Design of an Electrical Prosthetic Gripper using EMG and Linear Motion Approach

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Abstract: *The objective of this research work was to design and construct a prosthesis that will be strong and reliable, while still offering control on the force exerted. Consequently, the design had to account for mechanical and electrical design reliability and size. Targeting these goals by using Electromyogram (EMG) in the electrical control system and a linear motion approach in the mechanical system. The prosthetic gripper uses EMG to detect the amputee's intended movement. EMG is defined as the electric potential measured on a skin surface when a muscle contracts. It can be generated from amputee's remaining muscle. Two control systems were implemented for the gripper: (1) Electrical control to convert the amputee impulses into the gripper actions. (2) Mechanical control to regulate the force exerted by the prosthetic fingers. The control system requires an adaptation mechanism for each amputee's characteristics. EMG is a complex signal and is different for each person, making the design of the prosthesis more challenging. For practical use, the electrical control needed to be embedded in the prosthetic hand for the process in a timely manner. The mechanical control of the system was accomplished by a pseudo-clutch on the linear actuator. This system controls the friction exerted in the actuator, hence regulating the strength exerted by the fingers of the gripper. The integration of these two control systems was critical in the development of the prosthetic hand controller, to result in a flexible, reliable, and power efficient design.*

BACKGROUND

The design of body-powered upper-limb prostheses in particular has experienced few, if any, major breakthroughs since the early 1960s [1]. Upper-limb prostheses are either hook or hand-shaped, and are actuated by body or external power. There is a greater preference for hand-shaped prostheses. Compared to hooks, prosthetic hands generally offer less function and durability at greater weight and cost. Nonetheless, many individuals still choose hands over hooks, primarily for cosmetic reasons. Yet continued advances in materials science make more functional and realistic-appearing prostheses increasingly possible.

Persons with amputation frequently express dissatisfaction with the current state of upper-limb prosthesis technology, noting numerous deficiencies with their prostheses, for example functionality, reliability, ease of use, weight, and energy consumption [1].

Current prosthetic hands can require high-energy consumption. Since bending is typically restricted to two joints that cannot move independently, the grip is not adaptive. That is, the fingers do not wrap around the object as fingers in the human hand do. Consequently, there is little contact area between hand and object, requiring high pinch forces at the fingertips to grasp the object. The prosthetic gripper that locks itself into place and avoid a constant current drain to maintain the force exerted in the fingers.

ELECTROMYOGRAPHIC CONTROL

Electromyographic control uses the EMG electrical signal due to depolarization of the cell membrane of the muscle fibers during contraction. It was first used in prosthetics by Reiter in the early 1940s [3]. For the EMG detection, groups of muscles involving reciprocal movements were targeted [4]. Biceps v. triceps, biceps v. pectoral, and flexor-pronator group v. extensor-supinator group were tested. The flexor-pronator v. extensor-supinator group was selected due to their isolation to movement of the arm as a whole and the close relation to the hand muscles. These groups allow for a better control of the prosthesis to the amputee.

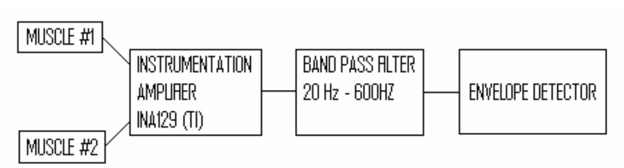

Fig 1. EMG Block diagram

The designed EMG processing circuit consists of two identical circuits, each connected to one of the reciprocal muscles that were previously selected. Even though two independent circuits are implemented, both of them share the common of the instrumentation amplifier to be able to compare them with the reference point each individual circuit consists of two electrodes, one instrumentation amplifier, a band pass filter and an envelope detector.

A company named Gereonics donated the electrodes used in the proposed design. These electrodes are plastic encased silver/silver chloride electrodes that are designed to have a very low DC offset potential, minimal motion artifact and good low frequency response. The EMG electrode bodies are manufactured using FDA quality high impact plastic, which is chemically resistant to collodion which is a highly flammable, colorless or yellowish syrupy solution of pyroxylin, ether, and alcohol, used as an adhesive to close small wounds and hold surgical dressings and in topical medications. The body is 12mm in diameter and has a 2mm hole in the top for gel addition. A very flexible, small and durable lead wire of 3 feet is used.

