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Design of Above Elbow Prosthesis articulated with Electro-myogram signal and electrical switch

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A motion control strategy for 3 Degree of freedom prosthetic arm actuated with EMG signal from muscle activity to move end gripper and wrist; and electrical switch to move elbow joint has been proposed as a mimic to the biological hand. The design and control is carried out in accordance with precise electronic control, sufficient drive torque, requirements of variable grip force and ease of attachment with limbs. The features like grasping objects of different weights with variable grip force, wrist rotation and elbow movements are available with auto-locking features. Two Electro-Myogram (EMG) electrodes are used to tap the bio-electric potential from two antagonistic residue stump muscles. A novel decision making strategy has been implemented to realize the real-time EMG control of the end gripper and wrist. The arm is able to accomplish functions useful for both robotic & prosthetic industry.

Keywords: Prosthetics, Back-drive, Electro-myogram, Proportional grip-force, Electrical switch

Introduction

Prosthetic limbs are used by people with acquired amputation and congenital deficiency to restore some of the functions and cosmetics. Kulken TA proposed a rotational mechanism of elbow joint by implanting a permanent magnet into the distal end of a residual bone[1]. Lau CY and Chai A presented anthropomorphic robotic hand with 16 degrees of freedom implemented using pneumatic air muscles[2]. Chatterjee A *et al.* Kumar S. *et al.* and Veerubothla A *et al* developed circuit to process and condition the EMG signal [3,4,10] of residual stump of amputee followed by variable Grip Force features[3,4]. Jang G *et al.* proposed robotic index finger prosthesis controlled using EMG signals from *flexor digitorum superficialis* and *extensor indicis* in a lower arm[5]. Verma S *et al*. developed a Myo-electric controlled prosthesis controlled using single actuator[6]. Veer K proposed different control strategies of EMG signal to characterize arm movement[7,8]. Mathew Dyson *et al.* focused on Myo-electric control using linear filtering[9]. As per the prior research, several laboratory based EMG controlled prosthesis are being developed but are not available in Indian market. So a light weight, user friendly above elbow prosthetic arm (Table-1) is needed, which can be attached easily with residual limb of amputees.

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Materials and methods

The prosthetic arm system can be divided into two parts: Mechanical Assembly and Electronics Signal Processing.

Mechanical assembly

The 3 Degree of freedom (DOF) Arm prosthesis mechanism can be described as the individual movement of End-gripper, Wrist rotation and Elbow represents 1 degree of freedom each. The Arm prosthesis mechanism has three modules namely end-gripper, wrist and elbow. The hand movements such as finger opening, closing, grasping objects with variable grip force, wrist rotation and elbow joint flexion and extension is done through brushless DC motors with planetary gear head, which gives it a capability to carry 1.5 kg load and elbow rotation speed of 45 degrees per second. The main design considerations include light weight, user friendly operation and ease of attachment with amputees stump. Fig. 1 illustrates the correlation of the various structural elements of the device. A pair of fingers is attached with the thumb through a linkage connector and both rotate around their respective axes. The slider and screw assembly is coupled with DC motor-1 through universal coupling, which transmits the required torque to the end gripper for grasping. Due to this, continuous power to the motors is not required for position locking as the design is non-back-drivable unless driven by the electrical power.

Table 1 — Specifications of prosthetic arm

SPECIFICATION	VALUE
Operating Voltage	12V
Current Consumption	260 mA at no grip 750 mA at full grip
Opening Width for palm	0-100 mm
Wrist rotation	0-180 degrees
Elbow rotation	0-135 degrees
Resolution	1 degree
Max. weight that can be grasped	1.5 Kg
Average Finger opening speed	18 mm/sec (approx)
Average Elbow rotation speed	45º/sec (approx)
Weight of the Arm	1.2 Kg
Operation	By EMG signal and Switch

The speed and torque for opening and closing of fingers and thumb depends on the DC motor. DC motor-2 rotates the wrist through pins and base rotary disc. Limit switches confines the movements of the end gripper and the wrist rotation. DC motor-3 operates the elbow joint mechanism through manual electrical switch circuit. The elbow rotation around the hinge pivot is limited by two Opto-switches. The overall device is connected with amputees stump using a suitably shaped adapter.

