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Slippage Control for a Smart Prosthetic Hand Prototype via Modified Tactile Sensory Feedback

By

Girish Sriram

A thesis submitted in partial fulfillment of the

requirements for the degree of

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in

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To the Graduate Faculty:

The members of the committee appointed to examine the thesis of GIRISH SRIRAM find it satisfactory and recommend that it be accepted.

Dr. Steve Chiu, Major Advisor

Dr. Marco P. Schoen, Co-Advisor

Dr. Jim Creelman, Graduate Faculty Representative

Dedication

I dedicate this thesis to my father R.SRIRAM, my mother LATA SRIRAM and my sister PRIYA SRIRAM for their continuous support, help, encouragement, and motivation for the completion of this research work.

Acknowledgements

I would like to extend a special thanks to my major advisor, Dr. Steve Chiu, for his assistance and guidance in completing this thesis. My sincere thanks to him for having faith in me and inspiring confidence in me.

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I take this opportunity to record my gratitude towards my fellow classmates, teachers and friends who helped me during this work.

Last, but not the least, I wish to thank my family for their help and support while working on this research.

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Abstract

The human hand is one of the most complex structures of the human body, having the fingers that possess one of the highest numbers of nerve endings in the body. The hand thus has the capacity for the richest tactile feedback and excellent positioning capabilities. This rich tactile feedback that is present, also adds to the complexities when it comes to replicating the controls of a human hand using smart prosthetics. The existing hand control systems used in controlling smart prosthetics have many drawbacks because of these features in a human hand.

This thesis proposes a new technique of controlling slippage which is, one of the major drawbacks for a prosthetic hand. A Force Sensing Resistor (FSR®) is modified to be used as a slippage detection sensor. A fuzzy logic control algorithm with multiple rules is designed to be working alongside a traditional Electromyography (EMG) or Electroencephalography (EEG) based position control system.

A 5 Degrees of Freedom (DOF) hand, which has one micro servo motor as an actuator for each finger was used to test the slippage control strategy in real time. First a reference EMG signal was used for getting the 5 DOF hand to grasp an object, using position control. Then a slip was introduced to see the slippage control strategy at work to hold the grasp on the object. The results based on the plain tactile sensory feedback and the modified sensory feedback is discussed. Finally the advantages of this slippage control strategy are highlighted.

1 Introduction

1.1 Problem Statement

More than 2 million Americans live with a lost limb [1]. That number is slated to grow drastically each year. The main causes for amputations are mainly vascular diseases, trauma, cancer, diabetes and injuries. Many amputations which are caused due to injuries are mainly due to traffic accidents, injuries sustained during wars etc. With the wars in Afghanistan and Iraq coming to an end the number of soldiers with amputations will reduce drastically, but with the advent of diabetes and other debilitating diseases which cause cardio-vascular problems, which is the main cause of amputations, the number of amputees in The United States of America will increase by around 200,000 each year [1].

Research related to upper extremity prostheses over the recent past has been focusing on increasing the functionality of the prostheses coupled with reducing the psychological and emotional aftermath of dealing with limb loss. To regain mobility, increasingly capable prostheses are being developed to improve the quality of lives of those with loss of limbs, regardless of whether the loss of limbs results from war, accidents, diseases or birth defects.

With the advancement in technology the latest prosthetic hand comes with electrodes which are invasive in nature and require surgery to place the prosthetic hand in the human arm and replacement of it is difficult. With the advent of newer surface electromyography (sEMG) based prosthetic devices, [2] invasive and costly medical procedures for having the state of the art prosthetic hand is a thing of the past.

1.2 Slippage Control

According to the dictionary [3] slippage is defined as an act, instance or process of slipping. In the context of hand prostheses slippage can therefore be interpreted as an act of slipping, of an object which has been gripped. Slippage control is the act of holding/griping the object under slippage.

Generally arm movements are done involuntarily by humans as they grow up and learn. Slippage control in a human hand is done involuntarily by the muscles with feedback from the various skin receptors in the somatosensory system [4] in our bodies. Slippage control in the human hand is accomplished via the feedback from the glabrous skin receptors, which include mechanoreceptors, thermo receptors, chemo receptors and photoreceptors. These skin receptors along with the spinal cord and the brain make up the somatosensory system of the human body. Slippage control in humans involves mostly involuntary hand movements, but it can also be voluntary based on feedback from these receptors.

Tactile perception (touch) is considered one of the five primary senses of the human body. The other senses include sight, hearing, smell, and taste. Thus tactile sensing is the most important part for an effective slippage control system. Tactile sensing in humans starts with haptic perception [5] which is the recognition of objects through touch. Then the information is transferred to the brain through the spinal cord for analysis of the information.

1.3 Challenges for Slippage Control

A slippage control strategy or algorithm should mimic the tactile perception (sensing) of human beings. It is a fast process in human beings and is mostly involuntary. Thus an artificial slippage control should be capable of executing actions rapidly and involuntarily. The tactile sensing for the slippage control strategy should be robust, dynamic and should have characteristics of the human tactile sensing system. Most of the slippage control strategies that have been researched till now are mainly for end manipulators for industrial robots. These control strategies come as an individual product without taking into account the influence of EMG signals as required for hand prostheses for controlling position nor do they take other industrial parameters. Thus what we require is a slippage control structure which can accommodate the EMG based position control structure. Thus EMG position control and tactile sensing based slippage control must work together as complementing strategies, where EMG based position control system grasps the object and the slippage control system makes sure the object doesn't slip.

1.4 Thesis outline

This thesis highlights techniques to overcome the challenges mentioned above and proposes a strategy which involves EMG based position control, an independent slippage control working together complementing each other. The proposed design is robust, platform independent and cost effective. The proposed designed is tested and validated using real time embedded system consisting of a microcontroller and plant model (consisting of five degrees of freedom (DOF) prosthetic hand, tactile sensory, interfacing circuitry). The present chapter (Introduction) is followed by:-

- Chapter 2: Theory: It discusses the Biological background on slippage control in humans, It also discusses the theory of past slippage sensors and the theory of the Force sensing resistor.
- Chapter 3: Design: This chapter discusses the steps involved in the design of the slippage control system. It includes theoretical design process followed by Simulink® models for the entire system.
- Chapter 4: Experimental Setup: This chapter discusses the theory of the hardware used in the experiment and also enumerates the process of experimentation.
- Chapter 5: Results, Conclusion and Future work: This chapter discusses the results for the different experiments conducted in validating the working of the slippage controller and also explains the main advantages of the slippage control strategy in the conclusion. Future work intended to advance the work done in this research is also recommended.

2 Theory

The biological sensing of slippage in humans and the literature review including the principal, theory, construction and features of the artificial tactile sensors which have been used in this thesis project and in past research have been discussed in this chapter.

2.1 Slippage Sensing in the Hand

The human upper limb extends from the shoulder to the fingers including the elbow, arm, forearm and hand. The hand is the main part of the upper limb responsible for detecting and acting against slippage. It comprises of many mechanoreceptors and nerve endings and is one of the most sensitive parts of the human body. There are also lots of tendons in the hand region. Most of the muscles that operate on the hand are present in the forearm and connect to the hand via tendons. These muscle tissues act voluntarily or involuntarily depending on their types.

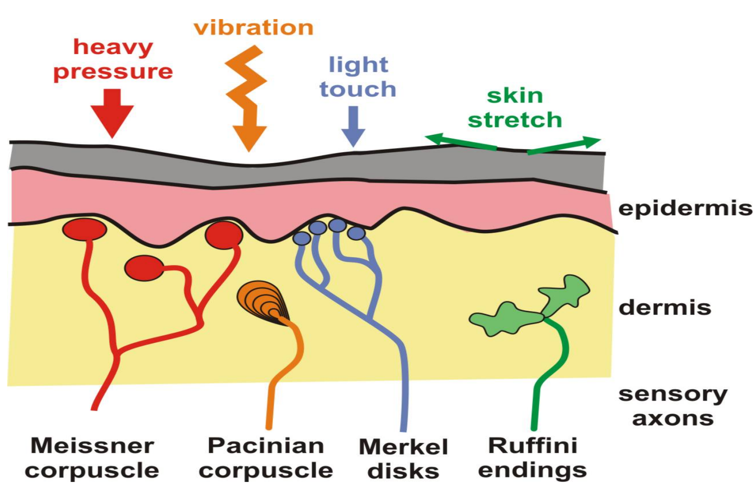

Figure 1: Mechanoreceptors in the Human Hand **[6]**

There are two types of touches that the human hand can detect: active and passive touch [7]. Both the touches evoke similar responses from the mechanoreceptors. They vary in the cognitive features that affect the sensation, position, actuation etc. of the hand. The passive touch sensation is mainly for getting information regarding the gesture, texture of an object, orientation of the object etc. while active touch sensation is used for grasping, controlling positions, hand manipulations etc. Some examples of an active touch sensation are shaking hands, drinking water from a bottle etc. Passive sensations are when a person finds out the texture of a grasped object, orientation of an object etc.

The glabrous skin in the hand is responsible for detecting and controlling object grasp and avoiding slippage. There are 4 main types of mechanoreceptors namely Pacinian corpuscles, Meissner's corpuscles, Merkel’s discs and Ruffini endings. These mechanoreceptors come under two classes of fibers namely slowly adapting fibers and rapidly adapting fibers. Figure 1 shows the various mechanoreceptors in the human hand. The slowly adapting fibers are the Merkel cells and Ruffini nerve endings. The Merkel cells are situated in the epidermis i.e. the superficial layer of the skin. The Ruffini nerve endings are located in the dermis layer which is deeper than the Merkel cells. These slowly adapting fibers detect object pressure and form. The Merkel cells which are slowly adapting fibers detect object curvature, edges, points and distinct object features. Blind people read through Braille using the Merkel cells mainly as they are situated on the epidermis layer, which is the topmost layer of the skin. The Ruffini nerve endings detect the skin stretch. Figure 2 shows the cross section of the skin holding the mechanoreceptors.

