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# UNDERACTUATED MECHANICAL HAND CONTROL BY EMG SENSORS

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ABSTRACT

The control of the human hand uses several neural impulses to control muscles and tendons, which allow an almost limitless range of gestures and movements. If we want to consider only the most common gestures - greet, indicate, open palm, shake hands - use should be made of monitoring and acquisition of at least four pairs of muscle impulses. To acquire this large quantity of pulses in a patient fitted with a prosthesis, it would require a large number of electrodes, placed on different areas of the arm and forearm. However, this is not always possible due to the different degrees of impairment to which the patient may be subject. In addition, the yield of the movement to be faithful to that of a human hand, would require the use of at least 15 motors. The studies carried out at the Department of Industrial Engineering of the University of Naples, allowed the realization of an prosthetic hand prototype equipped with a single pair of electrodes and a single motor.
In this paper different types of control developed for the above prototype, are described. By means of such control techniques, making use of a finite state language, the user is able to control the hand with on-off and proportional techniques, that provide a wide range of situations in which the prosthesis is effective and responsive.

Keywords: undercatuated mechanism, control, hand prostheses, EMG sensor.

## 1 INTRODUCTION

The hand can be considered the first instrument of the humanity. In the last years there has been a more careful research regarding the development of projects related to creating prostheses, artificial limbs or simply machinery for motor rehabilitation [1].
Some of the most significant developed projects have led to the realization of artificial hand control systems based on sensors that interface with the user even at the neurosensorial level [2-4]. The main aim of these studies is to manage different types of grip without being a cognitive challenge for the user.
The basic idea behind this type of control is that the user needs to store only one type of switch signal - "Trigger". The trigger in this case may be represented by a signal or by a signal sequence.

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The purpose of this paper is the development of a electromyographic control system that makes use of a simple and effective language, capable of interpreting the signal acquired by a single pair of electrodes, in order to control the hand prosthesis developed by the Department of Industrial Engineering of University of Naples "Federico II" [5-8].

## 2 MECHANICAL HAND

Generally, to grasp an object with an irregular shape a mechanical hand would need at least 4 motors: one to move the thumb, one for the index, one for the medium and one for the ring finger and the little finger. An alternative to the use of four motors could be represented by the use of elastic tendons connected to a single motor. In such a case, the motor transmits the same force on each tendon, causing each finger performs the same movement. However, during the grasp of an irregularly shaped object, when the first fingers touch it, they meet an obstacle and they stop their movement, while the other fingers continue to close, because they have not any obstacle. This implies that the fingers which first touched the object and remained more open, exert a minor force on it than the others, because they have lost force in stretching the tendons.

To avoid the above described behaviour a mechanical hand characterized by a series of differential mechanisms was conceived, that is shown in Figure 1 [5-8]. Unlike the mechanical hand with elastic tendons, in this one the difference among the elongations of the tendons is compensated by the rotation and the translation of the pulleys. The prototype object of this paper, results to be very inexpensive, as it is realized by means of ~~a~~ simple kinematic pairs. In addition, the force exerted by each finger is constant, whatever the configuration to be achieved is. This property enables the prototype to grasp very different objects and permits to adjust the closing force, by acting on the only motor.

Figure 1 Prototype of mechanical hand.

## 2.1 PROSTHESES PROTOTYPE

The mechanical hand has been used to assemble a prototype of the prosthesis.

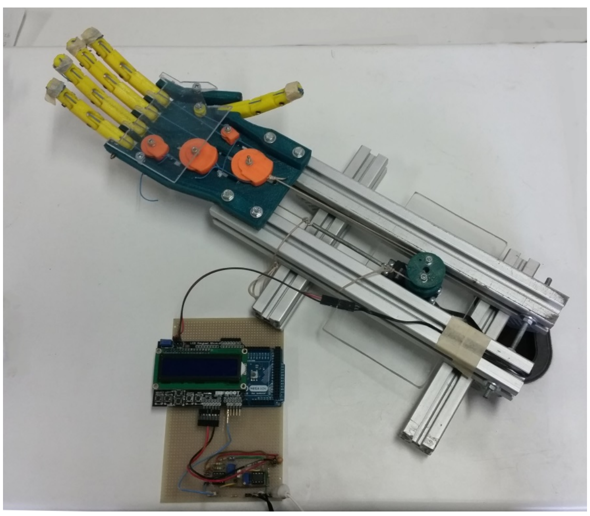

Figure 2 Prostheses prototype.

The main elements of the prototype are:

- Electronic board for the acquisition of EMG signal;
- Microcontroller Arduino Mega ADK;
- Servomotor Hitec HS-5990TG;
- Shield LCD Keypad SKU: DFR0009;
- Mechanical hand above described.

The prototype of the prosthesis is shown in Figure 2.

### 2.1.1 Electronic board for the acquisition of EMG signals

An electronic board prototype has been made to interpret, capture and filter an electrical signal from a muscle impulse, using three electrodes placed on the muscle that is being monitored.

In order to have a correct acquisition, it is necessary to place a pair of electrodes on the muscular band of which you want to capture the pulse and a third electrode on an area without sensorial relevance, to provide to the board a reference threshold for the correct interpretation of the signal.

An example of connection is shown in Figure 3.

