Surface Electromyographic Control of a Humanoid Robot

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ABSTRACT

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Surface Electromyographic Control of a Humanoid Robot

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This thesis details the development of an open-source surface electromyographic interface for controlling 1-DOF for the DARwIn-OP humanoid robot. This work also details the analysis of the relationship between surface electromyographic activity of the Biceps Brachii muscle and the angle of the elbow joint for the pseudo-static, unloaded arm case. The human arm was mechanically modeled for a two link system actuated by a single muscle. The SEMG activity was found to be directly proportional to joint angle using a combination of custom joint angle measuring hardware and a surface electromyographic measuring circuit. This relationship allowed for straightforward control of the robot elbow joint directly. The interface was designed around the Arduino Microcontroller; another open-source platform. Software for the Arduino and DARwIn-OP were drawn from open source resources, allowing the entire system to be comprised of open-source components. A final surface electromyographic measuring and signal conditioning circuit was constructed. Data recording and processing software was also coded for the Arduino, achieving control of the robotic platform via surface electromyography.

DEDICATION

*This work is dedicated to my family for their unending support and love and to Erin for
her love and patience during this time.*

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TABLE OF CONTENTS

	Page
Abstract.....	3
Dedication	4
Acknowledgments	5
List of Figures	8
1 Introduction	9
1.1 Project Introduction.....	9
1.2 Teleoperation	9
1.2.1 History	9
1.2.2 Motive for Development of New Teleoperative Systems	11
1.2.3 Example	11
1.3 Robotic Platform DARwIn-OP	13
1.3.1 Technical Specifications.....	13
1.3.2 Merits of Open Source.....	15
1.4 Electromyography	15
1.4.1 History of Electromyography	15
1.4.2 Biology of Electromyography.....	16
1.5 Thesis Objectives	18
1.6 Thesis Outline	18
2 Modeling	19
2.1 Human Arm Anatomy	19
2.2 Biceps-Arm Mechanical System Analog	20
2.3 Simulation Results	26
3 SEMG Measuring System	32
3.1 Circuit Design	32
3.2 Reference Angle Measurement Device	34
3.3 Labview Measurement System	35
3.4 Results and Discussion	39
4 Final System Design	46

	7
4.1 Arduino Microcontroller	47
4.2 Robot-Sensor Interface	48
5 Conclusion.....	51
5.1 Future Work.....	52
References.....	53
Appendix a: Simulation Code	56
Appendix B: Alternate Joint angle Reference.....	59
Appendix C: Arduino Code	61

LIST OF FIGURES

Figure 1: The Ohio University Virtual Haptic Back	10
Figure 2 Robonaut 2	13
Figure 3: DARwIn-OP	14
Figure 4: The Neuromuscular System	17
Figure 5: Diagram of the Human Arm Anatomy.	20
Figure 6: Mechanical Model of the Human Arm	23
Figure 7: Vector Loop Closure.....	25
Figure 8: Muscle Tension versus Joint Angle.....	27
Figure 9: Muscle Length vs. Joint Angle.....	28
Figure 10: Biceps Insertion Angle vs. Joint Angle	29
Figure 11: Relative Biceps Insertion Angle vs. Joint angle.....	30
Figure 12: SEMG and Angle Position Circuit.	33
Figure 13: Joint Angle Measuring Device.	35
Figure 14: Data Collection System.....	37
Figure 15: User Interface for Data Collection.....	38
Figure 16: Back end of the VI.....	38
Figure 17: Processed SEMG and Normalized Joint Angle Reference	40
Figure 18: Rectified SEMG and Joint Reference.....	41
Figure 19: Filtered Normalized SEMG vs. Joint Rreference.....	42
Figure 20: Mechanical Analog of the Muscle.....	43
Figure 21: Muscle Tension Force vs. Muscle Length.	44
Figure 22: Final SEMG capture circuit	47
Figure 23: The Arduino Uno Microcontroller	48
Figure 24: USB Arduino interface circuit.....	50

1 INTRODUCTION

1.1 Project Introduction

This thesis seeks to design an open-source basic human-machine interface for the development of a teleoperation system for the control of a humanoid robot. Applying a teleoperative control system to a humanoid robot is clearly appropriate. The majority of systems are designed for human interaction. This is normally not an issue, but in the event of an emergency these critical systems may be inaccessible by living people. The proposed system will further integrate the operator into the robot's control scheme by responding to the operator's surface muscle tissue signals. By directly reading and mimicking the operator's muscle activity a full one-to-one teleoperative system can be realized. Not only will the operator be able to affect the robot's environment, he or she will control the robot as naturally as they control their own body, leading to more proficient and natural operation of robotic platforms.

1.2 Teleoperation

1.2.1 History

Haptic teleoperation uses of robotic systems have been in place since the 1950's but did not pick up steam until NASA began heavy development in the 1980's. Systems then were called Bilateral Master-Slave Manipulators (MSMs) and were used largely in the nuclear sector. Virtual systems, such as the GROPE-IIIb project, tried to allow humans to interact virtually on the molecular level. [1] This research branched out into various exoskeleton systems, tactile interfaces, and surgical devices operating today. Up until the early 1990's the distinction between teleoperation (practice) and telepresence

(ideal) had not been defined. The main goal, however, has remained; to fully immerse the user in a virtual operating environment such that “... the operator feels physically present at the remote site”. [1]

By creating a system that naturally integrates with human perception, telepresence systems (instead of teleoperative ones) can be developed. Haptic systems are developed here at Ohio University. The Virtual Haptic Back project allows for Osteopathic Students to train on a virtual human back. This eliminates the need for live subjects, allows for rare disease cases to be presented, and provides a repeatable level of intricate tactile detail. The device is depicted below in Figure 1. [2]