Electronics signal processing

As shown in Figure. 1, Surface EMG is picked using electrode sets from skin surface, which is processed and conditioned using a differential

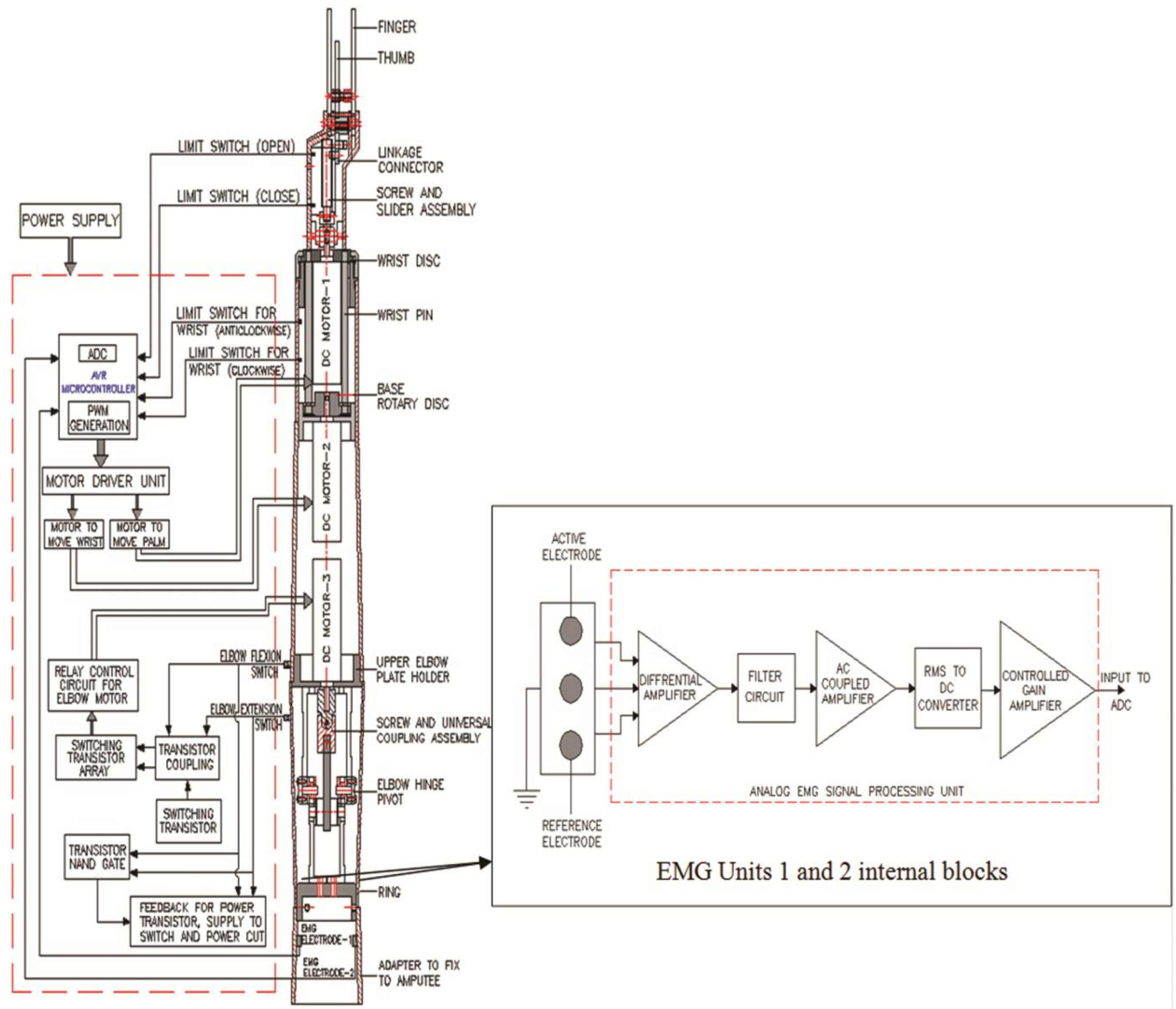

Fig. 1 — Overall Diagram of the arm along with Electronic signal processing blocks

amplifier with high input impedance followed by a low pass filter, AC coupled amplifier. Next an RMS to DC converter[3,4] to acquire the DC counter part of the signal. The signals are further processed by microcontroller based circuitry to set the decision to set in motion the respective DC motors, linked with end gripper and wrist. The signal from *Biceps* muscle is used for palm opening and wrist rotation, whereas signal from *Triceps* muscle is used for closing the arm with variable grip force. Both the motors are controlled by a single motor driver chip interfaced with microcontroller and ADC.