The specially compounded sensing element of silver/silver chloride is the key to precision low drift design. As a result, offset voltage and polarization-two key performance parameters, are unsurpassed. The electrodes never need to be chloridized. Since only the plastic body touches the skin, motion artifacts are significantly reduced compared to metal cup electrodes. Gereonics' EMG silver/silver chloride electrodes can be used many dozens of times and maintain their quality performance characteristics. Performance is significantly superior to gold and silver cup electrodes.

Testing show the necessity implementing an extra electrode to the ground of the circuit would help the circuit to obtain a better ground and stabilize the signal. This is very important in the case where the patient is using rubber sole shoes, which can isolate him/her electrically, and can cause offsets in the signals and undesired behavior.

After the electrodes have been used to obtain the signal from the muscles, an instrumentation amplifier is used to compare both of the signals to give an output of the difference between them. The INA129 designed by Texas Instruments was used as the instrumentation amplifier. The INA 129 is a low power instrumentation amplifier offering excellent accuracy. This chip is laser trimmed to have a very low offset voltage (50uV) and a high common mode rejection ratio (120 dB at G>100). At the same time it is very user friendly, and by using a single external resistor, the gain can be setup to be from 1 to 1000 V/V. Choosing R = 2.2K, and making the input gain of the circuit be: G = 1+49.4k/2.2k = 23.45 V/V.

After the signal has been differentiated and amplified by the instrumentation amplifier it is cascaded with a band pass filter designed to have a pass band frequency of 20 Hz to 650 Hz. Cascading a first order High Pass Filter with a cutoff frequency of 20 Hz and a second order KRC Low Pass Filter with a cutoff frequency of 650 Hz created this filter. The 20 Hz frequency was selected to help attenuate any small frequencies due to motion artifact between the electrode and the skin. It was not necessary to make the filter to attenuate the 60 Hz signal from a 120 V outlet, because the instrumentation amplifier attenuates that noise since the signal enters through both of the electrodes and then canceled in the differentiation. The 650 Hz frequency was selected because by doing some research it was found that the muscles signal is between DC – 1000 Hz, but the strongest signal is between 50 Hz – 350 Hz. So, by making the corner frequency 650 Hz, maximum performance and filtering high frequencies is guaranteed.

The HPF was set to have a gain of 12.2 V/V and the LPF was set to have a gain of 10 V/V. By combining all the gains, the circuit ends up with a total gain of 2861.45 V/V. It seems to be very high, but the signal of the muscles was in the range of millivolts and microvolts.

The schematic for the pass band filter using 5% tolerance resistors and 10% tolerance capacitors is:

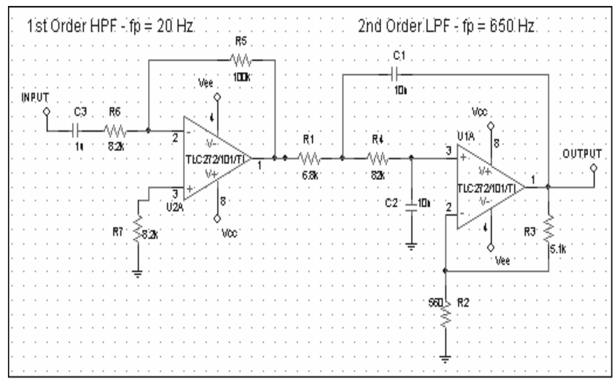

Fig 2. Band Pass Filter

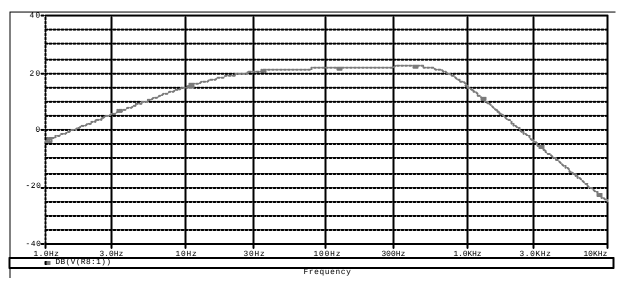

Fig 3. PSPICE Simulation

After the signal passed through the BPF and only the desired output had been generated, the signal was passed through an envelope detector. The purpose of this envelope detector is to convert the AC signal from the muscles into a regulated stable output that would change in accordance to the frequency and the RC constant in the circuit. This signal will enable direct comparison by means of a simple comparator made with TLC272 op amps. (Fig 4.)

