DESIGN AND DEVELOPMENT OF AN EMG DRIVEN MICROCONTROLLER BASED PROSTHETIC LEG

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ABSTRACT: Over the past years prosthetic legs have become much improved although complex. However their costs are high and are not within the reach of most people in the Third World. Low-cost fixed prostheses are available in the Third world countries of Asia and Africa, but these offer very basic movement with unnatural gait; climbing stairs gets quite difficult. The prosthesis being worked upon in the present work are for amputees with legs removed above the knee, and would offer a limited rotational movement of the knee joint under voluntary control of the wearer, driven by the EMG signals extracted from thigh muscles. The aim is to make it at a low cost, may be at a cost slightly higher than the passive ones, but allowing a better gait in walking, and in climbing stairs. An initial work was done in this direction by our extended group earlier; the present work gives further improvements. This involves redesigning of the motor and the gear system and that of the electronic circuitry for processing the EMG signals extracted from thigh muscles, interfacing the output to the microcontroller, rotating the motor in two directions thereby accomplishing the movement of the knee joint. The motor, geared down, is mounted horizontally and a pulley system drives the artificial knee joint. When complete, this will benefit a large number of handicapped people in the Third World.

Keywords: Prosthetic leg, Voluntary control of Prosthesis, EMG driven

1. INTRODUCTION

The human body is a remarkable piece of biological machinery, and our limbs are no exception. When someone loses a limb due to injury or disease, the functionality once offered by that limb is lost as well. Therefore prosthetic limbs are incredibly valuable to amputees because the replacement by an artificial body part can help restore some of the lost capabilities. Human leg provides numerous complex functions and multiple degrees of freedom. These wide varieties of functions of human leg cannot be imitated immaculately by any artificial means. However, incredible advancements have been achieved for active prosthetic legs in the recent years. One researcher found that his limbs used twenty-five percent less energy than those of an able-bodied runner moving at the same speed [1]. However, these super-prosthetic legs are highly complex and extremely expensive for use by general people, more so in the Third World countries.

On the other hand passive fixed leg prostheses, primarily made of wood and metals have been in use for a long time throughout the world, and many of these have been in use in the Third World as well. A significant advancement was the 'Jaipur foot' [2] made of rubber which requires much less time to fabricate and are very cheap in cost. Due to financial and indigenous technological constraints common people in the third world countries still depend on passive prostheses.

For an above-knee amputee, a fixed passive leg prosthesis allows walking in a rather artificial way. The wearer has to drag the leg since it has no provision of bending of joints, as would happen in a natural leg at the knee and the ankle. Previous members of our extended group initiated the idea of bridging the gap [3], to make an affordable simple leg prosthesis which would have at least a knee bending function, controlled by the will of the wearer. They used a motor mounted with a vertical axis which subsequently drove the artificial knee joint with a horizontal axis through a worm gear arrangement as shown in Fig.1. This would offer a limited knee bending action around a horizontal axis, which is expected to make walking easier. EMG signals were obtained from two sets of muscles, one from the front of the thigh, and one from the back. If the EMG signal from the back was greater than that from the front, the motor would turn to bend the knee (flex). On the other hand, if the EMG signal from the front was greater than that from the back, the motor would turn to straighten the knee (extend). No ankle joint movement was attempted in this plan. A prototype of the leg prosthesis was made and a control hardware based on a microcontroller was developed which demonstrated the possibility of the desired function. In the present work the mechanical design of the leg prosthesis was fully redesigned. The motor was mounted with a horizontal axis which seemed to have some advantages over the previous vertical axis. This allowed the use of simple gears which may allow forced rotation of the leg if need arises because of a loss of battery power. The previous design used a worm gear which cannot be operated unless the motor turns, causing it to lock in case something goes wrong, and this situation is avoided in the present design. The EMG amplifier was also redesigned and a new microcontroller based control unit was also developed. This work is presented in this paper.

