Myoelectric Transradial Prosthesis Prototype with Intuitive Single-grasp Capability

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ABSTRACT
An electromyography (EMG) acquisition/analysis circuit was created to facilitate intuitive, real-time control for a human/computer interface (HCI). Electrical activity in the user's target muscular region, which exceeds a specified threshold, translates into actuation of the designated primary grasp for the commercial product, MechaTE robotic hand. The interface was successful in a real-time demonstration where a user was able to catch a billiard ball moving across a pool table. This prototype provides the foundation for a more advanced HCI, with dexterous, multi-grasp capabilities. Future work aims to create a novel non-invasive brain computer interface (BCI) which can be used to restore partial functionality to transradial amputees.

Categories and Subject Descriptors
H.5.2 [**Information Interfaces and Presentation**]: User Interfaces – *Prototyping.* I.2.9 [**Artificial Intelligence**]: Robotics – *Operator interfaces*.

General Terms
Algorithms, Design, Reliability, Human Factors.

Keywords
EMG Interface, HCI.

1. INTRODUCTION
Bodily movements are produced when the brain sends electrical signals through the nervous system to activate muscular regions. Surface electrodes placed on the skin are good conductors, and allow for acquisition of small electrical signals. These signals correlate to the voltages of the specific bundles of muscle fibers underneath the electrodes. This non-invasive tool allows for measurements to be made in order to determine muscle activation patterns used in specific human movements. The specific pattern that is relied upon in this research is the activation of the flexor carpi radialis muscle found in grasping movements. The prototype uses surface electrodes to facilitate intuitive control of the robotic hand by amplifying and analyzing the voltage potential of small myoelectric signals which are generated from the flexor carpi.

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The purpose of this research is to eventually provide a control interface for a user of a robotic prosthetic limb. Specifically, this research is useful for transradial amputees who have lost their hands. In place of a genuine robotic prosthesis, the MechaTE animatronic hand is used in this prototype. The MechaTE is an under-actuated hand (fewer actuators than degrees of freedom), with 14 joints, and 5 actuators. The prototype has one degree of machine control; the hand is either in the closed or open state.

Although any muscle location could be utilized, using the flexor carpi makes the HCI intuitive. The flexor carpi is a muscle of the human forearm that acts to flex and abduct the hand. Therefore, a sufficient increase in the myoelectric signal of the flexor carpi is processed as an indication to make a fist with the robotic hand. In this way, when the user squeezes his hand into a fist (physically, or mentally if the hand is amputated), an electrical signal travels from the brain, through the median nerve, propagates through the muscle fibers of the flexor carpi into the HCI, allowing for intuitive control of the robotic hand. If the flexor carpi is not available due to transradial amputation closer to the elbow, the biceps brachii, or the pectoralis major may be a suitable substitution.

Various considerations affected the development of this prototype: portability, reliability, and temporal accuracy. These considerations are discussed in detail in the technical sub-sections of this report: electrodes, amplification, power supply, the brain, and the MechaTE.

1.1 Related Work
Control interfaces and robotic prosthetics, or bionics, for users with a range of arm amputations, have been significantly improved in the past decade. Although surface electromyography (EMG) has been used since the 1960's to control one or more degrees of freedom (DOFs) for mechanical prosthetics, its full potential is yet to be realized. The i-Limb hand by Touch Bionics utilizes forearm EMG analysis, similar to what is used in this prototype [1]. The i-Limb, a commercially available bionic hand, has been proven to assist amputees in daily life, with an intuitive control interface which uses a standard machine learning algorithm to achieve a high real-time grip posture classification rate.

In some cases, there are not enough muscle, or residual nerve endings, to use forearm EMG analysis, so a new procedure was invented called targeted muscle-reinnervation (TMR) [2]. TMR relocates the residual nerve endings to a location, typically the chest, where EMG analysis is possible. TMR also provides a platform from which sensory feedback can be administered to the user, so that the user can "feel" the missing limb in action. It is worth noting that sensory feedback can also be achieved through many other mechanisms [3]. TMR is most notably utilized by Dean Kaman, from DEKA research, with his DARPA funded "Luke Arm".

In general, there are a variety of products being developed that use a plethora of innovative classifiers and control algorithms. Some cutting edge bionics being developed with a large number of DOFs which will necessitate enhanced control interfaces are the SmartHand [4], and the CyberHand [5], to name a few. Both of these bionic hands support sensory feedback, furthermore, the ultimate goal of the SmartHand is to develop a neural user prosthesis interface, a deviation from the traditional EMG-based control. Although EMG is a viable control solution, which has not yet been fully exploited, it is expected that EMG will probably accommodate a lower amount of degrees of machine control than devices controlled directly from the brain.

