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SURFACE ELECTROMYOGRAPHIC CONTROL OF A HUMANOID ROBOT

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ABSTRACT

This paper 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, thus achieving control of the robotic platform via surface electromyography.

1. INTRODUCTION

This paper details the development of part of a telepresence system from first principles to a completed modular single degree of freedom teleoperation system for a humanoid robot using surface electromyographic (sEMG) signals to affect 1:1 motion between the user and the robot. For the initial system development a single degree of freedom was chosen; the right elbow due to the joint's simplicity and large controlling muscle. The design of the system was also made to be modular so that additional degrees of freedom would be simple to incorporate. To create this system the relationship between elbow joint angle and sEMG signals was determined and verified experimentally. After this the sensors, robot interface, and control software were designed and implemented.

The purpose of this system is to facilitate the development of biologically-interfaced telepresence systems for humanoid robots. Being able to combine the adaptability of the human mind with the physical capabilities and robustness of a robot solves many issues in humanoid robotics (locomotion, stability), as well as allows humans to directly operate in any environment as if they were actually there. This project also seeks to open up this research to the open-source knowledge base by using open-source materials and components. The work begins with biomechanical modeling, continues with experimental verification of results, and then a final system design of the modular 1 DoF interface ensues.

2. BACKGROUND

The DARwIn-OP robotic platform is an open-source humanoid robot with 20 degrees of freedom, integrated accelerometers, gyroscopes, cameras, Dynamixel MX-28 servos, and an onboard Intel Atom FitPC. It stands 455 mm tall and weighs 3 kg. Each leg has 6 DoF. The arm has 3. This system nears the human body's DoF with only those of the manipulators missing. The platform was developed by a joint venture between Robotis and Virginia Tech with a grant from the NSF.T he open source platform is intended for research and teaching purposes. The platform is shown below in Figure 1. [1]

Figure 1: DARwIn-OP humaniod robotic platform

Surface electromyographic signals used in the system originate from the activity of human muscle tissue. Impulses from the brain travel down through major nerves that branch into motor units that split again in order to innervate individual muscle cells. This branching behavior amplifies the original neural pulse. The stronger the signal the harder the muscle is working. The exact relationship between force and joint angle is complex and varying for each joint. The signal is measured via invasive needle probes or conductive surface pads. Surface signals, while less invasive, are orders of magnitude smaller than those of needle probes and are much noisier. This can be overcome with additional processing. [2,3]

It is common to use differential measurements tied into a high Common Mode Rejection Ratio (CMMR) amplifier. Simple notch filtering of ambient noise is not appropriate as the majority of signal information is found within the 30 to 300 Hz band, centered at 50-70 Hz. Typical post amplification filtering is the application of a band pass to remove low frequency motion and cardiac signals as well as high frequency ambient noise.[4]

2. BIOMECHANICAL MODELING

To create the interface a model is needed to understand the relation between sEMG activity and joint angle. For our system we focus on contractions of the Biceps Brachii muscle in relation to the elbow joint angle. The position of the user, sitting upright and relaxed and slowly moving, allows for simplifications of the mechanical model versus the anatomical model. The upright position allows for the Triceps Brachii's contribution to be ignored as it is only stabilizing the muscle. Slowly moving affords a pseudostatic model where motion effects need not be considered. The human anatomical model can be seen below in figure where the Biceps acts as a tension cable for a simple, hinged, fixed-free, two segment armature.

Starting from first principles, equations describing the forces at the elbow and muscle tension can be generated. The method is adapted from [5]

$$\sum \mathrm{F_x} = 0 \tag{1}$$
$$\sum \mathrm{F_Y} = 0 \tag{2}$$
$$\sum \mathrm{T} = 0 \tag{3}$$

From the mechanical system depicted below in **Error! Reference source not found.**, we can populate equations 1-3 with the force vector components and moments.