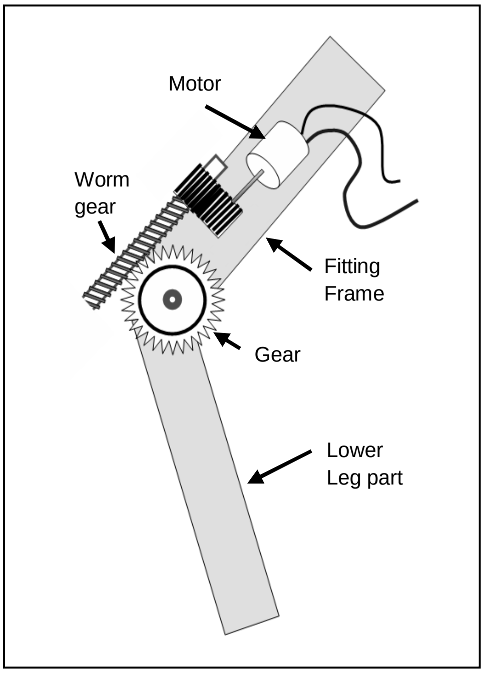

Fig. 1 Mechanical system of the previously implemented design by our

2. METHODS

The project aims at providing prostheses for above-knee amputees. The two separate parts of the work, the electro-mechanical part for the prosthetic leg producing rotation at the artificial knee, and the electronic part where EMG signals are picked up from the body and analysed to provide drive control signals to the motor using a microcontroller, are described separately below.

2.1 Design of the Electro-mechanical Structure

The entire mechanical structure consists of two main parts which are the upper part and the lower part as shown in Fig.2, joined together through a hinge like horizontal pivot. The upper part will attach itself with the thigh muscles like a ‘socket’ together with braces to support the whole thing from a belt in the waist. It is to be constructed in such a manner so that it can accommodate all the devices including electrodes, circuits, battery and the motor. The lower part carries out the work of the leg. That is why it must be robust enough to carry the body weight but light in weight for easy maneuvre of the prosthesis. For this part, strong and light metal or carbon fiber could be chosen.

A wooden prototype was made to study the motion of the mechanical structure and the action of the motor. The motor was mounted with its axis horizontal within a chamber in the upper part of the prosthesis. The motor housing had a built-in gear to reduce the speed and thus increasing the torque. A pivot type joint (hinge

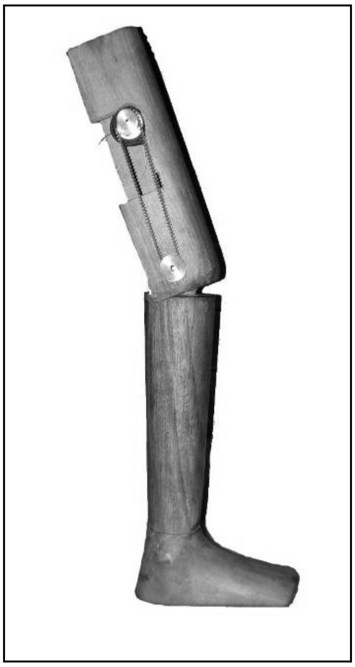

Fig. 2: Mechanical design of the developed leg prosthesis

like) was used between the two parts. In the prototype, a pulley system was used to rotate the lower part of the leg with respect to the upper part as shown.

2.2 Electrical part

2.2.1 EMG Signal extraction

A muscle normally is 'relaxed'. When an electrical signal comes from the central nervous system through a specified set of nerves, electrical action potentials are generated in a muscle which causes it to contract. EMG is the recording of this electrical action potential as picked up by skin surface or needle electrodes. There is no active 'extension' in a muscle. So it has only these two modes – 'relaxed' and 'contracted'. However, when a set of muscle is ordered by the brain to contract, say the muscles on the front of the thigh, the ones in the back side must keep relaxed, and the brain ensures that too. Muscles on such opposite sides of a limb never contract simultaneously in a normal healthy person.