Figure 1: The Ohio University Virtual Haptic Back teaching device. The operator, through haptic feedback, can interact physically with a virtual object. The system allows the student to experience scenarios that are difficult to replicate in the clinical setting but vital to the student’s education. Source : <http://www.oucom.ohiou.edu/iinr/images/VHB1.jpg>

1.2.2 Motive for Development of New Teleoperative Systems

Robots allow the accomplishment of tasks that are too tedious, dangerous, or simply impossible for living beings to perform. This gain in functionality comes at the price of a complex control system necessary to perform a handful of tasks. On the opposite end of the spectrum, the physically limited human body can perform a nearly infinite range of tasks. The field of control systems engineering has been striving to develop control systems that mimic the capability of the natural neural control systems. However, this is a futile task as machine systems cannot integrate the sheer number of sensory inputs. In addition, machine learning algorithms are far behind their biological counterparts.

What technology does have the ability to do is to integrate input from a biological system while providing information to a robotic controller. This closed loop system forms the basis of robotic teleoperation. The recent Fukushima nuclear plant disaster, for example, is one such incident where a humanoid telepresence robot would have been effective. High radiation levels made control systems inaccessible, and they had to be interacted with via robotic means. These robots were not humanoid in nature and were limited to simple lifting or sampling tasks. [3] A humanoid robot would have been able to perform these tasks and interact with machinery as well, providing a faster response to the crisis and hopefully averting the radiation leaks that occurred.

1.2.3 Example

Recently NASA deployed a humanoid telepresence robot named Robonaut 2 (R2), seen in Figure 2 . This robot was designed to mimic the anatomy and range of

motion of an astronaut. The platform will be fixed in place where it will assist in basic tasks and routine maintenance of space machinery. This robot is a test program to evaluate the functionality and feasibility of using robots in space, possibly replacing their human counterparts [4]. This is a contentious issue, as removing the astronaut makes the mission logistically simpler and removes certain design constraints (such as keeping said astronauts alive). Opponents to using robots in space see cutting out the human presence as losing the precision of control and, ideologically, something fundamental in the spirit of exploration. By integrating a haptic teleoperation/telepresence system, a happy medium between both sides can be achieved by keeping humans directly involved in the exploratory experience.

Figure 2 Robonaut 2 humanoid teleoperation robot showing its strength and dexterity [4]

1.3 Robotic Platform DARwIn-OP

1.3.1 Technical Specifications

The DARwIn-OP robot, or Dynamic Anthropomorphic Robot with Intelligence-Open Platform, is an exciting new development in the field of humanoid robotics. The DARwIn-OP, seen below in figure 2, is a humanoid robotics platform developed by Virginia Tech, the University of Pennsylvania, and Robotis Inc. The robot can be seen in Figure 3

Figure 3: DARwIn-OP robotic platform features.

source: <http://3.bp.blogspot.com/-pCYTqGFDrAY/TZuG07I6N7I/AAAAAAAAAFhs/JML4dPXcKh4/s1600/002.jpg>

It is a 20-DOF robot that is designed to be open-source and humanoid in nature. The platform stands 454.5 mm tall at full height and has a mass of 2.9 kg, with a total of twenty degrees of freedom. Each leg has six degrees of freedom with three residing in the hip, one in the knee, and two in the ankles. The arm accounts for three degrees (two in the shoulder and one in the elbow) but can be upgraded to five (including the gripper and wrist). The head accounts for the final two degrees of freedom. Each joint is driven by a single Dynamixel MX-28 servo by an internal CM-730 Robotis servo-controller [5].

In addition to the servo-controller the DARwIn-OP utilizes an HD digital video camera, tri-axis gyroscope/accelerometer, and two microphones. To integrate these sensors and communicate with the servo-controller the DARwIn-OP runs off of a 1.6 GHz Intel Atom Z530 FitPC2i with an onboard 4 GB SSD with an Ubuntu Linux operating system. The DARwIn is coded in C++. The platform is able to operate in both tethered and battery powered modes. The LiPO 3CELL 11.1v 1000mAh battery allows for up to 30 minutes of operation. In the event of a low battery, the DARwIn-OP's dual power system allows for battery changing without shutting down the unit [5].

1.3.2 Merits of Open Source

As the DARwIn-OP robot is open source, all technical diagrams and programming documentation is available and includes a large database of user generated code. By opting to make the system open source the platform as a whole will benefit from incentivized growth, as well as faster and higher quality developments. Commercialization will be deemphasized in favor of academic research. By choosing this platform the research presented in this work allows Ohio University to become involved with the DARwIn-OP community at its base [6].

1.4 Electromyography

1.4.1 History of Electromyography

Electromyography (EMG), or reading the electrical activity of muscle tissue, has been studied since the late 1600's with Galvani's classic twitching frog leg experiment. [7] Some experiments involve the use of intra-muscular needle electrodes, but an alternate method is recording the signals at the skin's surface. It took until the

development of electrical signal processing and the necessary circuitry in the 1960's for surface EMG to become applicable in the clinical field. Furthermore, until the computer revolution of the 1980's, conducting wide scale research was difficult. Since then the number of research papers and clinical diagnostic work has skyrocketed and made sEMG an integral part of medicine and kinesiological research. [7]

1.4.2 Biology of Electromyography

The EMG signal is derived from bipolar or unipolar measurements of voltage potentials across the muscle. When a signal from the brain travels to the muscle, the signal branches to groups of muscle cells called motor units. Each of the four nerves of the arm branches into single neurons, and then these separate into several hundred or thousand motor units. A nerve signal, in the form of an action potential, triggers the muscle cells in the motor unit to contract. Each motor unit acts to amplify the muscle. [8]

Each motor unit's contraction sums together to shorten or hold the muscle length constant depending on what the limb is doing. This pulsatile method allows the brain to exercise very precise control over muscle activation. It also allows the brain to increase how much force is exerted by either recruiting more motor units or by pulsing them at a higher frequency. [8] The signal routing of this system is depicted below in Figure 4.