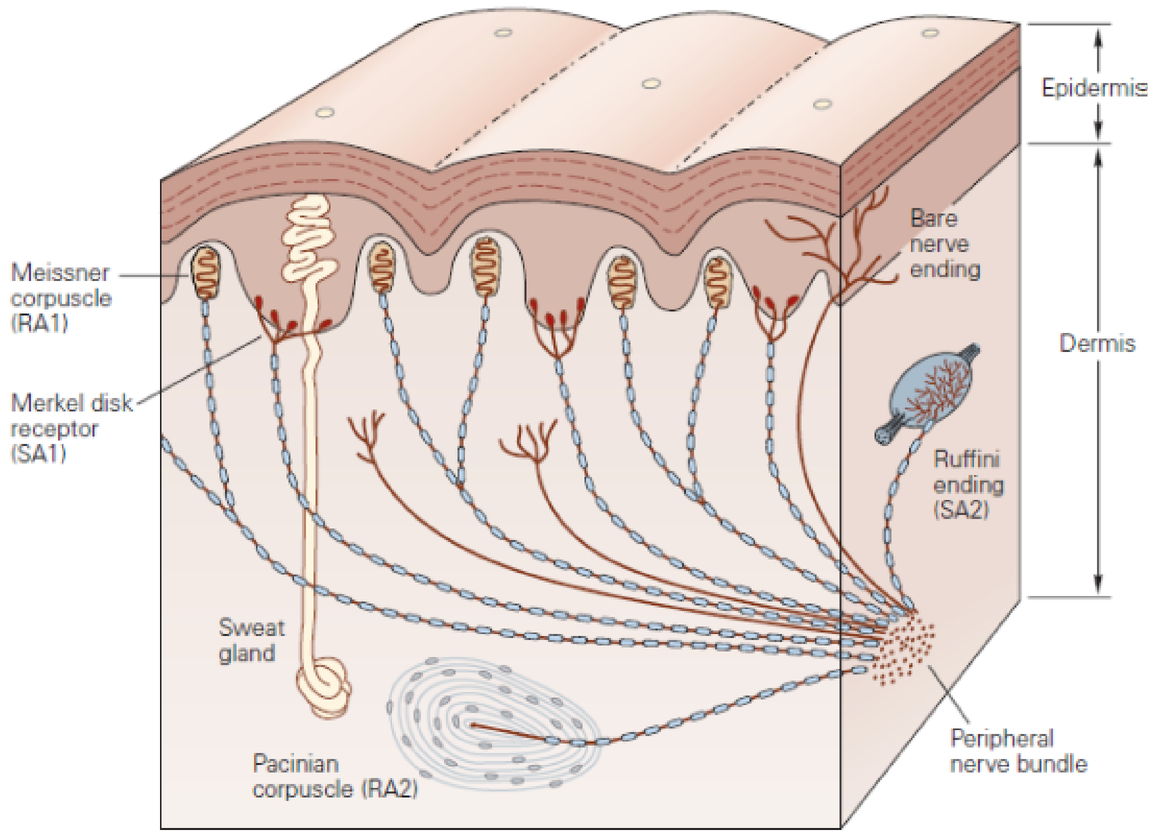

Figure 2: Cross Section of Glabrous Skin with Mechanoreceptors **[7]**

The rapidly adapting fibers on the hand detect motion and vibration to sustain grasp, and hence the most important biological parts for slippage control in human beings. The Meissner's corpuscles and the Pacinian corpuscles are the rapidly adapting fibers in the hand. The Meissner's corpuscles are located in the upper region of the dermis and are the close to the epidermis layer of the skin, while the Pacinian corpuscles are located deep within the dermis close to the bottom of the dermis layer. The Meissner's corpuscles are responsible for helping the Merkel cells of blind people to read Braille. The Pacinian corpuscles are the most sensitive of all mechanoreceptors in the somatosensory system.

The Pacinian corpuscles detect and amplify high frequency vibrations when it comes to object grasp.

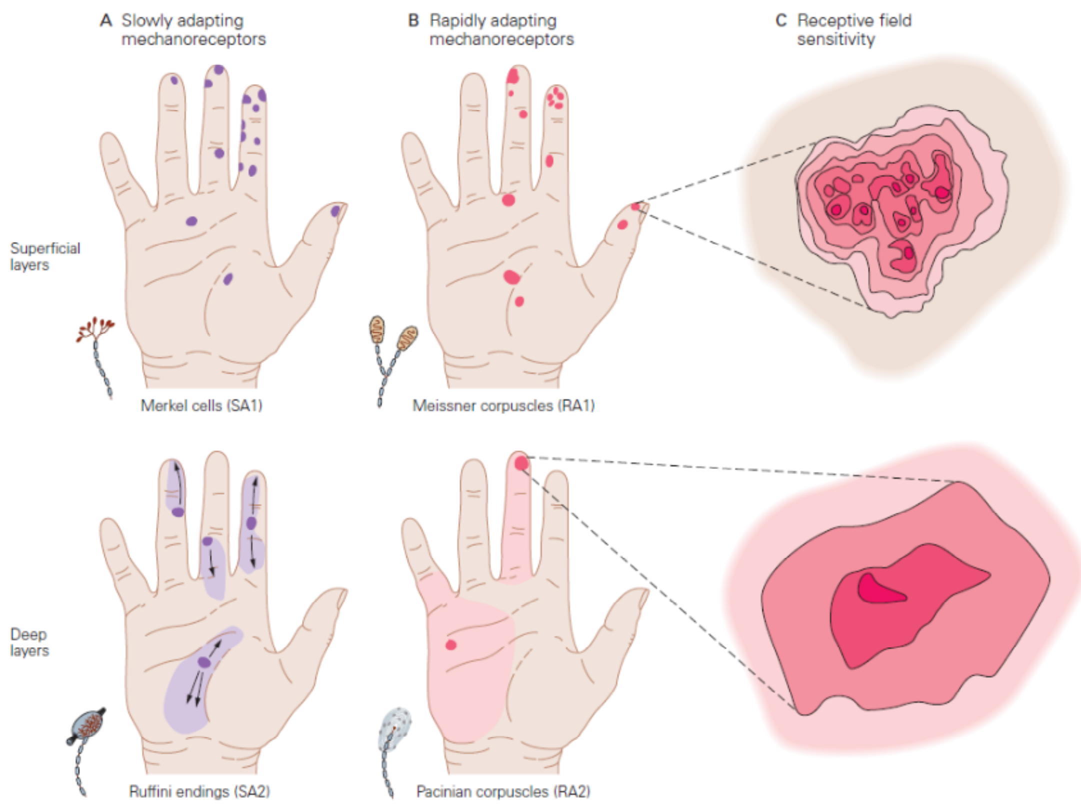

Figure 3: Location of Mechanoreceptors in the Hand **[7]**

The mechanoreceptors are spread across the hand in many locations. From the figure above it can be inferred that the fingertips have the highest concentration of these mechanoreceptors. The fingertips are thus one of the most sensitive parts of the human body. The palm also has many mechanoreceptors at strategic locations, which help in detecting vibrations, pressure, skin stretch etc.

Thus the sensor which is used to replicate the human hand should be able to mainly detect touch among other parameters.

2.2 Piezoresistive Effect

Piezoresistive effect have been used in detecting slippage of objects in industrial robotic manipulators from the 1990's. Some conducting and semiconducting materials show changes in their inter atomic spacing when pressure is applied on them. This results in electrons moving freely to the conduction band and thus resistivity decreases. The relationship between strain and resistivity is linear in most of the materials that possess piezoresistive effect. Piezoresistive constant is enumerated by the following equation [8].

$$\rho_\sigma = \frac{\delta p}{p} / \in, \quad (1)$$

where

ρ_σ represents piezoresistive coefficient

δp represents change in resistivity

p represents resistivit

$\in$ represents mechanical strain

2.3 Array Sensors

Array sensors have long been used to detect pressure, force and other parameters. Array sensors have been used to detect slippage [9]. Array sensors are generally a group of sensors arranged in a certain geometrical pattern depending on the application for which it is used. The advantage of using an array sensor as opposed to a single sensor lies in the fact that array sensors help to improve gain and better resolution of data, thus improving the Signal to Noise Ratio (SNR) of the sensor system. Generally array sensors improve the overall quality of detection of data.

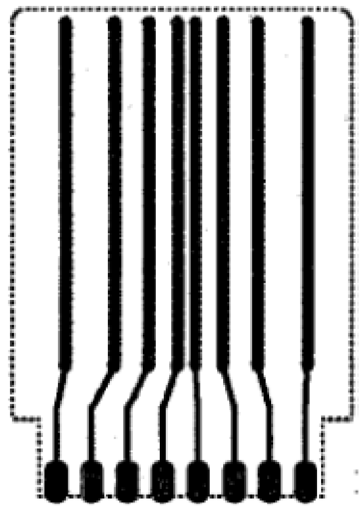

Figure 4: Array Sensor used for slippage [9]

Figure 4 shows a picture of an array sensor used for slippage detection in robotics [9]. This array sensor can be one part of a bigger sensor system, thus helping with improved sensing capabilities.

2.4 Force Sensing Resistor

2.4.1 Working of the Sensor

The name Force Sensing Resistor (FSR®) is a registered trademark of Interlink Electronics Inc [10]. Force sensing resistors are made up of a conductive polymer that changes their electrical conductivity based on the force applied on it by another object. The FSR consists of 2 membranes which are separated by an air gap. The membrane on top is called the FSR layer and is coated with carbon ink. The membrane at the bottom is a conductive layer which has access to the circuit. The conductive layer consists of an interdigitated circuit pattern. When the FSR® layer comes in contact with the conductive layer it shorts the various conductive interdigitated pathways on the conductive layer. Depending on the pressure applied on the FSR® layer the resistance of the entire system changes. Thus a change in value of resistance gives an indication of force [11].

2.4.2 Construction

The FSR® is constructed using a space adhesive which acts as a base to hold the sensor together and also is essential for creating the air gap between the two layers of the sensor. The conductive layer consists of circuit patterns which are made from silver polymer ink [11]. The FSR® layer is made with proprietary carbon based ink which changes resistance with applied force.