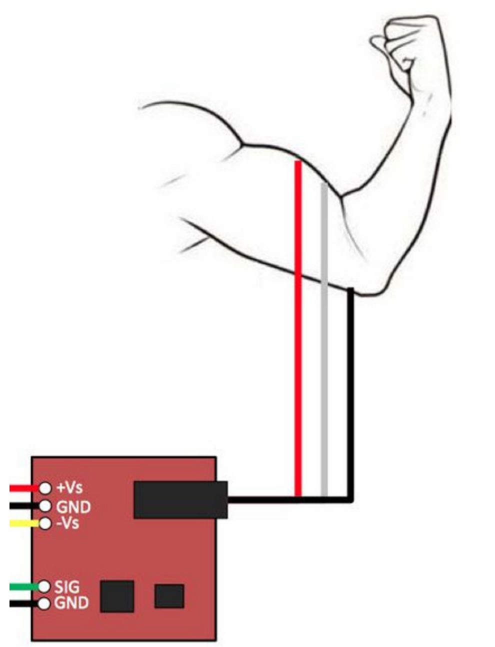


Figure 3 Connection scheme of EMG sensors to the biceps.

Once the raw EMG signal has been acquired, this is rectified and subsequently filtered by means of a low-pass filter. The control logic, implemented on the microprocessor that is connected to acquisition board of the EMG signal, integrates the signal itself with variable window. In this way, it becomes possible to increase the number of states available from the superficial acquisition of the electromyographic signal [9].

This expedient, although providing a wide range of parameters for the discernment of the amplitude of the EMG signal, allows the distinction of not more than two classes of movement. To obtain a control based on the recognition of multiple classes of gestures, more pairs of electrodes are needed, associated with a type of control based on transient states rather than on the static levels of threshold [10].

### 2.1.2 Microcontroller

Arduino Mega ADK is a microcontroller board based on protocol ATmega2560 [11].
It has a USB interface protocol based on standard MAX3421eIC. Each of the 50 digital pins of the Mega ADK can be used as input or output, using the function pinMode(), digitalWrite(), and digitalRead().They operate at 5 V and each pin can provide or receive a maximum of 40 mA and has an internal resistance of pull-up (disconnected by default) of 20-50 kOhms.
Arduino Mega ADK has 16 analog inputs, each of which provides 10 bits of resolution.
The serial communication with Arduino Mega can be administered by means of an auxiliary software, called "Processing". It is also possible, using this software, manage the acquired data with the board to display the values on the screen, show them on a graphic, or write them to a file for postprocessing.

### 2.1.3 Servomotor

The prosthesis has been equipped with a digital servomotor HSR-5990TG.
This servo motor has digital systems to control the positioning and provides, therefore, a quick and accurate response.
The motor is, therefore, driven by means of a PWM signal at the frequency of 250 Hz, with a duty cycle between 10% and 60%:

- with a duycycle of 10%, the servo rotated 90° clockwise;
- with a duty cycle of 60%, the servo rotated 90° counterclockwise;
- with a duty cycle of 35%, the servo is stabilized in the central position.

## 3 CALIBRATION OF EMG SIGNAL

In order for a prosthesis proves responsive and efficient in a large number of environments, it is necessary to provide control laws that can adapt to the context in which it is used, as well as to the individual who uses it. In this regard, the "user training" is accompanied by what that IEEE defines "system training" [12]: a set of calibration techniques, pre-processing and interpretation of intent, that give flexibility in the control of prostheses.
Below the choices employed for the calibration of the prosthetic system in question, will be discussed; in particular, it will exhibit the techniques implemented to achieve the following purposes:

- setting the minimum threshold of EMG signal;
- recognition of mean threshold of the EMG signal noise;
- setting of maximum threshold of EMG signal;
- estimate of the trend of the response of the EMG signal to a progressive contraction of the muscle.

### 3.1 MINIMUM THRESHOLD OF THE EMG SIGNAL

Having no a constant reference of mass, due to the variable position of the ground electrode, the signal value at rest is highly variable and it differs of significant quantities for each positioning of the electrodes on the user.

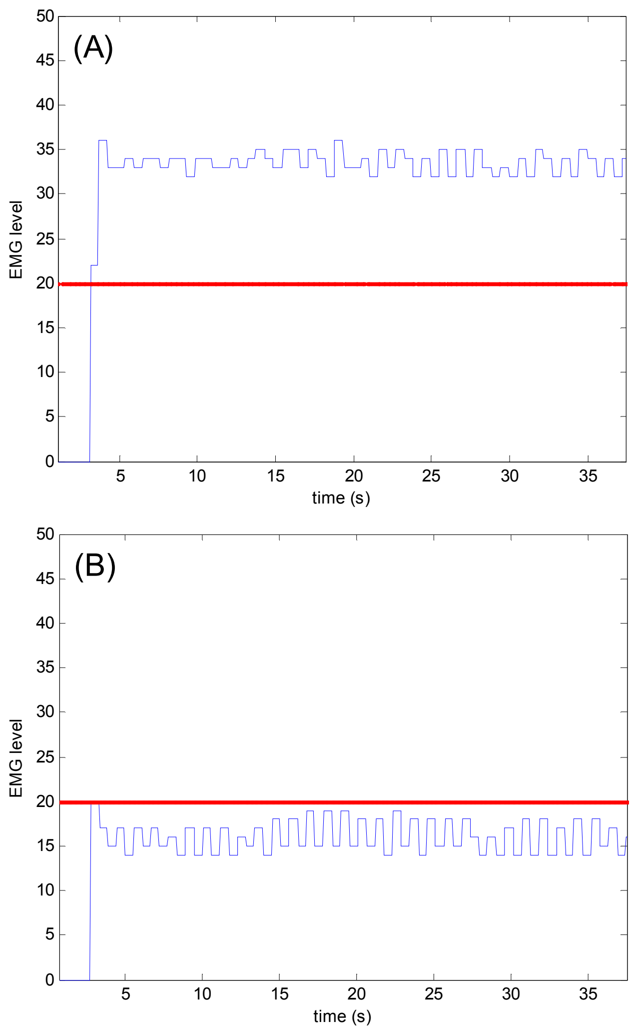


Figure 4 EMG signal minimum threshold connecting the electrodes to the forearm (A) and to the biceps (B).