According to the function of the thigh muscles they may be classified into two units: Extensor unit (in the front) responsible for extension or straightening of the knee and flexor unit (in the back) causing flexion or bending of the knee. EMG signal available in those muscles are extracted using suitable electrodes. Electrodes are usually made of metal but this is not always the case, and indeed there can be considerable advantages in terms of reduced skin reaction and better recordings if non-metals are used. Three types of common electrodes for EMG are Surface electrodes, Needle electrodes and Microelectrodes, where the last two are invasive and not suitable for the present application. In the surface electrode a metal touches the skin and picks up the relevant electrical potential through a metal-electrolyte (the body contains electrolytes) interface. One of the common problems associated with such simple surface electrodes is that with skin movements the contact potential changes slightly and causes a noise to be generated, called motion artifacts. This type of problems are usually solved by interposing a thick pool of viscous jelly like electrolyte in between skin and metal in a configuration known as the 'Floating Electrode' [4]as shown in Fig.3. Here the metal-electrolyte interface is moved away from the skin to the top of the viscous jelly-like electrolyte pool, and skin movements are not transmitted to this interface due to the high viscosity of the electrolyte pool. In the present work floating electrodes, available commercially as self adhesive disposable electrodes, are to be used initially. However, this may become expensive in the long run, therefore, an improvised re-usable floating electrode has been devised which uses either a carbon electrode or a Ag-AgCl electrode mounted in an appropriately shaped plastic holder. An electrode jelly is to be applied to this electrode daily before use.

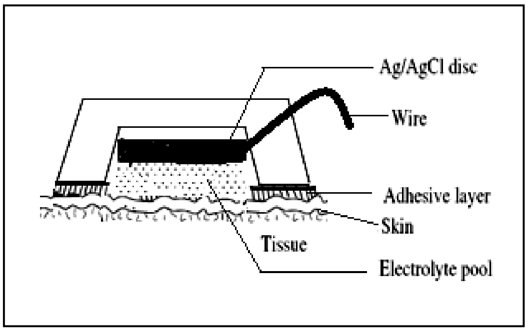

Fig.3: Floating surface electrode

2.2.2 Bioelectric Amplification and signal analysis

It is well established that the amplitude of voluntary EMG signal (produced by willful contraction) is stochastic (random) in nature and can be reasonably represented by a Gaussian distribution function. The usable energy of the signal is limited to the 10Hz to 5KHz frequency range for surface electrodes, with the dominant energy in the 10-500 Hz range [5]. EMG signals picked up using skin surface electrodes are of very tiny amplitude, typically of the order of mV, and are associated with moderately high source resistance, typically about 10kΩ. Besides it is associated with a large common mode signal coming from ac mains at 50Hz, which falls within the signal range, and is difficult to filter out later. Therefore the common mode 50Hz noise has to be eliminated at the very beginning as much as possible. For this a differential amplifier employing two inputs with respect to a common reference is needed which should have a very high Common Mode Rejection Ratio (CMRR). It should also have a very high input impedance to eliminate the effect of the contact resistances of the skin electrodes, which again may not be equal. For this an improved version, typically known as the instrumentation amplifier or a Bio-electric amplifier is used. The CMRR should be greater than 80 dB for EMG signals of the type mentioned above. Usually a bandpass filter is provided afterwards in order to filter out noise beyond the required frequency range. As mentioned above, typical range of EMG signal is between 10Hz to 5kHz, but significant information is carried between 10Hz and 500 Hz. Therefore, a bandpass filter having a pass band of 10Hz to 1 kHz has been designed and implemented.