Figure 4: The Neuromuscular System showing how signals are sent from the brain and spine down to the individual muscle cells.

Source: <http://www.dynamicscience.com.au/tester/solutions/biology/spotsmedicine/motorunit.jpg>

This signal can be read either via surface electrode or intramuscular needle. The surface pad is less invasive but yields noisier results. Interpreting the signal is performed either on the raw signal or an amplified, rectified, and filtered signal known as the “Integrated EMG”. Information in the frequency domain below 10 Hz is considered to be movement artifacts. Past 500 Hz the signal becomes negligible [9]. The relation between SEMG, joint angle, and muscle force is complex. That said, SEMG does vary with respect to joint angle as the limb pose varies. [10]

1.5 Thesis Objectives

This thesis will detail the work done to satisfy the following objectives

- Develop a mechanical model for the human arm
- Create a device to record SEMG and joint angle
- Determine the relationship between SEMG and elbow joint angle
- Use SEMG readings to command robot joint angle
- Ensure all work and materials can be considered open source

1.6 Thesis Outline

This thesis details the development of a 1 degree of freedom EMG-based Teleoperation system for the DARwIn-OP robot. Section 2 deals with anatomy and modeling of the mechanical motion of the human Biceps Brachii muscle. Section 3 details the design and revision of an EMG measuring system, including recorded results and analysis. Section 4 is the final system linking the EMG measurement system to the DARwIn-OP robot. This thesis is then concluded with a discussion on the developed EMG-Angle relationship as well as overall system performance and future work.

2 MODELING

2.1 Human Arm Anatomy

This thesis seeks to fully replicate human motion of the elbow joint. The basic first step is to develop a mathematical model governing the system. The system considered is the human elbow joint held in the neutral position; hanging at the side while standing erect. The arm is composed of many muscles, tendons, ligaments, and bones all combining and cooperating to produce one of nature's most versatile manipulators. We will only be considering components of the human arm involved with elbow flexion. In human anatomy the forearm is actuated about the elbow joint via opposing extensions and contractions of the Biceps Brachii and Triceps Brachii. The muscles attach across the joint, linking the Humerus to the Radius and the Ulna. Other muscles are involved with stabilization as well as motion. However, these two muscles are directly involved with the motion and are the largest. [11] The configuration of the human arm is depicted below in Figure 5

Figure 5: Diagram of the human arm anatomy. This diagram is simplified but shows the position of the key elements to this system; The two parts of the arm and the Biceps muscle. Source: <http://saburchill.com/images02/020107002.jpg>

2.2 Biceps-Arm Mechanical System Analog

The anatomy of the human arm lends itself to be replicated with a cable driven robot, on account of the push-pull nature of the manner in which the Biceps and Triceps articulate the forearm about the elbow. The DARwIn-OP robot is not a cable driven robot with a single servo replacing the muscles. It is fortunate that the natural operational orientation of the robot for this one-degree of freedom movement is such that the Biceps muscle is always in tension regardless of joint angle. The Robot stands vertically with the arm at its side pointing towards the ground. This allows us to disregard any action of the Triceps muscle in modeling. When the system is extended to additional degrees of freedom, this model will become invalid as there are positions where the Biceps would be

under negative tension and thus the Triceps would need to activate to hold the desired position.

The mechanics of the arm will be considered from a pseudo-statics perspective. This means that the arm, from the mechanics point of view, is being held still. The arm may actually be moving, but it is moving sufficiently slow enough to ignore the effect of dynamics. The reasoning behind this approach is to limit the number of activated muscles during motion. Many muscles act in concert to affect motion, thus it is necessary to restrict the motion for this 1 DOF system in a way that does not unduly limit the user. A final consideration is that the user is not holding any weight in their hand. This is also to limit contractions not associated with joint angle movement.

The mechanical analog becomes a two link system connected by a revolute joint. The linkage is articulated by the contraction of the Biceps Brachii muscle. This pseudo-static system is a straight-forward force-moment balance. The moment applied by the Biceps Brachii is balanced against the moment due to gravity acting on the mass of the forearm. For modeling purpose averages, drawn from tabulated medical data, arm segment mass and lengths for an adult male are used. The goal of the model is to determine a relationship between joint angle and muscle tension, which will then be compared to lab collected data for EMG-joint angle data to develop the model on which the teleoperative system will function.

The following method is adapted from [12]. The arm is being considered in a pseudo-static, unloaded state. This means the arm is not moving fast enough for dynamics to be considered and the arm holds no weight. The static balance operates on

three equations describing the sum of lateral and vertical forces and moments. We are considering the arm in a static configuration, thus these three sums add to zero.

$$\sum F_x = 0 \quad (1)$$

$$\sum F_y = 0 \quad (2)$$

$$\sum T = 0 \quad (3)$$

From the mechanical system depicted below in Figure 6, we can populate equations 1-3 with the force vector components and moments.