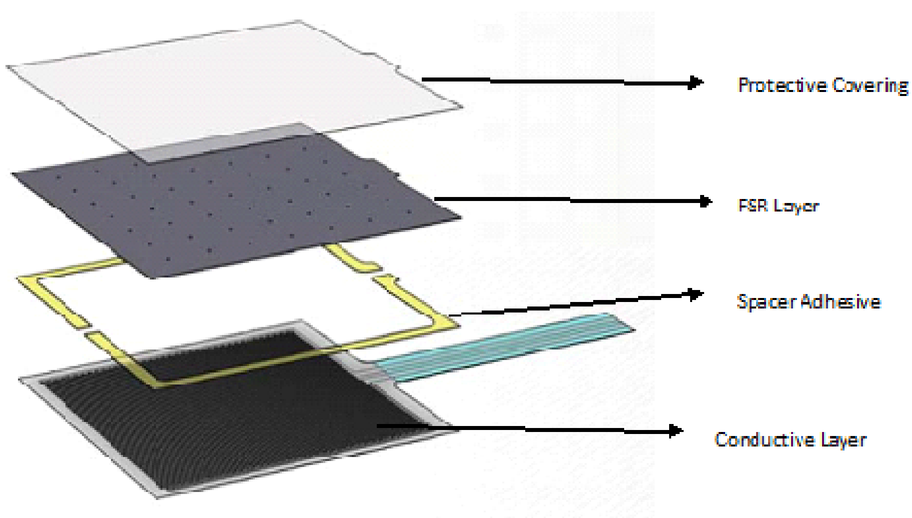

Figure 5: Construction of FSR® **[11]**

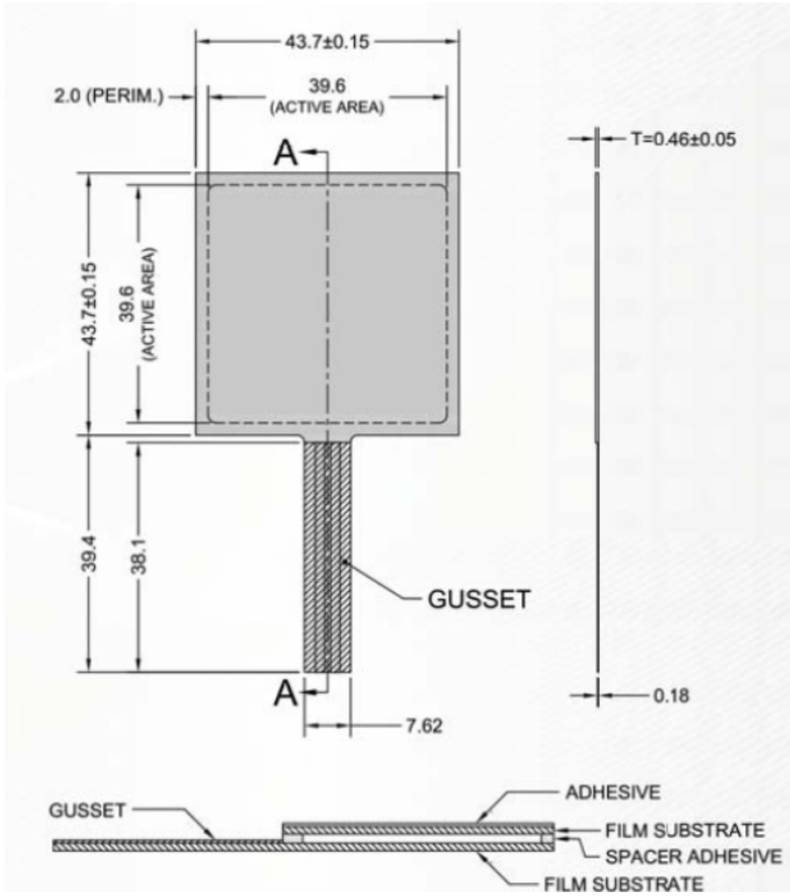

Figure 6: Dimensions of FSR® **[11]**

2.4.3 Force Curve

The force curve or the Force Vs Resistance curve indicates the behavior of the FSR®. It depicts the reaction of FSR® to force and the effect of change in force to the resistance it offers. The Force Vs Resistance curve depends largely on the construction of the FSR® i.e. the air gap between the membranes, the type of spacer adhesive etc. There is an "actuation force" or a turn on threshold for the FSR®, which is the lowest force for which the FSR® offers resistance [12]. If a force is applied below the actuation force level the FSR® acts as an open circuit without offering any resistance. For larger forces, the resistance goes into a minimum value. Further increase to the force does not impact the resistance value but will cause damage to the FSR®.

From the graph in Figure 7, it can be inferred that the resistance offered by the FSR® decreased with increase in force.

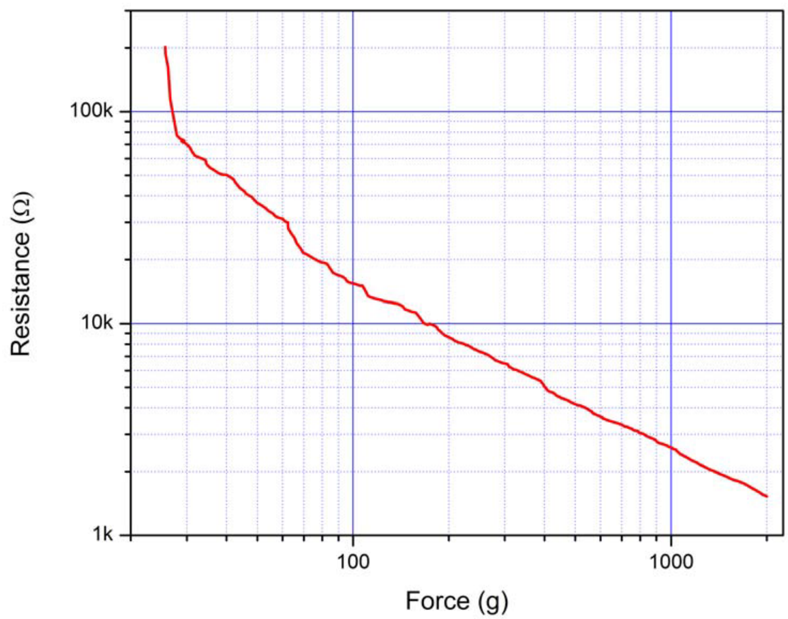

Figure 7: Force Curve for a FSR **[12]**

2.4.4Advantages of FSR®

- Size typically less than 0.5mm.
- A vast range of operation can detect forces from 0.2 Newton to 20 Newton.
- Available in various shapes and sizes depending on the requirements of usage.
- Low cost (typically costs less than $10 per piece).
- Robust construction which offers good shock resistance.
- Repeatable performance with long life (up to 10 million actuations per sensor).

2.4.5 Interfacing with FSR®

To interface the entire circuit with the FSR®, a voltage divider circuit is used.

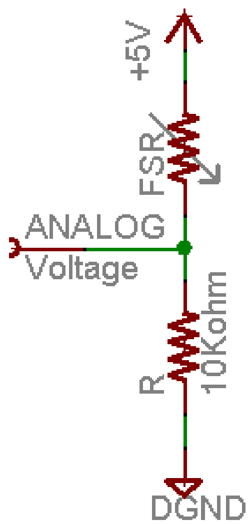

Figure 8: Voltage Divider Circuit **[13]**

We can derive the voltage out of the FSR® using the formula [13];

$$Vo = Vcc \left(R / (R + FSR) \right), \qquad (2)$$

where

Vo is the analog voltage which is used for calculating force

Vcc is the voltage from the Microcontroller i.e. 5v or 3.3v

R is the constant source of resistance

From the formula an inference can be made that the voltage is proportional to the inverse of the FSR® resistance.

3 Design

3.1 Tactile Slippage Sensor Design

Figure 9: Slippage Sensing Glove

The core of the slippage sensor is a force sensing resistor (FSR®) made by Interlink Electronics. The FSR® is mounted on a soft pad to avoid deformation of the sensor. It is square shaped with a side of length 1.5inches. The soft pad is made of cotton cloth with a soft stuffing inside it. This makes the soft pad a perfect platform for the FSR® sensor to rest on. The soft pad and FSR® sensor are sewed on to a glove such as to cover the palm region of the prosthetic hand. The glove is universal and can fit a wide variety of prosthetic hands. This design makes the tactile sensor universally compatible. The slippage sensing glove used in this thesis experimentation is shown in Figure 9.

The FSR® sensor is modified with the addition of a rubber filament-which is a tactile keypad from an old cell phone that has small protrusions, to improve the sensitivity of the FSR®. The extra filament also helps in changing direction of force i.e. converting vertical force into horizontal force, thus enabling the FSR® to work in different orientations. Previous research [14] [15] on tactile sensing clearly demonstrated that using tactile sensing for slippage is the way to go forward on slippage sensing. FSR® modifications by using rubber elements have yielded better results in previous research [16]. The addition of the rubber filament to the FSR® makes it more robust and offers better clarity and resolution. The rubber filament with protrusions, used for modifying the FSR® is shown in Figure 10.

Figure 10: Rubber Filament

3.2 Fuzzy Logic

Fuzzy logic is a complex set of rules system that gives approximate results instead of precise results. A fuzzy logic controller embodies human like thinking into a control system. Fuzzy logic can induce deductive thinking into a system where it is used to emulate how humans perform tasks based on known or borrowed knowledge. It can be implemented particularly in places where human like thinking/behavior is required in making decisions. Fuzzy logics have been used widely in machine control. Lately it has found tremendous applications in embedded control systems and neural network based systems.

The flow structure of a fuzzy logic controller is described in Figure 11.

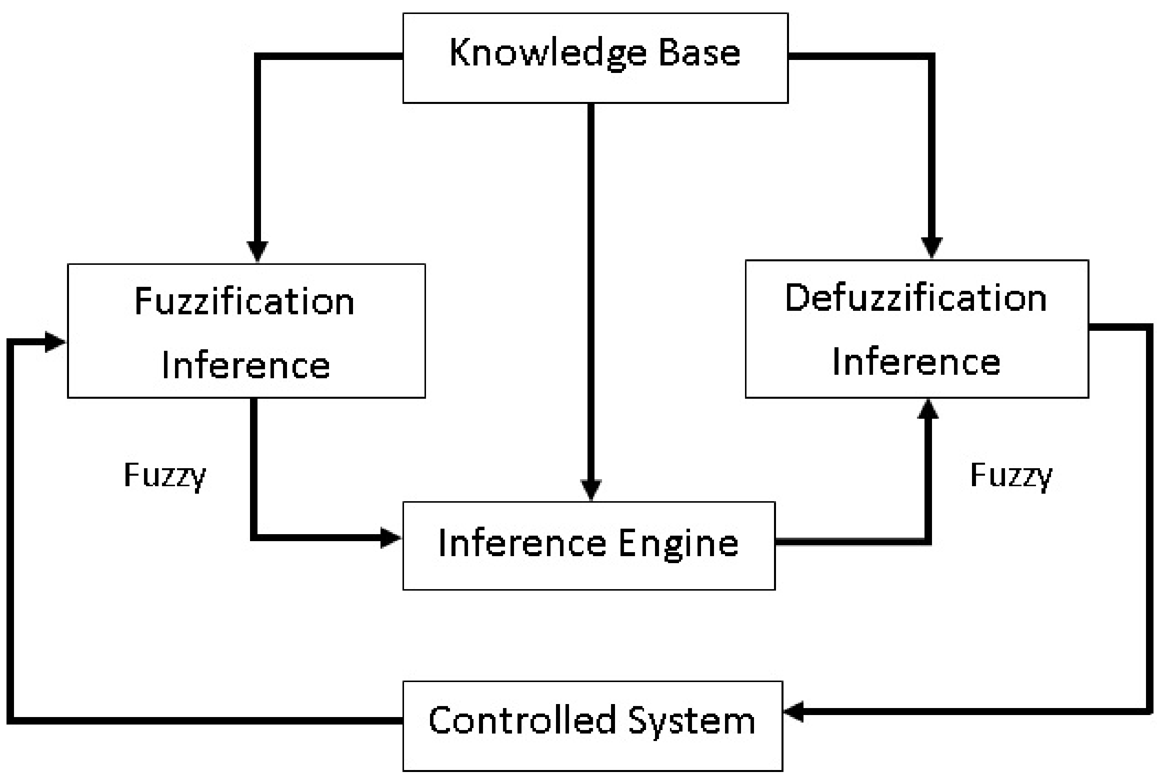

Figure 11: Fuzzy Logic Flow Chart [17]

The first stage of working of a fuzzy logic controller is the fuzzification of input data. Fuzzification is a process by which crisp data is converted into a more vague data based on membership functions associated with the data. The input values are fuzzified and fed to the inference engine where the fuzzy rules are associated with the input data and a fuzzy output is generated. The knowledge base is the set of rules associated with the controller. This can also be called the brain of the fuzzy controller. After getting the fuzzy output, the value goes through a defuzzification interface which gives a crisp, discrete output value.