In Figure 4 it is possible to see the different minimum threshold obtained by connecting the electrodes to the forearm (a) and to the biceps (b).
To make possible the use of a larger number of muscular bands it was thought to rescale the EMG signal by a value equal to the first reading of the signal itself, in this way it is possible to assign a reference of mass very close to zero, on which to calculate the signal differences.
This is done using an appropriate function, loaded on board microcontroller, which initializes the EMG signal five seconds after the power.
The result obtained can be appreciated in Fig. 5.

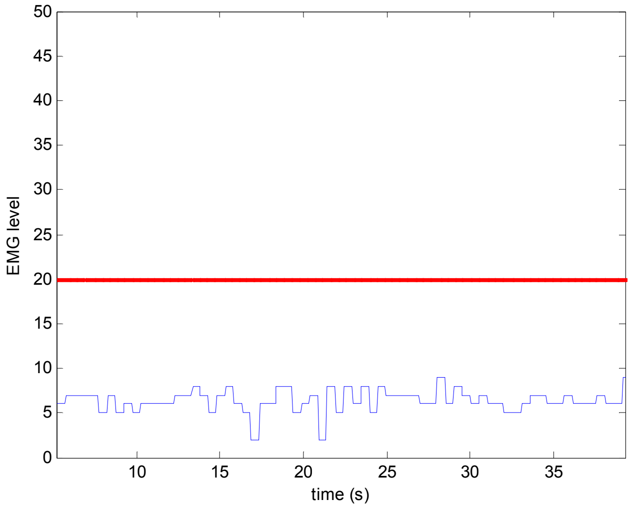


Figure 5 Minimum threshold setting of EMG signal.

## 3.2 MEAN THRESHOLD OF THE EMG SIGNAL NOISE

An important data to provide an estimate of the quality of the control system is the mean threshold of the EMG signal noise. By studying this parameter it is possible to evaluate the accuracy attainable with the control laws. So it was conducted a qualitative analysis of the nature of the disturbances to provide some indications on the main defects of the acquisition board of the EMG signal, on which to act in the construction of a prototype future.
A first test was carried out by shorting the terminals of the electrodes of acquisition with the purpose of highlighting the noise captured by the individual connectors, Figure 6.

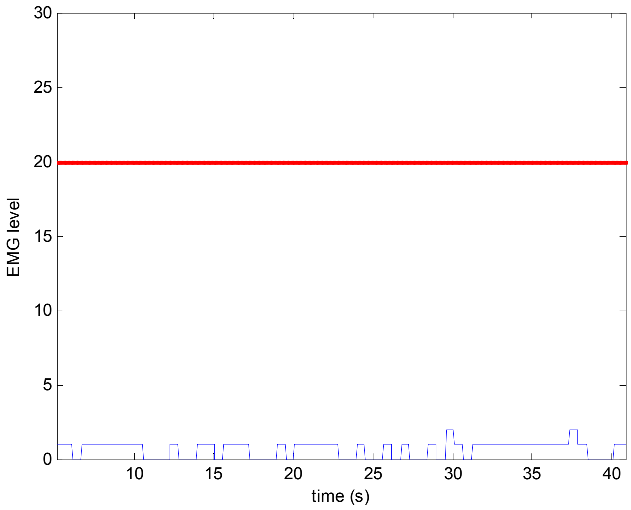


Figure 6 EMG signal noise by shorting the electrodes

A second test was conducted by placing the electrodes on the user and observing the output signal in the absence of voluntary contractions, in this way it can be appreciated the quality of the "filtering" of the EMG board towards other electrical signals of the human body differ from those associated with muscle contraction, Figure 7.

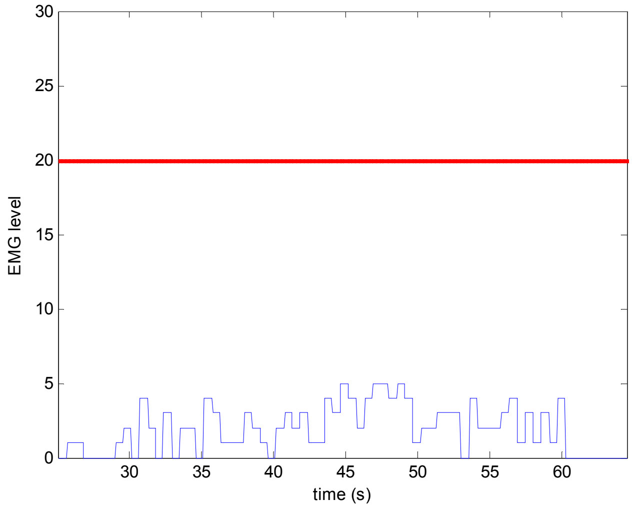


Figure 7 EMG signal noise in absence of voluntary contractions.

