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Conference Paper

The Development of Body-Powered Prosthetic Hand Controlled by EMG Signals Using DSP Processor with Virtual Prosthesis Implementation

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The state of the art in the technology of prosthetic hands is moving rapidly forward. However, there are only two types of prosthetic hands available in Libya: the Passive Hand and the Mechanical Hand. It is very important, therefore, to develop the prosthesis existing in Libya so that the use of the prosthesis is as practical as possible. Considering the case of amputation below the elbow, with two movements: opening and closing the hand, this work discusses two stages: developing the operation of the body-powered prosthetic hand by controlling it via the surface electromyography signal (sEMG) through dsPIC30f4013 processor and a servo motor and a software based on fuzzy logic concept to detect and process the EMG signal of the patient as well as using it to train the patient how to control the movements without having to fit the prosthetic arm. The proposed system has been practically implemented, tested, and gave satisfied results, especially that the used processor provides fast processing with high performance compared to other types of microcontrollers.

1. Introduction

Worldwide, every year the number of amputees increases from 150,000 to 200,000, which are added to the existing four millions; 30% of these amputees have suffered from upper limb amputation, 60% of the arm amputations are found in people between 21 and 64 years old, whereas 10% of them are patients under 21 [1]. According to Amputee Coalition of America's National Limb Loss Information Center (NLLIC) [2], 70% of the amputations, due to a trauma or an accident, involves the upper limbs.

In Libya, especially after the 17 February revolution, the number of amputees has increased and the subject of prosthesis has become very important and worth investigating.

Therefore, it is important to provide the technology of prosthesis since it can offer those patients a significant support so that they can normally practice their life activities and involve in the community.

Different types of prosthetic hands have been developed, some of which are just for cosmetic purposes with no functions, known as the Passive Hand. Other types have some functioning ability such as the Body-Powered Prosthesis, the Electrical Hand, and the Myoelectric Hand. The Body-Powered Prosthesis (so called mechanical prostheses) is operated with straps that commonly pass over the amputees' shoulders and is controlled by scapula abduction; the Electrical Hand is operated by a motor driven by microswitches; and the Myoelectric Hand is operated by a microprocessor and a motor which are controlled by electromyography signals (EMG). The EMG signals are biological signals that occur in the residual limb and can be collected with sensors to control the movement of the prosthesis.

However, there are only two types of prosthetic hands available in Libya, namely: the Passive Hand and the Body-Powered Prosthetic Hand or the Mechanical Hand as shown in Figure 1. These kinds of prostheses are considered impractical and hard to use. It is very important, therefore, to develop the prostheses existing in Libya so that the use of the prostheses is as practical as possible.

Considering that human hands have more functions than legs, and arm amputation causes a huge disability, the authors have decided to develop this Body-Powered Prosthesis to provide some support to the amputees.

As mentioned earlier, the body-powered prosthesis is operated by some motioning of the amputees' shoulders to control the prosthetic component with the necessary force. In other words, there is a line attached to the body-powered prosthesis and it controls the opening and closing process, pulling the line to open the hand and releasing it to close the hand. Thus, it is possible to control the movement of the body-powered prosthesis with an electronic circuit instead of scapula abduction; that is what the authors are trying to discuss in this work.

One of the most challenging areas in this research is to connect neural signals of a human to the artificial hand and exploit these signals to control the prosthesis. The electromyography signal (EMG) is used to operate the servo motor through a microprocessor to control the line of the body-powered prosthesis. In a previous work, the authors have produced a prototype of body-powered prosthetic hand controlled with PIC 16F877A microcontroller. That prototype, shown in Figure 2, was tested on both an able-bodied man and on an amputee. However, the test has indicated a time delay in the response and that is not satisfying for prostheses operation. Thus, this work is aimed to overcome that issue using dsPIC30f4013 processor which provides fast processing with high performance compared to other types of microcontrollers.

Interestingly, this work also presents a virtual prosthesis using Matlab software based on fuzzy logic concept that can be used in the training stages so that the patients learn how to control the prostheses with their EMG signals. In addition, the software can be used to decide the best area of the residual limb to collect the EMG signals.

An overview of the paper is described as the following. Section 2 illustrates a background of body-powered prostheses and their development. Section 3 proposed the system architecture of the work where the virtual reality software and hardware stages are explained. In Section 4, the results of the designed model are discussed. The conclusions with future prospect are given in Section 5.