3.3 Fuzzy Logic Slippage Controller Design

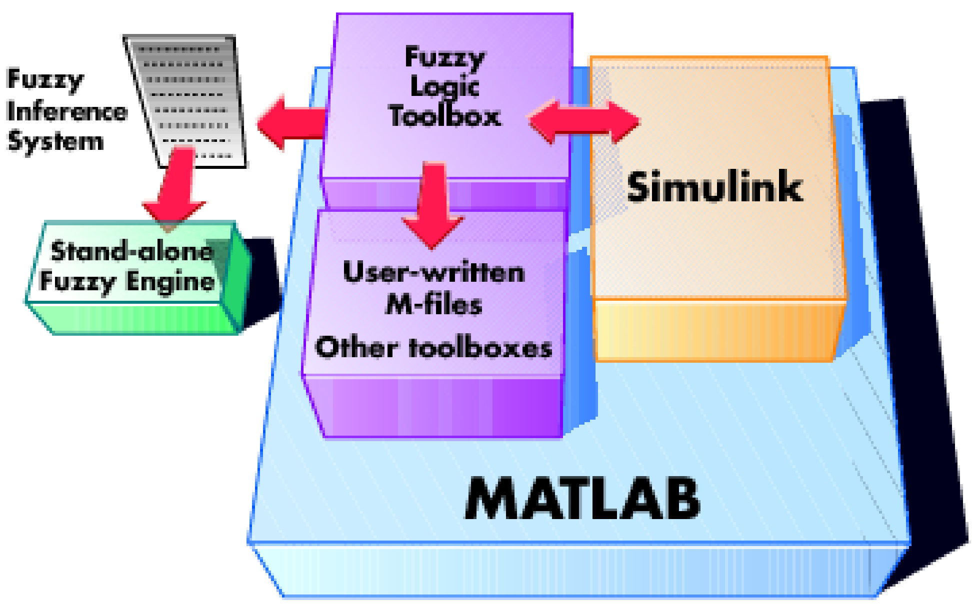

Figure 12: Development Environment **[18]**

The fuzzy logic based slippage controller is designed in MATLAB® platform. Figure 12 shows the development environment utilized in developing this controller. The Fuzzy Logic Toolbox™ in MATLAB® is used to enter the various parameters i.e. the knowledge base of the controller.

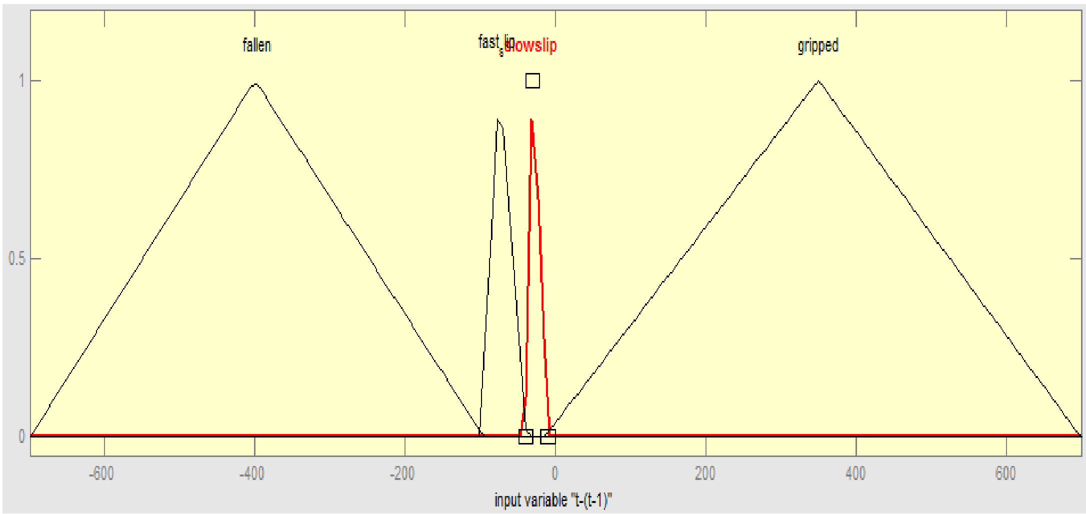

Figure 13: First Input to the Fuzzy Logic Controller

The slippage controller designed is a multiple input single output controller. The inputs are the analog voltage values from the FSR interface circuit. The first input to the controller is the difference between the analog voltage across the FSR at time T and (T-1). Here (T-1) represents the analog voltage at a time which is 1 sample time before the current time. Figure 13 shows the first input membership functions. These are 4 triangular membership functions namely slow slip, fast slip, gripped and fallen. The range of the input values is between -700 and 700. It means that the slippage controller accepts values between -700 and 700 and junks any other value outside this range. When input is between -10 and -40, it is classified as slow slip. When the input is between -38 and -100, it is classified as a fast slip. When the value falls in the range between -15 and

700, it is classified as gripped. Lastly if the value falls between -95 and -700, it is classified as fallen. The various membership functions for the first input are classified based on different scenarios possible for slippage.

Figure 14 represents the second input function in the Fuzzy Logic Toolbox™. The second input also has 4 triangular membership functions representing various scenarios possible based on the input. The value fed as input to the second input function is the difference between the analog input voltages at time (T-1) and (T-2), where (T-2) represents the input voltage at 2 sample times before the current time. (T-1) and (T-2) represent historical input values. For the second input function in the fuzzy logic controller, slow slip is represented by values ranging from 0 to -40, fast slip is represented by values ranging from -38 to -100. The fallen and gripped portions are represented by values ranging from -95 to -700 for fallen and -5 to 700 for gripped.

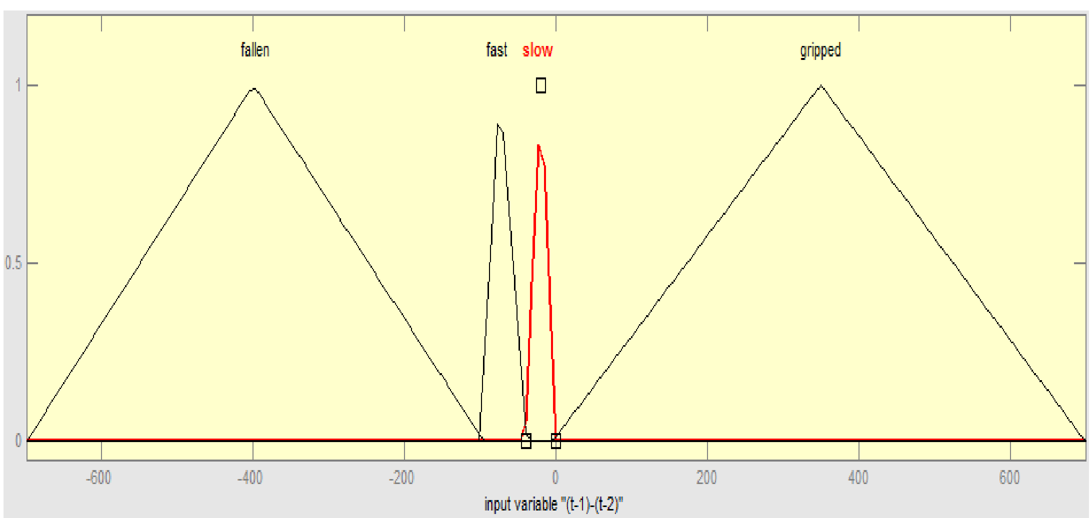

Figure 14: Second Input to the Fuzzy Logic Controller

The output function in the Fuzzy Logic Toolbox™ has 3 triangular membership functions, one for 'slow slip' ranging from 10 to 20, the second being 'fast slip' with values ranging from 20 to 40 and 'nothing' with a 0 value. Figure 15 represents the output fuzzy logic controller membership functions.

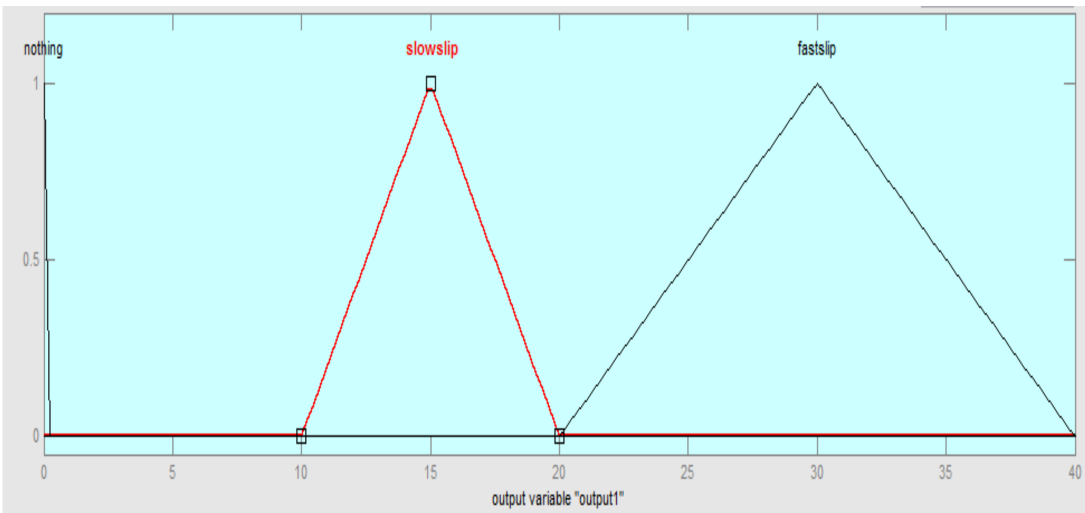

Figure 15: Fuzzy Output Variable

The fuzzy logic controller is based on a set of rules. The rules are as follows:-

- If Input 1 is slow slip and Input 2 is slow slip then the Output is slow slip (1)
- If Input 1 is slow slip and Input 2 is fast slip then Output is slow slip (1)
- If Input 1 is fast slip and Input 2 slow slip then Output is fast slip (1)
- If Input 1 is fast slip and Input 2 is fast slip then Output is fast slip (1)
- If Input 1 is fallen or Input 2 is gripped then Output is nothing (1)
- If Input 1 is gripped or Input 2 is fallen then Output is nothing (1)

The above fuzzy rules are understood in a format where the first input membership function is followed by the logical 'AND' or 'OR' gates. This is then followed by the second input membership function. The weight of the rule is added at the end. So if a value is considered in 2 rules then the weights are checked and the rule with a higher weight will be executed by the fuzzy logic controller. Figure 16 shows the rules editor in Fuzzy Logic Toolbox™ in MATLAB®. Figure 16 shows the rule viewer where the user can examine various control scenarios by simulating input values and examining the controller outputs. Figure 17 shows the fuzzy rule editor in Fuzzy Logic Toolbox™ where rules can be framed/edited.