Researchers at the University of Pittsburgh have implanted electrodes directly on the motor cortex of a monkey, and developed a highly accurate user prosthesis interface [6]. The monkey learned how to feed himself with a mechanical arm at a high level of complexity. This breakthrough illuminates motor cortical activity and encourages the direct use of the brain for human/computer interfaces, yet it is very invasive.

2. TECHNICAL DESCRIPTION

This prototype uses two commercially available products, the MechaTE animatronic hand (see figures 1 - 3) from Custom Solutions, and non-active, Dermatrode surface electrodes from American IMEX. The interface by which these two components communicate is the scope of this project (see figure 4). The prototype is meant to be easily adapted to similar robotic hand platforms; under-actuated, with each finger controlled by one servo motor. Furthermore, this prototype may be easily adapted to work with different users, and a variety of wet or dry electrodes. In addition, although the prototype may only perform a single grasp, it can easily be modified to perform a different grasp. Currently, the primary grasp has been designated as a closed fist.

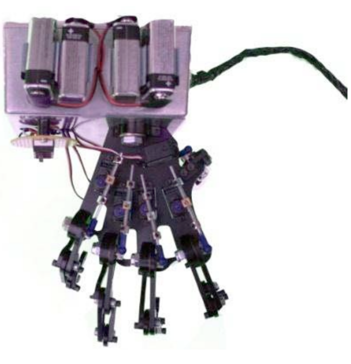


Figure 1. (Top View) The MechaTE hand, mounted on a metal box. The box houses various components needed to operate the hand, and rests at electrical ground to shield a Peripheral Interface Controller (PIC microcontroller) from spurious signals in the air. The 16-bit PIC microcontroller is available from Microchip Technologies Inc at www.microchip.com

Figure 2. (Front View) Four switches on a circular printed circuit board, left of the MechaTE hand, correspond to each of the four 9V batteries.

Pre-Amp

Figure 3. (Side View) The direct connection from the pre-amplifier to the metal box is shown. The preamplifier has three coaxial cables terminating in alligator clips, to connect with surface electrodes. A black wristband is attached underneath to make the preamp wearable.

2.1 Electrodes

The prototype is currently configured to work with reusable, Dermatrode reference electrodes. These electrodes have a conductive adhesive on one side. They are circular, with a diameter of 5 cm. For the sake of reliability, the area where the electrodes are to be placed is shaved, and cleaned with alcohol. Although the electrodes are reusable, reliability decreases with use, and proper preparation of the target muscle area can help to extend the life of the electrode.

The size of these electrodes is relatively large with respect to other electrodes since they are generally used as reference electrodes. However, considering the large size of the target muscle, the flexor carpi radialis, these electrodes are adequate, and cost effective. If one were to use a smaller electrode, for instance an EKG electrode, the prototype should have its amplification settings changed accordingly.

The myoelectric signals that are picked up by these electrodes are extremely small, on the order of 10^{-5} V. An essential part of this interface is to detect when the myoelectric signal of the target muscle exceeds a certain threshold. In order to make this determination reliably, one electrode is used as a reference and placed on the wrist, and two electrodes are placed on the target muscle, flexor carpi. If the wrist is unavailable the ankle is a suitable reference location.

The wrist (or the ankle) is a suitable reference location because it is electrically inactive. This electrode is connected to the shell of the preamplifier through a shielded coaxial cable, which is subsequently connected to the metal box housing the brains of the prototype, and provides the ground for the entire circuit. It is essential that the myoelectric signal is shielded from spurious electrical noise, from its origin at the electrode, through its culmination at the brains, a PIC microcontroller. Shielding the signal with a common ground ensures the veracity of the signal, so each of the paths into the preamplifier use properly grounded coaxial cable.

The signal from the two electrodes placed on the target muscle is fed into the preamplifier via these coaxial cables. Flexor carpi is the ideal target muscle in order to create an intuitive user interface. Currently, the prototype only has single grasp capability, closed fist, and the flexor carpi is naturally activated in this action. If a different target muscle is selected, the prototype should have its amplification settings changed accordingly. An alternate target muscle may be necessary if the user has a transradial amputation closer to the elbow, and there is not sufficient muscle mass, or residual nerve endings to acquire the signal. Amplification settings may need to be altered for different users.