2. Background and Related Works

Many of upper limb amputees wear body-powered prostheses, either a hook or a hand-shaped, and these devices offer limited functionality with motions of elbow flexion and extension, hook articulation, and wrist rotation [3]. These gestures are controlled by the needed force from the body with a shoulder harness and cable for operation [4].

Body-powered prostheses are the most commonly used, most inexpensive, and commercially most available prostheses [3, 5]. However, the motion of this kind of prostheses comes with a large mechanical disadvantage [5], since it takes much energy to move the prosthesis, so it puts more strain on the body of the amputee as, in long-term use, this causes shoulder issues and anterior muscle imbalances [3].

In the 1950s–1960s, the myoelectrically controlled prosthetics was introduced, where the prosthesis controlled by reading and processing signals generated by flexing of the remaining muscles of a limb [6].

This type of signals is called EMG signal. EMG signal is a summation of all action potentials occurring in a muscle at a single time. It can be recorded on the surface of the skin with standard electrodes. Figure 3 shows an EMG signal of three opening gestures in 5 seconds. The EMG lays on the range of 20–400 Hz as shown with its spectrum in Figure 3.

EMG signals are widely used in prosthesis research because they represent the electrical currents caused by the muscle contractions and actions. Moreover, they are more acceptable and convenient for the amputees because they can be acquired through surface sensors [7].

The electrical activity naturally generated by contracting muscle in a residual limb is amplified, processed, and used to control the flow of electricity from a battery to a motor, which operates an artificial limb [8].

Two examples of early electric prosthetic arms were cited in [9] the "Boston Arm," developed in the late 1960s, and the "Utah Arm," developed in the early 1980s. Both are myoelectric arms; this means that they are controlled by reading the electrical signals generated by the flexing of human muscles.

The "Boston Arm" was mainly designed as a proof of concept to show that the prosthetic could be controlled by EMG signals [9].

In contrast to "Boston Elbow," the Utah Arm provides multiple degrees of freedom where it provides elbow flexion and wrist rotation. This hand is able to move slowly or quickly to any position by using proportional control [10].

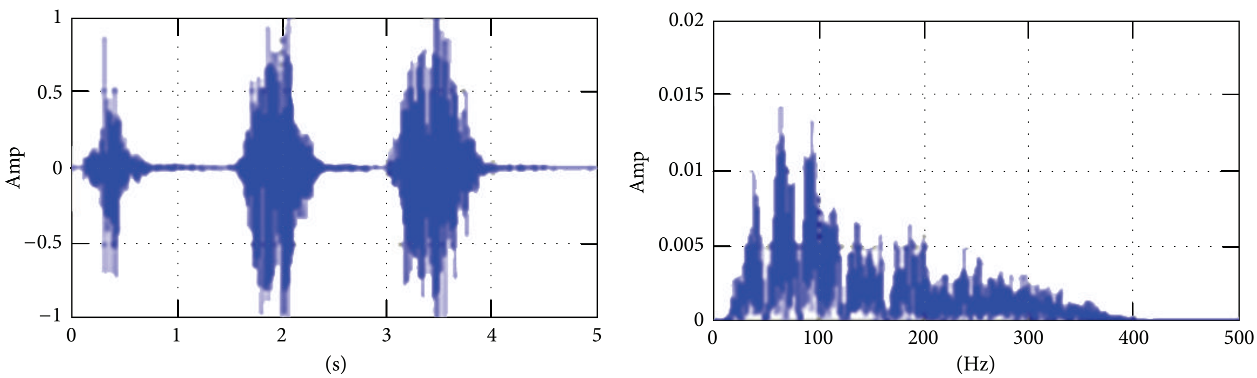
Several years ago, robotic prosthetic jointed fingers were released commercially such as the Otto Bock Sensor Hand [3, 11] and Touch Bionics I-Limb [10]. Commonly, the used myoelectric arms are one degree of freedom that represents in opening and closing. It uses only two EMG sensors to increase training efficiency and practical reliability of the device. However, these devices do not have the manipulation capabilities of the human hand. For instance, their active bending is restricted to three joints maximum, which are actuated by a single motor, while other joints can bend only passively or cannot bend at all [7].

Nevertheless, in the field of research there is impressive development in myoelectric prosthetics with multiple DOF. The main challenge is how the prosthesis mimics the human arm and that depends on several components which are Electrode Placement; Signal Conditioning; Feature Extraction; Feature Evaluation; Classification [12]. The nature and

(a) Passive Hand (b) Body-Powered Prosthesis Hand

Figure 1: Types of prosthetic hands in Libya.