Figure 6: Mechanical Model of the Human Arm for simple Biceps Brachii muscle action. All forces and moments originating from the actions of the Biceps and gravity are shown. Part lengths and radii are present as well.

$$\sum F_x = R_x + T_B \cos(\theta) = 0 \quad (4)$$

$$\sum F_y = R_y + T_B \sin(\theta) = 0 \quad (5)$$

$$\sum T = T_B r_B (\cos \Phi \sin \theta - \sin \Phi \cos \theta) = r_{CG} \cos \Phi W_{23} \quad (6)$$

These equations can be arranged into matrix form below.

$$\begin{bmatrix} 1 & 0 & \cos \Phi \\ 0 & 1 & \sin \Phi \\ 0 & 0 & r_B(\cos \Phi \sin \theta - \sin \Phi \cos \theta) \end{bmatrix} \begin{bmatrix} R_x \\ R_y \\ T_B \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ r_{CG} \cos \Phi W_{23} \end{bmatrix} \quad (7)$$

It can be seen from the matrix, the Biceps tension is decoupled from the reaction forces present within the elbow. This allows for an expression of the Biceps tensions in terms of muscle and joint angle.

$$T_B = \frac{r_{CG} \cos \Phi W_{23}}{r_B(\cos \Phi \sin \theta - \sin \Phi \cos \theta)} \quad (8)$$

We cannot measure the internal angle the Bicep makes in attaching to the forearm, but the angle can be expressed in terms of the joint angle via vector loop closure. The loop consists of the vectors forming the upper arm, radius of the Bicep attachment, and the length of the Bicep. The vector loop can be broken into both vertical and horizontal components, and from that the angle can be determined via trigonometry. The loop is seen graphically below in Figure 7.

Figure 7: Vector Loop Closure for the length and angle of the Biceps muscle.

$$L_B + L_1 + r_B = 0 \quad (10)$$

$$L_B = -L_1 - r_B \quad (11)$$

We can break this equation into both vertical and horizontal components.

$$\begin{bmatrix} L_{Bx} \\ L_{By} \end{bmatrix} = \begin{bmatrix} L_B \cos \theta \\ L_B \sin \theta \end{bmatrix} = \begin{bmatrix} -r_B \cos \phi \\ L_1 - r_B \sin \phi \end{bmatrix} \quad (12)$$

We can use the classical Cartesian to Polar coordinate transformation function to determine an expression for muscle angle in terms of joint angle.

$$\tan \theta = \frac{Y}{X} \quad (13)$$

$$\theta = \text{atan} \frac{Y}{X} \quad (14)$$

$$\theta = \text{atan} \frac{L1 - r_B \sin \Phi}{-r_B \cos \Phi} \quad (15)$$

We can also write an expression for the length of the Biceps muscle from the vector loop closure.

$$L_B = \sqrt{(X)^2 + (Y)^2} \quad (16)$$

$$L_B = \sqrt{(-r_B \cos \Phi)^2 + (L1 - r_B \sin \Phi)^2} \quad (17)$$

2.3 Simulation Results

A Matlab simulation was developed to evaluate the model. The range of tested angles covered full extension to full flexion. Code associated with this simulation can be found in (Appendix). The Human elbow joint range was taken from [13] to be a total of

150 degrees starting from full extension at -90 degrees to an end point at full flexion at 50 degrees. To avoid the singularity at full extension the simulation starts at -89.9 degrees.

Trends for muscle tension, muscle length, and muscle angle versus joint angle are plotted by the program. The results are seen below in Figure 8 through Figure 9 respectively.

Figure 8: Muscle Tension versus Joint Angle. The total tension within the muscle decreases as the forearm flexes.

Figure 9: Muscle Length vs. Joint Angle. The length of the muscle decreases with increasing joint angle because the motion of the limb is due to muscle contraction.

Figure 10: Biceps Insertion Angle vs. Joint Angle. The angle at which the muscle connects to the forearm varies as the forearm completes its flexion. The angle is referenced to 0 degrees on the standard X-Y coordinate frame.

As expected, the muscle length and tension decrease over the span of the human joint range. The length is explained by the geometry of the arm and fits logically. The tension decreasing can be explained by the angle of Biceps insertion relative to the joint angle. Seen below in Figure 11, the angle is largely unfavorable for most of the motion. This coupled with the small distance from the point of rotation induces high tensions at low joint angles. The moment due to gravity fluctuates as the arm moves above and below the zero angle, but as the Biceps insertion is favorable for ± 45 degrees about that point, the effect is reduced. As the arm reaches maximum flexion the Biceps insertion angle changes little from that favorable point. Thus tension is minimal at the upper joint

limit. The opposite is true for the lower limit of the joint angle where the insertion angle makes the tension almost parallel to the limb. This produces maximal torque.

Figure 11: Relative Biceps Insertion Angle vs. Joint angle. This plot shows the angle the Biceps muscle makes with respect to the forearm. For the arm fully extended we see the muscle running parallel to the limb. As the limb moves through its range the muscle angle decreases.

We can conclude two opposing theories from the above simulation. The first conclusion relies on SEMG activity to be directly related to the effort the muscle is exerting to maintain its pseudo-static position. As the tension in the muscle decreases and the joint angle increases the SEMG will decrease. The other possibility is that SEMG is related to muscle length and so SEMG will increase with joint angle. With these two possible theories, it was necessary to begin collecting data to determine how SEMG was

related to joint angle in an isolated sense. The behavior of SEMG in lab settings will indicate a conclusive link to one of these theories.

3 SEMG MEASURING SYSTEM

3.1 Circuit Design

Building a SEMG amplification circuit is simple to do with modern electronics. Many designs are publicly available and well understood. The goal of the circuit is to filter and amplify an extremely low level signal with low signal-to-noise ratio. Typical signal levels for SEMG can be considered to be around 1mV. As the signal will be amplified greatly, any noise in the signal can quickly drown out SEMG signals. The most common method for the first, and most critical, stage is the use of an instrumentation amplifier. The instrumentation amplifier is an amplifier configuration that has a very high common mode rejection ratio (CMRR). Any ambient hum and cardiac signals will be omnipresent across the muscle area and as such it will be rejected by the amplifier. The amplifier has a gain of 77.