As can be seen in Figure 7, the EMG signal has a mean oscillation amplitude equal to 5 units. This parameter will be useful for the implementation of a proportional control, specifically in the dimensioning of the amplitude of the floating window of recognition of the intent.

## 3.3 MAXIMUM THRESHOLD OF THE EMG SIGNAL

To make the prosthesis usable by many users, is necessary to determine and set a maximum threshold of the EMG signal, to which is mapped a complete closure of the hand.
Since the EMG signal is directly proportional to electric impulse of the muscle to which the electrodes are connected, it is intuitive to understand that the user's physical prowess has a decisive role in generating the maximum amplitude of the pulse that he is able to produce.
For this purpose, several acquisitions were conducted on several volunteers, in order to find a method which gives a satisfactory result in the determination of the pulse necessary to act a tight and to maintain closed the hand.
The test was conducted by asking users to maintain a constant contraction corresponding to the total closure of the hand, followed by a contraction at maximum effort.
The data obtained for three users are shown in Table I.

Table I - Experimental values.

| User | Mean value (mv) | Maximum value (Mv) | Ratio (Mv/mv) |
|---|---|---|---|
| 1 | 70.52 | 230 | 3.26 |
| 2 | 60.26 | 234 | 3.88 |
| 3 | 97.85 | 352 | 3.59 |

From the analysis of the experimental data, a calibration procedure at startup of the control software has been implemented. This procedure, following the acquisition of a pulse under maximum stress, sets the threshold of closing of the hand in the ratio 1: 3.5 with such peak value.

### 3.4 EMG SIGNAL IN A PROGRESSIVE MUSCOLAR CONTRACTION

From the analysis of the acquired response signals, it was found that an attempt to progressive contraction of control muscle, corresponds to a non-linear increase of the value acquired by the EMG board. On the basis of this consideration, many tests were carried out in which users have performed a single continuous contraction and progressively greater in amplitude. The study of these data, allowed to search for a function that approximates the response of the EMG signal.
The approximation function with mean square error less is the sum of exponential terms:

$$f(x) = a\, e^{b \cdot x} + c\, e^{d \cdot x} \qquad (1)$$

An example of approximation of the EMG signal relating to a progressive muscle contraction, with a function of type (1), is shown in Figure 8.

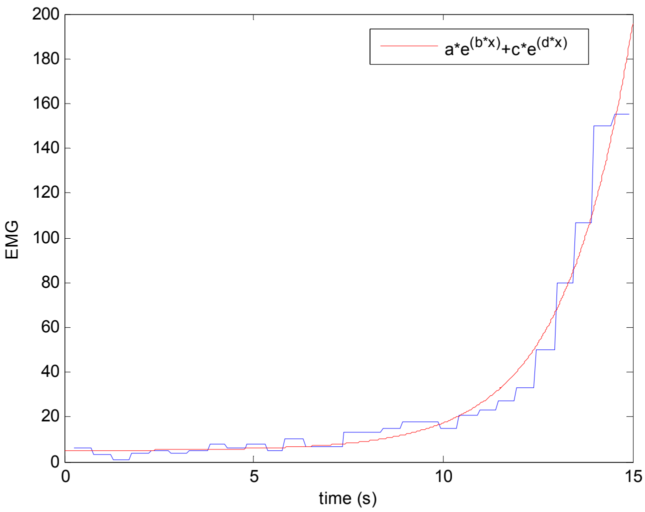


Figure 8 Approximation function for EMG signal in a progressive muscular contraction.

This result may be relevant in order to improve the proportional control of the prosthesis, because the control signal can be scaled with a function of type (1) rather than linear.

## 4 PROSTHESIS CONTROL

On the basis of the common classification of prosthetic control, [13], as a first step, operating logics based on on-off control and proportional control, has been implemented. The following step has been to create a hybrid logic, more elaborate, which makes use of both the simple controls.
For each type of control, different algorithms were developed and tested.

### 4.1 ON-OFF CONTROL

#### 4.1.1 Single rising edge

The most banal operating logic implementable is based on the detection of a rising edge to a preset minimum threshold.
When this threshold is exceeded, a trigger starts the function that activates the closure of the hand (or the opening, if this had already closed). This function controls the servomotor in position, by providing a command of maximum - or minimum - motor angular position that matches the configuration of the opening or closing of the hand.
The results obtained by means of this operating logic are shown in Figure 9, in terms of the EMG signal and motor angular position.

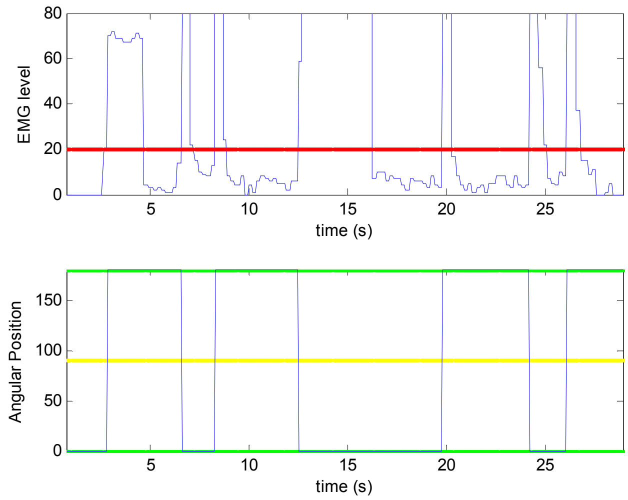


Figure 9 Single rising edge ON-OFF control.