Figure 2: Testing the first prototype of the EPET.



(a) Time domain (b) Frequency domain

Figure 3: An EMG signal.

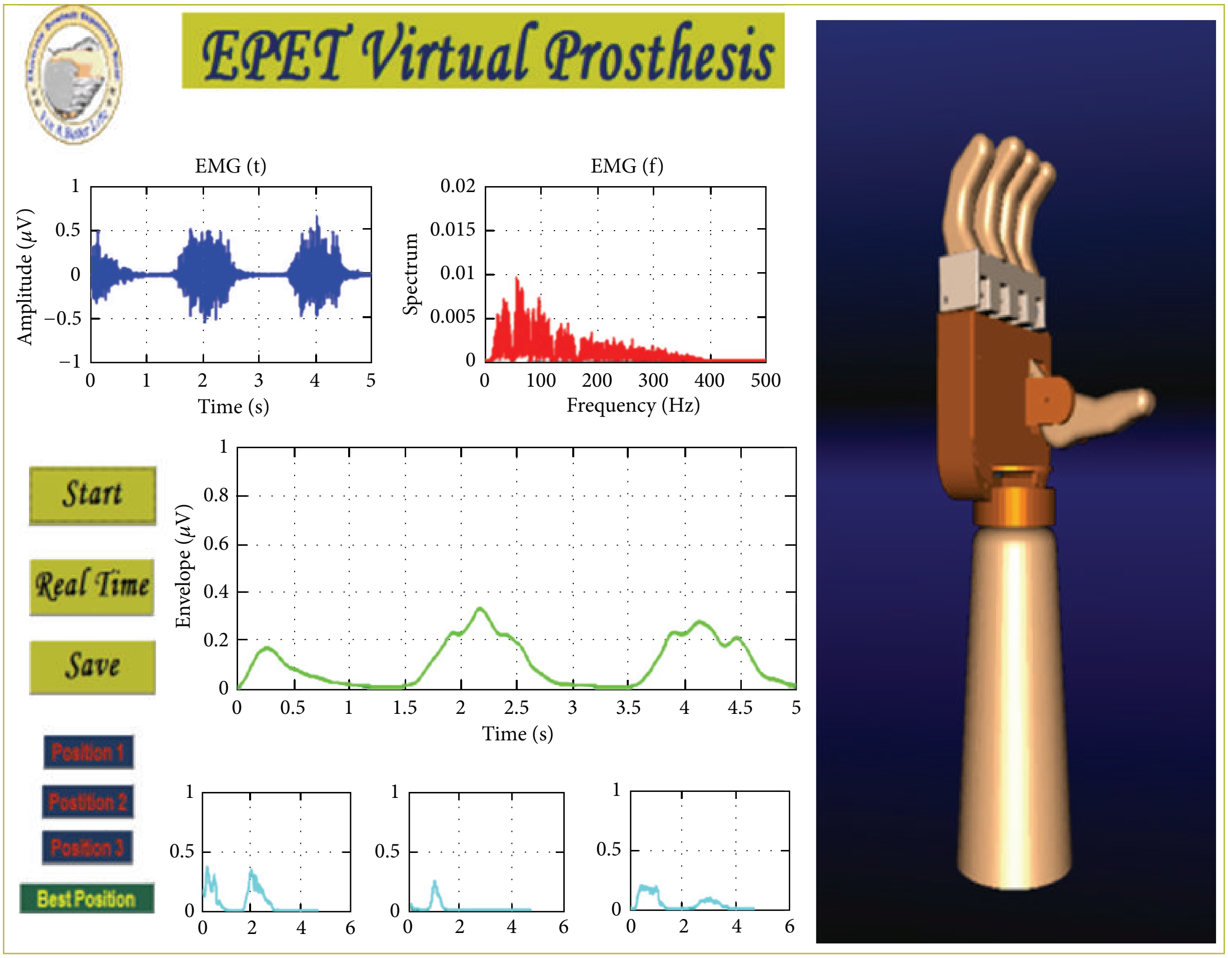


Figure 4: A view of designed virtual reality software.

characteristic of EMG signal can be properly interpreted, where extensive efforts have been made in order to develop better algorithms and existing methodologies and to improve detection techniques to extract accurate EMG signals to be easier to classify [13].