2.2 Amplification

The two myoelectric signals acquired from the target muscle are fed into a preamplifier to protect the integrity of the signal as it travels to the microcontroller. Two signals are required so that they can be used in a differential amplifier. Voltage common to both electrodes is rejected, and only the difference is amplified. The voltage difference between two electrodes is less likely to vary with muscle fatigue than the voltage obtained from a single electrode. Thus, more reliable electromyography (EMG) acquisition is provided.

Because of the extremely low voltages being fed into the pre-amp, the OP77 operational amplifier from Analog Devices Inc (www.analog.com) was selected. The OP77 is an ultra-low offset voltage operational amplifier which is configured as a precision, high-gain differential amplifier in the pre-amp. The gain of the pre-amp is 1,000. It is portable, small, and light weight, so that the device can be worn unobtrusively using the embedded wristband.

A system of braided wires joins the pre-amp with the rest of the interface. One wire connects the shell of the pre-amp, to the metal box, to form a common ground. One wire delivers 3V, and another -3V; these are the rail voltages of the op-amp used in the pre-amp. One wire is used as output.

After pre-amplification, the signal travels through the output wire, into another amplification stage in the metal box. The second stage is a non-inverting amplifier with a gain of 10,000. In total, the voltage difference between the target muscle electrodes is amplified by a factor of 10×10^6. Capacitors are placed in shunt with the operational amplifiers' voltage sources and ground, in order to reject pickup voltages.

2.3 Power Supply

The power supply, consisting of four 9V batteries, enable this prototype to be portable. The 9V batteries are mounted on the exterior of the metal box, and the voltages are fed into the box onto a printed circuit board, where voltage regulators (LM317, LM237) are configured to provide the appropriate current and voltage levels to the prototype's components. There are four switches on the exterior of the box, one for each battery.

The voltage regulators provide up to 1.5A at the following DC voltage levels: -3V, 3V, and 5V. The OP77's use +/-3V as the rail voltages. The PIC microcontroller operates at 3V. The servos in the MechaTE operate at 5V. The voltage regulators ensure that the proper voltage is delivered to each component. No more than two servos are run from a single battery/voltage regulator, to ensure sufficient current is available. For each voltage regulator, input and output capacitors are placed in shunt with ground to remove pickup errors.

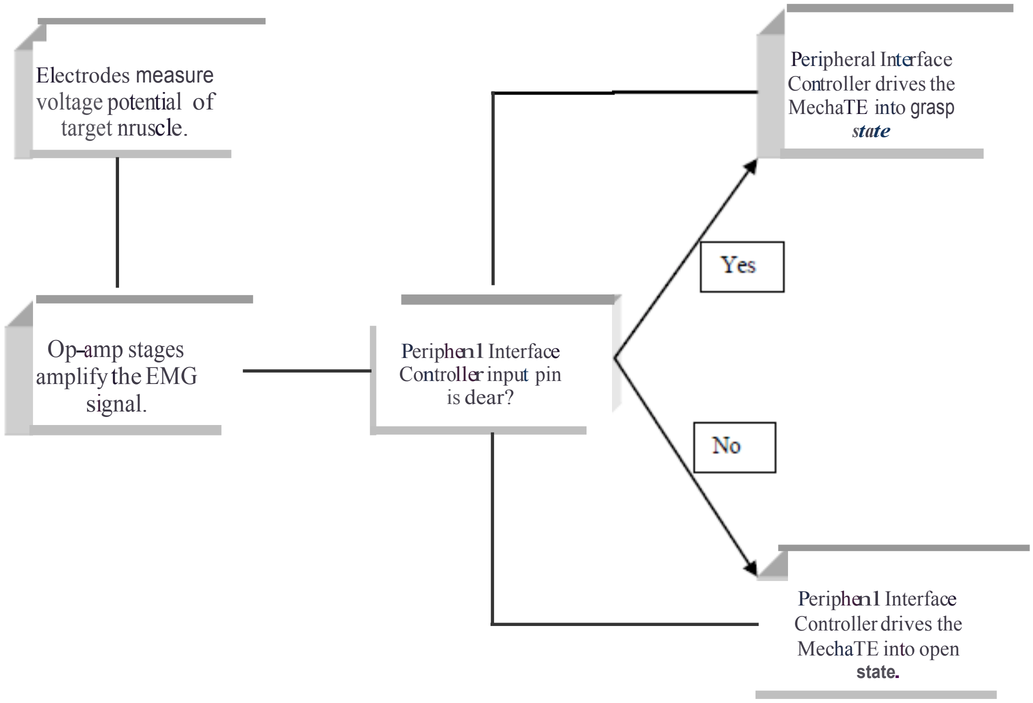
2.4 The Brain

The brain of the prototype is a PIC 24HJ32GP202 microcontroller by Microchip Technologies Inc (www.microchip.com). This microcontroller provides very high temporal accuracy, virtually real time. The high processing speed of the microcontroller creates a seamless, life-like response.

