Two-Dimensional Myoelectric Control of a Robotic Arm for Upper Limb Amputees

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Abstract. Rehabilitation engineering and medicine have become integral and significant parts of health care services, particularly and unfortunately in the last three or four decades, because of wars, terrorism and large number of car accidents. Amputees show a high rate of rejection to wear prosthetic devices, often because of lack of an adequate period of adaptation. A robotic arm may appear as a good preliminary stage. To test the hypothesis, myoelectric signals from two upper limb amputees and from four normal volunteers were fed, via adequate electronic conditioning and using MATLAB, to an industrial robotic arm. Proportional strength control was used for two degrees of freedom (x-y plane) by means of eight signal features of control (four traditional statistics plus energy, integral of the absolute value, Willison’s amplitude, waveform length and envelope) for comparison purposes, and selecting the best of them as final reference. Patients easily accepted the system and learned in short time how to operate it. Results were encouraging so that valuable training, before prosthesis is implanted, appears as good feedback; besides, these patients can be hired as specialized operators in semi-automatized industry.

1. Introduction

Robotic teleoperation by means of myoelectric signals has become in recent years an area of growing interest still under study and development. A relatively early attempt was proposed by Farry, in 1996, for an anthropomorphic hand in space activities [1]. Thereafter, in 2003, Fukuda [2] introduced the operation of a manipulator with electromyographic signals and stump spatial positioning. More recently, in 2006, up to seven degrees of freedom were reached by a robotic arm [3] for placing and catching objects in front of the operator; however, only healthy subjects were tested in the latter. Two new reports can be found in the proceedings of the IEEE/EMBS 29th Lyon Conference [4, 5] to control robotic hands.

Such EMG commands do not require complex interfaces because they rely on natural residual movements of the user that are reflected on the robot itself and, thus, appear as attractive advantage. Besides, rehabilitation engineering and medicine have become integral and significant parts of health care services, particularly and unfortunately in the last three or four decades, because of wars,
terrorism and large number of car accidents. The victims, -amputees-, show a high rate of rejection to wear prosthetic devices, often because of lack of an adequate period of adaptation. A robotic arm might become a good preliminary stage. To test this hypothesis was the main objective of the present project while specific necessary objectives were: 1-To develop an experimental acquisition protocol of surface EMG signals from normal volunteers and from upper limb amputees (mapping protocol); 2-To recognize elementary residual movements in order to reach a control strategy; 3-To implement with these signals the actual control of an industrial robotic arm; and 4-To preliminarily evaluate patients’ acceptability and training possibilities.

2. Materials and Methods

2.1. Participants

Two upper limb amputees and four healthy subjects were volunteers of the project, all agreeing to the signed informed consent. The age range was 22-30 years; two were women. The first volunteer (Figure 1), male, age 24, has a high amputation level of the left arm due to accident in early infancy. The second volunteer (Figure 2), male, age 24, shows congenital right arm malformation (phocomelia or flipper limbs) with a partially preserved elbow joint. Both were medically and radiographically studied by a traumatologist displaying an excellent degree of adaptation and good disposition.

Figure 1. Volunteer #1. The left shoulder joint has disappeared completely. A large scar area (center) shows unbearable hypersensitivity.

Figure 2. Volunteer #2. Five non operative fingers are part of the pathology but residual muscles of difficult identification in the stump region produce clear and well controllable EMG signals.
2.2. Equipment
The patient was connected to an EMG signal conditioner and from there to a processing unit and controller, which finally, acted upon the robotic arm (Figure 3). The differential amplifier (0.05 Hz low frequency cut off, supplied by a previous passive filter) is implemented with an AD 620 (Analog Devices®) followed by a linearized opto-coupled circuit. Thereafter, an active band-pass fourth order 10-500 Hz filter bounds the signal. A/D conversion is done with the PCI 6024-E (National Instruments®) with an SC-2075 kit supplied by the same manufacturer. Channel configuration and sampling frequency are carried out by MATLAB® 2006a while the rest of the processing and control is performed within the SIMULINK environment.

![Figure 3. Overall schematic of the arrangement.](image)

The electrodes were of a commercial type (3M Red Dot), disposable, meeting the international requirements of SENIAM [6] regarding material (Ag/AgCl), shape and size. All records were bipolar placing the electrodes 20 mm apart (Figure 4).

![Figure 4: Volunteer #2 with two pairs of disposable electrodes connected to the system. EMG signals generated by the subject are displayed on the computer monitor.](image)
The BOSCH SR-800 is a SCARA (Selective Compliance Assembly Robot Arm) industrial manipulator with articulations arranged according to cylindrical coordinates. It has four degrees of freedom associated with the EMG command signals. In our case, the number of channels (four) was limited to the available sensing sites on the volunteers’ stumps.

The horizontal x-y plane is swept by articulations 1 and 2 (Figure 3); articulation 3 covers the vertical displacement while number 4 supplies rotation of the free end (twist or screwdriver movement). The circular overall reach is 800 mm.

The manipulator comes with a unit controlled by a CPU with a proportional-derivative controller accessed via TCP/IP protocol from the acquisition PC, which sends the necessary coordinates. Besides, we have the mathematical model to describe the robot dynamics in order to simulate and test its behaviour so facilitating users’ training.

2.3. EMG Descriptors

After the initial EMG processing, mostly electronic (see above), a second stage calls for calibration to determine the maximum voluntary contraction (MVC) along with measurement of the background noise. All signals are normalized to MVC. Thereafter, SIMULINK rectifies them and removes noise, which otherwise, becomes an annoying arm drift (Figure 5).