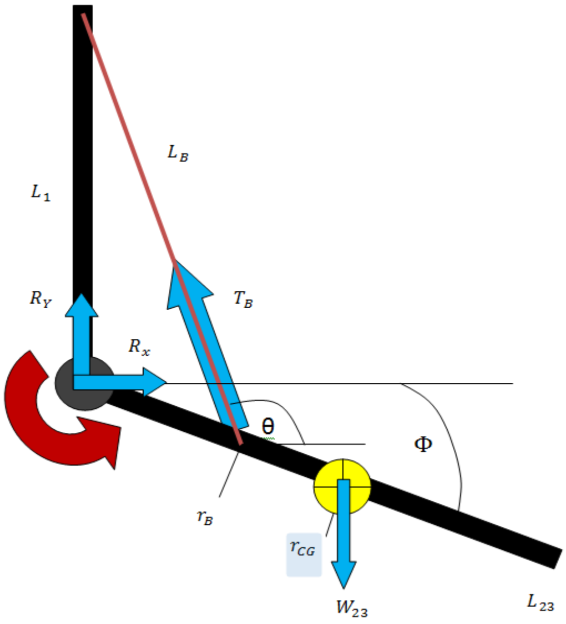


Figure 2: Human arm mechanical model

$$\sum \mathrm{F_x} = \mathrm{R_x} + \mathrm{T_B}\cos(\theta) = 0 \tag{4}$$
$$\sum \mathrm{F_Y} = \mathrm{R_Y} + \mathrm{T_B}\sin(\theta) = 0 \tag{5}$$
$$\sum \mathrm{T} = \mathrm{T_B}\,\mathrm{r_B}\,(\cos \quad \sin\theta - \sin\Phi\cos\theta) = \mathrm{r_{CG}}\cos\Phi\,\mathrm{W_{23}} \tag{6}$$

These equations can be arraigned into matrix form below.

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

From (7), it is seen that the Biceps tension is decoupled from the reaction forces. This allows for an expression of the Biceps tensions in terms of muscle and joint angle only

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

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 loop is seen graphically below in Figure 3.

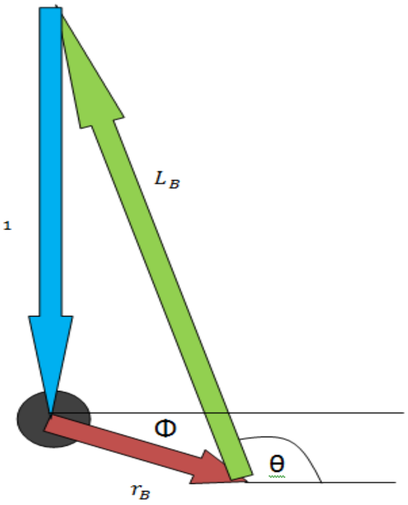


Figure 3: Human arm vector loop closure

$$L_B + L_1 + r_B = 0 \tag{10}$$
$$L_B = -L_1 - r_B \tag{11}$$

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

$$\begin{bmatrix} L_{Bx} \\ L_{BY} \end{bmatrix} = \begin{bmatrix} L_B\cos\theta \\ L_B\sin\theta \end{bmatrix} = \begin{bmatrix} -r_B\cos\Phi \\ L1 - r_B\sin\Phi \end{bmatrix} \tag{12}$$

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

$$\theta = \operatorname{atan}\frac{L1 - r_B\sin\Phi}{-r_B\cos\Phi} \tag{13}$$

$$L_B = \sqrt{(-r_B\cos\Phi)^2 + (L1 - r_B\sin\Phi)^2} \tag{14}$$

2. MODELING RESULTS

A Matlab simulation was developed to evaluate the model. The range of tested angles covered full extension to full flexion. The Human elbow joint range was taken from [6] to be a total of 150 degrees starting from full extension to full flexion; -90 degrees to 50 degrees. The results are seen below in Figure 4 and 5.

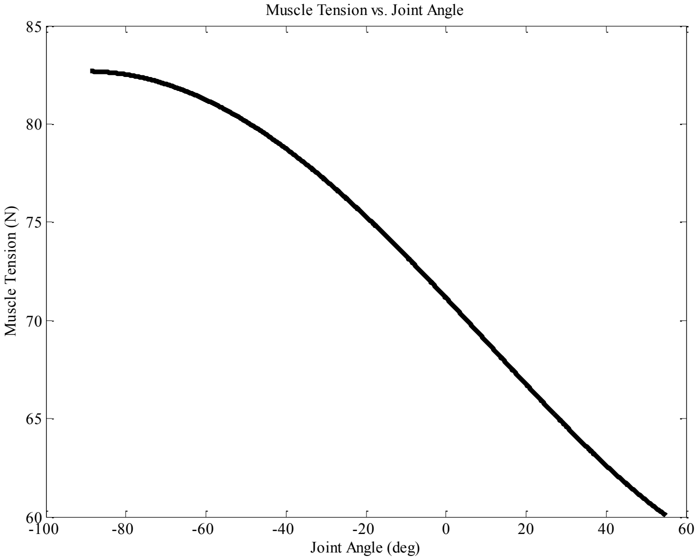


Figure 4: Muscle Tension (N) versus Joint angle (deg)