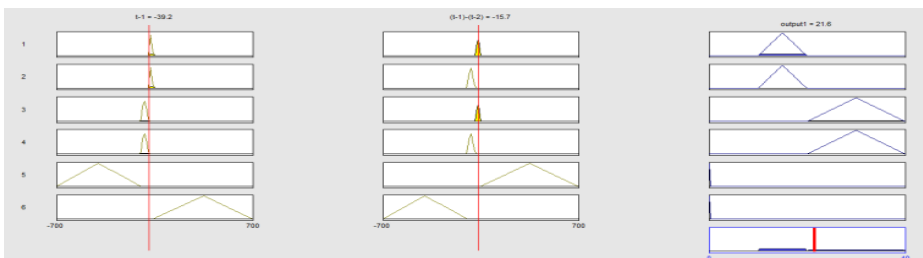

Figure 16: Rule Viewer in Fuzzy Logic Toolbox™

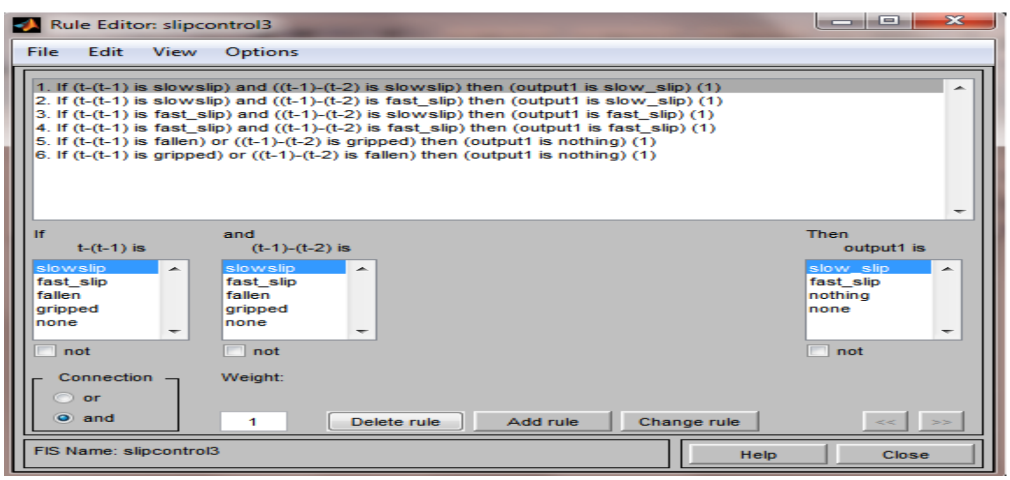

Figure 17: Rule Editor in Fuzzy Logic Toolbox™

3.4 Slippage Control Simulink® Model Design

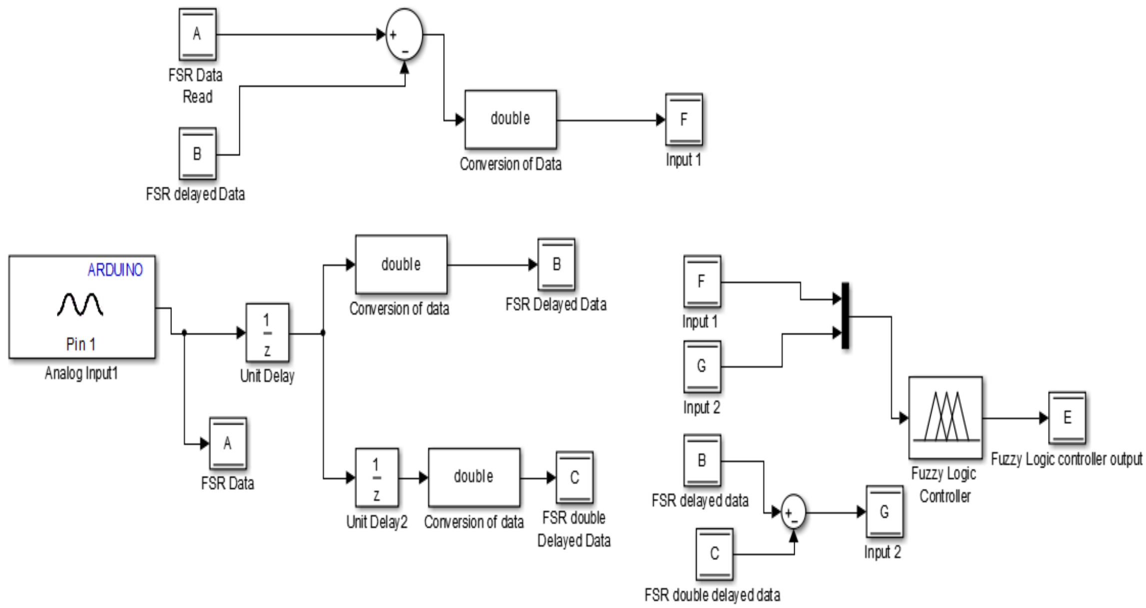

Figure 18: Slippage Control Model

Figure 18 shows the Simulink® model for slippage control strategy. The analog voltage across the FSR is acquired from the analog input block and a couple of delays are introduced. A unit delay holds and delays the input by one sample time. The sample time is specified in the blocks parameters. The data type of the input signal is converted to double format for the microcontroller to process the data. The input 1 as seen in the model is the difference between the present FSR® input and the delayed FSR® input. The input 2 is the difference between the single delayed and the double delayed FSR® data. Double delay is introduced by cascading 2 unit delay blocks together in Simulink®. The 2 inputs are multiplexed using a Multiplexer and sent to the fuzzy logic controller for processing. The data store memory block can be utilized to store and retrieve data at any part in the model. This feature makes it easy for data to be used at different parts in the model.

3.5 Slippage Control Flow Diagram

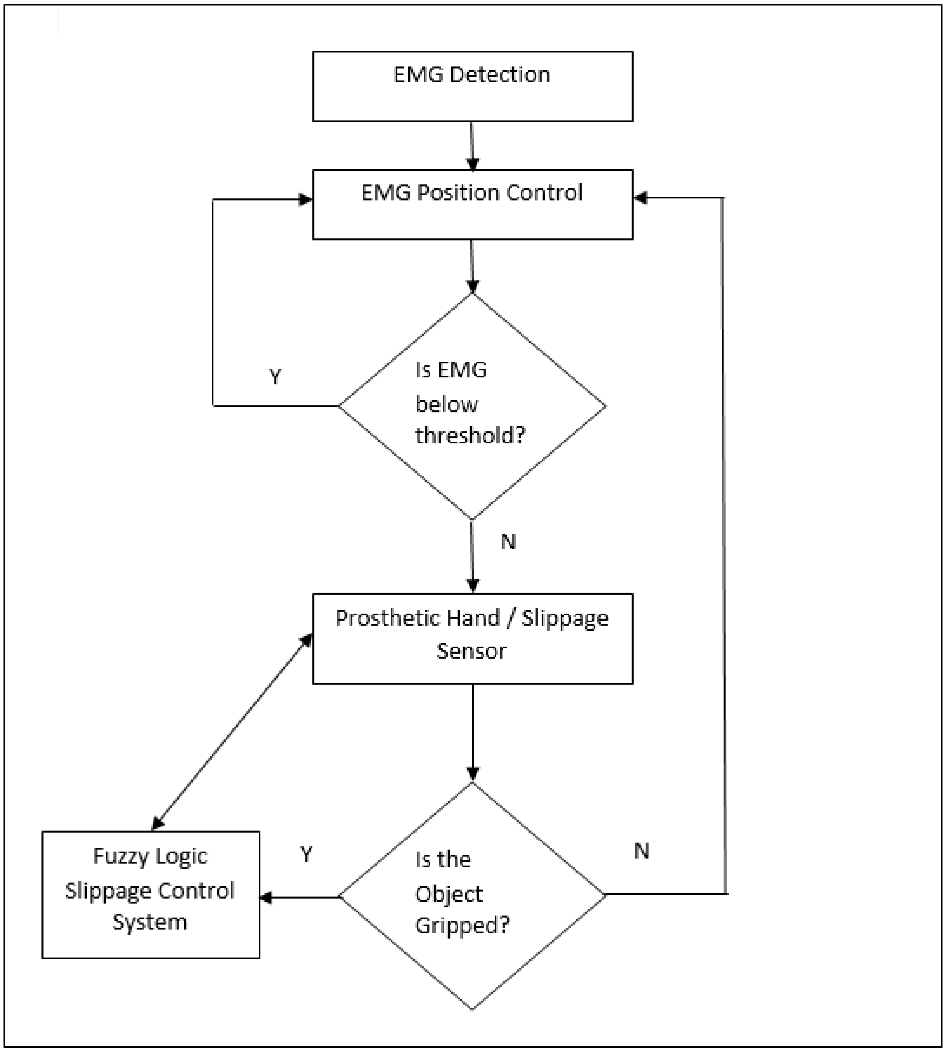

Figure 19: Slippage Control Flow Diagram

Figure 19 represents the slippage control flow strategy. When EMG is detected by the system, it goes into EMG based position control mode. This is the mode where the fingers go into the desired position based on the value of the EMG signals. The EMG signals then go through a first check point where its value is checked. There is a predetermined value which is a minimum threshold value below which it can be determined that the user wants the hand to be in a relaxed mode using position control.

After the check for EMG is executed the system waits for feedback from the slippage sensor. If there is a feedback relating to object grasp (value from the FSR sensor is above a certain threshold limit predetermined by analysis), the system goes into slippage control mode and remains in this mode to ensure object grasp.

Both slippage control scheme and the position control strategy work simultaneously. There is a switching technique where the system switches from position control to slippage control to ensure efficient object grasp and object maneuverability. Thus both the position control system and the slippage control system act as complementing strategies to ensure hassle free operation of the prosthetic hand to the user.

