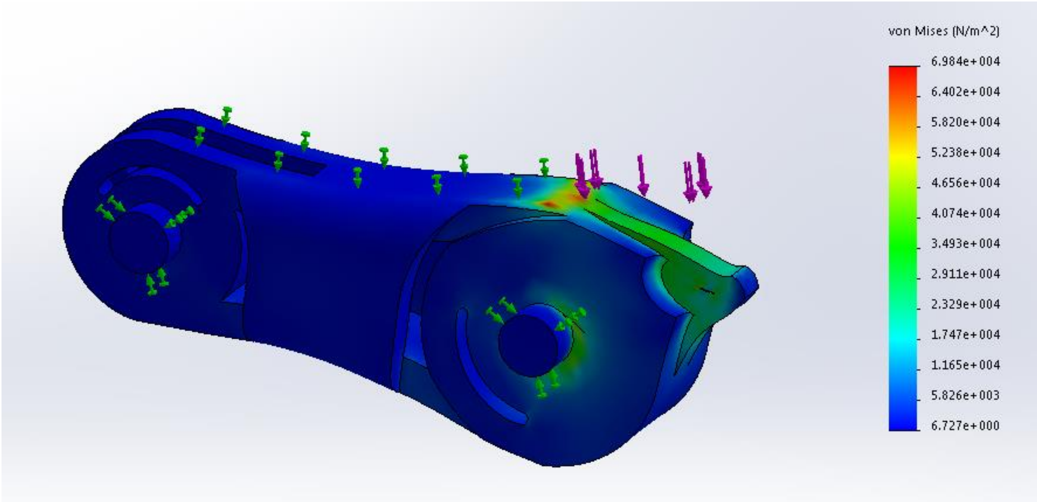

Figure 5.5: Stress plot of proximal phalange index finger

Each finger experienced the largest amount of stress on the proximal phalange where the ball link was mounted. The geometry of later models included bulking this area to account for the increased stresses present. The fingers now perform well and are able to withstand the many uses the hand is expected to be subject to.

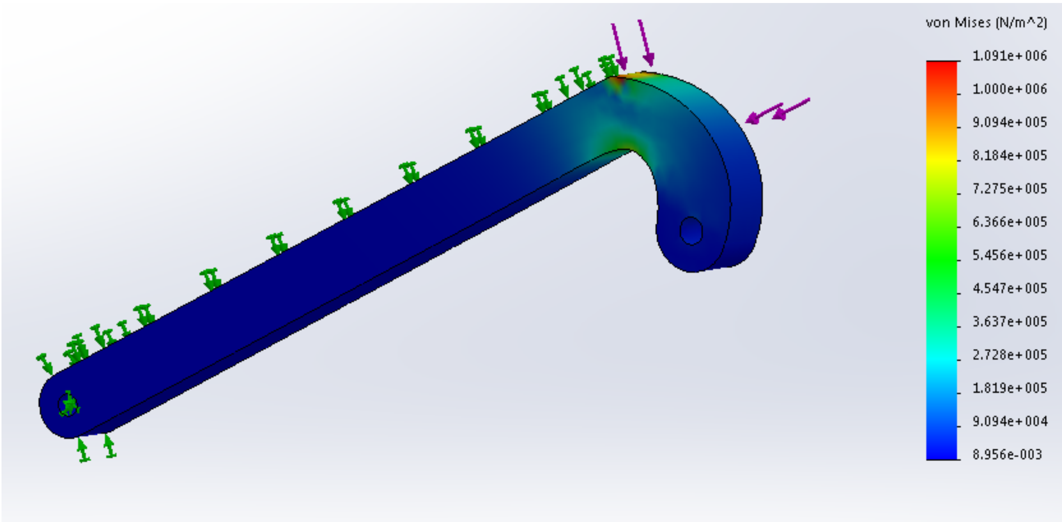

Figure 5.6: Stress plot of rigid linkage

The rigid links (Figure 5.6) in each finger tended to be too flexible and break in the earlier models of the hand. After examination the stresses experienced by these links originated from the friction generated by the poor design of the proximal interphalangeal joint. Improvements in the joints of the hand decreased the stress on the part however these parts will not withstand the repeated stress applied to them over extended periods of time. The links will perform better if made from a stronger material with little flexion.

5.1.3 Conclusion

A prosthetic hand has been developed and successfully controlled using signals from the brain. This chapter has evaluated the performance and aesthetics of the designed hand. The hand based on the human skeleton is similar in appearance to the human hand and moves naturally. There are issues with the performance of the hand which are directly related to the method of actuation chosen. The hand has performed as expected and is natural looking. There is plenty of room for improvement and therefore further development of the hand is required. Chapter six will conclude the research and revisit the aim of the work.

Chapter Six

6.1 Conclusion

A brain controlled, under actuated, Prosthetic hand has been designed and developed for upper extremity amputees. The hands function is based on micro servo actuation. Its configuration consists of eleven joints actuated by six servo motors. The platform has been designed to use multiple force sensors to improve control. The hand has been primarily developed as a foundation for future research into brain controlled prosthetics at the University of Waikato.

Emphasis has been placed on the mechanical design and control of the hand. This research is set apart from others because of its aim to control a prosthetic using brain signals. The hand is responsive to signals emitted from the brain and is functional. It is capable of executing five grips/gestures.

A major contribution of this work is to aid the rehabilitation of amputees. A dominant reason for prosthetic abandonment is the lack of sense of belonging between prosthetic and amputee. Controlling the hand depends upon the mental state of the user and does not depend on physical movements. By virtue of the research the sense of belonging has increased by creating a relationship between the prosthetic and amputee that cannot be replicated by physical motion. The aim and objectives of the work have been realised.

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Appendices

Appendix 1

Electronic and mechanical components

This appendix describes the electronic components and mechanical component used in the research.

Mindwave mobile

Figure A 1: Neurosky Mindwave Mobile

The MindWave Education turns your computer into a private tutor. The headset takes decades of laboratory brainwave technology and puts it into a bundled software package for under $100. It safely measures brainwave signals and monitors the attention levels of students as they interact with math, memory and pattern recognition applications. Ten apps are included with experiences ranging from fun entertainment to serious education.

- - Lightweight
- - Wireless
- - Safe passive biosensors
- - 8-hour AAA battery life

- - Includes bonus CD with 10 neuroscience apps
- - Supported OS:
- Window: XP, Vista, Windows 7, Windows 8, Windows 8.1
- Mac: 10.7.5, 10.8.x, 10.9.x, 10.10
- Hardware Overview:- Portable EEG brainwave headset- TGAM1 module, with TGAT1 ASIC- Automatic wireless computer pairing- Static headset ID- Single AAA battery - 6-8 hours battery run time

Specifications

- Weighs 90g- Sensor arm up: Height: 225mm x Width:155mm x Depth: 92mm Sensor Arm down: height: 225mm x width:155mm x depth:165mm 30mW rate power; 50mW max power 2.420 - 2.471GHz RF frequency- 6dBm RF max power- 250kbit/s RF data rate 10m RF range- 5% packet loss of bytes via wireless-UART Baudrate: 57,600 Baud - 1mV pk-pk EEG maximum signal input range - 3Hz – 100Hz hardware filter range - 12 bits ADC resultion- 512Hz sampling rate-1Hz eSense calculation rate,

Measurements:- Raw signal- Neuroscience defined EEG power spectrum (Alpha, Beta, etc.- eSense meter for Attention- eSense meter for Meditation- eSense Blink Detection- On-head detection

Arduino Uno

Figure A 2: Arduino Uno Micro-board

The Arduino Uno is a microcontroller board based on the ATmega328 (datasheet). It has 14 digital input/output pins (of which 6 can be used as PWM outputs), 6 analog inputs, a 16 MHz ceramic resonator, a USB connection, a power jack, an ICSP header, and a reset button. It contains everything needed to support the microcontroller; simply connect it to a computer with a USB cable or power it with a AC-to-DC adapter or battery to get started.

The Uno differs from all preceding boards in that it does not use the FTDI USB-to-serial driver chip. Instead, it features the Atmega16U2 (Atmega8U2 up to version R2) programmed as a USB-to-serial converter.

Revision 2 of the Uno board has a resistor pulling the 8U2 HWB line to ground, making it easier to put into DFU mode.

Revision 3 of the board has the following new features:

- 1.0 pinout: added SDA and SCL pins that are near to the AREF pin and two other new pins placed near to the RESET pin, the IOREF that allow the shields to adapt to the voltage provided from the board. In future, shields will be compatible with both the board that uses the AVR, which operates with 5V and with the Arduino Due that operates with 3.3V. The second one is a not connected pin, that is reserved for future purposes.