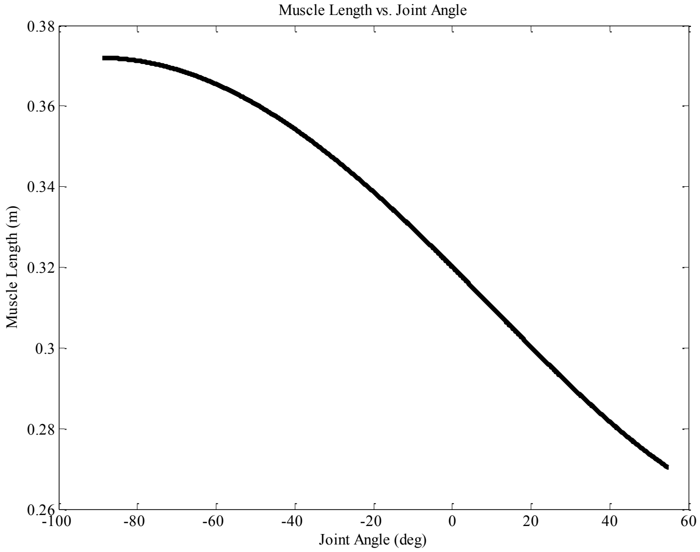


Figure 5: Muscle Length (m) versus Joint Angle (deg)

From biology we know that sEMG is involved with both the force of muscle contraction and the length of the muscle. With that in mind, two opposing theories were drawn from the above simulation. The first conclusion is that sEMG is directly related to muscle tension, the other being that sEMG is related to muscle length. As joint angle increases the behavior of sEMG will indicate the correct theory for this specific case of motion. With these two possible theories it was necessary to begin collecting data to verify the correct theory.

4. EXPERIMENTAL RESULTS

To determine which theory was correct an experimental setup was designed and constructed for simultaneous joint angle and sEMG readings. Having time-locked sEMG readings with a golden standard joint angle were vital to the final system design.

The sEMG circuit consisted of an instrumentation amplifier with a high CMRR, single pole, Butterworth passband filter set to 50-300Hz, and a single stage non-inverting amplifier. Typical sEMG readings are around 1mV and are very noisy. This circuit conditions the sEMG signal and amplifies desired signals in the passband by 385, bringing the final signal to DAQ appropriate levels. The recording circuit design for SEMG measurement is seen in **Error! Reference source not found.**.

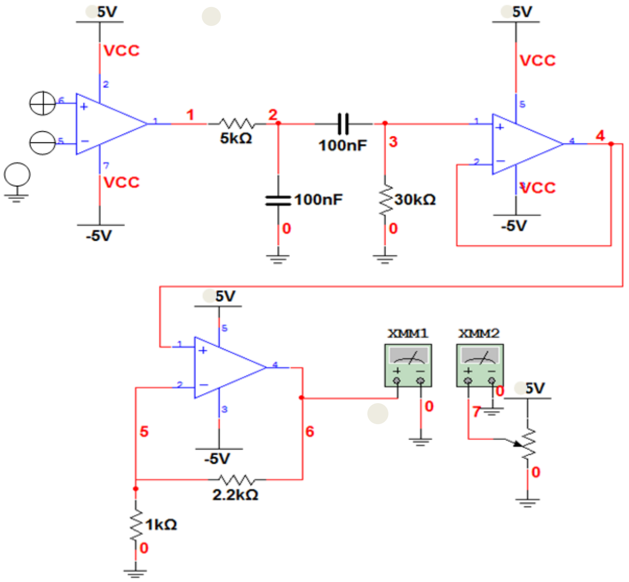


Figure 6: sEMG capture circuit

To measure the joint angle a rotary encoder was constructed from a simple 3-tap potentiometer and mounted to a wearable armature. The wearable armature, shown in Figure 7, is a sports elbow brace designed for maximum mobility and joint stability. The joint angle is converted to a variable voltage signal. This signal is not calibrated to a set angle and must be zeroed in software.