Many researches focus on the feature extraction and EMG classification, as there are several classification techniques including time-frequency analysis, wavelet analysis, neural network, and fuzzy classifications [7, 14].

Feature extraction is used to extract significant information in surface EMG signal and eliminate the unwanted EMG parts and interferences [14, 15]. In order to have a better classification, many studies of the EMG signal classification have implemented a feature set that has contained a number of redundant features [16]. For good results and after having a set of features with high classification, it must be implemented in high performance processor such as DSP-based controller.

Despite the huge development in the area of myoelectric upper prosthesis, there are still some challenges in order to classify EMG signals from multichannel surface electrodes into control signals that can direct complex prosthesis movements.

3. System Architecture

The proposed system is based on the use of EMG signals to support the mechanism of the body-powered prosthesis. For the aim of the project, the proposed system was established through two stages as follows.

3.1. Virtual Reality Software. The Matlab was used to design the software that is responsible for extracting the EMG signal from the patient and analyze it to figure out the most suitable position on the stump of amputee to collect the signals, and a view of the GUI interface is illustrated in Figure 4. Also, this software can help to train the patient how to control the three-dimensional hand in the program, which was designed by EPET using solid work and virtual reality tool box, and learn how to control it by sending commands from the brain.

This part consist of the following three steps.

(1) *Collecting Data*. The EPET technical support has designed and built a surface electromyography (sEMG) sensor to collect the EMG signal from the residual limb muscle. The collected signals were treated as sounds; that is, the output of

the sensors was amplified and then entered to the computer through the sound card and saved as MAT files. More details about the sEMG are described in Section 3.2.1.

(2) *Preprocessing: Digital Filtering*. The EMG signals are difficult to analyze due to their small amplitude (micro/millivolts). Consequently, these signals are easily affected by impure signals that come from different sources of noise. Several types of noise might occur as a result of inherent equipment noise, electromagnetic radiation, motion artifacts, or others. Therefore, preprocessing is a must in order to acquire the raw EMG signal. The system used in this work applied two digital filters; the first one is notch filter that was used to remove the 50 Hz electromagnetic induction from power lines, according to Libyan standard, and the other one is a second-order band pass Butterworth filter with cut-off frequency 20–400 Hz to filter out the unwanted signals.

(3) *Signal Processing*. After preprocessing stage, the absolute value of the EMG signal is calculated so that the envelope of the signal can be determined, which can then be used with a threshold to decide whether to open or close the prosthesis as follows: simply, if the amplitude of the signal is above the threshold the hand opens, and otherwise the hand closes. The flowchart shown in Figure 5 describes the software suggested by the authors.

3.2. Hardware. The system architecture of the proposed design is demonstrated in the block diagram shown in Figure 6. It consists of three main parts: sEMG sensor circuit, embedded system circuit, and servo motor. The system is connected to Otto-bock body-powered arm that was offered by Benghazi Rehabilitation Center. The three parts are described in the following sections.

3.2.1. sEMG Sensor Circuit. Figure 7 shows the sEMG sensor circuit that was designed and built by the EPET technical support to acquire the EMG signal from residual limb muscle and amplify it, so that it can be used as an input to the controller of the prosthesis. The circuit consists of three electrodes; one is acting as the reference electrode, another acts as the active electrode, and the third as the ground electrode. The difference signal between the reference and the active electrode is processed by AD620 Operation Amplifier to reduce noise in the system as demonstrated in Figure 8.

The nature of the electrodes pick up unwanted signals from the surrounded environment. Therefore, the signals acquired by electrodes must be fed into AD620 instrumentation amplifier via wires. Hence, the noise in both inputs will be illuminated, remaining the action potential (the EMG signals) [17].