- Stronger RESET circuit.
- Atmega 16U2 replace the 8U2.

"Uno" means one in Italian and is named to mark the upcoming release of Arduino 1.0. The Uno and version 1.0 will be the reference versions of Arduino, moving forward. The Uno is the latest in a series of USB Arduino boards, and the reference model for the Arduino platform; for a comparison with previous versions, see the index of Arduino boards.

Microcontroller	ATmega328
Operating Voltage	5V
Input Voltage (recommended)	7-12V
Input Voltage (limits)	6-20V
Digital I/O Pins	14 (of which 6 provide PWM output)
Analog Input Pins	6
DC Current per I/O Pin	40 mA
DC Current for 3.3V Pin	50 mA
Flash Memory	32 KB (ATmega328) of which 0.5 KB used by bootloader
SRAM	2 KB (ATmega328)
EEPROM	1 KB (ATmega328)
Clock Speed	16 MHz
Length	68.6 mm
Width	53.4 mm
Weight	25 g

DFrobobt Bluetooth V3

Figure A 3: Dfrobot bluetooth module

DF-BluetoothV3 Bluetooth module uses a unique double-board design, it is beautiful and aim to prevent electrostatic damage to the module. It is designed to have 2 DC power input, wide voltage supply (3.5V ~ 8V) and 3.3V power supply, suitable for various applications. STATE LINK is indicated by a clear and bright LED which is used to display module status and connection status (STATE state: Search state (high 104ms 342ms 2.9Hz cycle flicker) connection status (high 104ms period 2s 0.5Hz flashing), LINK state: paired). It has build-in on-board antenna which provides high quality signals. DIP switch is designed to set the module status, LED Off to turn off the LINK light to enter power saving mode, AT Mode allows the module to enter AT command mode, AT commands can modify the baud rate and the master and slave mode. This module can also be used as a pair which provides a transparent serial data communication. This module has been tested and compatible with most Bluetooth adapter in the market (Bluetooth dongle, including laptops and mobile phones). This module has been tested and compatible with Android Phones.

- The Bluetooth chip: CSR BC417143
- Bluetooth protocol: Bluetooth Specification v2.0 + EDR
- USB Protocol: USB v1.1/2.0
- Operating frequency: 2.4 ~ 2.48GHz unlicensed ISM band
- Modulation: GFSK (Gaussian Frequency Shift Keying)
- Transmit Power: ≤ 4dBm, Class 2
- Transmission distance: 20 ~ 30m in free space
- Sensitivity: ≤-84dBm at 0.1% BER
- Transfer rate: Asynchronous: 2.1Mbps (Max) / 160 kbps; Synchronous: 1Mbps/1Mbps
- Safety features: Authentication and encryption
- Support profiles: Bluetooth serial port
- Serial port baud rate: 4800 ~ 1382400 / N / 8 / 1 default: 9600
- LED indicator: STATE state: Search state (high 104ms 342ms 2.9Hz cycle flicker) connection status (high 104ms cycle 2s 0.5Hz flashing), LINK Status: Always after match
- Input Voltage: +3.5 V ~ +8 V DC and 3.3V DC/50mA
- Working temperature: -20 ℃ ~ +55 ℃
- Module Size: 40 × 20 × 13mm

Futaba Micro Servo

Futaba S3114 - Micro High-Torque Servo

Basic Information

Modulation:	Analog
Torque:	**4.8V:** 21.0 oz-in (1.51 kg-cm) **6.0V:** 24.0 oz-in (1.73 kg-cm)
Speed:	**4.8V:** 0.10 sec/60° **6.0V:** 0.09 sec/60°
Weight:	0.28 oz (7.8 g)
Dimensions:	Length: 0.87 in (22.1 mm) Width: 0.43 in (10.9 mm) Height: 0.79 in (20.1 mm)
Motor Type:	3-pole
Gear Type:	Plastic
Rotation/Support:	Bushing

Brand:	Futaba
Product Number:	FUTM0414
Suggested Retail:	? (add)
Street Price:	29.99 USD
Compare:	add

Special Notes

- Manufacturer Notice: "Using any voltage higher than 6.0 volts or applying high load to the servo will shorten its life."
- Manufacturer Notice: "Always use the servo horn specially designed for this servo. Do not use conventional servo horns."
- Manufacturer Notice: "Excessive force or shock to the servo horn may damage the ultra mini precision gears inside the servo."
- Futaba S3114M is the same servo, but with a micro connector.

User Reviews

Number of Reviews:	5
Average Rating:	5.0 / 5.0

Additional Specifications

Rotational Range:	? (add)
Pulse Cycle:	? (add)
Pulse Width:	? (add)
Connector Type:	Universal

Figure A 4: Futaba micro servo spec from the internet

Du-Bro Micro ball link

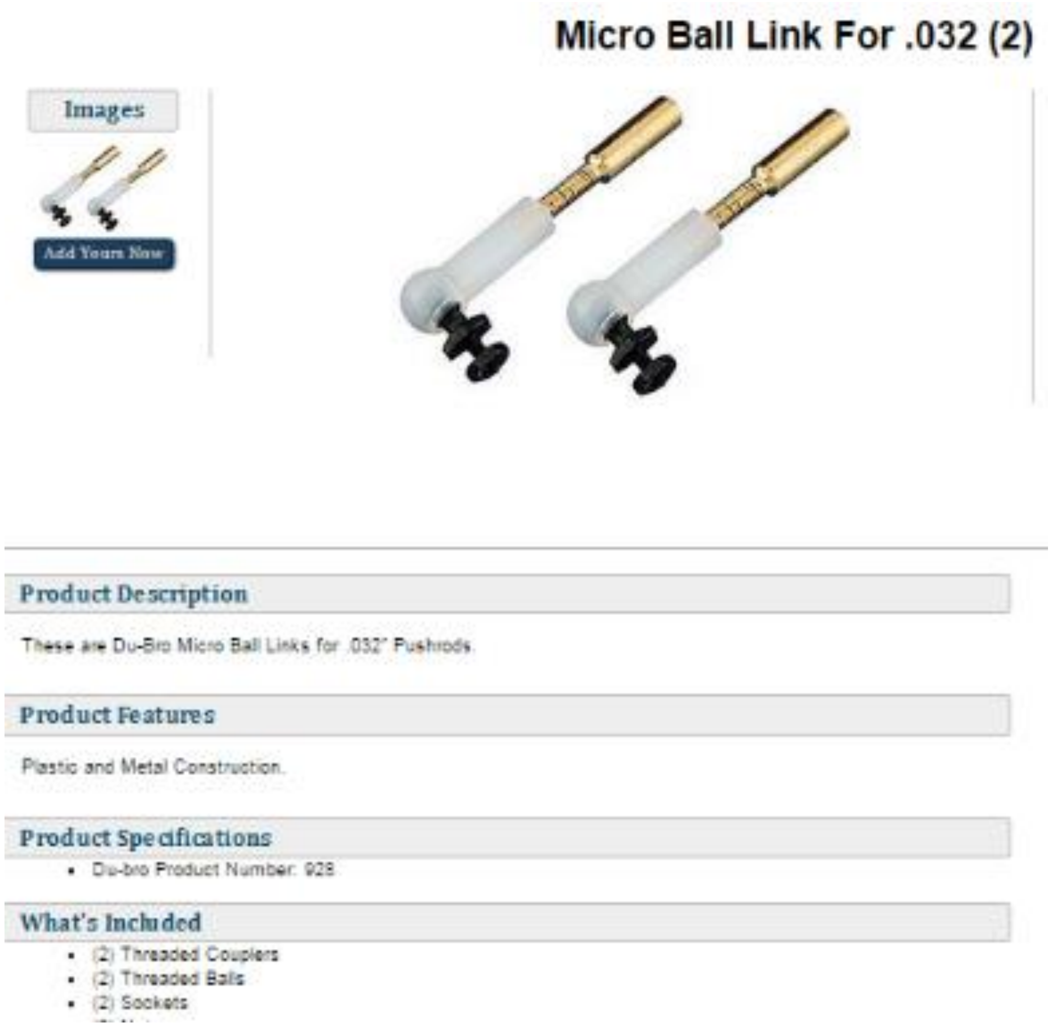

Figure A 5: Ball link spec from the internet

Appendix 2

This appendix contains drawings produced of the designed hand.