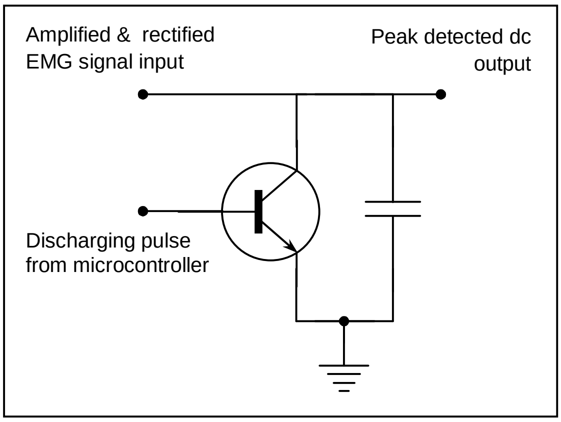

Fig.4: EMG peak detector & hold circuit

For the present work two pairs of electrodes are needed for the front and back muscles of the thigh together with a single common electrode placed suitably. The two signals, whether positive or negative, have to be compared to assess which of the two groups of muscles have been contracted. In order to do this the amplified and filtered EMG signals were rectified to allow only a single polarity, the positive part, for which a precision full wave active rectifier was designed. Just a simple diode rectification cannot be used here since this will take away about 0.7V from the small signal to provide the forward voltage drop. To measure the signal amplitudes, the rectified dc voltage was smoothed and held almost constant using a capacitor. However, the smoothing has to be optimized to allow sudden changes in EMG signal which is likely in our application. Simple smoothing of the rectified signal using a capacitor has a problem that the capacitor takes a long time to discharge, although charging can take place almost instantaneously because of different time constants involved in the two parts of the circuitry. Therefore to monitor changes in the EMG signal amplitude as it changes, a peak amplitude detector and hold circuit was designed, under microcontroller control as shown in Fig.4. It has a transistor switch across a smoothing capacitor which is activated by program control (through a 'Reset' signal) from the microcontroller. Normally this transistor is switched on through the reset signal, allowing the capacitor to be discharged to zero voltage almost instantaneously since there is no significant time constant in this path. Just before taking a reading this transistor is switched off when the capacitor gets charged almost instantaneously to the input voltage which is essentially the rectified EMG signal.

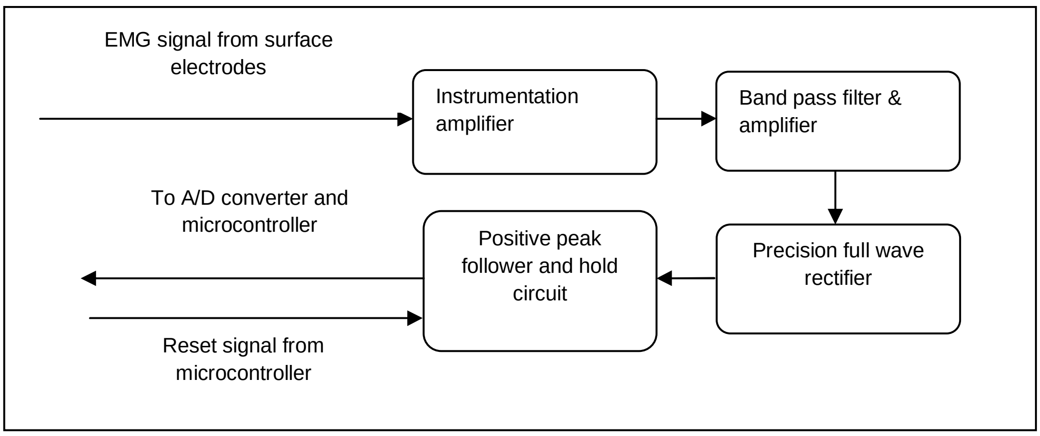

Fig.5: Block diagram of signal flow and process control

This voltage is acquired through the A/D converter built into the microcontroller IC. After the reading is taken the transistor is again switched on through program control. This process is repeated as long as necessary, again through programme control. The logical flow of the data acquisition process is shown in Fig.5.

The measured EMG signal is in the mV range, while the A/D converter in the microcontroller requires inputs in the range of volts, therefore, the signal needs to be amplified accordingly. The instrumentation amplifier is usually set to have a gain of about 10. This is done to avoid the amplifier being saturated due to large contact potentials created at the electrodes. The remainder of the gain is provided through subsequent stages, usually after the band pass filter.

2.2.3 Controlling Unit

Controlling unit is the brain of the total signal processing system. The central component of this unit is a microcontroller. The main objective of using a microcontroller in the design is to control the motor driving unit when appropriate depending on the presence or absence of EMG signals from one of the two channels. After careful analysis of the requirements and availability in the local market, a PIC16F877A [6] microcontroller was chosen for this work for its versatile characteristics and more advanced features. One of the key features behind this choice is the built in A/D converter, which eliminates the necessity of using an extra A/D converter chip and associated circuitry. PIC16F877A has a 10 bit A/D converter with multiplexed 8 channels. The A/D converter has a unique feature of being able to operate while the device is in 'Sleep' mode. To operate in this mode, the clock for the A/D converter circuit must be derived from its internal RC oscillator.