By and large, the amplitude of the EMG increases with the contraction level, thus, estimates of the EMG amplitude been investigated as an indicator of muscle force [7]; however, such relationship is not straightforward, especially in amputees due to the diversity of the injuries and the consequent residual muscular distribution. Thus, an adequate descriptor must be searched based on one or several EMG features and such descriptor controls in the end the robotic arm. Traditional simple statistics provides a first set of four possible descriptors, i.e., the Mean Value ($\bar{x}$), the Variance ($\sigma^2$), the Standard Deviation ($\sigma$) and the Root Mean Square Value (RMS). Moreover, more sophisticated descriptors can be the Energy $E$ contained in the EMG and other more specific as the Integral of the Absolute Value $IAV$, the Waveform Length $WL$, the Willison Amplitude $WAMP$, and the signal envelope [8]. Find below their respective mathematical definition where $x_i$ stands for the $i$-th sample and $N$ represents the window size where calculations are performed.

$$E = a \sum_{i=1}^{N} x_i$$  

(1)

$$IAV = \frac{1}{N} \sum_{i=1}^{N} |x_i|$$  

(2)

$$WL = \sum_{i=1}^{N} |\Delta x_i| \quad \Delta x_i = x_i - x_{i-1}$$  

(3)

$$WAMP = \sum_{i=1}^{N} f(|x_i - x_{i-1}|) \quad f(x) = \begin{cases} 1 & \text{if } x > \text{threshold} \\
0 & \text{if } x \leq \text{threshold} \end{cases}$$  

(4)
2.4. Experimental Procedure

After careful mapping of the stump area or of the region from where the EMG raw signal was recorded, a reference signal (a step-like function generated by the agonist and antagonistic muscles) was chosen to calculate the nine descriptors defined above. The envelope was discarded soon because of its inherent excessive delay as anything leading to overshoots. Peak values are not recommendable for they do not represent faithfully a subject’s movement or might bring the robotic arm beyond its working range. Within these general concepts, IAV y WAMP appeared as the most adequate probably because of their integrative characteristics, tending to soften curves and overshoots (Figure 6). The rest of the calculations was carried out using IAV, which has the added advantage of almost no delay.

From two opposing movements (say, agonist-antagonistic, forward-backward), each connected to separate channels, the deciding criterion for the robot movement was the sign obtained from the difference, that is, \( \text{sign}(\text{channel 1} - \text{channel 2}) \). Thus, and by convention, moving the shoulder forward produced a rightward displacement of the robotic arm and vice-versa. Numerous trials were carried out with the 6 volunteers recording from different muscles.
3. Results

In usual operation, the subject instructs the robotic arm with a set of points so that the manipulator free-end describes a certain trajectory by means of a mathematical model. As the manipulator moves, internal sensors verify the position point by point. Figure 7 shows both sets, the instructed (continuous semicircular trace) and the sensed points (circles), on the x-y plane; all corresponds to the information supplied by the EMG signals displayed in Figure 5. There is full overlap meaning zero error.

![Figure 6](image_url)  
*Figure 6. Step reference to compare the nine tested descriptors.*

![Figure 7](image_url)  
*Figure 7. Step by step positioning of the robotic arm tip.*
Figure 8, instead, shows the activation command on channel 1 and the simultaneous pathway on the other channels. The picture is the actual trace drawn with a pen attached to the manipulator free-end. The precise placing of the free-end responds proportionally to the muscle effort, which is regulated by the subject, either in one or several movements, according to his/her skill and eventual fatigue.

![Figure 8](image)

**Figure 8.** EMG’s (up); upper channel 1, from stump; Channel 2, from biceps; Channel 3, from triceps. Down: Trajectory drawn on plane x-y.

4. Discussion

Resolution of positioning and registry tasks in all volunteers and without exception, fulfilled the control objective. Although the results are similar in all tests, they were not identical, which appears as consistent with the biological variability. Besides, it must be underlined that the system is not totally robust to variations, calling for improvement in this respect, as for example by means of some kind of adaptive mechanism or a learning scheme, in order to improve the robustness of the control algorithms.

In addition, user training is important to attain precision in the positioning of the manipulator. In consecutive tests the approach to the target at the beginning was made by several steps, being replaced by a decreasing number as the subject became more skillful. This it is a remarkable aspect of the work, and demonstrate the feasibility of the myoelectric proportional control even for manipulators and prosthesis.

The degrees of freedom depend not only on the equipment but also on the user’s ability to discriminate muscle groups and on the sensing possibilities. In amputees the recording areas are usually limited and interference between channels (crosstalk) is rather frequent due to the irregular shape of the residual muscles. Therefore, optimal control depends essentially on the signal quality rather than on the numbers of channels.
In conclusion, the intended objective appears as feasible and a preliminary training stage with a robotic arm seems advisable before a final prosthesis is implanted. The response of both amputee volunteers was excellent, thus encouraging us to proceed with more candidates, even envisioning a rehabilitation program where patients would exchange experience, feelings and opinions. As far as we know, the overall approach described herein is novel, with only a few marginally related reports.

5. References

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6. Acknowledgment

This work was supported by the Consejo Nacional de Investigaciones Científicas y Técnicas de la República Argentina (CONICET), Grant PIP-6555 and by the Universidad Nacional de San Juan. The authors wish to thank Mr. Julián Ledesma and Mr. Juan E. Güell for their assistance.