Drawings

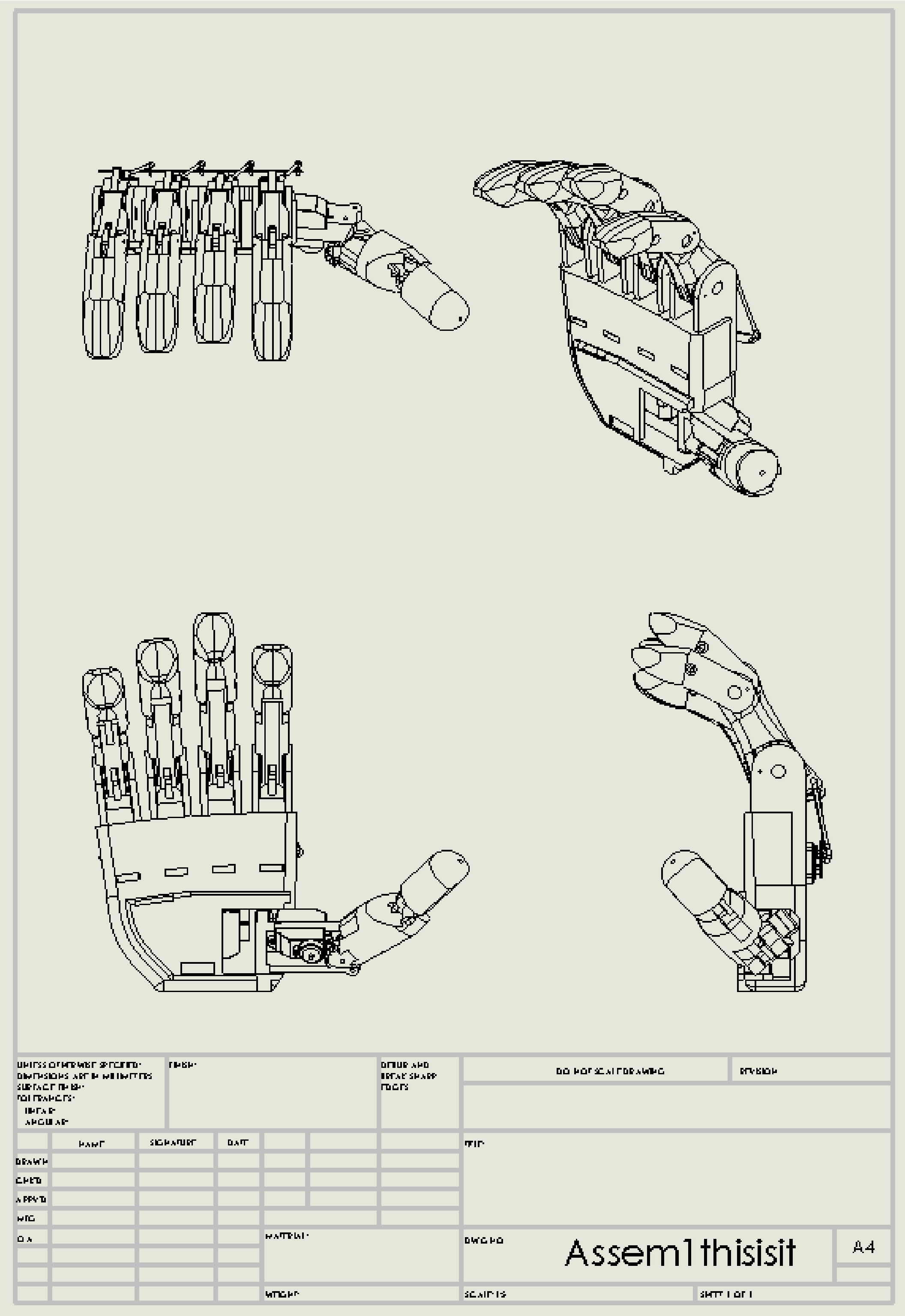

Figure A 6: Whole hand drawings

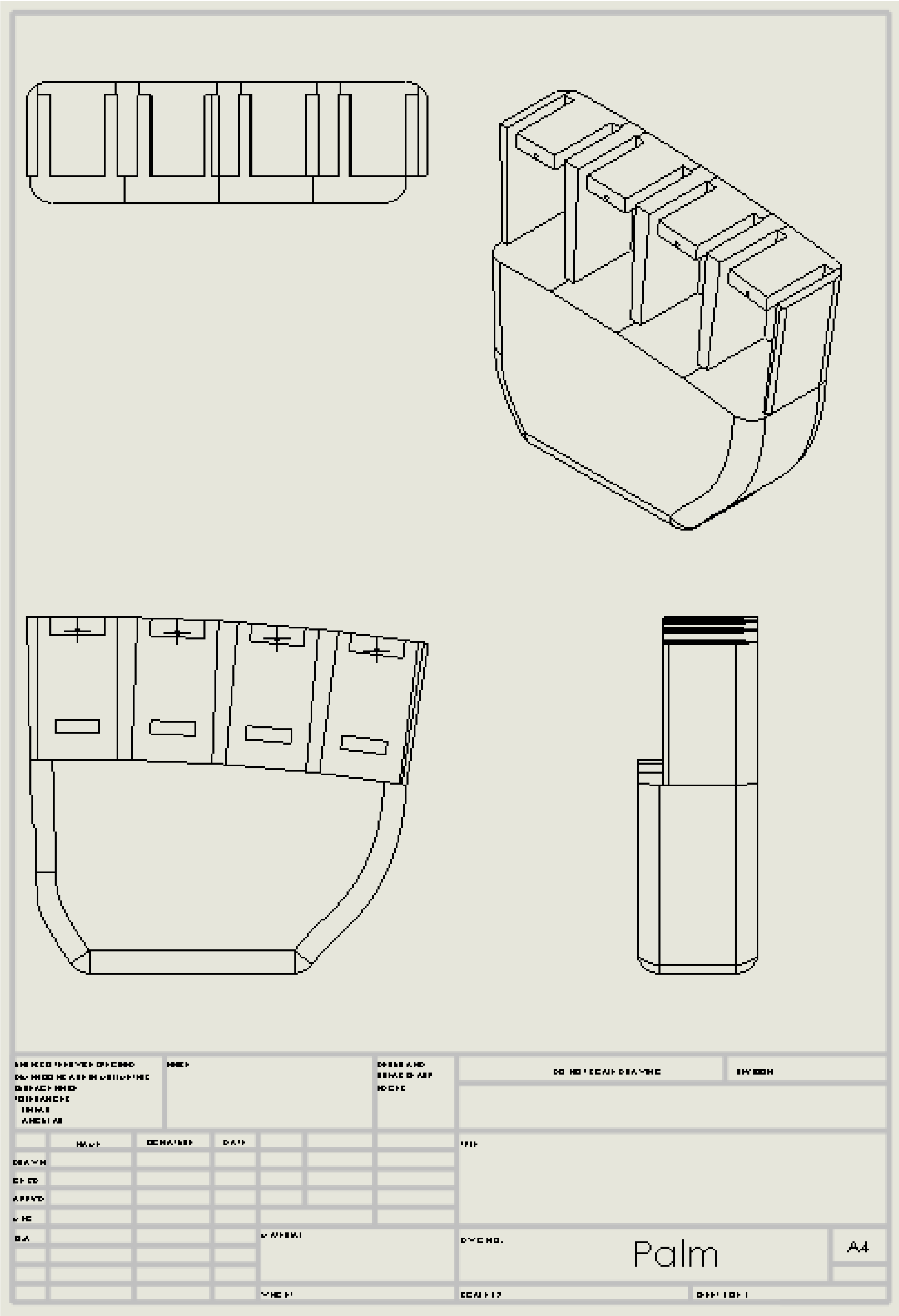

Figure A 7 palm drawings

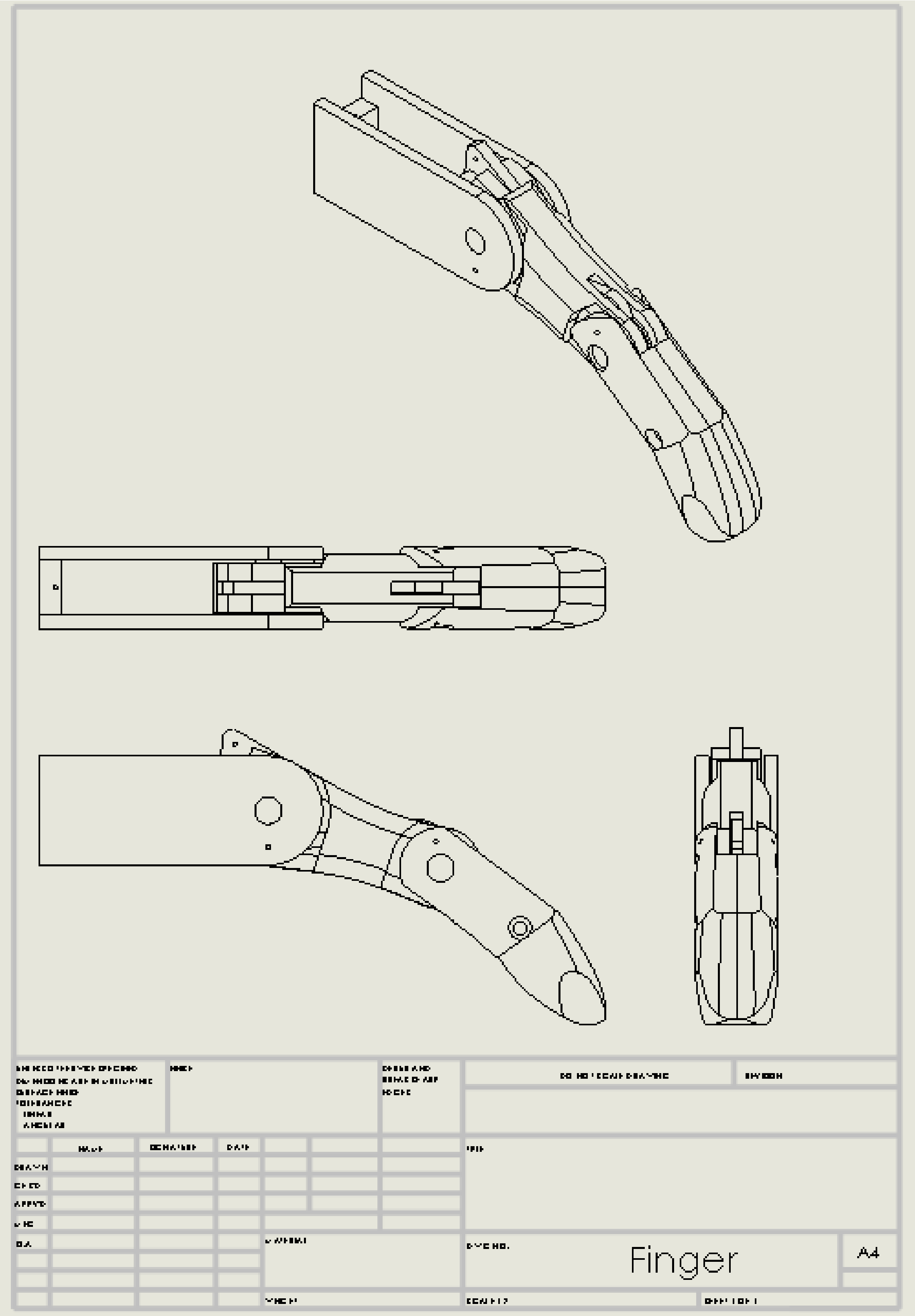

Figure A 8 index finger drawings

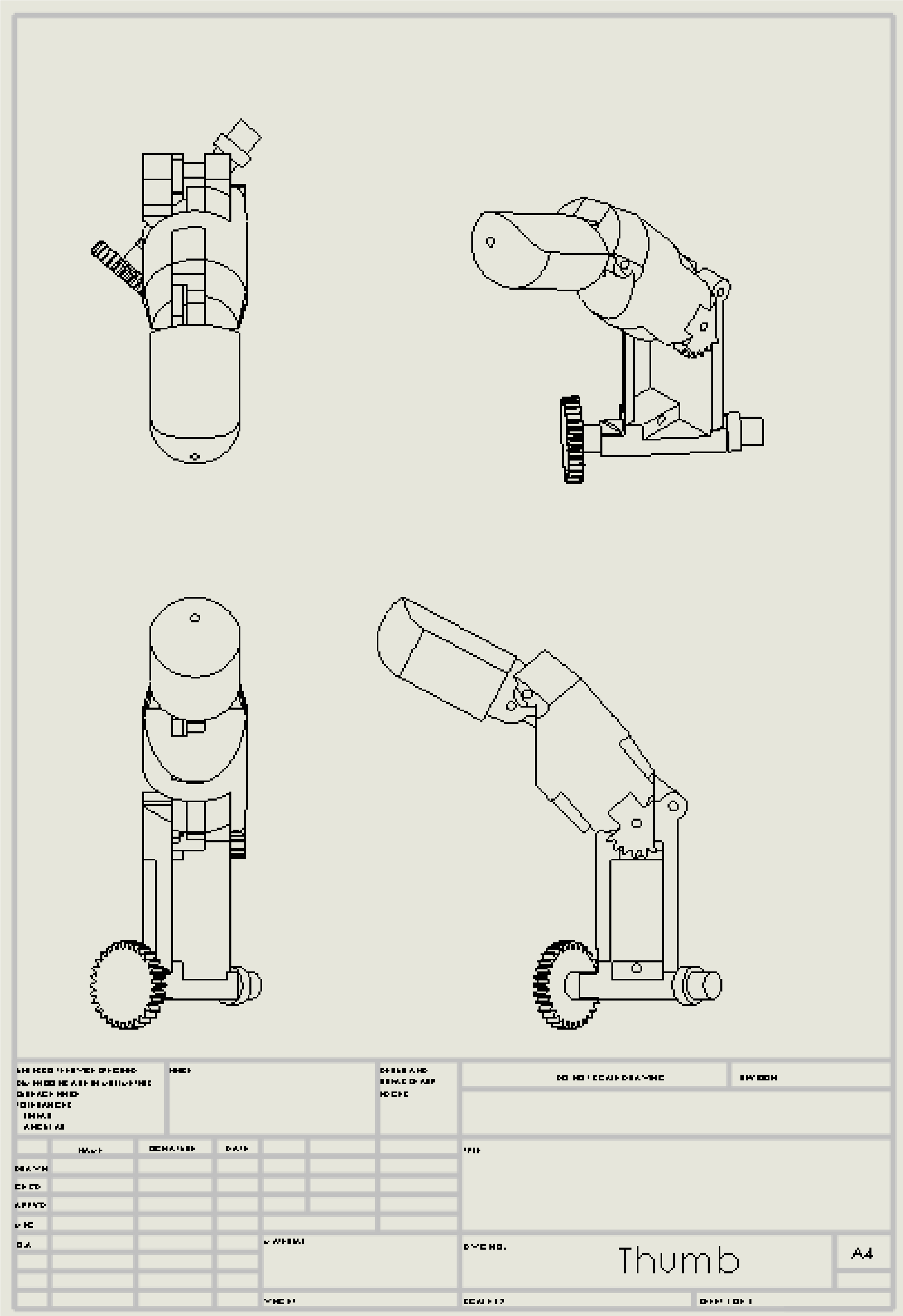

Figure A 9 thumb drawings

Appendix 3

This appendix describes a brief history of robotics and evaluates fourteen current electro mechanical hands.

Milestones in the History of Robotics

The following table lists the milestones that led to our current state of robot technology.

- 1947 — the first servo electric powered teleoperator is developed
- 1948 — a teleoperator is developed incorporating force feedback
- 1949 — research on numerically controlled milling machine is initiated
- 1954 — George Devol designs the first programmable robot
- 1956 — Joseph Engelberger, a Columbia University physics student, buys the rights to
- Devol's robot and founds the Unimation Company
- 1961 — the first Unimate robot is installed in a Trenton, New Jersey plant of General
- Motors to tend a die casting machine
- 1961 — the first robot incorporating force feedback is developed
- 1963 — the first robot vision system is developed
- 1971 — the Stanford Arm is developed at Stanford University
- 1973 — the first robot programming language (WAVE) is developed at Stanford
- 1974 — Cincinnati Milacron introduced the T3 robot with computer control
- 1975 — Unimation Inc. registers its first financial profit
- 1976 — the Remote Center Compliance (RCC) device for part insertion in assembly is

- developed at Draper Labs in Boston
- 1976 — Robot arms are used on the Viking I and II space probes and land on Mars