2.2.4 Microcontroller programming

An MPLAB IDE software tool [7] has been used for building programming code in assembly language. The code is converted to the corresponding hex format and stored in the IC using a programmer. The program sequence is described below with the help of Fig. 6. Let two extracted EMG signals be A and B taken from the front side and back side of the thigh muscles respectively. These are fed to two input channels AN0 and AN1 of the microcontroller chip. Analog Channel Select bits CHS2:CHS0 (bit 3-5 of ADCON0 Register) are initialized properly for selecting the above two channels. Just after reading each of these inputs A and B, the A/D converter within the microcontroller chip will convert these into corresponding digitized values and store these in any two of the four built-in registers. Then it will compare the input signals to find out which of the two signals, A & B, is higher. The motor will be driven in a clockwise or anticlockwise direction accordingly but after a threshold check as described below.

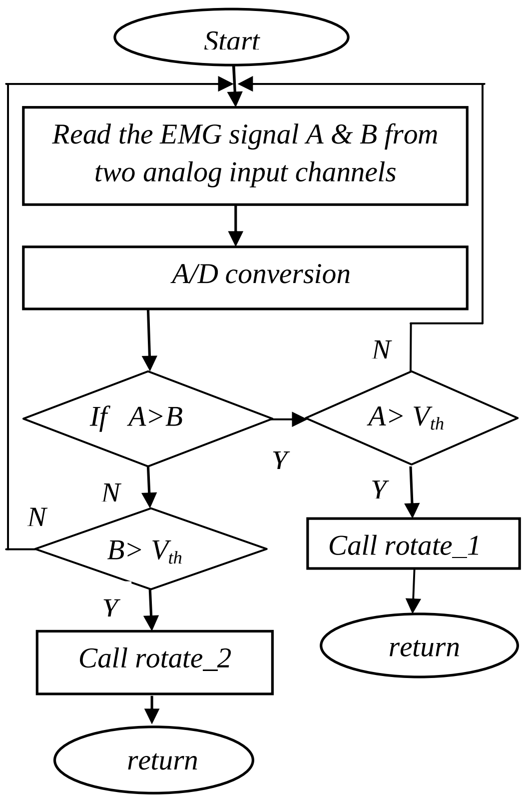

Fig. 6: Flowchart of microcontroller operation

Suppose the microcontroller finds out that A>B. However, before executing further actions, it will check whether A is greater than a threshold voltage

V_{th} or not. Due to motion artifact and noise, there might be a small input signal which should not cause any action on the motors. So a threshold value is used to get rid of this noise. If the muscle signal exceeds this threshold value, a subroutine named *rotate_1* is called, which will cause the motor to rotate in a particular direction. If the opposite case happens, i.e. if B>A, then again after a threshold check of B, if B exceeds a threshold value, the subroutine *rotate_2* is called. This will cause the motor to rotate in the opposite direction. If neither A or B is present (i.e., below threshold), the motor will not rotate. Thus depending upon the commands provided in the subroutine, the dc servo motor will rotate as necessary to provide the necessary gait action. To have a rotation through a fixed angle for each direction of rotation the pulse width modulation (PWM) function of the microcontroller [8] was used.

In the microcontroller there are five I/O ports (PORT A-PORT E) each between five to eight bits wide. In this work, two of the pins of PORT C have been set as the output. As mentioned above for controlling the PWM output two subroutines *rotate_1 and rotate_2* have been written. The PWM output is made logic high by setting the corresponding bit. The duration of the output will remain high as long as needed for bending a typical human knee. Precise timing for rotation action of the motor has been obtained through the clock cycle timing needed for instructions in the microcontroller. If necessary, extra delay loops were introduced into the program. It has been observed from the datasheet that pic16F877A takes 1µs (2 µs for some special instructions) in default clock frequency to execute each instruction. The time in each delay loop has been calculated based on this timing cycle. The motor driving control voltages are given out through pins 18 and 19 of the microcontroller.