The output from the second amplification stage is passed through a low-pass RC filter, and then connected to a pin on the microcontroller which is configured for input. The signal arriving at the input pin of the PIC is equal to 3V DC when the user is not making a fist. DC voltages in the range of ~2.4V to ~3.3V correspond to 1, or logically, high. As the user squeezes his hand, the DC voltage applied to the input pin drops below the threshold needed to register high, logically, thus the input pin clears, it registers 0. The amplification stages provide an inverted output.

The control algorithm is simple. When the input pin reads 1, drive the MechaTE into the open state; when the input pin reads 0, drive the MechaTE into the designated primary grasp, closed fist. It takes careful calibration and testing in order to ensure that the hand operates well. The microcontroller generates the requisite signal in order to drive the MechaTE into the appropriate state. The transition from state to state is also governed by the microcontroller in order to ensure smoothness. In other words, the signal is not always changed instantaneously, but gradually, to represent a natural response.

LOGICAL OVERVIEW



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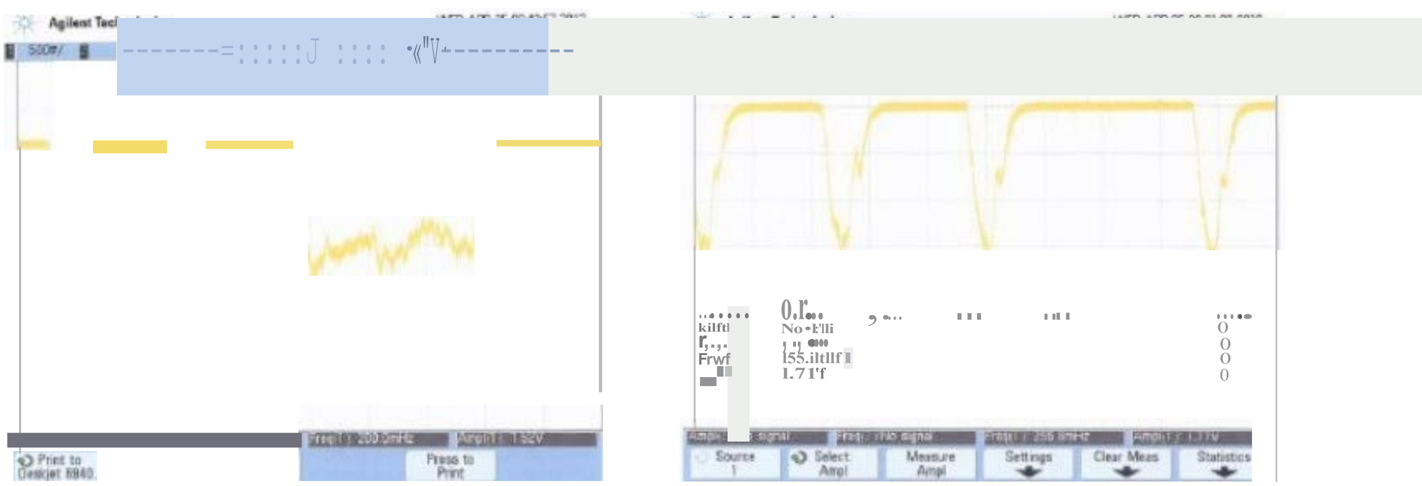