The AD620 is a low cost, high accuracy instrumentation amplifier that requires only one external resistor to set gains of 1 to 1000 with its high accuracy of 40 ppm maximum being ideal for use in precision data acquisition systems, such as weigh scales and transducer interfaces. Furthermore, the low noise, low input bias current, and low power of the AD620 make it well suited for medical applications. The AD620 works well as a preamplifier due to its low input voltage noise

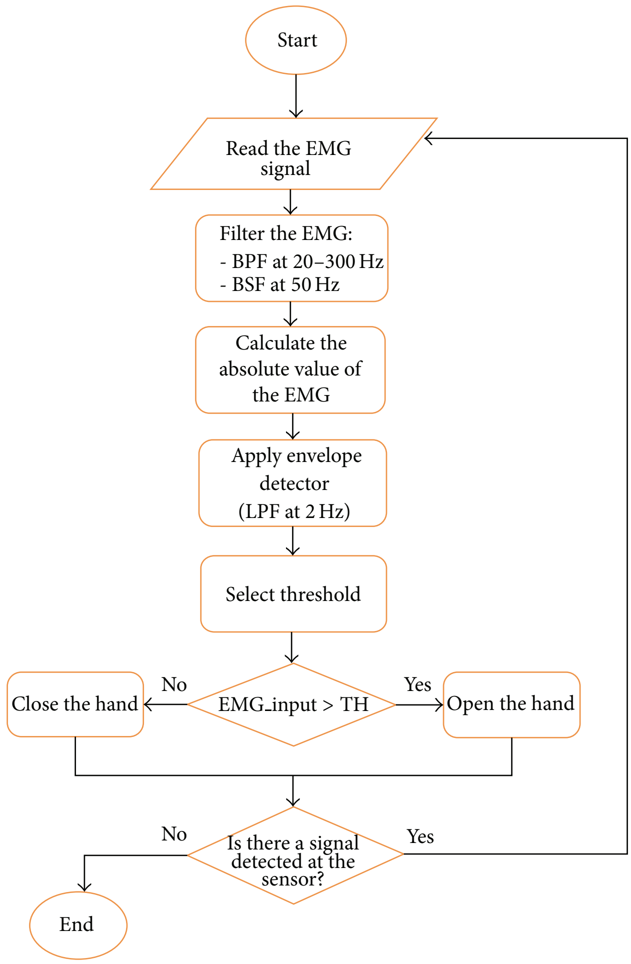


Figure 5: The flowchart of the proposed software. This flowchart describes two softwares one for the virtual reality which reads the EMG signal from the card sound and the other is for dSPic which reads the EMG signal from the ADC, so it must be generalized.

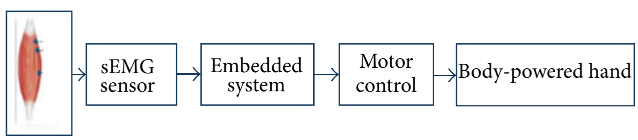


Figure 6: Block diagram of overall system design.

[18]. Each patient has a different signal as variable resistor to change the gain suitable for every patient individual.

3.2.2. Embedded System Circuit. This circuit depends on a digital signal processor; this processor is a specialized microprocessor with a modified Harvard architecture and a single cycle multiply-and-accumulate required for the fast operational needs of processing and for mathematically manipulating real-world signals like voice, audio, and video [19].

In the system design, the speed of computation and ADC resolution is considered as the most important characteristic.

Figure 7: The double sides of sensor circuit designed by EPET.

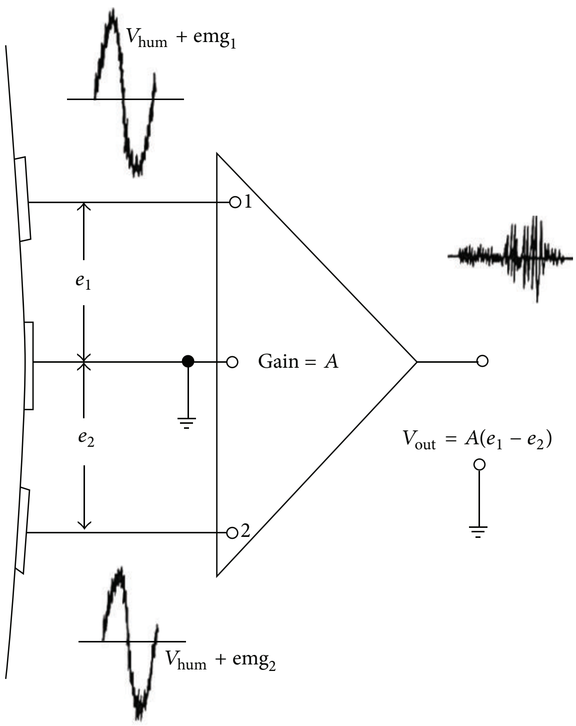


Figure 8: The operation of differential amplifier.