- 1978 — Unimation introduces the PUMA robot, based on designs from a General Motors
- study
- 1979 — the SCARA robot design is introduced in Japan
- 1981 — the first direct-drive robot is developed at Carnegie-Mellon University
- 1982 — Fanuc of Japan and General Motors form GM Fanuc to market robots in North
- America
- 1983 — Adept Technology is founded and successfully markets the direct drive robot
- 1986 — the underwater robot, Jason, of the Woods Hole Oceanographic Institute, explores
- the wreck of the Titanic, found a year earlier by Dr. Robert Barnard.
- 1988 — St¨aubli Group purchases Unimation from Westinghouse
- 1988 — the IEEE Robotics and Automation Society is formed
- 1993 — the experimental robot, ROTEX, of the German Aerospace Agency (DLR) was
- flown aboard the space shuttle Columbia and performed a variety of tasks under both
- teleoperated and sensor-based offline programmed modes
- 1996 — Honda unveils its Humanoid robot; a project begun in secret in 1986
- 1997 — the first robot soccer competition, RoboCup-97, is held in Nagoya, Japan and
- draws 40 teams from around the world
- 1997 — the Sojourner mobile robot travels to Mars aboard NASA's Mars PathFinder
- mission
- 2001 — Sony begins to mass produce the first household robot, a robot dog named Aibo

- 2001 — the Space Station Remote Manipulation System (SSRMS) is launched in space
- on board the space shuttle Endeavor to facilitate continued construction of the space
- station
- 2001 — robots are used to search for victims at the World Trade Center site after the
- September 11th tragedy
- 2002 — Honda's Humanoid Robot ASIMO rings the opening bell at the New York Stock
- Exchange on February 15th

History of robotics from [26].