The signal is then passed through a single order bandpass signal designed to only pass signals that are related to the SEMG. The filter has a passband between 50 and 300 Hz. This range captures the most significant spectrum of the SEMG signal while rejecting low frequency movement artifacts and high frequency noise. Any signal outside of the passband is rejected at the level of an order of magnitude per frequency decade.

Lastly, the capture circuit has a dual op-amp amplification stage. The signal passed out of the filter is fed into a unity gain follower to buffer the signal. The buffered signal then enters a non-inverting amplifier and is multiplied by 5. This leads to a gain in the passband of 385. This gain allows the DAQ to read a range of SEMG signals from +/-

13 mV. This can be increased by supplying a higher voltage range to the amplifiers. However, as stated previously we are expecting signals that are usually less than 1mV. The signal will be rectified and further processed in MATLAB. The recording circuit design for SEMG measurement is seen in Figure 12.

Figure 12: SEMG and Angle Position Circuit. The SEMG is read from a bipolar electrode with a referenced ground. This signal is then passed through an instrumentation amplifier, bandpass filter, unity gain buffer and non-inverting amplifier. The reference angle measurement device is simply a potentiometer acting as a voltage divider.

3.2 Reference Angle Measurement Device

A relationship between joint angle and SEMG needs to be derived, thus a reliable measure of joint angle is needed. Measuring the angle of a mechanical link is a common sensory task. Shaft encoders are high precision devices. With that in mind, it must be said that they require support hardware to interpret the dual signal output. Another solution trades precision for simplicity. Potentiometers translate rotational motion into a variable resistance. Using the 3-tap potentiometer as a voltage divider, a DAQ compliant signal is created that is directly related to joint angle. The circuit is shown above in Figure 12.

The rotary encoder was attached to a commercially available support brace made of comfortable fabric that attaches above and below the elbow with Velcro straps. A hinged structure was attached to the brace above and below the elbow with the hinge centered at the elbow. This configuration allows for the lower segment to follow the movements of the forearm while the upper arm remains fixed. The rotational motion of the lower segment was then mechanically linked to the potentiometer shaft via 1:1 gearing. The device is shown in use in Figure 14.

Figure 13: Joint angle measuring device. This is worn by the user to provide a stable reference to the current joint angle via potentiometer position.

This device is not calibrated and zero points vary. This does not pose a problem as the readings can be normalized in post-processing and the range of motion of the subject is determined by doing a calibration sweep during testing. The calibration sweep is a slow movement of the arm through the whole range of motion to introduce the maximum and minimum voltages into the signal for proper normalization.

3.3 Labview Measurement System

To collect the data from multiple analog sources, a National Instruments DAQ was purchased to be used in conjunction with Labview. The Labview program allows the development of graphical data logging and processing interfaces. This interface was

designed to perform three tasks; zeroing of the reference angle, data logging, and visualization. The reference angle voltage reading can be zeroed to a user-specified point. This point is taken to be full arm extension. The user fully extends and the recorder presses the zeroing button. All recorded readings for the joint angle are referenced to that baseline voltage. EMG is directly recorded with no alterations. The LabView system displays the data to the user as it arrives in real time. Recording a set of data is simple. The user runs the VI, positions the subject in the neutral (fully extended) position, zeros the reference, and hits record. Data is stored in a tab delineated list that is able to be imported into most data processing programs. The system can be seen being worn in

FFigure 14: This shows the data collection system in use. The joint angle reference is being worn on the right arm in conjunction with the SEMG measurement system. The VI fore and backgrounds are shown as well in Figure 15 and Figure 16.

Figure 14: This shows the data collection system in use. The joint angle reference is being worn on the right arm in conjunction with the SEMG measurement system.

Figure 15: User interface for data collection. The Flex Zero Button is pressed to reset the zero reading for the joint angle reference measurement. The Enable and Stop buttons control recording while both graphs show live data as it streams in.

Figure 16: Back end of the VI shown before. This diagram shows how the signals are routed and how the zeroing for the joint angle reference works.

3.4 Results and Discussion

After many trials using the measurement system a consistent pattern emerged. As the user fully flexed their arm the SEMG readings increased in proportion. The higher the joint angle, the more pronounced the SEMG activity was. To test our hypothesis a series of single flexion-extensions were performed to determine to what degree the SEMG reading and joint angle were related, as well as to test repeatability. The flexion-extensions were combined into a single profile, several of which can be seen below in Figure 17. A linear regression was fitted to the data and the Coefficient of Determination of .9588, indicating that SEMG is linearly related with the joint angle. For clarity and comparability all data values are normalized to their maximum values. Testing also demonstrated high repeatability in results with only minimal variations in SEMG.

Figure 17: Processed SEMG and Normalized Joint Angle Reference

The method of processing the data is as follows. In Figure 18, the normalized rectified raw SEMG and joint angle references are shown for a series of three full extension-flexion motions.

Figure 18: This plot demonstrates the rectified SEMG and joint reference readings for three full extension-flexions. SEMG is clearly directly related to joint angle.

The SEMG data was clearer when a 2nd order lowpass Butterworth filter with a corner frequency at 30 Hz was applied. The filtered result is seen below in Figure 19.

Figure 19: Filtered Normalized SEMG vs. joint reference for three full flexion-extension motions. The cleaned up data shows the SEMG trend well. Variations during static hold are attributed to the unsteadiness of the user.