As previously mentioned, two of these same circuits were built independently so that we could get separate signals from two different muscles. Now that the signals have been amplified and filtered, they we have to compare with a special circuit that sends two different outputs for the motor driver. A driver chip made by Allegro was used to drive the motor, which is the

A2919SB Dual Full-Bridge PWM Motor Driver. This chip has the following features:

- 750 mA Continuous Output Current
- 45 V Output Sustaining Voltage
- Internal Clamp Diodes
- Internal PWM Current Control
- Low Output Saturation Voltage
- Internal Thermal Shutdown Circuitry
- Half- or Quarter-Step Operation of Bipolar Stepper Motors

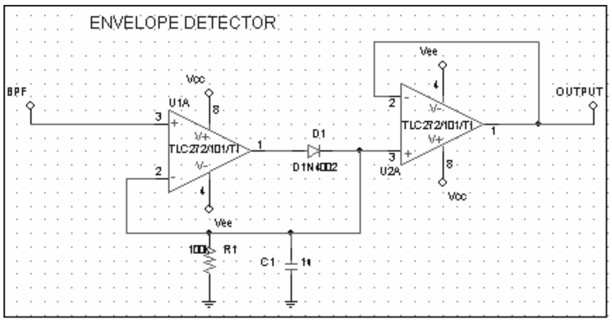

Fig 4. Envelop Detector

The A2919SB IC controls the motor by having an input that controls the phase of the motor and another input that controls the current. Both of the inputs are controlled by the following truth tables:

TRUTH TABLE

PHASE	OUT_A	OUT_B
H	H	L
L	L	H

CURRENT-CONTROL TRUTH TABLE

I_0	I_1	Output Current
L	L	$V_{REF}/10\ R_S = 100\%\ I_{TRIP}$
H	L	$V_{REF}/15\ R_S = 67\%\ I_{TRIP}$
L	H	$V_{REF}/24.4\ R_S = 41\%\ I_{TRIP}$
H	H	0

The design was planned to drive the motor at full current and zero current, so we shorted I_0 and I_1 making the following truth table:

I_0-I_1	Output Current
L	100% I_{TRIP}
H	0

The I_{TRIP} current is to determine the maximum current that the motor is going to draw from the voltage source. This current I_{TRIP} is calculated with the following equation: $I_{TRIP} = V_{REF}/(10Rs)$. Since 9 V is used as V_{REF}, then Rs is calculated to be 5 ohm so that the current would not exceed 180 mA.

The A2919SB IC allows the user to adjust an RC constant that is used as a small delay when the phase signal is changing in order to prevent drastic current spikes that could lead to failures or even damaging of the circuit. For the design, the calculated RC constant is calculated to give us approximately 2 μsec. The values used were: R = 22 K ohm and C = 100 pf. This chip also has the advantage of using different voltage ratings between the voltage that is supplying the power of the circuit and the voltage that is being applied directly to the motor. This certifies that the motor will not draw the current from the circuit but straight from the power supply, ensuring circuit safety and reliability.

In order to drive the current input in the chip, the design had to account for a circuit that would set the input at High when both muscles are inactive and to set it at Low whenever one or both muscles are being activated. It is desired activate the circuit when both of the muscles are activated because even though both of the muscles are sending a signal, the muscle that is sending a stronger signal will be the one that drives the phase input. The circuit created to implement these design parameters is figure 6.

As it can be seen the Phase control is connected directly into both of the outputs of the envelope detector. A resistance of 1k ohm is used in the input of this comparator just in case there is no signal coming in, so the input would be pulled down to ground.

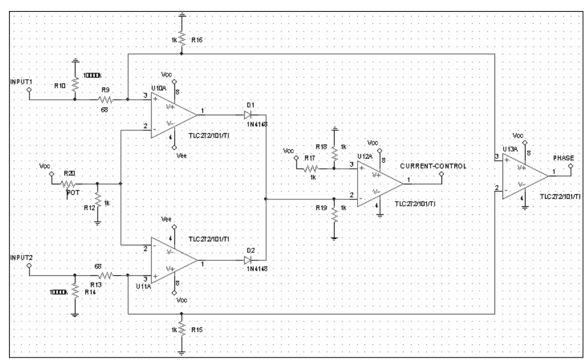

Fig 6. Analog motor control schematic

In the other circuit it is observed that the comparator is connected to a voltage divider that maintains a constant voltage in the negative input, this makes the comparator to saturate at -Vee when no signal is applied, making the output low. When there is a signal higher that the threshold voltage coming from the envelope detector in either channel, then the comparator goes to high. Given that the motor controller is active low, an inverter was implemented with an opamp as seen in the figure. This emulates the logic NOR gate needed for the control.