As can be seen, each passage for the rising edge associated with the value 20 (in red in Figure 9), corresponds to a variation of the angular position of the motor from 0° to 180° and viceversa. This change results in a total closing movement - or opening - of the hand.
This type of control is convenient in the management of the prosthesis in situations where the response need for short processing times. On the basis of tests carried out in the laboratory, this kind of control is the most effective in tests in which users must grasp an object in motion. This efficiency is primarily due to the reduction of the length of the processing window guaranteed by the simplicity of the control type.

#### 4.1.2 Double rising edge

To make the On-Off control more robust from a point of view of interferences of the external noise or the user control, it is possible to implement a control that takes account of the recurrence of two consecutive rising edges - separated by a time interval fixed inside the observation window - to control the total closing and opening of the hand. The sizing of the observation window is proportional to the duration of the acquisition cycle. In the case shown in Figure 10, the time needed for the execution of each cycle is about 390 ms. Four cycles (opening and closing of the hand), therefore, correspond to a time window of just over 1.5 seconds.

In Figure 10 two different cases that may occur with this operating logic are shown. In the case (A) the two pairs of pulses are both performed in the established time window and the hand is closed with the first pair and is opened again with the second. In the case (B) only the second pair of pulses is performed in the established interval and the hand only closes.

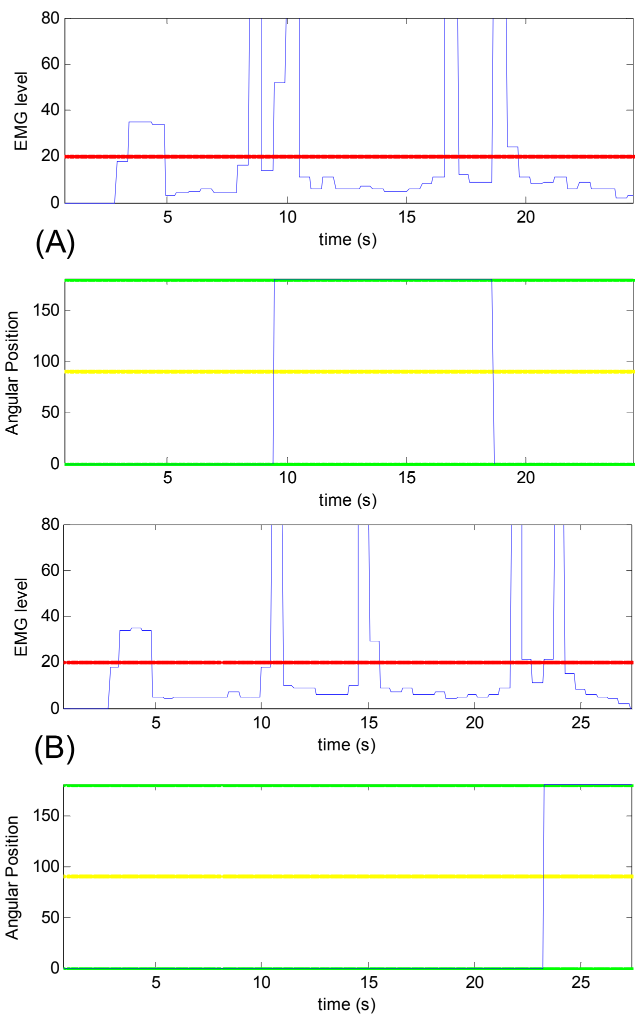


Figure 10 Double rising edge ON-OFF control

A logic based on double rising edge may become necessary in the case in which the monitored muscle can contract in situations not dependent on the user control (eg. weight lifting, moving an object). In such situations the double consecutive contraction in a given interval, provides greater security of voluntariness.

### 4.1.3 Consecutive rising edge

To avoid the necessity of waiting for the signal falls below the minimum threshold, an operating logic has been implemented that, always in a fixed time interval, after a first rising edge, recognizes a second pulse only when it is a signal increase following a peak of descent of established amplitude. In this way, a more responsive recognition of the two pulses is possible, making more reactive the elaboration of the intent.

The time interval dimension, in which the second pulse must be recognized, sets the elaboration speed of the control.

In figure 11 an example of the signals associated with the control just described is shown. It is possible to see that all four consecutive rising edge, even if are different, are recognized like user's intent.

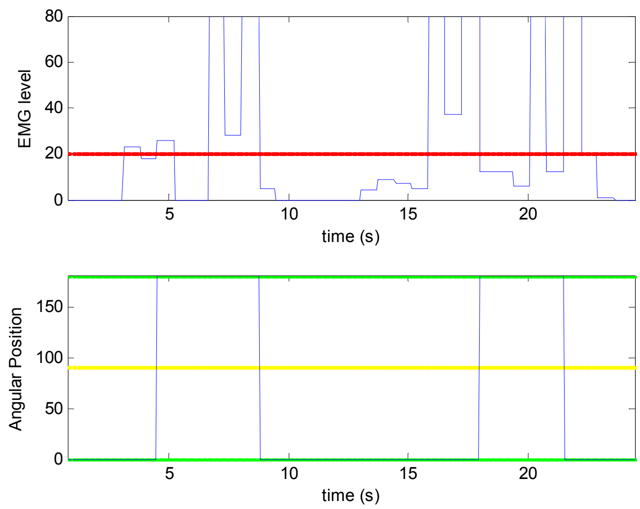


Figure 11 Consecutive rising edge ON-OFF control

## 4.2 PROPORTIONAL CONTROL

### 4.2.1 Without filtering

The control logic proposed below, provides the ability to control the closure of the hand with an accuracy equal to the angular resolution of the motor which activates the hand itself. The proportional control is implemented by means of a scaling of the electromyographic signal so that that the minimum threshold, corresponds to the position of the motor that generates the opening of the hand, and the maximum threshold to the position of total closure.