Since dsPIC30F4013 device has these properties, it has been chosen for the proposed design. This chip has the following specifications:

(i) perform up to 30 MIPS operation;

(ii) dual data fetch;

(iii) two 40-bit wide accumulators 17-bit × 17-bit single-cycle hardware fractional/integer multiplier;

(iv) all DSP instructions are single cycle;

(v) multiply-accumulate (MAC) operation;

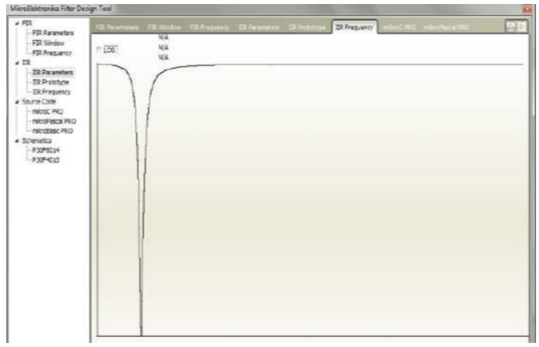


Figure 9: The frequency response of notch filter using the software.

(vi) 12-bit analog-to-digital converter (ADC) with 200 ksps conversion rate [20].

The dsPIC is programmed by MicroBasic language. The procedures of the software can be summarized in the flowchart illustrated in Figure 5.

One of the most important properties of the proposed device is to filter analog signals in real-time digital filtering manner. The filters are designed by "Digital Filter Design Tool" of MicroBasic-PRO for dsPIC30/33, and Figure 9 shows the design of the notch filter using the Filter Design Tool [21]. As the power spectrums of the EMG signal are approximately concentrated in the range 20 HZ–300 HZ and the power line noise is 50 HZ, a band-pass Butterworth filter and a notch filter were used to perform the proper filtering. Frequently, the infinite impulse response (IIR) filters are the most efficient filters to obtain a better magnitude response for a given filter. In other words, IIR filter can run fast in low order. In this work, the authors designed a band-pass filter and a notch filter with the following parameters:

(i) device clock: 12 MHz;

(ii) sampling frequency: 600 Hz;

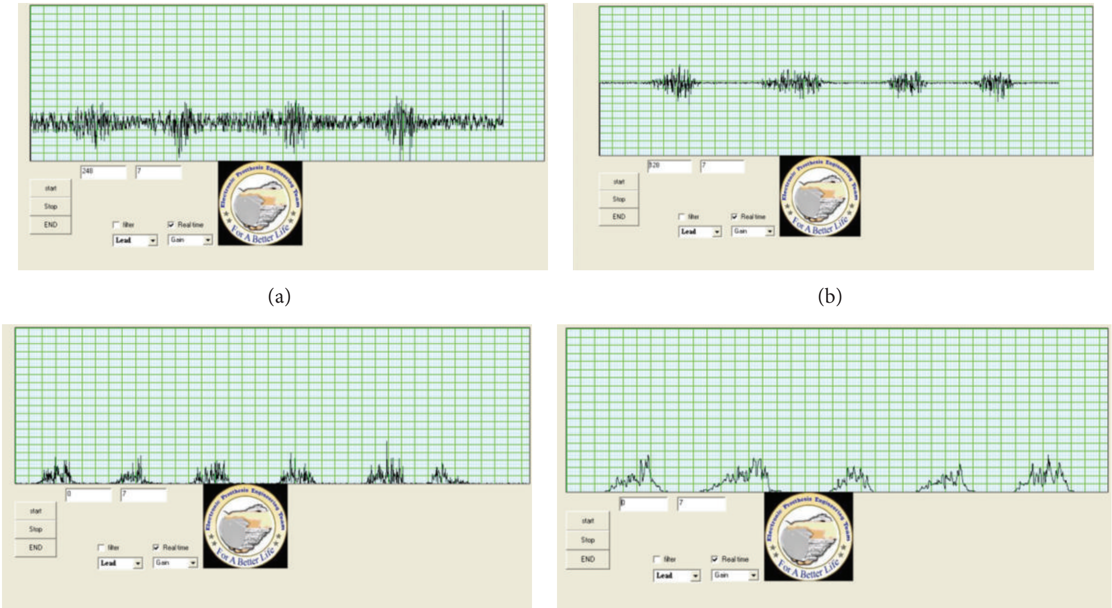
(iii) filter order: 2.