The whole circuit will be powered with two 9-volt batteries, to create +9V and –9V. These batteries will be connected through a switch to a positive 5V regulator (78M05) and a negative -5V (79M05) regulator to maintain a constant voltage and also because the TLC272 operational amplifiers that are being used for the filters, envelope detector and comparator are rated to operate at a maximum of 18 V and it is desired to maintain a considerable margin with these limits to ensure reliability. Even though the circuit is operating at the regulated voltage, the +9 V battery is connected directly to the motor driver so that the motor will drive at a higher voltage and independently from the current that the circuit is drawing. This will also enable us to drive the motor independently to produce the maximum available torque and maximize efficiency and speed.

MECHANICAL DESIGN

The first requirement that was tackled in the design process was the movement mechanism for the hand. The most widely used was a ligament based design, where motors would pull on strings that would flex a joint based on pulleys. The design was very straightforward, and apparently was easy to design and implement, but it had a very evident problem of strength at the closing end of the range of motion; the force component towards the gripped object seemed very small. The torque ratio between produced torque at the motor, and perceived at the finger tips, was very poor.

Another design approach was based on several small motors placed in the joints. This would be a more challenging implementation, but the one problem lied in the compromise between precise motion and torque. Motors can be very precise, but their strength tends to be proportional to its size and weight, which would make the hand very heavy. The most important problem was that the user will have to drive these motors independently with his/her muscles, and unless he/she is a contortionist, the results did not seem promising.

It was decided to try and think of alternative ways of producing a single movement of opening and closing, but that would meet the desired requirements, and that would be feasible to make in the time available, with the tools available, and that could be easily be manipulated by the user.

Several designs were proposed by the team, but linear motion movement, based on a linear actuator, seemed a very good choice for its excellent force ratio, for its sturdy design, and because it is easy to control by the user. It was also an original concept produced by the team. No similar mechanism was found on the existing devices studied. This made the design process more challenging and fulfilling.

DESIGN DESCRIPTION

The design was based on a linear device that transformed the rotation of the motor into linear movement that could be used as a piston based mechanism to close and open the hand. Linear movement will push on the fingers, making them rotate on a pivot point based on the lower base of the arm. This allows a very direct transference of torque in the whole range of motion. Yet another advantage of this approach is that the hand possesses strength in both directions, and not only in the agonist (closing) motion like in the tendon based mechanism. Depending on the speed of rotation of the motors, precision could be controlled without compromising so much strength like in the case of a direct motor drive. This method also allowed us to implement a very easy method of "lock-in" position, which allows the user to relax the stimulating muscle once the position is achieved. This was possible by the characteristics of the motor, which is based on heavy internal gearing, and a very smart transmission system.

The transmission was based on a very special linear actuator. The rotation of the motor was transferred by means of gears to a stainless steel shaft that ran in the longitudinal axis of the arm. The shaft passes through a very special aluminum block that contains angled bearings that cause the box to move in one direction or other (linearly), depending on the direction of rotation of the shaft and hence the motor. A very important characteristic of this transmission is that it avoids current surges at the limits of motion, or when the hand grabs a hard object. When the hand encounters resistance to its motion the system responds accordingly by increasing the current supply to the motor to exert more strength; this process would continue indefinitely, until either the motor or hand are damaged, unless a control mechanism is used. The aluminum block has two special screws that allow the trimming of the slip strength (Pseudo-Clutch); this means that at a certain resistance, the aluminum block will slide on the shaft, preventing the motor to keep drawing more current. The tighter the screws, the more resistance it needs to encounter to start slipping, thus the more pressure it can exert on the object, but the higher the current the motor will draw. This feature can be easily controlled by the user depending on his/her needs, by the use of a simple hex key. (Fig. 7)

The following are some features that are desired of the system as a whole, but that are not required for a practical device. They are features that were strived to accomplish to make the design more useful and convenient. (1)POSITION LOCK SYSTEM: A locking system for the position of the hand is desirable given that it is not electrically efficient to need a constant current to maintain a strong grip; this will drain any battery in the matter of minutes if used continuously. (2)ADJUSTABLE ERGONOMICS: The fingers, although firm and with fixed joints, can be easily adjusted