Results and Discussion

Arm simulation and analysis

Two groups of linkage mechanisms were adopted in series to realize the transmission of power for the movement of fingers and elbow. Dynamic simulation and kinematic analysis of mechanical assembly was done using Autodesk INVENTOR to estimate the stresses and force distribution throughout the mechanism components to select the suitable materials. The von Mises yield criterion, also known as the maximum distortion energy criterion, was used to estimate the yield stresses in ductile materials. The von Mises criterion states that failure occurs when the energy of distortion reaches the same energy for yield/failure in uniaxial tension. Mathematically, this is expressed as:

where σ_1, σ_2, σ_3 are the principal stresses and σ_y is the von Mises stress or equivalent tensile stress. Principal stresses can be calculated as:

$$\sigma_{1,2} = \frac{\sigma_x + \sigma_y}{2} \pm \sqrt{\left(\frac{\sigma_x - \sigma_y}{2}\right)^2 + \tau_{xy}^2} \quad \ldots(1)$$

$$\frac{1}{2}\left[(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2\right] \leq \sigma_y^2 \quad \ldots(2)$$

where σ_x, σ_y are the plane stresses in x and y direction, τ_{xy} is shear stress in x-y plane.

Two different sets of materials were used to evaluate the performance of the arm. One of them is Nylon, Brass and Nylon group while the other is Aluminium, Brass and steel group. The torque in the lead screw and linkages is assumed to be equal to the torque generated by the motor. Maximum torque was calculated based on the links design and material. Using the above Equation 1, Equation 2 and INVENTOR simulation software, it was found that slot pin and lead screw develops the maximum stresses, as shown by the red color in Figure 3. These parts were further investigated to select the suitable material. Several actuator and linkages designs were developed and analyzed in terms of transmitted torque, stresses generated, overall weight and required movements of the mechanism. The overall weight of the arm is the sum of weight of hand, elbow and its connecting members. Kinematic and dynamic simulation was carried out to evaluate the linkages performance and finger displacement. The simulation was carried out at 17 Nm, i.e. with a safety factor of 2.5 for 1.8 second time period. This time includes duration of free motion of finger, followed by duration of collision between fingers and objects to be grasped followed by the effective reaction force with 1N damping force while gripping the object in real time simulated environment. The graph shown in Figure. 2(a) reveals the force distribution on the weakest link i.e. Slot Pin, wherein the maximum force generated is about 4 N. The graph as shown in Figure. 2(b) shows the force distribution on the driving lead screw, wherein the maximum force generated is about 5 N. The torque required at elbow for carrying load of 1.5 kg is estimated to be 6.0 Nm. As shown in Figure. 3 the stresses induced are very less. So, Aluminium, Brass and Nylon material group was chosen for the mechanism. Selection of this material group also resulted in lower weight of the arm along with the required strength.

Electronics control

The overall operation can be divided into three parts:

a) **Closing the palm with variable grip force**

b) **Opening the palm & rotation of wrist**

c) **Elbow joint movement**

Following assumptions were made to define the activity of overall system:

1) V_1 = Applied voltage output from EMG Unit 1
2) V_2 = Applied voltage output from EMG Unit 2
3) V_{MAX} = Threshold Voltage level for high grip generation
4) V_{MID} = Threshold Voltage level for medium grip generation
5) V_{MIN} = Threshold Voltage level for low grip generation
6) V_{OPEN} = Threshold Voltage level to open the palm