The joint angle device and sEMG circuit signals were integrated and recorded using LABVIEW software. The user was instructed to first place their arm in the neutral position so the software could zero the joint reference. After this they made slow, full sweeps of the arm covering the full range of motion. The system can be seen being worn in Figure 8 and the VI in Figure 9.

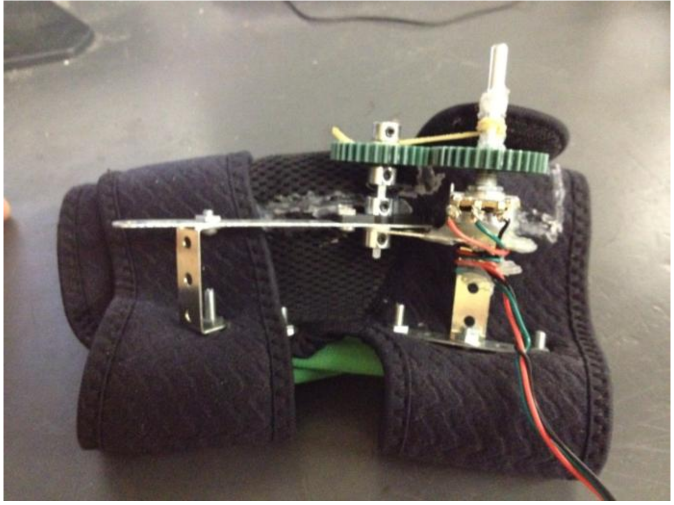


Figure 7: Joint angle reference armature

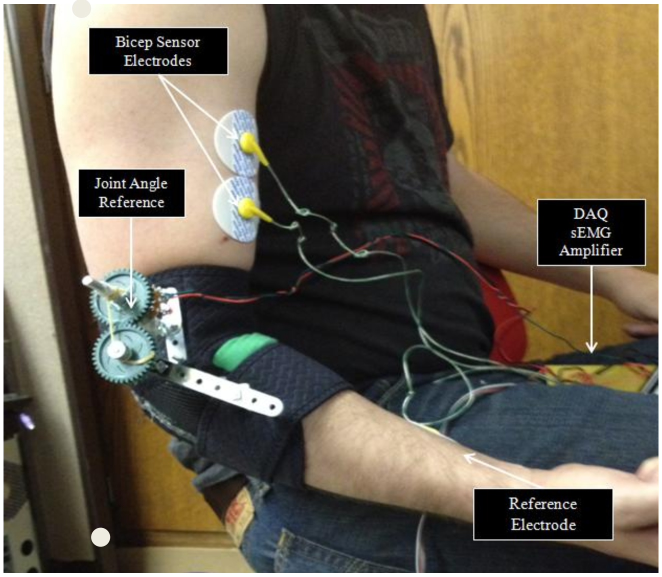
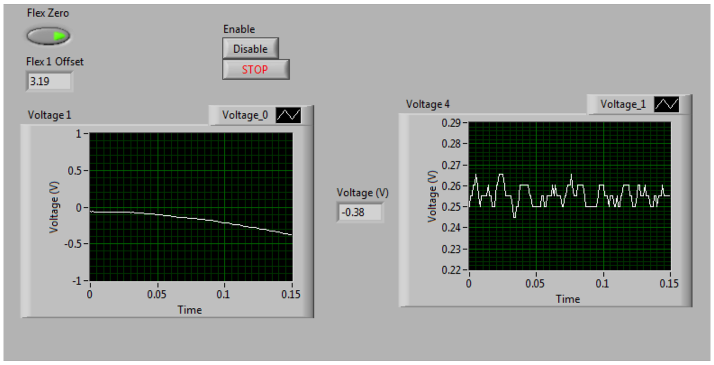


Figure 8: Experimental Setup



Flex 1 Offset: 3.19

Voltage (V): -0.38

Figure 9: Labview VI for data capture

After the data was collected it was imported into MATLAB for further processing. It was found that sEMG had a linear relationship with joint angle with a correlation coefficient of .9588. The repeated trials can be seen below. It was necessary to normalize the readings to their maximum and minimum values after applying a low pass filter (2 pole butterworth at 30 Hz). The repeated and processed trials are shown in Figure 10. A more detailed view of the raw and processed signals can be seen in Figure 11 and Figure 12.