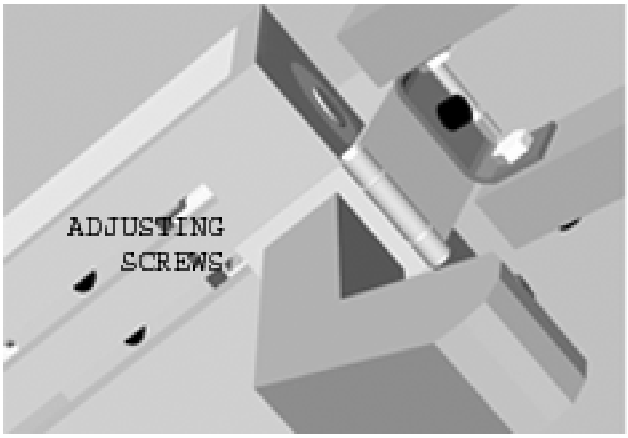

Fig.7 Slip Control-Pseudo Clutch detail

for finger position to hold a wider range of objects and to limit the amount of pressure exerted over a surface.

RESULTS

As expected from the planned device, the obtained results fulfilled the proposed objectives, strength and ease to use. The circuit design was developed and tested in Pspice, but as it is well know simulation result do not necessary represent the real implementation of a project. Consequently, real testing was performed on the finished circuitry (Fig. 8) to demonstrate the performance of the amplifiers, filters, and envelop detectors connected to the myoelectric signals coming from the muscles.

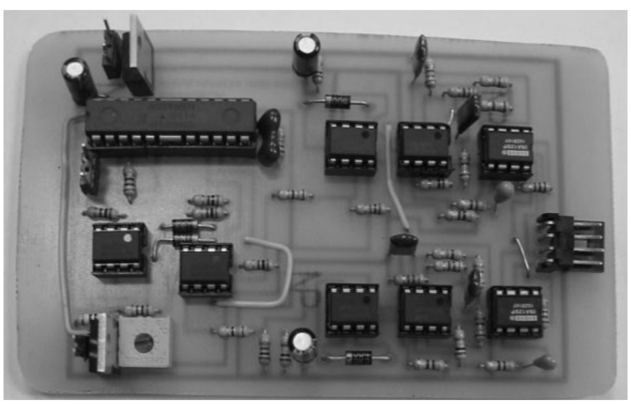
Fig 8. Finished Circuitry

These results are dependent on the subject muscular complexion, location of the electrodes, and subject's ability to control the different muscles. These dependences make myolectrically-controlled prosthesis difficult to implement and mass-produce because the development is user dependent. The design was developed to allow a user to have enough control on the prosthesis without wasting energy and holding and exhausting contraction on the muscle while maintaining a fix position. The following are some illustrations of the finalized project. (Fig 9, 10 & 11)