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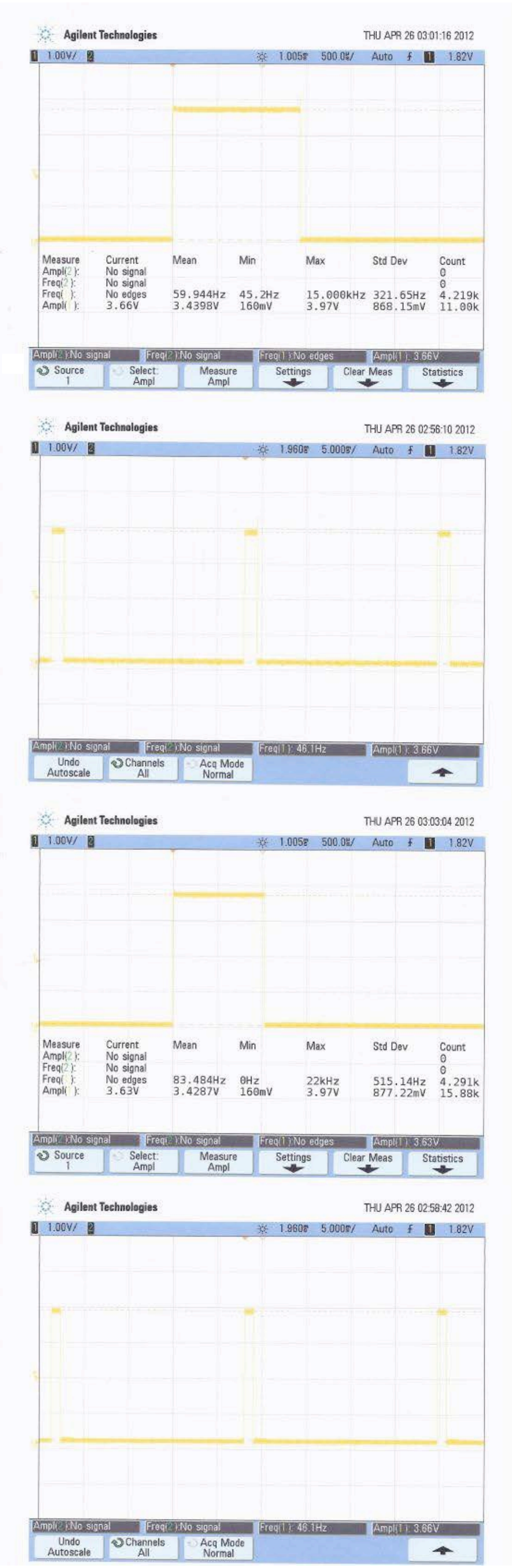

Figure 6. Oscilloscope measurements taken from pin RP15 of the Peripheral Interface Controller (PIC). (Upper 2) Show pulse generated during open state. (Lower 2) Show pulse generated during closed state.

2.5 The MechaTE

The MechaTE is an under-actuated animatronic hand with 14 joints, and 5 actuators. The five actuators are Futaba s3114 micro servos (one servo per finger). These RC servos respond to a pulse width modulated (PWM) signal with a peak of 5V, at a frequency of 50Hz. The PIC does not normally output 5V, so the output pins of the PIC are modified into open drain configuration. Each finger/servo is assigned to a single PIC reprogrammable pin (RP), and the PIC generates the appropriate pulses needed for the given state (see figure 7).

The pulses are determined during mechanical calibration. The response of each finger is dictated by the tension in springs on either side of the servo arm. The tension in these springs determine where the finger will rest at a given pulse width. The range for servo arms is centered at 1.5ms (this is standard for all RC servos like the s3114). Pulse widths longer and shorter than this center pulse will drive the finger to open and close, respectively. After careful calibration (adjusting the springs), each finger is assigned a pulse width for a given state. The PIC has a limited number of output compare peripherals, thus a limited number of pulse widths that can be created using the PWM module. Therefore, it is important to maximize the number of fingers that are calibrated to function within the same pulse width limits, so that they can use the same pulse width for a given state. It is essential to limit the pulse widths properly, and that none of the servos are "over-traveled" because excessive resistance from the springs will damage the servo. The calibration process should not have to be repeated.

Inside the metal box the weight of the MechaTE is counterbalanced with bonded metal. This allows the hand to function horizontally during testing. This hand would never be, and should never be, actually attached to an amputee's body because it is not a clinically approved prosthesis.

	THUMB - RP15	POINTER - RP13	MIDDLE - RP10	RING - RP9	PINKY - RP6
OpenState	1.4ms	1.9ms	1.9ms	1.9ms	1.9ms
ClosedState	1ms	1.3ms	1.3ms	1.3ms	1.3ms

Figure 7. The PIC pin (RPx) and the finger/servo connection, versus state. The pulse widths are provided for the specified state.

3. CONCLUSION

The prototype processes information in real-time with a high standard of reliability, and it is portable. It has tested successfully with one user who has a healthy extremity. When the user makes and releases a fist, the robotic hand parallels the action. The prototype was able to catch a billiard ball moving across a pool table. If reliability decreases, it is probably time to replace the electrodes being used. During normal operation, there can be a deviation from real-time when observing the user's physical hand verses the MechaTE. In some instances, the interface reacts late, and in some instances it reacts early. The user can control when these instances occur.