The trend in the data suggests that SEMG is directly related more to muscle length rather than muscle tension in the pseudo-static unloaded case. This seems counterintuitive to the idea that when the muscle is under tension the muscle needs to work harder to maintain its position. To reconcile this finding a more complex model of muscle behavior is needed. The accepted model for muscle Force-Length relationship is the Hill-Muscle Model. [14] This model approximates the muscle as a three element system consisting of the contractile element and two springs. The first spring represents

Figure 21: Muscle tension force versus muscle length. Stretched muscles dissipate tension in their passive components while contracted muscles take up the tension in their active contractile elements. Source:http://medim.sth.kth.se/neuronik/projects/FEM/FEM-neck/summerad_kraft_bild-eng.jpg

The muscle acts in two phases depending on the length of the muscle. For periods when the muscle is stretched from its resting state, much of the muscle tension is taken up by the passive connective tissues. During contraction stages the muscle force is purely on the contractile element. Tension in the muscle also decreases as the muscle contracts. This model fits with both experimental and theoretical results. It can be concluded that in the case of the pseudo-static unloaded arm the SEMG is directly a result of the muscle activity associated with keeping the muscle contracted to the length that results in the commanded joint angle. [14]

To test the hypothesis a series of single flexion-extensions were performed to determine to what degree the SEMG reading and joint angle were related. Repeatability was also tested.

4 FINAL SYSTEM DESIGN

The next stage is filtering and rectification of the signal. Amplified SEMG varies above and below ground, and as such it must be processed to be compatible with the DAQ. A simple bridge rectifier is inappropriate for this application so a precision rectifier must be used. This is also a common circuit and simple op-amp examples exist. The two stages are capacitively coupled to remove the DC offset. This provides a DC signal that varies from 0 to 5V. Lastly, the signal is put through a 2nd order Butterworth lowpass filter similar to the one used in post processing the earlier recorded SEMG signals. The device is then hooked into one of the Arduino's ADC input pins. The circuit is shown below in Figure 22

Figure 22: Final SEMG capture circuit. The signal is read, amplified, filtered and conditioned before being passed to the Arduino ADC.

4.1 Arduino Microcontroller

The Arduino device is a modified Atmel microcontroller board intended for use by hobbyists and students to quickly develop applications. The specific chip utilized is the ATmega328 microcontroller featuring 32kb of program memory and 6 ADCs. It can operate up to 20 MHz. The system features a simplified coding syntax and support hardware to facilitate rapid prototyping. Each device is configured for multiple analog inputs and digital output pins, as well as programming over USB. The Arduino is an open-source platform. The intention is to open up microcontroller development by creating a free knowledge base. As with the DARwIn-OP all aspects of the device, from

schematics to source code, are freely available. The Arduino used in this system is depicted below in Figure 23.

Figure 23: The Arduino Uno Microcontroller. This is a the standard Arduino board complete with USB programming interface, DC power supply circuit and pre-socketed I/O pins. The heart of the device is the ATMEL microcontroller.

Source: http://arduino.cc/en/uploads/Main/arduino_uno_test.jpg

4.2 Robot-Sensor Interface

As the DARwIn-OP is a complex machine, there is no simple method of integrating external sensor readings into pre-coded architecture without invasively changing the source code or hardware. The robot does have two USB ports for externally connecting to devices. However, there is the issue of limited hard drive space. Since processing software proved too large to run, an alternative solution was devised. The

Arduino is configured to poll the SEMG circuit via the built in ADC. The ADC compares the signal to a 5v configurable reference source. The reference voltage can be configured to a lower voltage for greater resolution. Although sampling rate is dependent on the speed of the program execution, sampling rates over 1 kHz are common. The signal is conditioned by off-board hardware and fed into the microcontroller.

As DARwIn-OP is an open source platform a plethora of publicly available code exists and is ready for use. One such program is TellDarwin. TellDarwin is a command line parser for the robot. The Linux terminal that the program is run from is able to accept plain English commands to control the robot. We do not need to do any complex commands at this time except control of a single joint. This allows the Arduino to take over sensor processing through the use of a second open-source program. [15]

The Arduino is collecting the ADC values of the SEMG circuit. The last step is to convert the readings into plain text commands to the DARwIn. The simplest method is to directly transmit the commands over USB to the robot. This is done by using another open source program from Practical Arduino that turns the Arduino in to a plug-and-play keyboard [16]. This program requires that a USB interface be made and connected to the Arduino. The schematic is shown below in Figure 24

Figure 24: USB Arduino interface circuit. This interface allows the Arduino to connect to any USB slot directly through its digital output pins. [15]

As the program runs, the ADC values are parsed into text commands that are compatible with the TellDarwin program and are typed out, letter by letter, into the command line. Though throughput of the system is slightly reduced because of this interface, the Arduino is able to directly communicate with the DARwIn-OP.

5 CONCLUSION

The results of this investigation show that for the unloaded, pseudo-static case of arm flexion-extension, the intensity of SEMG is directly related to the joint angle of the elbow. The constraints on motion are permissible as long as the operator in a teleoperative system is not performing any type of lifting and also is moving sufficiently slowly for the sake of precision. The direct relationship of SEMG to joint angle makes the creation of an interface a simple task of signal processing and utilizing appropriate interface hardware.

From biology we know that muscle activity is the motivating force behind joint motion, and this activity can be read by SEMG. The muscle generates a force through contraction. The necessary force is determined by a number of factors including joint angle, arm load, limb motion, and body position. The scenario used for this system involved the user in an upright, unloaded position, engaging in sufficiently slow movements to negate dynamics. It was seen in data taken during the experimental phase that SEMG was directly related to the length of the muscle and not to tension. This conflict between length and tension was resolved with the use of the Hill-Muscle Model. An alternative explanation may be related to changes in muscle tissue concentration between each electrode. Muscle shortening would increase the number of active muscle units between the electrodes and thus increase the SEMG signal.