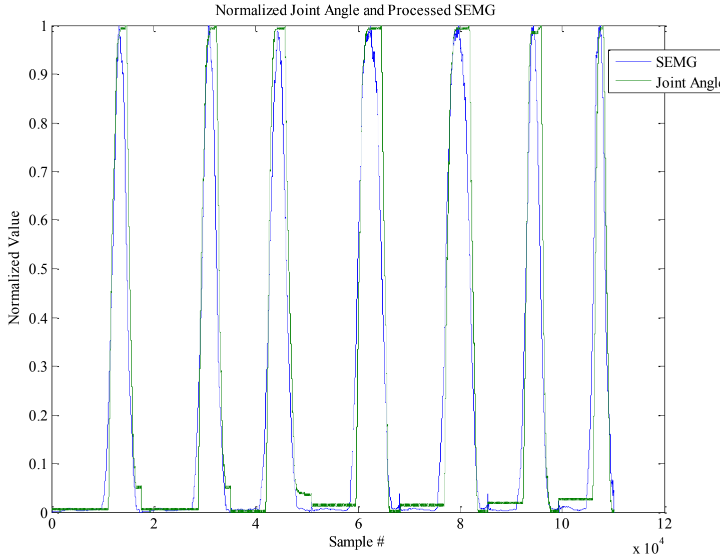


Figure 10: sEMG and joint angle reference signals for multiple contractions. Repeatability of measurements is sufficiently demonstrated

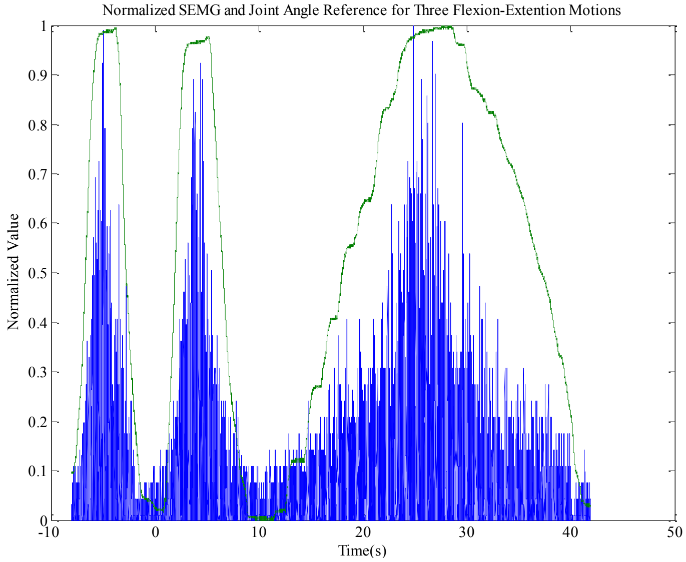


Figure 11: Raw sEMG and joint angle reference for three contractions.

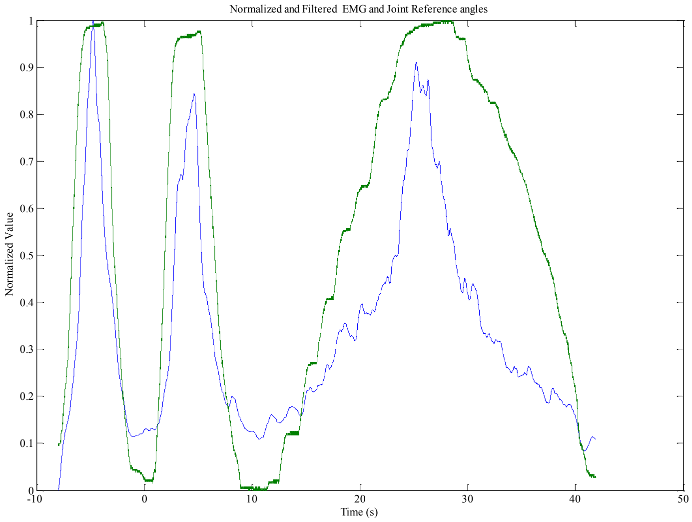


Figure 12: Filtered sEMG and joint angle reference for three contractions.

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. However, the data does not indicate a clear reason for this. To reconcile this finding a more complex model of muscle behavior is needed, but for the construction of the system a linear relationship is best suited for implementation.