Current electro mechanical hands

I-Limb

Figure A 10: The i-Limb prosthetic hand.[71].

The I-Limb is a myoelectrically driven prosthetic developed by Touch Emas Ltd. It has 4 independently driven fingers with an independently driven opposable thumb. The fingers consist of three separate phalanges. The fingers are mechanically connected via linkages and are moved as the knuckle joint rotates. One motor is responsible for the movement of a whole finger. The thumb is also controlled by a motor and is free to rotate ensuring that the fingers and thumb can meet. Control of the hand is accomplished by microprocessors evaluating feedback. Grip strength is detected as the motor encounters resistance, when the motor stops the hand is locked until an open signal is received. The hand is pre-programmed to perform the following grips: Key grip, power grasp, precision grip and index point.[45].

The Bebionic 3

Figure A 11: The Bebionic 3 prosthetic hand. [8]

The Bebionic 3 is a five fingered DC motor driven anthropomorphic hand with 14 selectable grip patterns. The hand has an individually actuated opposable thumb that can be manually changed into two positions: opposed and non-opposed. Each finger is controlled by one motor. The control of the hand is achieved by powerful microprocessors and proportional speed control. The hand features an auto grip that automatically senses when a gripped object is slipping and adjusts the grip force accordingly. The hand is capable of the following opposed and non-opposed grips: Tripod, pinch, power, key, column, mouse, precision open, precision closed, hook and finger adduction. [8].

The Dextrous hand

The Dextrous hand developed by Joel Gibbard is a five fingered robotic hand built for research, robot builders and amputees. The hand is 3D printed out of a durable plastic compound in order to keep costs down. The Dextrous has four fingers and an opposable thumb. Each finger is actuated by an individual DC motor. Motor feedback is used to control the grasping force of the hand. The hand is currently being developed and improved.[72]

Figure A 12: The 3D printed dextrous hand [73]

Nasa’s Robonaut Hand 2

Figure A 13: Nasa's Robonaut hand 2. [47]

The Robonaut hand 2 is a five fingered completely self-contained unit. Each finger has four joints three of which have independent movement supplied by individual actuators. The hand has twelve DoF. Finger actuation is key to the Robonauts life-like size. Each motor actuator provides 35mm of linear travel and supplies a pulling force of 23 kg. The purpose of the hand is to complete a wide range of dextrous, subtle and powerful tasks.[47]

The Shadow Hand

Figure A 14: The shadow hand in comparison to a human hand. [74]

The shadow hand claims to have twenty degrees of freedom using a unique actuator called "air muscle". The actuator is pneumatically driven and controlled by two valves. One valve acts as an inlet while the other as an outlet. The amount of pressure at the inlet controls the desired contraction of the actuator. The hand consists of four fingers and a thumb. The shadow hand is unique in that it allows flexion in the palm of the hand to increase the movement of the little finger and to increase the grasping capabilities of the whole hand.[46].

Utah/MIT Hand

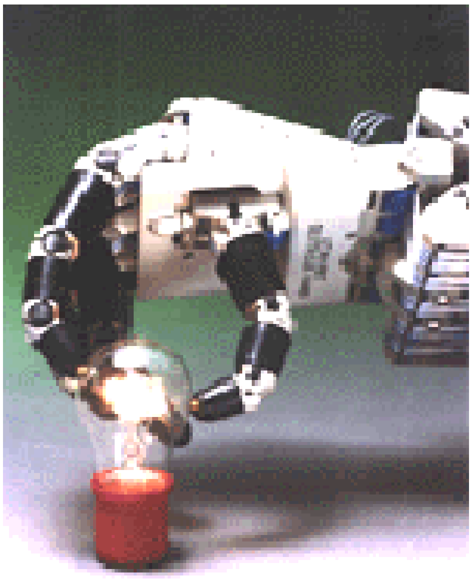

Figure A 15:The Utah/MIT hand.[75]

The Utah/MIT hand was designed for research purposes with the intention of increasing understanding of the issues related to machine based artificial dexterity. The hand has three fingers with four degrees of freedom. The thumb has four degrees of freedom. The entire hand is tendon operated and therefore finger actuation systems are not self-contained within the hand. There 38 pneumatically driven actuators providing up to 300 N of force. [75]

Hitachi Hand

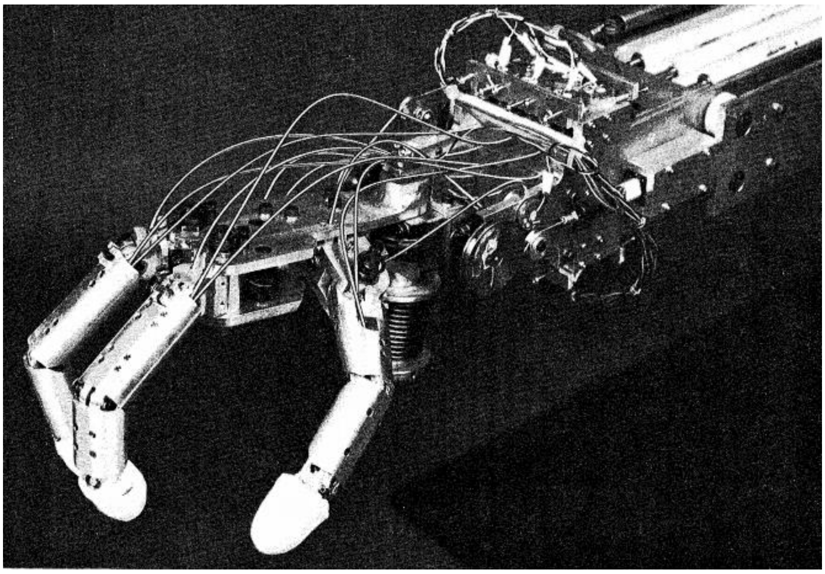

Figure A 16: The shape memory alloy driven hand called Hitachi's hand.[38]

Hitachi's robot hand is a shape memory alloy driven prosthetic developed by Hitachi, Ltd. It has three fingers which represent the middle finger, index finger and thumb. The fingers and thumb consist of three separate phalanges and four joints. Joint angle is controlled by varying the current passing through the wire. The fingers are driven by twelve actuators which allocates four actuators to each finger. The development of this hand was spurred on a rise in the demand of advanced automation of various operations. [38]

Rutgers Hand

The Rutgers hand is a shape memory alloy driven prosthetic developed by the university of New Jersey in the United States. It has five fingers and twenty degrees of freedom. The fingers consist of three separate phalanges. The joints are actuated by a set of cables routed within the structure of the finger. The cables are pulled in tension by a mechanism utilising shape memory alloys (SMA) and returns to the starting position via a spring force. [44]