This type of control offers the possibility to control the hand in a very wide range of values but is very susceptible to noise acting on the EMG signal and to the inability of the user to generate a perfectly constant pulse if he wants to keep a given configuration hand.

The results of this type of control are shown in Figure 12.

As can be seen, a variation of the EMG signal corresponds to a flickering on the control signal which results in a hand-shake. This undesired phenomenon, can, in the long term, be stressful for both the mechanical components of the prosthesis, both the electrical ones due to a not negligible current consumption.

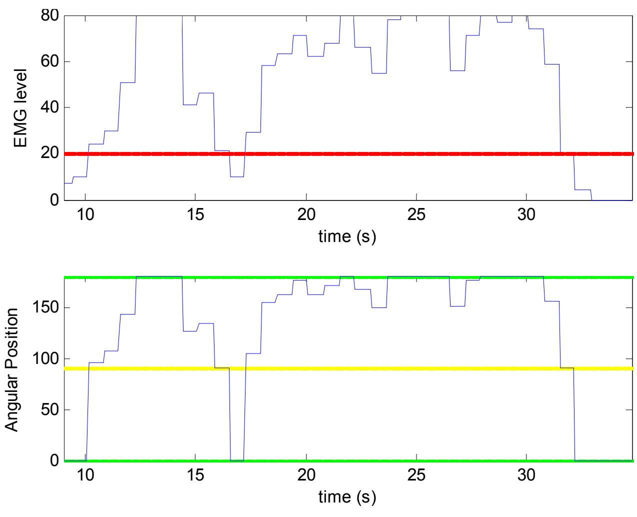


Figure 12 Without filtering proportional control.

### 4.2.2 Floating control window

Below a variant of the simple proportional control is discussed. The advantages of this variant are the absence of flickering on the control signal and the consequent reduction the current consumption by the motor.
To achieve this result is applied a mobile windowing on the EMG signal that changes the position of the actuator only if it differs, in absolute value, of 15 ° from the previous one.
The results obtained are shown in Figure 13, where it is possible to note the trend constant piecewise of the angular position of the motor and the reduction of its oscillations.

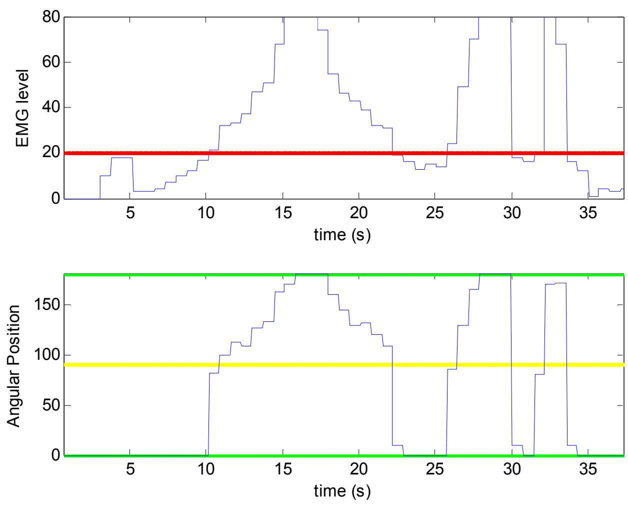


Figure 13 Floating control window in proportional control

## 4.3 HYBRID CONTROL LOGIC

### 4.3.1 Proportional control with on-off closing

In order to obtain a control that was usable in more situations, a hybrid operating logic was implemented: proportional type, but with the possibility to switch to a on-off control in consequence of a double contraction of the user.
The function that was developed for this type of control, provides a total closure of the hand when a double rising edge on a calibrated minimum threshold, of the EMG signal is received. The closure is then maintained until a further double pulse which resets the type of control in proportional logic.
The result that can be obtained with this type of control is shown in Figure 14.

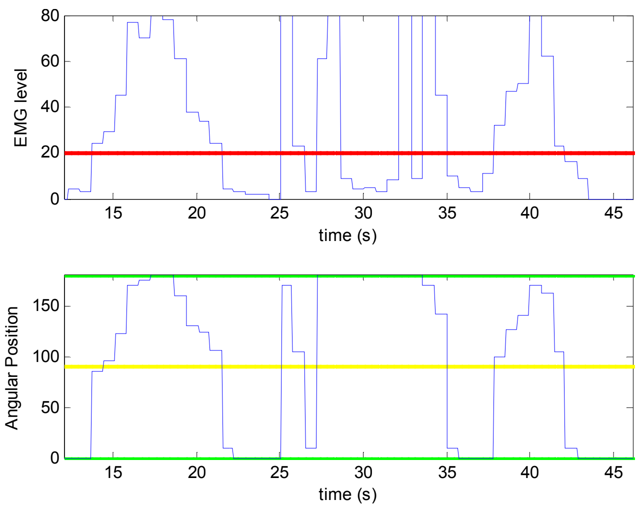


Figure 14 Proportional control with on-off closing.