5. FINAL SYSTEM

The final system needs to communicate with both analog sensors and the robotic platform. The challenge presented by the DARwIn-OP is that it has only two USB ports that connect to the onboard computer. To work around this limitation an Arduino microcontroller was used as an intermediary. The Arduino collected sEMG data via the built in ADC. Meanwhile, the DARwIn-OP ran the open-source command line interpreter “Tell DARwIn-OP” [7] to process any plain text commands. The Arduino then processed its ADC values by normalizing them to operational min/max values and averaging readings over 20 samples. The determined joint angle was then written into plain text. Next, using another open source code segment, the Arduino was able to spoof a plug-and-play USB keyboard [8] (with associated USB-UART circuit interface) and manually typed each character into the command line to allow the robot to affect the commanded joint angle. Finally, the sEMG circuit had to be upgraded to include a full-wave rectifier to make the sensor output compatible for 0-5V ADCs. The final circuit is shown in Figure 13 and the overall system layout in Figure 14.

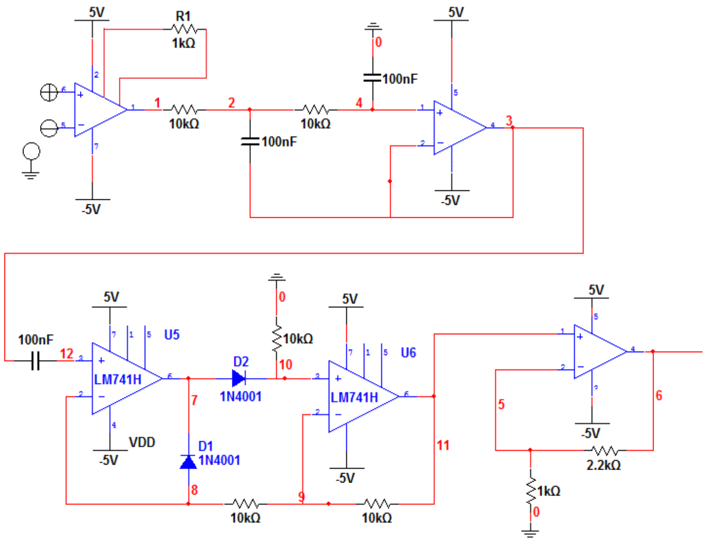


Figure 13: Final sEMG capture circuit

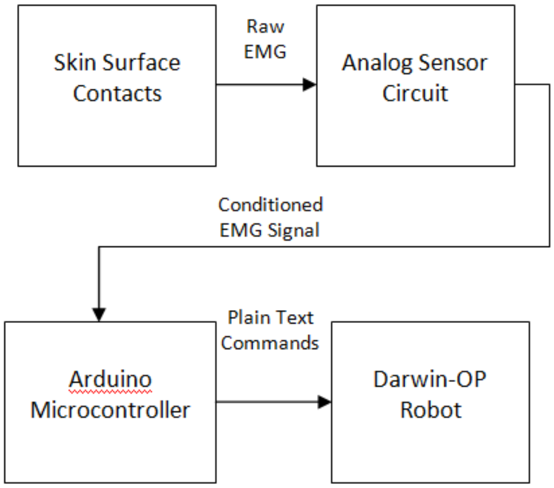


Figure 14: Final system layout.

6. CONCLUSION AND FUTURE WORK

The final system is a functional 1-DOF teleoperative system for controlling a humanoid robot via sEMG signals. For the elbow joint it was also found that for slow movements of the forearm in the upright sitting position the joint angle was directly related to the sEMG voltage level. The specific biology of this relationship is still unclear. It may be due to the level of muscle contraction, or simply a factor of increasing muscle density between the differential probes given a set neural impulse. Lastly, the entire system was designed to fully incorporate open source elements. This keeps with the theme of developing materials for the DARwIn-OP.

Future work remains in three key areas. The relationship between joint angle and sEMG needs further investigation to give a biological foundation to the theory. The system responsiveness also needs some improvement, as the conversion and communication elements of the system currently operate at a less than optimal rate. ADC times and board-robot communication needs to be increased dramatically to remove the delay between user movement and robot motion. Lastly, the system needs to be incorporated into a smaller, wearable package. When more DOF are added then the number of sensor leads will quickly become unmanageable.

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