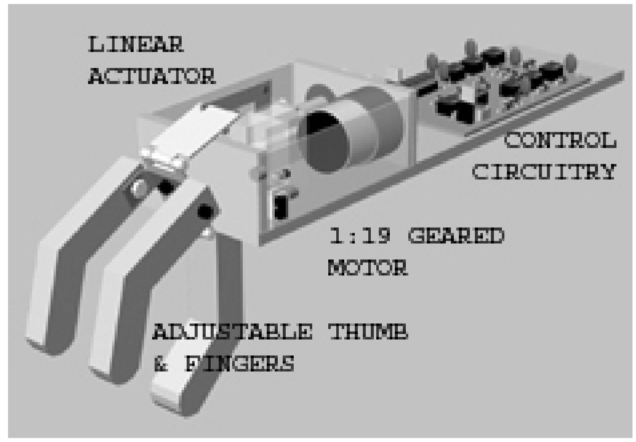

Fig 9. Complete Model

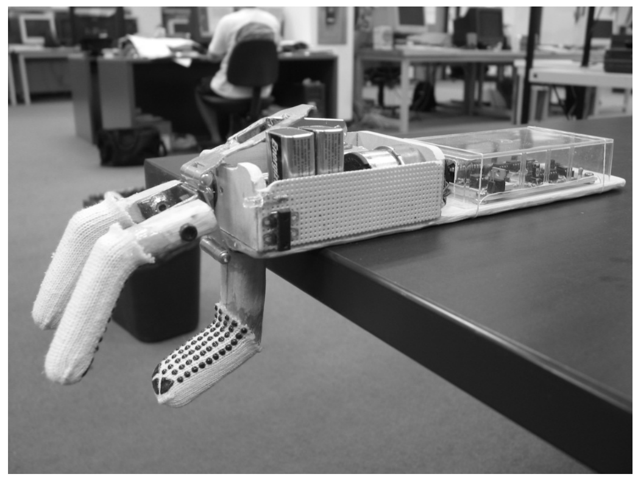
Fig 10. Completed prototype

FURTHER WORK

Given that the desire to make the hand as close in size to a regular hand, the localization of all the mechanical components was a very difficult task. Given that the main priority was functionality and not aesthetics, the components had to be in a place that did not affect efficiency. Positioning of the engine to produce the rotation of the shaft was a very difficult challenge due to the need for precision to avoid vibrations of the shaft, inconsistent torque transmission at all points of revolution, and fixation to avoid movement when a load was applied.

Direct fixation of the motor shaft to then actuator shaft implied a very high chance of oscillation and instability, therefore a system of transmission needed to be implemented. A band transmission was an option that implied another point for slip, and the need for a very consistent tension will add complications to the implementation. Gears were the best choice in this aspect, but required a very precise positioning of the motor, given

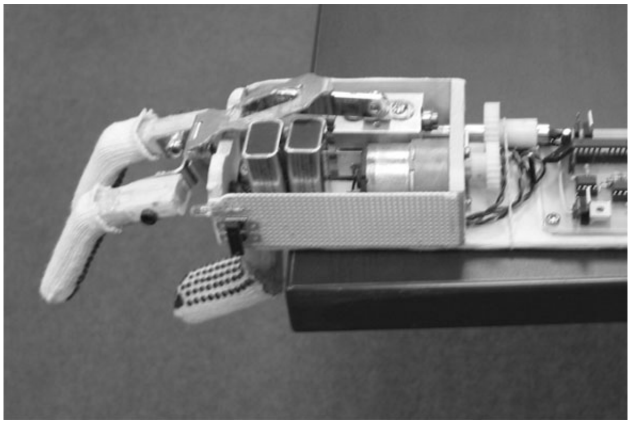

Fig 11. Prototype Top view

the little space available. But given that the infrastructure gave no chance to make special gears, the design depended on the ones available at hobby stores that could match the dimensions. Therefore the gear relation does not favor speed of motion, and the opening and closing of the hand is a bit slow. A bigger gear should be placed on the motor, while a smaller one should be placed on the main shaft. With a 2:1 ratio, the speed of the action will dramatically increase, making the movement more realistic and convenient.

The materials chosen for the chassis and main armature of the hand, as well as the fingers were chosen because of ease of manipulation, but with better tools, and a better budget it is possible to enhance the design with the use of polymer components with better elastic properties to mimic an actual human hand. Flexibility at the Metacarpal Interphalangeal joint and the Proximal Phalangeal joint is desired to enable better accommodation to irregular shaped objects.

Addition of the other two fingers for support would be a nice enhancement of the design because of aesthetic reasons, but it has some functional drawbacks, such as the difficulty to manipulate more fingers with only one actuator, and the additional source of back torque applied to the actuator by distal fingers. If fingers are fixed, then it puts a limit in the range of motion and may interfere with manipulation of certain objects.

Another very useful property that could be included is a mechanism or sensor that can provide the user with feedback, of the intensity of the gripping force being applied. Given that the prosthesis does not have sensory nerve endings, the judgment of force being exerted on an object may be very difficult. Current being drawn by the motor could be a good indicator of the force being applied, but it has to be displayed in a way that it is easy to understand and relate to strength by the user through a vibro-tactile module that will reflect the strength with a vibrating pattern on the skin.

CONCLUSIONS

Nearly all the requirements of our proposed design were achieved. A good compromise between strength, functionality, speed and efficiency was achieved, while still keeping the dimensions within acceptable ranges and the cost within our initial budget.

The choice of linear actuation proved to be very good, and given that it is an original design, it is very promising and it can be developed further to increase the level of the requirements.

The hand was tested in three different subjects with different muscular constitutions proving that it can support a wide range of users; Electrical and mechanical sensibility controls added were very important for this purpose. Although the hand is fully functional, it is clearly in its development stage. Further improvements in aesthetics, ergonomics, and circuit reliability and performance are possible and within our reach. It is planned to continue this project beyond this early stage to achieve these goals. The project was a success and it served as great hands-on experience for all the members of the team in engineering problem solving. Its multidisciplinary nature made the team have a broader view of engineering design.

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