5.1 Future Work

The goal of this project was to investigate the relationship between SEMG and joint angle as well as develop an interface between the SEMG signal and the DARwIn-OP robotic platform. Both tasks were accomplished. The following future tasks would enhance the system. The interface between the Arduino and the DARwIn-OP via TellDarwin is not able to work without some delay between input and joint motion. The code on both platforms should be reviewed for optimization, or another connection must be investigated. A more comfortable manner to acquire SEMG signals should also be looked into as the adhesive of the Ag/Cl leads make them difficult to quickly adhere and remove. They also leave behind a residue. Dry contact technology exists and should be considered. Lastly, the effects of fatigue and arm loading should be looked into to determine how strict the pseudo-static unloaded constraint is.

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APPENDIX A: SIMULATION CODE

```

function Thesis()
load emg.mat
load pot.mat
load time2.mat

% load time4.mat
% load pot4.mat
% load emg4.mat

close all
%Constants Adult Male

time = time-time(1)-8;
% time4 = time4-time4(1);

g = 9.81 ;
W2 = 16.64 ;      %N
W3 = 5.78 ;      %N
W23= (W2+W3) ;    %N

L1 = .315 ;      %m
L2 = .287 ;      %m
L3 = .015 ;      %m

r23= .178 ;      %m

rb  = .057 ;      %m

T2=[-89:.1:55];

TB = zeros(1,length(T2));
tb = zeros(1,length(T2));
lb = zeros(1,length(T2));

%constuct solution arrays, slow real locate method

figure
for i=1:1:length(T2)
    theta = T2(i);
    tb(i) = (180/pi)*atan2((L1-rb*sind(theta)), -rb*cosd(theta));

    TB(i) = (r23*cosd(theta)*W23)/...
            (rb*(cosd(theta)*sind(tb(i)))-sind(theta)*cosd(tb(i)));

    lb(i) = sqrt((L1-rb*sind(theta))^2+(rb*cosd(theta))^2);

```



```

        hold on
        axis square

    end

    hold off
    figure
    plot(T2,tb);
    figure
    plot(T2,TB);
    figure
    plot(T2,lb);
    figure
    plot(lb,TB);
    figure
    plot(T2,tb-T2)

    Hd = lpbw3rd70hz
    [X,f]=fdomain(emg,500);
    plot (f(length(f)/2:length(f)),X(length(f)/2:length(f)));
    figure

    [X,f]=fdomain(filter(Hd,abs(emg)),500);
    plot (f(length(f)/2:length(f)),abs(X(length(f)/2:length(f))));
    figure

    plot(time,mat2gray(abs(emg)),time, mat2gray(-pot));
    figure

    plot(time,filter(Hd,abs(emg))*50,time,-pot)
    NormPot= mat2gray(-pot);
    NormEMG= mat2gray(filter(Hd,abs(emg)));
    plot(time,NormEMG,time,NormPot)

    figure
    plot(time,smooth(mat2gray(filter(Hd,abs(emg))),1000))

    % Hd = lpbw3rd70hz
    % [X,f]=fdomain(emg4,500);
    %
    % figure
    % plot(time4,mat2gray(abs(emg4)),time4, mat2gray(-pot4));
    %
    % figure
    % plot(time4,filter(Hd,abs(emg4))*50,time4,-pot4)
    % NormPot= mat2gray(-pot4);

```

```

% NormEMG= mat2gray(filter(Hd,abs(emg4)));
% plot(time4, NormEMG, time4, NormPot)

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

function Hd = lpbw3rd70hz
%LPBW3RD70HZ Returns a discrete-time filter object.

%
% M-File generated by MATLAB(R) 7.10 and the Signal Processing Toolbox
6.13.
%
% Generated on: 18-Apr-2012 14:11:27
%

% Butterworth Lowpass filter designed using FDESIGN.LOWPASS.

% All frequency values are in Hz.
Fs = 48000; % Sampling Frequency

N = 2; % Order
Fc = 30; % Cutoff Frequency

% Construct an FDESIGN object and call its BUTTER method.
h = fdesign.lowpass('N,F3dB', N, Fc, Fs);
Hd = design(h, 'butter');

% [EOF]

```

APPENDIX B: ALTERNATE JOINT ANGLE REFERENCE

An alternative to the rotary potentiometer angle measurement system is the use of flexible resistive bend sensors. The device was intended to be applied to the surface of the elbow brace and conform to the contour of the arm. As the elbow bent, the sensor would bend with the limb and change resistance. A Wheatstone Bridge circuit was used to amplify and convert the changes in resistance to voltage changes. A variable potentiometer was swapped with a fixed resistor on the opposite branch to enable trimming of the voltage differential to zero for a zero joint angle. The sensor and circuit are seen below in Figure 25.

Figure 25: Flexible Bending Sensor and Wheatstone Bridge Circuit

This device was not used due to the inconsistency of the bending sensor resistivity. The device's resistive behavior is linear for a set bending profile of fixed-free with deflection increasing along the length. Any changes to this profile result in inconsistent resistive readings when compared to the baseline bending profile. The sleeve

the device was affixed to was not consistent in conforming to the user due to a non-smooth anatomical surface as well as shifting during use. The mechanical brace and potentiometer system provided repeatable and reliable results. As this device was intended as a “gold standard” sensor, any inconsistencies invalidated its use.