3.6 Simulink® Model of the entire system

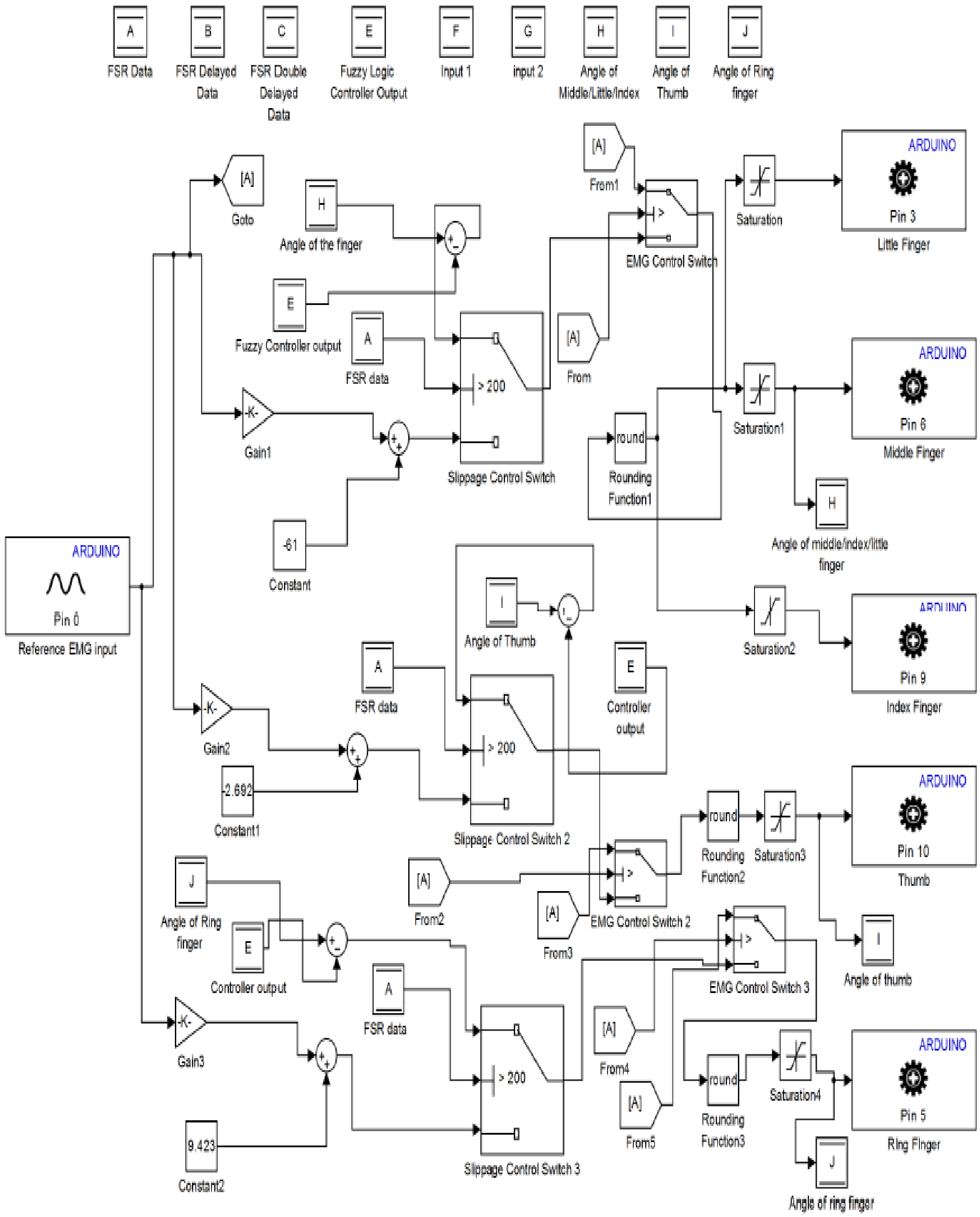

Figure 20: EMG Position Control and Entire System Model

Figure 20 shows the entire model of the slippage control strategy. This model replicates the flow diagram in Figure 19 as a graphical program capable of performing on an embedded platform. The model has various global variables that store data that is being processed by the system. These variables are represented as the letters A,B,... etc. These global variables can be utilized by any part of the program. The initialization of these variables makes it easy for data flow and storage within the program.

The reference EMG signal is acquired through an analog input channel at 100 samples per second. Although the microcontroller used can handle samples up to 10,000 samples per second, in this experimentation it is limited to 100. The reference EMG signal is acquired by using a potentiometer and a voltage divider circuit. The equation used for acquiring the signals is described in (2). The reference EMG signals then goes through a proportional open loop control system for position control. This is done by adding a gain that directly translates the movement of the potentiometer into movement of the fingers in the prosthetic hand. This position control system is used to grasp an object.

There is a slippage control switch which acts on the feedback from the slippage sensor. This is used for switching between slippage control mode and the position control mode. When the feedback from the slippage sensor is above a minimum threshold value, the switch passes only the control signals from the slippage controller. This makes sure that the control system acts on its own without relying on the EMG signals. It also makes the slippage control system work independently, complementing the EMG based position control system. When the value from the FSR sensor feedback is below the threshold limit, then the switch passes EMG position control signals. Both the slippage control signals and the EMG position control signals are in angular values for the servomotor.

There is also a second control switch which is based on EMG. When the EMG is below a specified threshold level, the system goes back into EMG based position control mode and stops the slippage control signals to pass through. This scenario is helpful when it is known that the user wants to drop the grasped object.

The design is made such that the actuator values of the fingers goes through a feedback loop where the last value is added/subtracted to the new controller input regardless of the controller being for slippage or for EMG based position control. The addition or subtraction of the values is based on the lower and upper limits of the servomotor. These values then go through a saturation block which has an upper and lower end. They are entered in the block based on the lower and upper limits of the servomotors. This prevents the servomotor from being operated outside its range and getting damaged. So even if the angle keeps increasing/decreasing due to the controller, the saturation acts as a safety barrier to the servomotors.

The slippage control model and the system models are executed together on an embedded platform. They are shown as different individual models but work together. The two systems will work in unison to get the desired prosthetic hand performance/execution.

4 Experimental Setup

4.1 Microcontroller

Controlling the 5 DOF hand requires a good microcontroller capable of handling 5 servo motors at a given point of time. The microcontroller used in this research is an Arduino Mega 2560 pictured as is in Figure 21. The Arduino Mega 2560 comes with an ATmega 2560 microcontroller which is manufactured by Atmel® Corporation. The ATmega 2560 has a RISC (reduced instruction set computing) design. The RISC design strategy is a CPU design strategy based on the theory that simplified instructions can give much better controller performance rather than complex instructions [19]. The Arduino Mega 2560 has 16 analog input pins, 54 digital input/output ports out of which 15 can be used to generate Pulse Width Modulated (PWM) output signal.

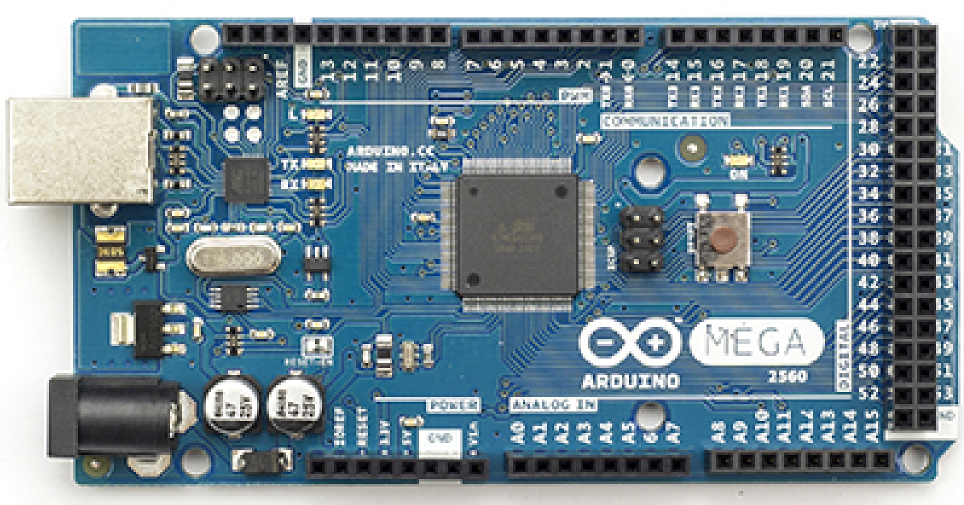

Figure 21: Arduino Mega 2560 **[20]**

The microcontroller comes with a 256 Kilo Bytes (kb) of flash memory out of which 8 kb is utilized for booting. There are voltage regulators on board the Arduino Mega 2560 to give a regulated 5 volts (V) output and a 3.3 V output [20]. The clock frequency of the microcontroller is 16 Mega hertz (MHz). It can handle 16 Million Instructions per Cycle (MIPS). Thus operating at 16 MHz and handling 16 MIPS, it gives a throughput of 1 MIPS per MHz clock cycle giving it an optimum power to processing ratio [21]. It is programmable using a Universal Serial Bus (USB) interface. It also has 4 Universal synchronous Asynchronous Receiver/Transmitter (USART) for easy communication purposes. The USART module is used in communicating data via USB to the computer to get the various values used in preprocessing or processing the data. The microcontroller also has a 10 bit Analog to Digital (A/D) converter which is used to convert signals from the analog pins and use the values for processing by the microcontroller.

The microcontroller also has a reset button and In Circuit Serial programming (ICSP) capability. The main use of the ICSP feature is for easy programming and communication.

The Arduino Mega 2560 is thus a compact, powerful and easy to use microcontroller which has a lot of features which makes it an ideal choice for programming embedded control systems. The easy programming capabilities of the Arduino Mega 2560 make it an ideal choice for embedded systems applications.

4.2 Prosthetic Hand

Figure 22: Prosthetic Hand **[22]**

The prosthetic hand used in this experiment shown in Figure 22 is a 5 DOF hand with each finger being operated by a micro servomotor. The hand is made from anodized aircraft aluminum [22]. It has 14 points of motion and can be controlled by any servo controller / PWM signal generator. It does not have a substantial gripping force, however it can be used for testing the various control algorithms/control schemes.

This hand is equipped with 5 Futaba S3114 micro servomotors. The servomotors operate at 4.8v - 5v range, and are powered by an external constant power source. The micro servos will be damaged if the voltage exceeds 5v. It can also be powered by a microcontroller's power supply or a battery source. For experimentation purposes, a constant 5v power source is used.

4.3 Experimentation

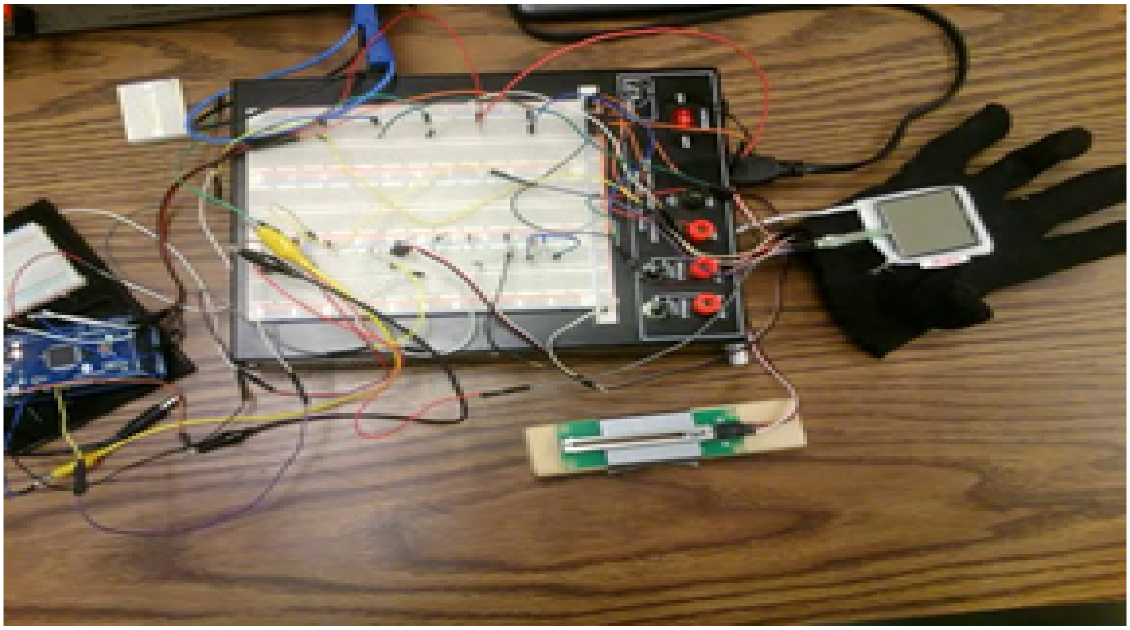

Figure 23: Experimental Setup

The experimentation consists of two parts, the first is the generation of reference EMG to produce a synchronous motion of the fingers to grasp the object and the second part is inducing a slip to the object and learning how the controller reacts to the object slip. Figure 23 pictures the experimental setup.