The limit of this logic is that the first impulse necessary for the transition to the on-off control is processed by the controller and causes a partial closing and opening of the hand.

### 4.3.2 Proportional control with continued closure

A partial solution to the problems described above, can be supplied by a proportional control logic with continued closure. The logic allows the user to control the prosthesis in a proportional manner and to keep the hand closed even in the absence of muscle contraction.
To achieve this result, the user, after a full grasp by means of proportional control, shall perform an fast contraction that is recognized when a threshold of maximum is crossed rapidly downhill and then uphill. In this way is possible to grasp an object also gradually and keep a secure grip without having to hold a constant muscle contraction.
Once activated the continued closure, the sending of a new pulse which exceeds the maximum threshold, returns the proportional control logic.
An inconvenience of this control logic consists in the

permanence of the hand in the closed configuration even in presence of an opening intention; this occurs during the time ł set for detection of the second pulse edge.
In Figure 15 it is possible to recognize a first section with a simply proportional control, a second section with a proportional control that reaches the maximum without holding it, a third section in which after reaching the maximum a pulse is sent to perform the continued closure, and a fourth section where, as a result of a further pulse, the control returns purely proportional.

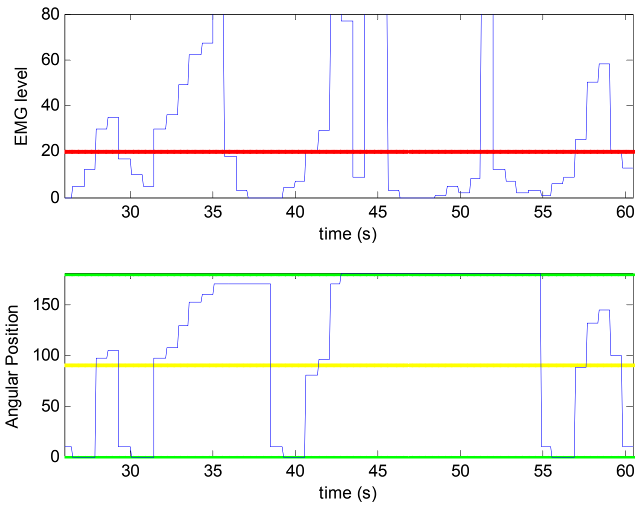


Figure 15 Proportional control with continued closure.

## 5 CONCLUSION

The control tests by the users who have experienced the prosthesis showed that it is intuitive and effective, as seen in Figure 16.
The results, therefore, are considered satisfactory as for the goals were set in this preliminary stage of the study of the prosthesis.
The development of many operating logics permitted to the mechanical hand to be usable in a wide range of environments; nevertheless there is a clear need to test the prosthesis on a greater number of users.
The few limits that the prosthesis currently shows, are largely due to its hardware components.
At this point of the investigations, the following improvements seem to be recommended.
To improve the control law, the detection of the thresholds of contraction and the elaboration of the intent of the user, a better noise rejection by the EMG acquisition board is needed.
To provide the user a more complex "language", reducing processing errors and providing the possibility to change the type of control logic, it is necessary to increase the number of sensors.
To guarantee users a more natural experience, it is possible to implement a feedback network by which provide the user with an indicator about the active type of control. A possibility would consist in installing pressure sensors on the fingertips of the mechanical hand and electric vibrators installed on the forearm of the user; in this way it would be possible to generate a vibration which amplitude is proportional to the force detected by the sensors.
To optimize actuator's law of motion, it is possible introduce a previously proposed algorithm, [14,15] in the motor control.