Belgrade/USC Hand

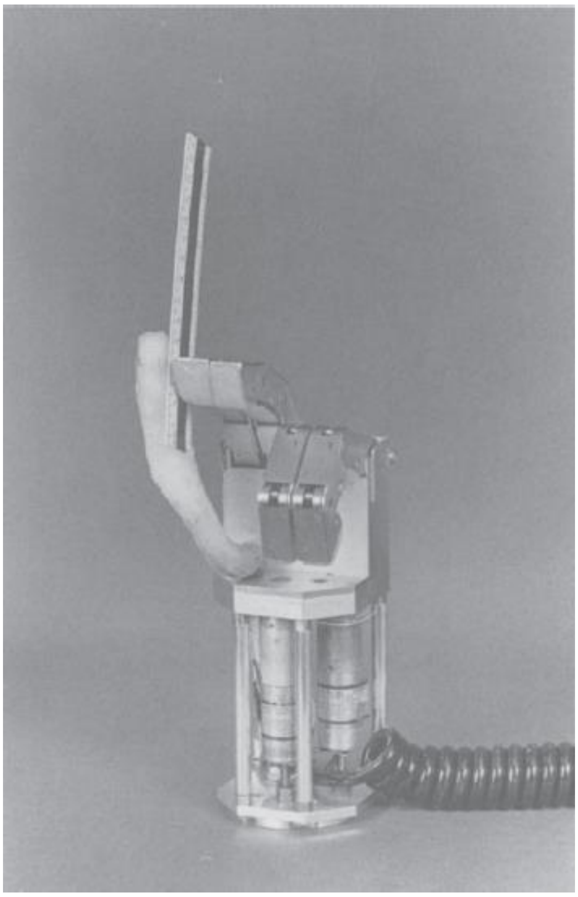

Figure A 17: The Belgrade/USC hand. [40]

The Belgrade/USC "hand is an anthropomorphic end effector for robot manipulators". The first model of this hand consisted of four articulated fingers and one rigid thumb. Model two of the hand was improved by re-dimensioning the hand to fit within the space of a human natural hand and giving the thumb two joints. The hand is controlled by four DC servo motors. Two motors control the thumb and the remaining two control two fingers each. Each finger consists of three phalanges that are connected by mechanical linkages. The hand has four degrees of freedom. Force sensing is used to grasp objects, this type of grasping is called “reflex grasping”. Once a finger senses an object the other fingers will continue to move in their respective positions until the force pads are equal in opposing force. When this point is reached the hand stops operating until an open signal is received. [40].

Stanford/JPL Hand

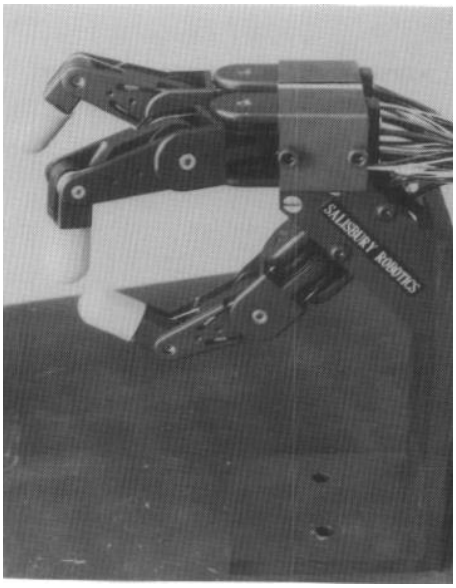

Figure A 18: The Stanford JPL hand. [41]

The Stanford/JPL hand designed by Dr. J. Kenneth Salisbury Jr. has three identical fingers consisting of three phalanges each. The fingers are positioned as two fingers with an opposing thumb. The hand uses forward kinematics to determine the position of the end effector in order to grip different objects. The hand is driven by DC motor and use cable tension sensors to evaluate the gripping force exerted on objects.[41]

NTU Hand

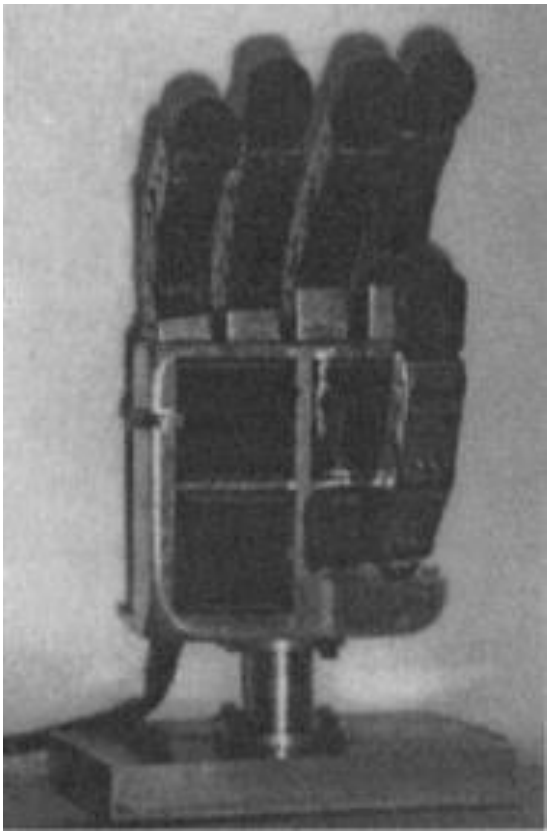

Figure A 19: The NTU hand. [42]

The NTU hand is a five fingered robot hand with seventeen degrees of freedom. The hand, developed by the National Taiwan University is almost completely self-contained and has an uncoupled configuration which means all joints are individually actuated. Each finger contains four segments namely: the distal segment, the middle segment, the proximal segment and the base finger segment. Each finger segment contains a high performance micro-motor that drives the gears responsible for moving each segment. Sensors are attached to each segment.[42]

DLR 2 Hand

Figure A 20: DLR 1 hand. The model preceding the DLR 2 hand. [43]

The DLR 2 hand is a device that was developed because of the lack in design of a previous model (DLR 1) developed in 1997. The DLR 1 hand was one of the first robotic hands with completely integrated actuators and electronics. DLR 1 has been in use for several years and has been a useful tool in the research and development of grasping, holding and manipulating objects. Each finger of the DLR 2 has three independent joints driven by brushless DC motors. The base of the finger has two degrees of freedom which is realised through a set of bevel gears. [43]

8E500 Michelangelo Hand

Figure A 21: The Michelangelo Prosthetic hand. [49]

The Michelangelo hand developed by Otto Bock is a fully articulated robotic hand prosthesis. It features an electronically driven thumb that moves into position and four individually actuated fingers. The hand has multiple grip functions and offers strength, speed and a natural anthropomorphic look. The hand uses electromyography (EMG) signal processing as a tool to control the hand. The hand has six joints and two degrees of freedom. Each degree of freedom is driven by an actuator. [49]

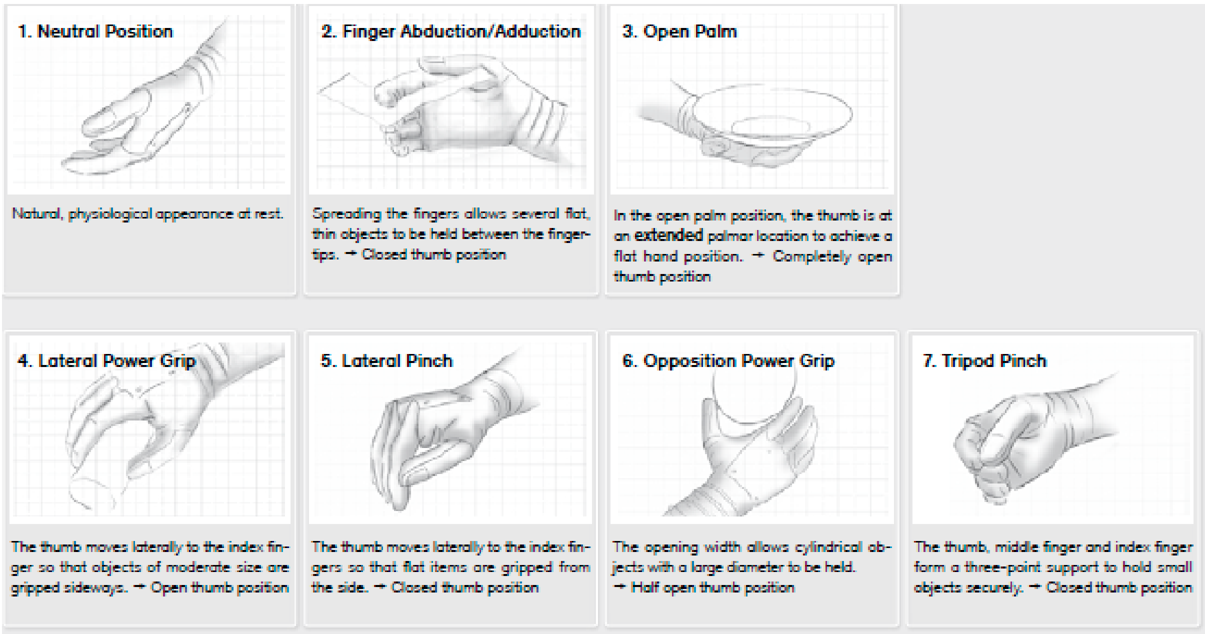

Figure A 22: Grips and grasps that can be accomplished by the Michelangelo hand. [49]