4.3.1 Generating Reference EMG Signals for Object Grasp

A reference EMG signal was generated by using a potentiometer. The prosthetic hand was made to do a synchronous motion, where all the fingers come towards the thumb. This is done using a normal proportional position controller. The lower limits and upper limits of the potentiometer were recorded. The lower and upper angle limits of the micro servo motors in the prosthetic hand were measured. Using these values, a voltage/angle proportion was calculated and the microcontroller was programmed such that the hand moves synchronously and proportionally in a synchronous motion, when there is input from the potentiometer.

4.3.2 Inducing Slip and Recording the Controller Output

The next step in the experimentation is to induce a slip to the gripped object. After inducing the slip the object goes into sliding motion and the controller action is recorded. This experiment is repeated for object slippage in the vertical direction and object slippage in the horizontal direction. The experiment is also conducted with the rubber filament on and off the top of the FSR® sensor. The object which was used in conducting this experiment is a wallet of length 3 inches and breadth 4 inches approximately. The reason for using the wallet is because of its orientation, which is of ratio 4:3 and its weight being very light. The wallet is a smaller load for the prosthetic hand as the hand is equipped with only micro servomotors which do not have a good torque rating. Various data values are recorded at different points of the experiment.

5 Results, Conclusion and Future Work

5.1 Graphical Results

5.1.1 Horizontal Slip with Modified Slippage Sensor

The prosthetic hand is oriented with the palm facing the sky. The object is placed on top of the palm and the prosthetic hand grips the object. Then a slip is induced. After a slip is induced the controller action is recorded. Figure 24 shows the feedback data, while figure 25 shows the slippage controller output for this induced slip.

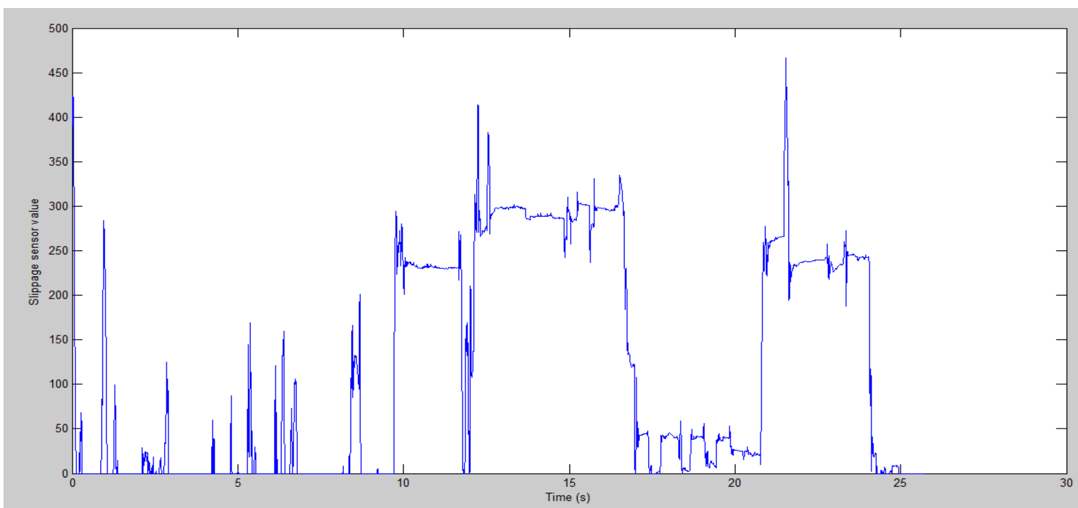

Figure 24 FSR® Data

The sharp ascending portion of the FSR® sensor data from figure 24 shows characteristics of object grip. The ascending values mean that the object is on the verge of being gripped. The sharp descending values are an indication of object slippage. Steady values represent constant force, which happens when the object has been gripped. Even when the object is gripped there will be variations in the sensor values because force exerted on the object varies continuously. Small variations can be neglected as corrections and no controller actions need to be taken. Figure 25 shows straight lines as controller output. Since the controller gives a discrete value at discrete moments of time the graph looks pointed. The output values are a measure of the angle for the servomotor.

Inference from Figure 24, which is the sensor data, shows slippage as a very fast process. It happens within milliseconds (ms). The controller does not have much time to react. An instance at sample time 1176 is taken to see how fast the controller reacts. The sensor value at sample 1176 was 201. The sensor value at sample 1175 was 213 and the sensor value at sample 1174 was 244. At the instance 1176 the controller processes these data and checks for the values. The controller data was 14.9479 at this sample instance. The controller action acts at the same instance of time as when the sensor value is read by the microcontroller. It is verified for other values of data as well, the controller acts within the same sample time. So it can be said that from reading to processing the values the microcontroller takes only one processing cycle.

The same features are tested for all the experiments conducted with the prosthetic hand and sensor combination. The speed with which the controller acts is very promising as slippage is a fast process and a moment of a second can determine whether the object is held or whether it slips.

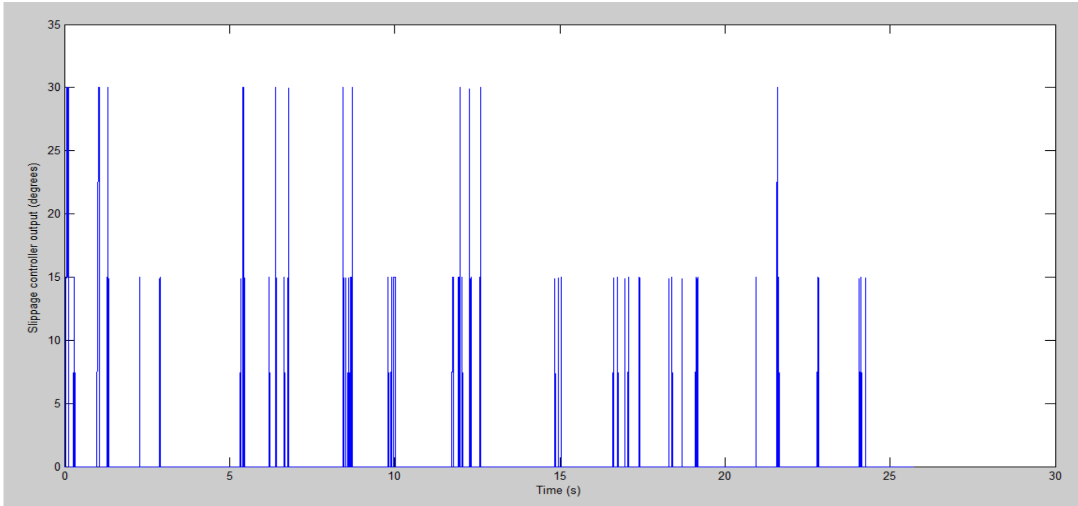

Figure 25 Slippage Controller Output

5.1.2 Horizontal Slip without Rubber Element attached

In this experiment the prosthetic hand is also kept with its palm facing the sky. For this experiment the sensor is without the tactile rubber element. The unmodified sensor data is collected and processed for determining slippage.

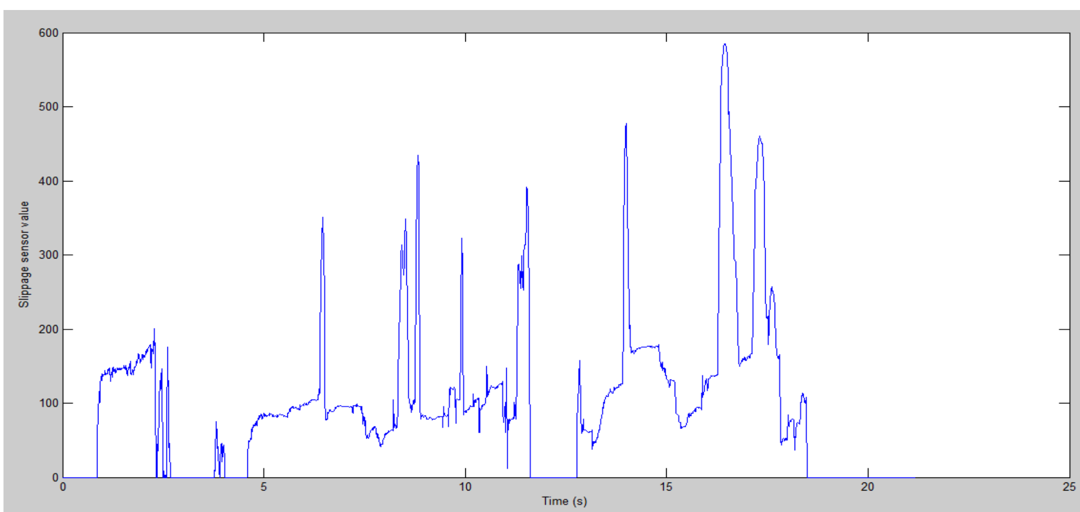

Figure 26: FSR® Data 2

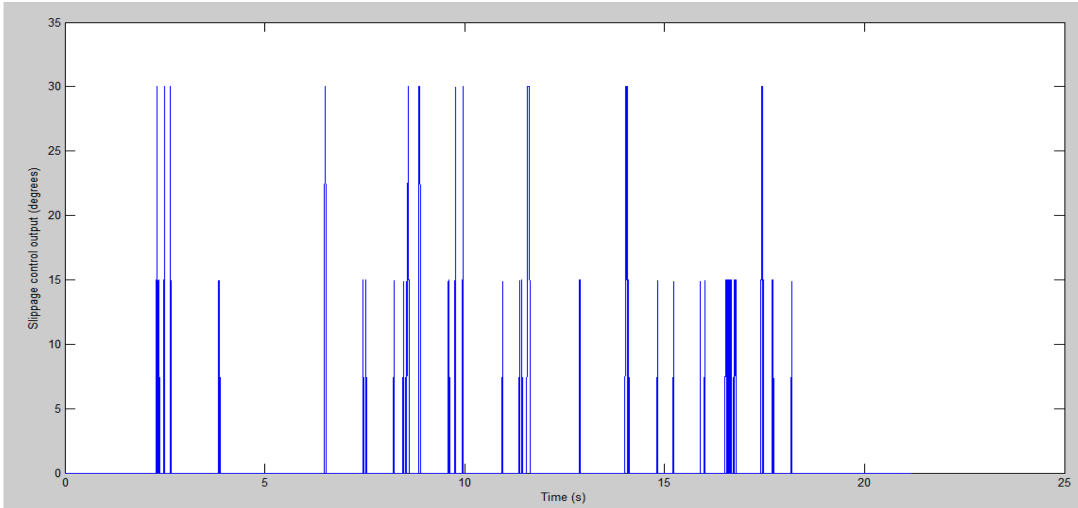

Figure 27: Slippage Controller Output 2

When data from Figure 26 and Figure 24 are compared i.e. the sensor data from the two experiments, an inference can be deduced that when the modified sensor is used the values of the sensor are more readable and not haywire like in Figure 26. Modifications to the sensor help in maintaining a more constant force when object is gripped.