APPENDIX C: ARDUINO CODE

```

#include "UsbKeyboard.h"

#define BUTTON_PIN 12

// If the timer isr is corrected
// to not take so long change this to 0.
#define BYPASS_TIMER_ISR 1
int sensorValue = 0;
int sensorPin = 2;
String reading =String(sensorValue);
int stringIndex = 0;
int stringLength = reading.length();
char char2Print = '0';
int setupFlag = 0;
int i = 0;
int myInts[50];
int indexSmooth=0;
int sum =0;

void setup() {

    for (int j=0;j<50;j++){
        myInts[j]=0;
    }
    pinMode(BUTTON_PIN, INPUT);
    digitalWrite(BUTTON_PIN, HIGH);
    #if BYPASS_TIMER_ISR
        // disable timer 0 overflow interrupt (used for millis)
        TIMSK0&=!(1<<TOIE0); // ++
    #endif
}

#if BYPASS_TIMER_ISR
void delayMs(unsigned int ms) {
    /*
    */
    for (int i = 0; i < ms; i++) {
        delayMicroseconds(1000);
    }
}
#endif

void loop() {

    sensorValue = analogRead(sensorPin);
    sensorValue = analogRead(sensorPin);
    sensorValue = abs(sensorValue-340);

```

```

myInts[indexSmooth]=sensorValue;

for (int k=0;k<50;k++){
  sum = sum + myInts[k];
}
sum = sum/50;

if (indexSmooth==50){
  indexSmooth=0;
}

indexSmooth++;

reading = "888";

if (sum>6){
  reading= "90";
}
else if(sum>2){
  reading="45";
}

else{
  reading = "0";
}

stringLength = reading.length();
stringIndex = 0;

UsbKeyboard.update();

digitalWrite(13, !digitalRead(13));

if (digitalRead(BUTTON_PIN) == 0) {

  if (setupFlag==0){
    UsbKeyboard.sendKeyStroke(KEY_R);
    UsbKeyboard.sendKeyStroke(KEY_I);
    UsbKeyboard.sendKeyStroke(KEY_G);
    UsbKeyboard.sendKeyStroke(KEY_H);
    UsbKeyboard.sendKeyStroke(KEY_T);
    UsbKeyboard.sendKeyStroke(KEY_SPACE);
    UsbKeyboard.sendKeyStroke(KEY_S);
    UsbKeyboard.sendKeyStroke(KEY_H);
    UsbKeyboard.sendKeyStroke(KEY_O);
    UsbKeyboard.sendKeyStroke(KEY_U);
    UsbKeyboard.sendKeyStroke(KEY_L);
    UsbKeyboard.sendKeyStroke(KEY_D);
    UsbKeyboard.sendKeyStroke(KEY_E);
    UsbKeyboard.sendKeyStroke(KEY_R);
  }
}

```

```

    UsbKeyboard.sendKeyStroke(KEY_SPACE);
    UsbKeyboard.sendKeyStroke(KEY_P);
    UsbKeyboard.sendKeyStroke(KEY_I);
    UsbKeyboard.sendKeyStroke(KEY_T);
    UsbKeyboard.sendKeyStroke(KEY_C);
    UsbKeyboard.sendKeyStroke(KEY_H);
    UsbKeyboard.sendKeyStroke(KEY_SPACE);
    UsbKeyboard.sendKeyStroke(KEY_0);
    UsbKeyboard.sendKeyStroke(KEY_ENTER);
}
setupFlag=1;
    UsbKeyboard.sendKeyStroke(KEY_R);
    UsbKeyboard.sendKeyStroke(KEY_I);
    UsbKeyboard.sendKeyStroke(KEY_G);
    UsbKeyboard.sendKeyStroke(KEY_H);
    UsbKeyboard.sendKeyStroke(KEY_T);
    UsbKeyboard.sendKeyStroke(KEY_SPACE);
    UsbKeyboard.sendKeyStroke(KEY_E);
    UsbKeyboard.sendKeyStroke(KEY_L);
    UsbKeyboard.sendKeyStroke(KEY_B);
    UsbKeyboard.sendKeyStroke(KEY_O);
    UsbKeyboard.sendKeyStroke(KEY_W);
    UsbKeyboard.sendKeyStroke(KEY_SPACE);

while (stringIndex < (stringLength-2)){
    char2Print = reading.charAt(stringIndex);

    switch(char2Print){
        case '0':
            UsbKeyboard.sendKeyStroke(KEY_0);
            break;

        case '1':
            UsbKeyboard.sendKeyStroke(KEY_1);
            break;

        case '2':
            UsbKeyboard.sendKeyStroke(KEY_2);
            break;

        case '3':
            UsbKeyboard.sendKeyStroke(KEY_3);
            break;

        case '4':
            UsbKeyboard.sendKeyStroke(KEY_4);
            break;

        case '5':
            UsbKeyboard.sendKeyStroke(KEY_5);

```

```

        break;

        case '6':
            UsbKeyboard.sendKeyStroke(KEY_6);
            break;

        case '7':
            UsbKeyboard.sendKeyStroke(KEY_7);
            break;

        case '8':
            UsbKeyboard.sendKeyStroke(KEY_8);
            break;

        case '9':
            UsbKeyboard.sendKeyStroke(KEY_9);
            break;

        default:
            UsbKeyboard.sendKeyStroke(KEY_A);
    }
    stringIndex++;
}

    UsbKeyboard.sendKeyStroke(KEY_ENTER);
    delayMs(20);
#if BYPASS_TIMER_ISR // check if timer isr fixed.
    delayMs(20);
#else
    delay(20);
#endif
}
}

```

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