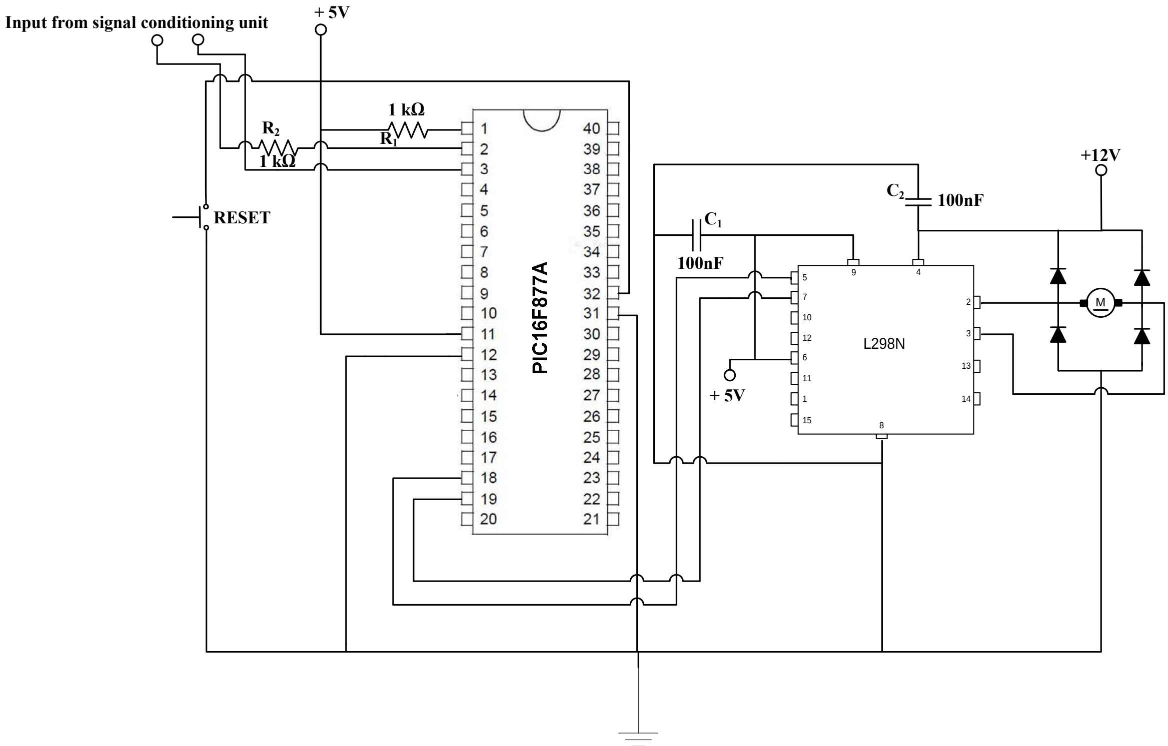

Fig. 7: Controlling and motor driving unit

2.2.5 Motor Driving Unit

The typical output voltage range of PIC16F877A is 4~5 V (V_{DD} - 0.7V). So a motor rated at 12V cannot be driven directly from this output voltage. Besides it would not give enough current to drive such a motor. A L298N motor driver chip [9] was used therefore to provide the necessary voltage and current drive to the motor as shown in Fig.7. The L298N is an integrated monolithic 15 lead multiwatt package. It has a high voltage high current dual bridge drive to accept standard TTL logic. It can provide output voltage and current up to 46V and 4A respectively. So it can drive a 12V motor (as used here) up to about 45 watts which is adequate for the present work. Pins 2 and 3 of this IC provide a reversible motor drive. One of these is maintained at high voltage while the other is low. This causes the motor to rotate in a particular direction. By reversing the voltages the rotation can be reversed. If none of these pins are high, the motor will not operate.

The voltages at output pins 2 and 3 are controlled by the voltages at the input pins 5 and 7 respectively which take +5V at low currents. In the present work these control voltages are obtained from pins 18 and 19 of the microcontroller as mentioned above. The four diodes, connected in reverse bias mode, provide protection to the IC.

2.2.6 The motor

One of the important parts of the work is the selection of an appropriate motor. The motor has to provide sufficient power and torque to the mechanical structure to overcome the load and weight of the prosthesis. At the same time the size of the motor should be small so that it can be accommodated within the upper part of the prosthesis. A small cylindrical 12V dc motor was used in the prototype. The rated power and speed were 5W and 3000 rpm respectively. In a real device a slightly higher power motor would be desirable.