The prototype can be manipulated into real time deviation due to target muscle selection for the experimental user. The electrodes that are placed along the flexor carpi radialis measure the user's muscle activation, and when this muscle is flexed sufficiently, the interface drives the MechaTE into the closed state. However, the flexor carpi radialis can be flexed sufficiently whether or not the fingers of the user's physical hand actually close. Thus, if the user were to sufficiently activate his flexor carpi before closing his natural hand, the MechaTE would appear to react early. This is not to say that the system does not process the information in real time; the moment that the muscle being read are sufficiently activated the MechaTE reacts, this is merely the consequence of a limited number of target muscles. If additional muscles were being read in concert with the flexor carpi, this manipulation could be avoided, and a system could be created with a more direct correlation to the user's muscle strategy.

For example, the extensor carpi, located on the back of the forearm, has long tendons that extend the fingers in the hand when activated. The way the prototype is set up now, the flexor carpi must be sufficiently activated to keep the MechaTE in the closed state, or in other words, the user had to actively squeeze his hand. Thus, if the user stops squeezing, and then later decides to open his fingers, the interface is early in its response to move from closed to open state. If information from the extensor carpi was added into the information processing scheme, this deviation could be avoided. The system could be built so that the user did not have to squeeze his hand the entire time. Sufficient muscle activation in the flexor carpi could initiate the closed state, and the MechaTE could remain in that state until sufficient activation is detected in the extensor carpi. Thus, temporal deviations could be removed by adding more channels of EMG information.

Some temporal deviation corresponds to muscle fatigue. A residual effect from the user squeezing his hand actively in order to keep the prototype in the closed state is that the voltage differential in the muscle will take longer to dissipate. Therefore, when the user has been squeezing his fist very tightly for an extended period of time he may encounter temporal deviation when he releases, the MechaTE may not open right away. Likewise, if the muscle is still fatigued when the user attempts to migrate from open to closed state, it may take additional time for the muscle to reach the requisite voltage potential. However, these deviations could be removed by adding more channels of EMG information and considering the dynamics of muscle strategy, or by building a more sensitive EMG acquisition circuit.

In order to use the prototype with a range of users and components, it is expected that certain adjustments will have to be made to the amplification settings. The factors that will affect how much amplification is required are specific user muscle mass, electrode type, and electrode placement (i.e. target muscle). If the flexor carpi is not available due to transradial amputation closer to the elbow, the biceps brachii, or the pectoralis major may be suitable substitutions.

The prototype functions reliably, as it was tested, with one user with a healthy extremity. When the input voltage to the PIC drops below the threshold voltage, the pin is cleared, and the PIC generates a series of pulses which correspond to the closed state and the MechaTE is driven into a fist. The user was able to navigate from open to closed state, and vise-versa, at will. When the input voltage to the PIC is high, the PIC maintains the MechaTE in the open state, with fingers extended, by providing the requisite signals.

3.1 Future Work

Further work will focus on developing novel control algorithms for this prototype. The amount of user information to analyze must be increased in order to increase degrees of machine control. This prototype could benefit from a power supply that is much smaller. Future work will scale down the power supply, achieve multiple grasps, and may possibly evolve to include a bionic hand with more degrees of freedom.

In order to achieve multiple grasps it is essential to have a sufficient number of signals to analyze. It has previously been shown that it is possible to achieve at least 5 degrees of machine control when several electrodes are used in a human computer interface [7]. The ultimate goal for this prototype is to evolve from myoelectric to encephaloelectric, reading the user's brain waves to achieve multiple grasps. Electroencephalography (EEG) is a promising direction for bionics because it is non-invasive, like EMG, but may allow control for a greater maximum number of DOFs.

A major concern with all control interfaces is how much training will be needed to learn to use it. The future of this research lies in classifying the EEG's of participants in a large scale investigation, to determine human-fundamental EEG components during complex hand movements. The users will wear data gloves during classification to normalize position. This will engender a smart control algorithm, so a new user could use the prosthesis to perform complex hand movements without training: a truly intuitive extension of self.

4. ACKNOWLEDGMENTS

This project was supported in part by Fairleigh Dickinson University (FDU) GHSCSE and FDU IEEE Student Chapter. Thanks to Dr. Mark Bai for his contribution to this project. View a brief demonstration of the project at: http://www.youtube.com/watch?v=Ie7UJV4zXdo&

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