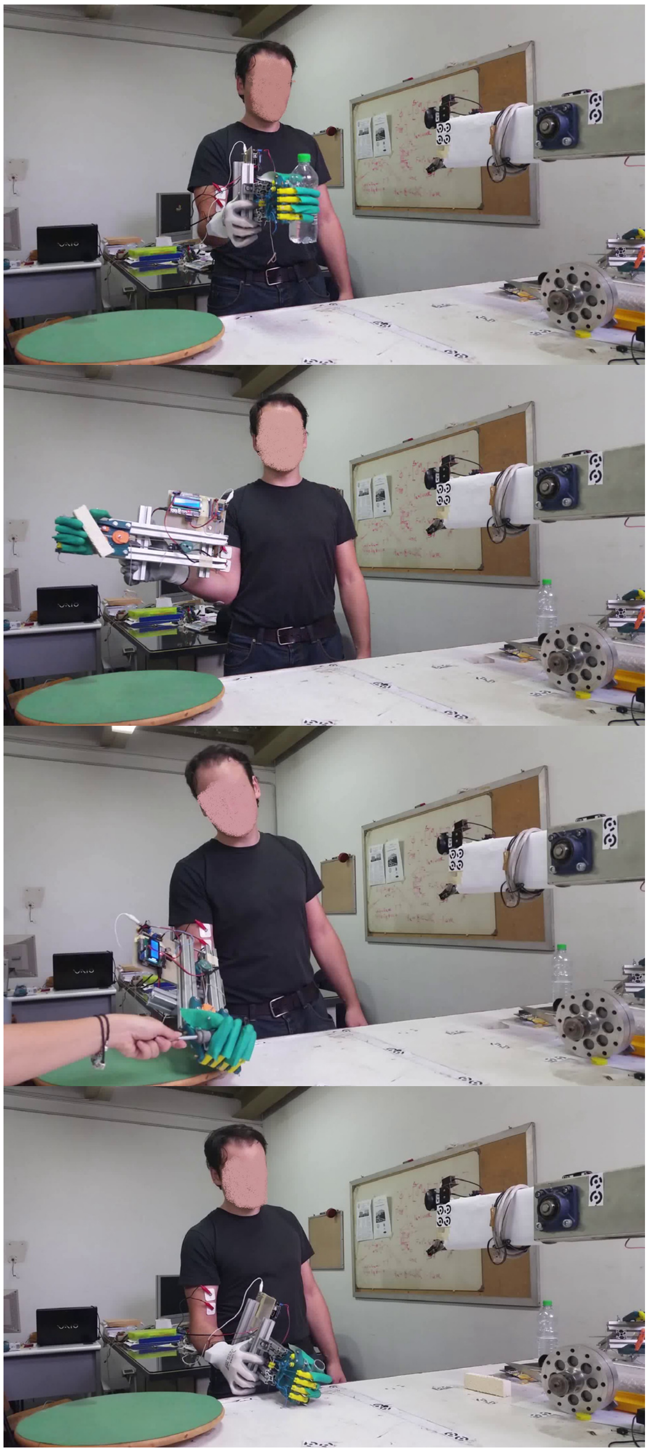

Figure 16 Laboratory tests of prosthetic hands.

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REFERENCES

[1] Belter J.T., Segil J.L., Dollar A.M. and Weir R.F., Mechanical design and performances specifications of anthropomorphic prosthetic hands: a review. *J. Rehabil. Res. Dev.*, Vol. 50, doi: 10.1682/jrrd.2011. 10.0188, pp. 599-618, 2013.

[2] Atzori M. and Müller H., Control Capabilities of Myoelectric Robotic Prostheses by Hand Amputees: a scientific research and market overview. *Frontiers in Systems Neuroscience*. Vol. 9, paper 162, doi: 10.3389/fnsys.2015.00162, 2015.

[3] Cipriani C., Antfolk C., Controzzi M., Lundborg G., Rosen B., Carrozza M.C., et al. Online myoelectric control of a dexterous hand prosthesis by transradial amputees. *IEEE Trans. Neural Syst. Rehabil. Eng.*, Vol. 19, pp. 260-270, doi: 10.1109/TNSRE.2011. 2108667, 2011.

[4] Atzori M., Gijsberts A., Castellini C., Caputo B., Hager A.G.M., Elsig S., et al. Electromyography data for non-invasive naturally-controlled Robotic hand prostheses. *Sci. Data*, 1:140053, doi:10.1038/sdata. 2014.53, 2014.

[5] Niola V., Rossi C., Savino S., A new mechanical hand: Theoretical studies and first prototyping. *International Review of Mechanical Engineering*, Vol. 8, No. 5, pp. 835-844, ISSN: 19708734, 2014.

[6] Rossi C., Savino S, An underactuated multi-finger grasping device. *International Journal of Advanced Robotic Systems*, Vol. 11, No. 1, 17 February 2014, Article number 20.

[7] Rossi C., Savino S., Niola V., Troncone S., A study of a robotic hand with tendon driven fingers. *Robotica*, ISSN: 0263-5747, doi: 10.1017/S0263574714001179, 2014.

[8] Penta F., Rossi C., Savino S., An underactuated finger for a robotic hand. *International Journal of Mechanics and Control*, Vol. 15, No. 2, ISSN: 1590-8844, 2014.

[9] Giorgetti G., Una mano tutta italiana. *Robotica Magazine*, Vol. 2, No. 2, pp. 10-17, 2011.

[10] Alley R.D. and Sears H.H., Powered upper-limb prosthetics in adults. *Powered Upper Limb Prostheses: Control, Implementation and Clinical Application*, A. Muzumdar, Ed. New York, Springer-Verlag, 2004, ch. 7, pp. 117-145.

[11] Kobrinski A.E., Bolkhovitin S.V., Voskoboinikova L.M., Ioffe D.M., Polyan E.P., Slavutski Y.L., Sysin A.Y. and Yakobson Y.S., Problems of bioelectric control. *Proc. IFAC Int. Congr. of Autom. Rem. Contr.*, Vol. 1, pp. 619-623, 1960.

[12] Fougner A., Stavdahl Ø., Kyberd P.J., Losier Y.G., Parker P.A., Control of upper limb prostheses: terminology and proportional myoelectric control. *IEEE Transactions on neural systems and rehabilitation engineering*, pp. 2-5, 2012.

[13] Losier Y., Shoulder complex motion based input strategies for prosthetic limb control. *Ph.D. dissertation*, Univ. New Brunswick, Fredericton, NB, Canada, 2009.

[14] Niola V., Rossi C., Savino S., Strano S., Robot trajectory planning by points and tangents, *Proc. 10th WSEAS Int. Conference on Robotics, Control and Manufacturing Technology*, Hangzhou, China, April 11-13, ISSN: 1790-5117 91, ISBN: 978-960-474-175-5, pp. 91-96, 2010.

[15] Rossi C. and Savino S., Robot trajectory planning by assigning positions and Tangential Velocities, *Robotics and Computer Integrated Manufacturing*. Vol. 29, No. 1, doi: 10.1016/j.rcim.2012.04.003, pp. 139-156, 2012.