3. RESULTS AND DISCUSSIONS

The gain of the amplifier enables mV ranged EMG signal to overcome the threshold voltage limit set in the microcontroller. If the gain is not high enough to surpass the threshold voltage, the drive control voltages will not be supplied from the microcontroller. A bioelectric amplifier was fabricated to provide the required gain in two stages. On actual measurement the following values were obtained.

Total gain of EMG amplifier = 191
CMRR = 93 dB

This was obtained against a designed gain of 200, and the performance is satisfactory taking view of the variations in the actual values of electronic components from the nominal ones. The conditioned EMG signal appeared almost noise free due to high CMRR value.

The useful EMG signal for this application was between 100Hz and 1kHz and mains borne 50Hz is a big source of noise to this EMG signal. Using a bioelectric amplifier with differential inputs reduce this noise to a great extent. However, not all noise can be eliminated, and the remaining 50Hz noise was eliminated using an active 2^{nd} order high pass filter with sharp cut-off at 100Hz. On the higher side, a normal 1^{st} order Low pass filter was provided with a cut off at 1kHz, to avoid unnecessary higher frequency signals to consume battery power.

The delay loops under the subroutine *rotate_1* and *rotate_*2 provide the total on time i.e. logic high in a single period of the PWM output. The total execution time of the delay loops set in the program is designed to be matched with approximate time taken for bending the knee for a single stride.

The designed execution time of delay_1 loop = 1296 ms

The designed execution time of delay_2 loop = 10.2 ms

So, total on time in the PWM output =delay_1 +delay_2=1306.2 ms

The PWM output can be varied by changing the execution time of the delay loops and the rotation time of the motor for each movement can be changed accordingly.
Using the EMG signal pick up and the microcontroller program, the motor was operated, and it performed as desired.

5. CONCLUSIONS

The main objective of the present work was the design of the electronic hardware and software for the prosthesis, which worked satisfactorily. Since this will be controlled by muscles of the thigh through deliberate contraction, the wearer has to be trained in its use.

Control of knee bending gives a one step improvement to a passive leg prosthesis. The developed prosthesis will need some further mechanical redesigning and refining before it can be made available to people for use. The present model was made using available motors and components, so there is scope for further improvement using more appropriate parts and components.

The main benefit of this home grown technology is the service that it can provide to the people in countries like ours at low cost. Usually microcontroller based applications involve sophisticated electronics and software control, detailed information about which are not provided by commercial manufacturers. Therefore repair and maintenance become almost impossible. Making the technology open will ensure repair and maintenance at low cost, and devices will give service for a long time.

REFERENCES

1. http://en.wikipedia.org/wiki/Prosthesis
2. http://www.jaipurfoot.org/03_Technology_compare.asp
3. T. Latif, C. M. Ellahi , T. A. Choudhury ,and K. S. Rabbani , " Design of a Cost-effective EMG Driven Bionic Leg", 5th International Conference on Electrical and Computer Engineering, 20-22 December 2008, Dhaka, Bangladesh.
4. B. H. Brown, R. H. Smallwood, D. C. Barber, P. V. Lawford and D. R. Hose, "Medical Physics and Biomedical Engineering", Medical Science Series, IOP Publishing, 2005.
5. W. Youn and J. Kim, "Development of a Compact-size and Wireless Surface EMG Measurement System", ICROS-SICE International Joint Conference, August 18-21, 2009, Fukuoka International Congress Center, Japan.
6. PIC16F877A, Microchip Technology Inc, Datasheet: http://ww1.microchip.com/downloads/en/devicedoc/39582b.pdf
7. Microchip Technology Inc, User's Guide: http://ww1.microchip.com/downloads/en/devicedoc/51519a.pdf
8. H. Kawano, H. Ando, T. Hirahara, C. Yun, and S. Ueha, "Application of a Multi-DOF Ultrasonic Servomotor in an Auditory Tele-Existence Robot", IEEE Transactions on Robotics, Vol. 21, NO. 5, October 2005.
9. STMicroelectronics, Datasheet: http://www.st.com/stonline/books/pdf/docs/1773.pdf