5.1.3 Vertical Slip with Rubber Element

The third experiment is done with the palm of the prosthetic hand perpendicular to the sky. We can see from the sensor data in Figure 28 that the sensitivity of the sensor is much lower as compared to previous scenarios. The gripped sensor threshold value is small i.e. sensor values from 15 to 20 second period shows the value barely over 100 at many instances and below 100 at some. Figure 29 shows the slippage controller output. We can see huge controller actions during the 15 to 20 second range when the object was gripped. This shows that for small variations during the gripped phase, the controller reacts really fast. Thus, the parameters in the program need to be tweaked in order to achieve optimum performance from the controller.

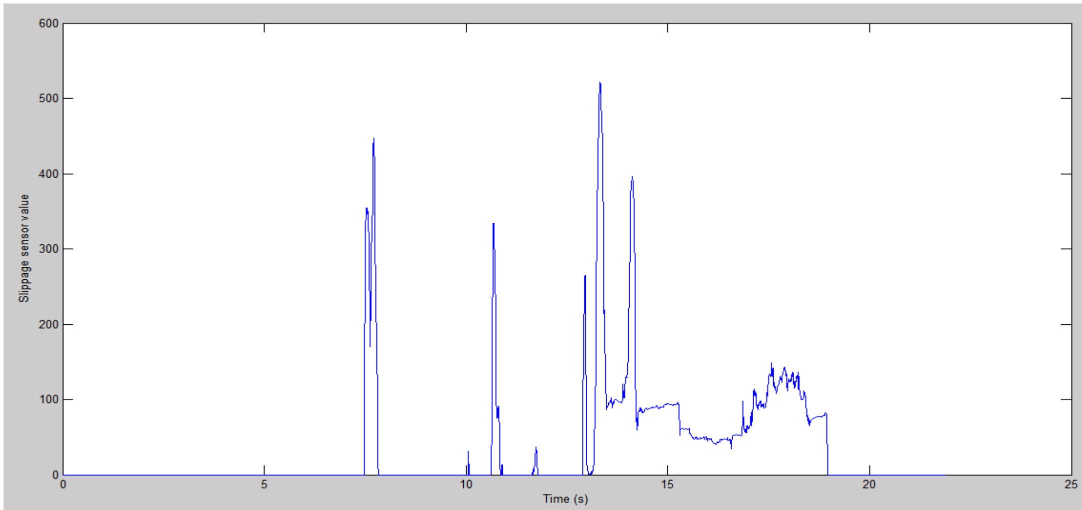

Figure 28: FSR® Data 3

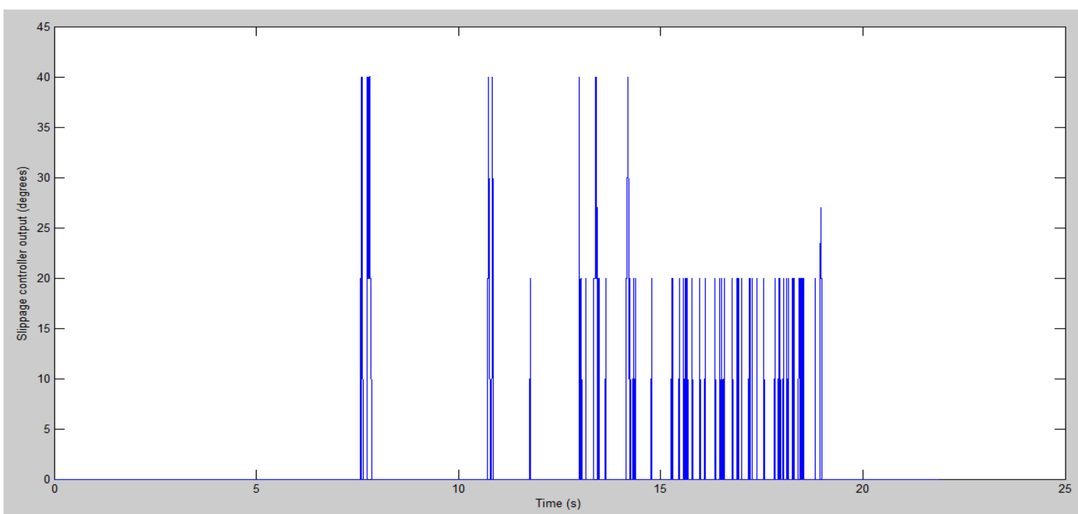

Figure 29: Slippage Controller Output 3

Without the rubber filament, when this experiment was carried out the sensor values recorded was negligible and unusable for feedback control.

5.2 Conclusion

Improved versions of Prostheses are being made available with advancing technology. To further advance prosthetics a unique inexpensive fuzzy logic slippage controller was designed along with a robust sensing system.

The modifications made to the sensor equip the FSR® to perform with better resolution and sensitivity. The sensor is more robust and rugged, making it suitable for hand prostheses.

The main problem of designing and integrating a slippage control system with EMG position control system for smart hand prostheses is addressed and a design is proposed. This can lead to further advancement in the development of smart features in hand prostheses.

The proposed design is platform independent and can work with any prosthetic hand. The objective of this thesis was to achieve a low cost, reliable, repeatable and platform independent slippage control system. It was achieved using a dynamic microcontroller sensor integrated embedded system with very few complexities.

5.3 Future Work

Figure 30: Future Slippage Sensing Glove

More FSR®s can be added to the fingertips because most of the hand motion/grips are executed by the finger tips. From the figure showing the concentration of the mechanoreceptors in the human hand it can be inferred that the fingertips have the highest concentration of mechanoreceptors and hence send out the richest tactile responses. Thus, by replicating the human hand and positioning tactile sensors on the fingertips of the glove a dynamic slippage algorithm can be developed. Different sensors on the fingertips combined with the palm slippage sensor can be used to formulate a fusion algorithm. This algorithm will consider different hand motions.

6 References

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Appendix

Interfacing Simulink® with Arduino Mega 2560

Arduino microcontroller can be programmed via Simulink® tools. Simulink® has a 'Run on hardware' tool which allows its users to program Simulink® models directly to the arduino microcontroller. The Simulink® model library also has a number of block sets related to the arduino microcontroller. The block sets include analog input, digital input/output, servo read/write, PWM generator, serial send/receive etc. These blocks can be used along with the regular Simulink® blocks to create a model and then the model can be executed on the arduino microcontroller platform.

Steps involved in programming the Arduino Microcontroller

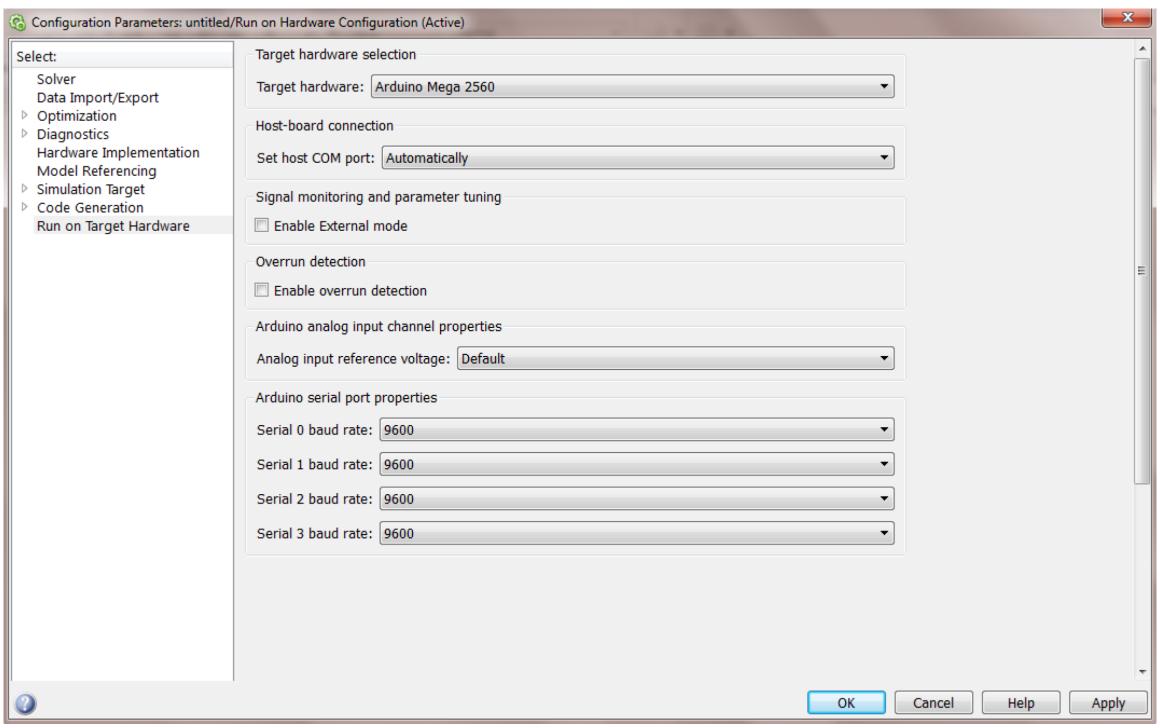

Figure 1: Configuration Toolbox for Real Time Target

There are 5 modes of operation namely normal, software in loop, Processor in loop, accelerator, rapid accelerator and external modes. External mode of operation was used in this thesis work. External mode allows the computer to communicate with the arduino to receive data values via USB port. This mode is good for debugging and testing the algorithms. In the configuration toolbox the communication port used to communicate with the arduino can be set manually or allow Simulink® to automatically detect it. The enable external mode should be checked in the configuration toolbox. The arduino Uno microcontroller does not support external mode in simulink®. Only the arduino mega 2560 supports external mode of operation from simulink®. Figure 1 shows the toolbox in simulink® where we need to click on run in external mode checkbox, so as to communicate with simulink®. Generally the set host communication port is set so that simulink® can detect the port automatically. We can also manually enter the communication port if there are errors while compiling and building the model. The communication port can be seen in windows devices and printers page in control panel.