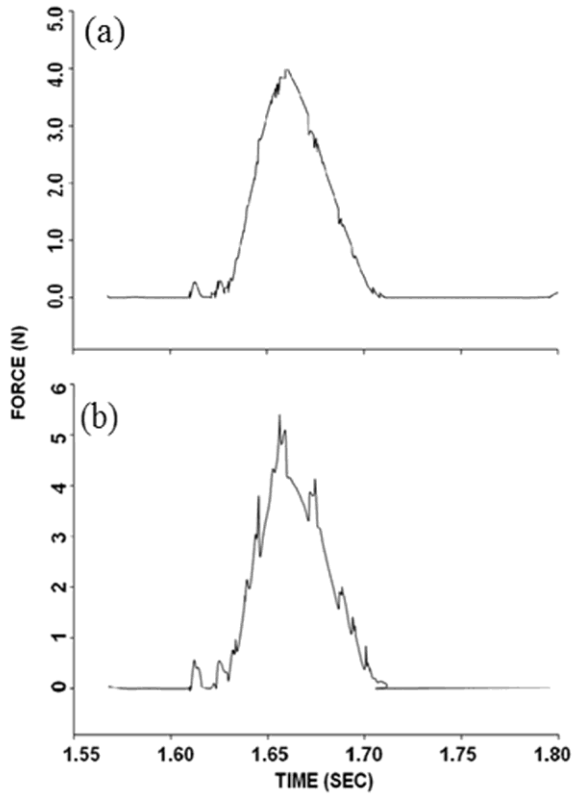

Fig. 2 — Force distribution on Slot pin (a) and Force distribution on lead screw (b)

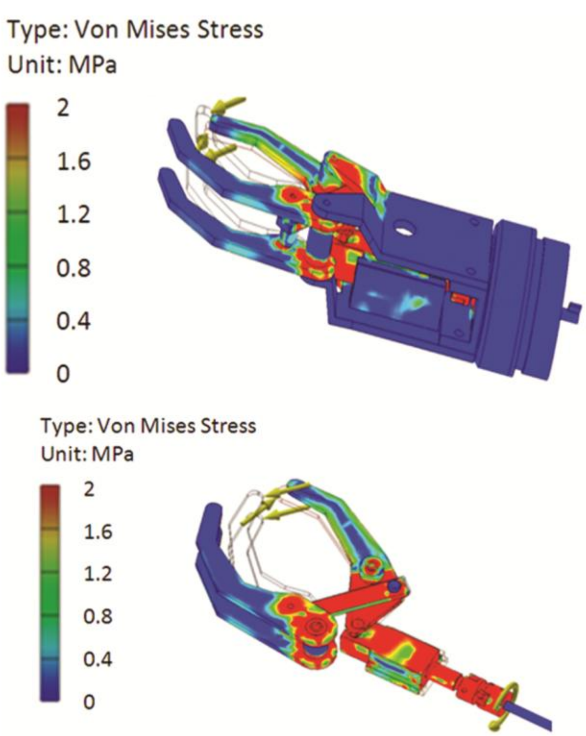

Fig. 3 — Von Mises stress distribution in Arm prosthesis and lead screw assembly

7) $V_{ANTICLOCKWISE}$ = Threshold Voltage level to rote the wrist anticlockwise
8) $V_{CLOCKWISE}$ = Threshold Voltage level to rote the wrist clockwise

Closing the palm with variable grip force

After power ON, the applied V_1 is compared with another voltage V_2. If $V_1 > V_2$, the status of the close limit switch is checked. If the output of the switch is high, it implies that the palm has not reached its maximum extent of closing. The input signal V_1, is compared with three threshold levels V_{MAX}, V_{MID} & V_{MIN} and three conditions arise as follows:

i) Condition 1: $V_{MIN} \leq V_1 < V_{MID}$

The microcontroller resets the driver control lines for minimum grip generation and sets the direction for closing. The minimum quantity of current passes through the armature of motor. As the output torque is directly proportional to armature current, the torque produced at the end gripper is low.

ii) Condition 2: $V_{MID} \leq V_1 < V_{MAX}$

Same as stated in case 1 above, but the armature current is greater than the previous one and the output torque produced is higher at the end gripper as compared to case 1.

iii) Condition 3: $V_1 \geq V_{MAX}$

Same as stated in the case 1 above, but the armature current is greater than the previous one and the output torque produced is higher at the end gripper as compared to the case 2.