IH2 Azzurra Hand

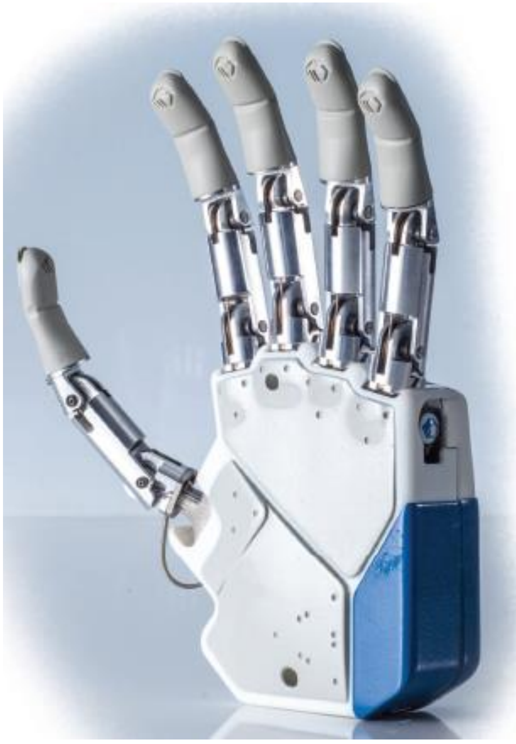

Figure A 23: The IH2 Azzurrra Prosthetic hand. [37]

The IH2 Azzurra hand is a self-contained, human-sized programmable anthropomorphic hand. Actuation of the hand is achieved by the use of brushed DC motors driving steel tendons with a 180 N max force. The hand has five fingers consisting of four fingers and an opposable thumb. The hand has eleven degrees of freedom. The thumb, index and middle fingers are independently driven. The thumb has flexion, extension, abduction and adduction while the index, middle and connected ring and little fingers are able to flex and extend only. The fingers are under actuated and self-adapting with a manually controlled stiffness. The IH2 is programmed to grasp a wide range of objects. [37]

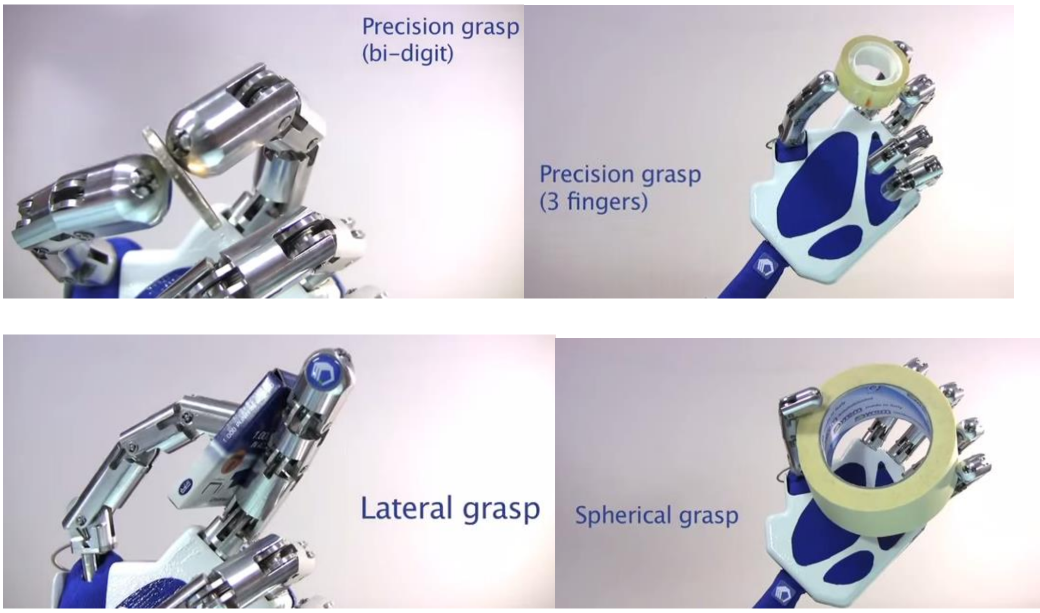

Figure A 24: Available grips that can be executed by the IH2 Azzurra hand. [37]

Appendix 4

This appendix contains the computer code used to perform a pinch grip on the designed hand. The code used to control the force sensors have not been included.

Programming

Below is an example of the pinch grip code to be uploaded to the Arduino uno. The other 4 grips can be found by emailing. Coding written by Aaron Matenga

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```
#include <Servo.h>
#define BAUDRATE 57600
#define DEBUGOUTPUT 0
#define powercontrol 10

// servo motors
Servo index;
Servo middle;
Servo ring;
Servo little;
Servo palm;
Servo thumb;

// checksum variables
byte generatedChecksum = 0;
byte checksum = 0;
int payloadLength = 0;
```

```
byte payloadData[64] = [30];
byte poorQuality = 0;
byte attention = 0;
byte meditation = 0;

// system variables
long lastReceivedPacket = 0;
boolean bigPacket = false;

//////////////////////////
// Microprocessor Setup //
//////////////////////////
void setup() {
  Serial.begin(BAUDRATE);           // USB

            index.attach(13);
  middle.attach(12);
  ring.attach(11);
  little.attach(10);
  palm.attach(9);
  thumb.attach(7);
}

////////////////////////////////
// Read data from Serial UART //
////////////////////////////////
byte ReadOneByte() {
  int ByteRead;

  while(!Serial.available());
```

```
  ByteRead = Serial.read();


#if DEBUGOUTPUT
  Serial.print((char)ByteRead);   // echo the same byte out the USB serial (for debug
purposes)
#endif


  return ByteRead;
}


/////////////
//MAIN LOOP//
/////////////
void loop() {



  // Look for sync bytes
  if(ReadOneByte() == 170) {
    if(ReadOneByte() == 170) {


      payloadLength = ReadOneByte();
      if(payloadLength > 169)                      //Payload length can not be greater than
169
          return;


      generatedChecksum = 0;
      for(int i = 0; i < payloadLength; i++) {
        payloadData[i] = ReadOneByte();            //Read payload into memory
        generatedChecksum += payloadData[i];
      }
```

```
    checksum = ReadOneByte();                    //Read checksum byte from stream
    generatedChecksum = 255 - generatedChecksum;   //Take one's compliment of generated checksum

     if(checksum == generatedChecksum) {

     poorQuality = 200;
     attention = 0;
     meditation = 0;

     for(int i = 0; i < payloadLength; i++) {    // Parse the payload
       switch (payloadData[i]) {
       case 2:
         i++;
         poorQuality = payloadData[i];
         bigPacket = true;
         break;
       case 4:
         i++;
         attention = payloadData[i];
         break;
       case 5:
         i++;
         meditation = payloadData[i];
         break;
       case 0x80:
         i = i + 3;
         break;
       case 0x83:
         i = i + 25;
```

```
          break;
        default:
          break;
        } // switch
      } // for loop

#if !DEBUGOUTPUT

      if(bigPacket) {
                                        if (attention >= 80) {
                                              Serial.print("Over 80; ");
                                              index.write(10);
                                        }
                                        else {
                                              Serial.print("Under 80; ");
                                              pinchOpen();
                                        }
        Serial.print("PoorQuality: ");
        Serial.print(poorQuality, DEC);
        Serial.print(" Attention: ");
        Serial.print(attention, DEC);
        Serial.print(" Time since last packet: ");
        Serial.print(millis() - lastReceivedPacket, DEC);
        lastReceivedPacket = millis();
        Serial.print("\n");
      }
#endif
      bigPacket = false;
    }
    else {
```

```
        // Checksum Error
      }  // end if else for checksum
    } // end if read 0xAA byte
  } // end if read 0xAA byte
}