Equations (1) and (2) represent the digital filters: notch filter at 50 HZ and band-pass filter between 20 and 300 Hz, respectively. Consider

$$H(z) = \frac{B(z)}{A(z)} = \frac{0.9502 * Z_0 - 1.6481 * Z_1 + 0.9502 * Z_2}{1.0000 * Z_0 + 3.6770 * Z_1 + 0.9004 * Z_2}, \quad (1)$$

$$H(z) = \frac{B(z)}{A(z)} = \frac{2.6569 * Z_0 - 3.6770 * Z_1 + 2.6569 * Z_2}{1.0000 * Z_0 + 3.6770 * Z_1 + 6.3138 * Z_2}. \quad (2)$$

Besides, a low pass filter with cut-off frequency 2 Hz was used to obtain the envelope of the signal. Figures 10(a), 10(b), 10(c), and 10(d) show the EMG signal collected by sensor after different stages of processing: (a) the raw EMG signal, (b) filtered signal by band-pass filter and notch filter, (c) the rectified filtered EMG signal, and (d) the envelope of the filtered signal. The amplitude value of the envelope is tested



(a) (b) (c) (d)

Figure 10: (a) The raw EMG signal. (b) The filtered EMG signal by band-pass filter and notch filter. (c) The rectified filtered EMG signal. (d) The envelope of rectified signal.

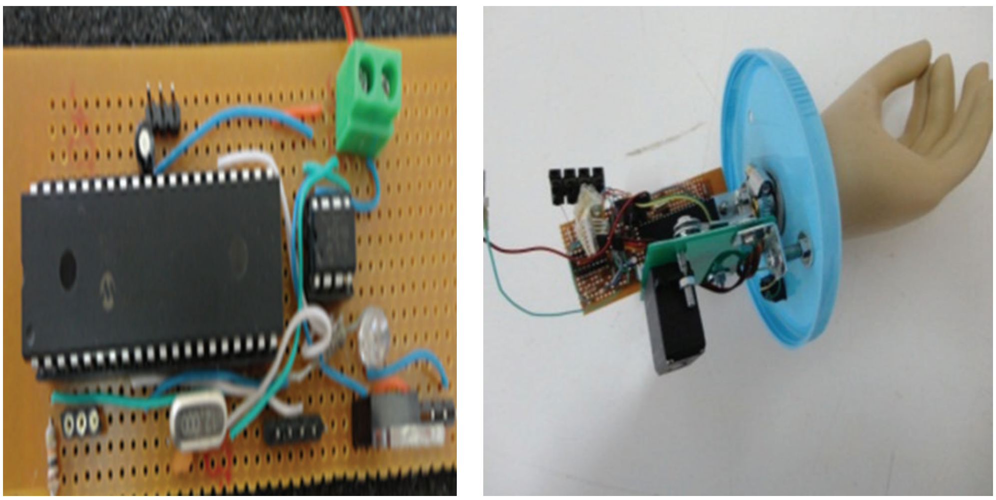


Figure 11: Embedded circuit and EPET prototype.

by the software as follows: if the value is greater than a given threshold, the processor will send a command to the servo motor that takes the command as a pulse width modulation signal, as the width of pulses is proportional to the position of the servo motor to open the body-powered hand as required.

4. Results

This system was designed, manufactured, and tested. A virtual simulation has been programmed to simulate the gesture of the signals from the amputee, identifying the best position to take the signal from as well as using it in the training stage. The collected data is classified using fuzzy control method and downloaded to the DSP processor.

The model successfully performs hand functions with its good cosmetic appearance. This prototype is of friendly use even in high level amputees. Figure 11 shows the prototype and the designed embedded circuit.

5. Conclusion

The development of the body-powered prosthetic hand is meant to help this marginalized group in Libya and that can be done by just inserting electronic circuits. This upgrade of body-powered prosthetic offers great comfort to the patient. However, the recognition stage was simple, and the predictions of the movements were very good.

One of the main requirements of artificial arm is the functionality, since it should be as natural hand as possible. In this study, a prototype of a prosthetic hand has been developed considering two movements—opening and closing the hand, and this is the result of several design iterations which have improved the size and time response of the embedded system. More comprehensive study to cover a wider range of gestures will be considered, for example, fingers' movements.

The designed model is intended to be a future product, where it will function in two stages: online and offline. The offline is the virtual reality part in the rehabilitation stage as well as collecting data to be used with suitable recognition method, while the online stage is when the product is installed to patient so that the recognition can be done in real time.

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