a) **Opening the palm & rotation of wrist**

If $V_2 > V_1$, three conditions arise as follows:

i) Condition 1: $V_{OPEN} \leq V_2 < V_{ANTICLOCKWISE}$

The status of the open limit switch is checked. If the output of the switch is high, it means that the palm has not reached to its maximum extent of opening. The microcontroller resets the driver control lines for maximum speed for opening and sets the direction for the same. This signal is sent to the motor responsible for palm operation.

ii) Condition 2: $V_{ANTICLOCKWISE} \leq V_2 < V_{CLOCKWISE}$

The status of the anticlockwise limit switch is checked. If the output of the switch is high, the microcontroller resets the driver control lines for maximum rotation speed and rotates the system in anticlockwise direction and sets the direction for the same. This signal is sent to the motor responsible for wrist rotation.

iii) Condition 3: $V_2 \geq V_{CLOCKWISE}$

The status of the clockwise limit switch is checked. If the output of the switch is high, the microcontroller sets/resets the driver control lines for maximum rotation speed and rotate the system in clockwise direction and sets the direction for the same. This signal is sent to the motor responsible for wrist operation.

Elbow operation

Two Push Button type switches are used to operate the elbow joint for flexion and extension. Both the switches are connected with a Transistor made NAND Gate and a Transistor Coupling circuit. The output from the NAND gate is connected with a Feedback Transistor through which the battery power is transferred to the Switches. Two Opto-switches along with a mechanical piston are used to define maximum extent of opening and closing of Elbow joint. Opto-switch Output and Elbow flexion and extension switch are coupled with a Transistor Coupling Block. The outputs from Transistor Coupling Block are fed to a Transistor Switching Circuit, which triggers two semiconductor relays, to move the motor in two different directions.

Testing and Evaluation

The subject was asked to lift and pour the water from soft thermocole glass to another container. When the subject applied minimum level of force at the triceps muscle, the palm started closing till the force was withdrawn. But, the glass was slipping out from the end gripper. The subject applied the next level of grip force and grasped the object successfully. Later, he applied the force from the biceps muscle to rotate the wrist in anticlockwise direction. The wrist rotated and the amputee was able to pour the water into other container. To restore the device to its normal state, the person exerted higher level of force at the biceps muscle as compared to previous one so that the wrist rotated in clockwise direction, to placed back the glass on the table. Other experiments like lifting the objects using elbow joint, drinking the water, grasping a 1.5 litre water bottle and writing on a board, etc. were carried out with other subjects.

The motion control strategy developed for above elbow prosthesis articulated with bio-electric potential provides an intelligent variable grip force patterns for gripping and releasing of objects according to the size and weight. These patterns are provided using Myo-electric potentials due to muscle activity. It is not required to provide the continuous power to the motor for position locking and power grip as the device has auto-locking features. During closing/opening of the hand, its direction may be changed midway and the reverse operation can be carried out whenever needed. The various grip force algorithms can be obtained by varying the motor current function as Linear Ramp, Cubic ramp, Cycloid, Sine, Polynomial, Harmonic, Modified Sine, Modified Trapezoid or Spline and their combinations. The multiple trace curves of movable points were generated with reference to different stationary and dynamic parts, which helped to visualize the complex dynamic motion path of constituent parts. User friendliness of the device ensures that no cumbersome training program is required for the amputee to operate the device.

Conclusions

The developed system is able to work under real conditions and the experimental work has been done after the trial with above elbow amputee personnel at ALIMCO, Kanpur. The overall specification of the system is as per the table attached. Microcontroller based programming makes the operation of the device more precise and responsive. Optimization of mechanical structure was done using software tools. The system performance can be further improved by choosing the materials with high strength to weight ratio, placing slip along with temperature and strain sensor strips at the finger tips and high performance microcontrollers like AVR/PIC. For miniaturization of electronic circuitry, all dual in line packages (DIP) can be replaced by surface mounted devices (SMD). The amputee person is able to operate it at his own desire and eliminated the need of other hand for wrist rotation. The chosen motion control strategy helps the device to accomplish several functions useful for both robotic & prosthetic industry and can be commercialized in the market.

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