// set the hand to prepare to pinch with the index finger and thumb
void pinchOpen() {
  index.write(170);
  middle.write(10);
  ring.write(10);
  little.write(10);
  palm.write(90);
  thumb.write(90);
}
```

(Coding provided by Aaron Matenga)

Appendix 5

This appendix contains the theory used to calculate the velocity kinematics of the hand.

Jacobian calculations

The Jacobian manipulator also called the Jacobian is used to relate the linear and angular velocities of the end effector of a robot manipulator to the joint velocities of the said manipulator. The forward kinematics describe a function between the space of Cartesian positions and orientations with the space of joint positions [26]. The Jacobian of this function then determines the velocity relationship between joints, positions and orientations. The Jacobian is represented by the letter J and is a matrix valued function.

The following mathematical description of the Jacobian focusses on the basic evaluation of the function and can be found here [76]. A comprehensive detailing of the processes involved in this method can be found in. [26]

Suppose there is m equations for end effectors and each has an $n$amontm of degrees of freedom. We can write.

$$\begin{matrix} x_1 \\ \vdots \\ x_m \end{matrix} = \begin{matrix} x_1(\alpha_{1,\dots,}\alpha_n) \\ \vdots \\ x_1(\alpha_{1,\dots,}\alpha_n) \end{matrix}$$

Deriving the above equation yields.

$$\begin{matrix} \frac{dx_1}{dt} \\ \vdots \\ \frac{dx_m}{dt} \end{matrix} = \begin{matrix} \frac{\delta x_1}{d\alpha_1}\frac{d\alpha_1}{dt} + \cdots + \frac{\delta x_1}{\delta\alpha_n}\frac{d\alpha_n}{dt} \\ \vdots \\ \frac{\delta x_m}{\delta\alpha_1}\frac{d\alpha_1}{dt} + \cdots + \frac{\delta x_m}{\delta\alpha_n}\frac{d\alpha_n}{dt} \end{matrix}$$

Re-writing in vector form gives.

$$v = J\frac{da}{dt}$$

The Jacobian is now seen as the partial derivatives of the kinematic equations. The relationship between end effector velocity and the joint velocity is fully described by the Jacobian. The end-effector velocity is a linear function of the joint velocities.

$$J = \begin{bmatrix} \frac{\delta x_1}{d\alpha_1} & \cdots & \frac{\delta x_1}{\delta \alpha_n} \\ \vdots & \ddots & \vdots \\ \frac{\delta x_m}{\delta \alpha_1} & \cdots & \frac{\delta x_m}{\delta \alpha_n} \end{bmatrix}$$

Example: Two link planar manipulator

Taking the example of the two link planar manipulator

$$x = x_2 = l_1\, cos \propto_1 + l_2\, cos(\propto_1 + \propto_2)$$

$$y = y_2 = l_1\, sin \propto_1 + l_2 \sin(\propto_1 + \propto_2)$$

Here the Jacobian is.

$$J = \begin{bmatrix} -l_1\, sin \propto_1 - l_2\, sin(\propto_1 + \propto_2) & -l_2\, sin(\propto_1 + \propto_2) \\ l_1\, cos \propto_1 + l_2 \cos(\propto_1 + \propto_2) & l_2 \cos(\propto_1 + \propto_2) \end{bmatrix}$$

Calculating end effector velocity using

$$v = J \frac{da}{dt}$$

Yields the following.

$$\frac{dx}{dt} = [-l_1 \sin(\alpha_1) - l_2 \sin(\alpha_1 + \alpha_2)] \frac{d\alpha_1}{dt} - l_2 \sin(\alpha_1 + \alpha_2) \frac{d\alpha_2}{dt}$$

$$\frac{dy}{dt} = [l_1 \cos(\alpha_1) + l_2 \cos(\alpha_1 + \alpha_2)] \frac{d\alpha_1}{dt} + l_2 \cos(\alpha_1 + \alpha_2) \frac{d\alpha_2}{dt}$$

Link 1	Link 2	Theta 1	Theta 2	rad 1	rad 2	Y	X	Jacobian	J11	J12	J21	J22	w1	w2	X velocity	Y velocity	W
44	50	90	90	1.570796	1.570796	-50	44		-44	-6.1257E-15	-50	-50	6.16	6.16	-616	-271.04	12.32
44	50	89	89	1.553343	1.553343	-49.2016	45.73827		-45.7383	-1.74497484	-49.2016355	-49.96954135	6.16	6.16	-610.894	-292.497	12.32
44	50	88	88	1.53589	1.53589	-48.3426	47.46102		-47.461	-3.48782369	-48.3426247	-49.87820251	6.16	6.16	-605.04	-313.845	12.32
44	50	87	87	1.518436	1.518436	-47.4233	49.16612		-49.1661	-5.22642316	-47.4233127	-49.72609477	6.16	6.16	-598.44	-335.058	12.32
44	50	86	86	1.500983	1.500983	-46.4441	50.85147		-50.8515	-6.95865505	-46.4441186	-49.51340344	6.16	6.16	-591.098	-356.11	12.32
44	50	85	85	1.48353	1.48353	-45.4055	52.51498		-52.515	-8.68240888	-45.405535	-49.24038765	6.16	6.16	-583.019	-376.976	12.32
44	50	84	84	1.466077	1.466077	-44.3081	54.15455		-54.1545	-10.3955845	-44.3081277	-48.90738004	6.16	6.16	-574.208	-397.629	12.32
44	50	83	83	1.448623	1.448623	-43.1525	55.76813		-55.7681	-12.0960948	-43.1525352	-48.51478631	6.16	6.16	-564.671	-418.044	12.32
44	50	82	82	1.43117	1.43117	-41.9395	57.35366		-57.3537	-13.7818678	-41.9394684	-48.0630848	6.16	6.16	-554.416	-438.195	12.32
44	50	81	81	1.413717	1.413717	-40.6697	58.90914		-58.9091	-15.4508497	-40.6697094	-47.55282581	6.16	6.16	-543.451	-458.058	12.32
44	50	80	80	1.396263	1.396263	-39.3441	60.43255		-60.4325	-17.1010072	-39.3441112	-46.98463104	6.16	6.16	-531.785	-477.607	12.32
44	50	79	79	1.37881	1.37881	-37.9636	61.92193		-61.9219	-18.7303297	-37.9635969	-46.35919273	6.16	6.16	-519.428	-496.818	12.32
44	50	78	78	1.361357	1.361357	-36.5292	63.37533		-63.3753	-20.3368322	-36.5291585	-45.67727288	6.16	6.16	-506.392	-515.667	12.32
44	50	77	77	1.343904	1.343904	-35.0419	64.79084		-64.7908	-21.9185573	-35.0418559	-44.93970231	6.16	6.16	-492.686	-534.13	12.32
44	50	76	76	1.32645	1.32645	-33.5028	66.16659		-66.1666	-23.4735781	-33.5028162	-44.14737964	6.16	6.16	-478.325	-552.183	12.32
44	50	75	75	1.308997	1.308997	-31.9132	67.50074		-67.5007	-25	-31.9132322	-43.30127019	6.16	6.16	-463.321	-569.805	12.32
44	50	74	74	1.291544	1.291544	-30.2744	68.79148		-68.7915	-26.4959632	-30.2743612	-42.40240481	6.16	6.16	-447.689	-586.971	12.32
44	50	73	73	1.27409	1.27409	-28.5875	70.03705		-70.0371	-27.9596452	-28.5875236	-41.45187863	6.16	6.16	-431.443	-603.66	12.32
44	50	72	72	1.256637	1.256637	-26.8541	71.23575		-71.2357	-29.3892626	-26.854102	-40.45084972	6.16	6.16	-414.599	-619.85	12.32
44	50	71	71	1.239184	1.239184	-25.0755	72.38589		-72.3859	-30.7830738	-25.0755389	-39.40053768	6.16	6.16	-397.173	-635.521	12.32
44	50	70	70	1.22173	1.22173	-23.2533	73.48586		-73.4859	-32.1393805	-23.2533358	-38.30222216	6.16	6.16	-379.182	-650.651	12.32
44	50	69	69	1.204277	1.204277	-21.3891	74.53407		-74.5341	-33.4565303	-21.3890515	-37.15724127	6.16	6.16	-360.645	-665.222	12.32
44	50	68	68	1.186824	1.186824	-19.4843	75.52901		-75.529	-34.7329185	-19.4842999	-35.96699002	6.16	6.16	-341.58	-679.213	12.32
44	50	67	67	1.169371	1.169371	-17.5407	76.4692		-76.4692	-35.96699	-17.5407489	-34.73291852	6.16	6.16	-322.006	-692.607	12.32
44	50	66	66	1.151917	1.151917	-15.5601	77.35324		-77.3532	-37.1572413	-15.560118	-33.45653032	6.16	6.16	-301.943	-705.385	12.32
44	50	65	65	1.134464	1.134464	-13.5442	78.17976		-78.1798	-38.3022222	-13.544177	-32.13938048	6.16	6.16	-281.411	-717.529	12.32
44	50	64	64	1.117011	1.117011	-11.4947	78.94748		-78.9475	-39.4005377	-11.4947433	-30.78307377	6.16	6.16	-260.431	-729.024	12.32

Figure A 25: Excel sheet of jacobian calculations