UNIVERSIDAD SAN FRANCISCO DE QUITO USFQ

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On the Use of 3D Printing Technology for the Development of a Low-Cost Prosthetic Arm Prototype Controlled by EMG Signals

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DEDICATORIA

A mis padres, mis hermanos, mi novia, mi familia y mis amigos.

RESUMEN

Este artículo presenta un diseño de prototipo imprimible en 3D para una prótesis de brazo que se puede controlar flexionando cualquier músculo del cuerpo de un usuario a través de un sensor que recolecta señales electromiográficas (EMG) del músculo. El desarrollo de este tipo de prótesis existe en la actualidad, pero es costoso; por lo tanto, el objetivo de este proyecto fue demostrar la viabilidad de utilizar la tecnología de impresión 3D para construir un prototipo de brazo controlado como un primer paso hacia el desarrollo de prótesis más baratas, y como una posible ayuda para personas con discapacidades de bajos ingresos.

Palabras clave: EMG, Prótesis, Prótesis de Brazo, Impresión 3D, Brazo Biónico, Prótesis de Bajo Costo, Sensor Mioeléctrico.

ABSTRACT

This article presents a 3D-printable prototype design for a prosthetic arm that can be controlled by flexing any muscle in the user's body through a sensor that collects electromyographic (EMG) signals from the muscle. The development of this type of prosthesis exists in the literature, but it is expensive; Therefore, the aim of this project was to demonstrate the feasibility of using 3D printing technology to build a prototype of a controlled arm as the first step towards the development of low-cost prosthetics as a possible aid for low income people with disabilities.

Keywords: EMG, Prosthesis, Prosthetic Arm, 3D-printable, Bionic Arm, Low Cost Prosthesis, Myoelectric Sensor.

TABLA DE CONTENIDO

On the Use of 3D Printing Technology for the Development of a Low-Cost Prosthetic Arm Prototype Controlled by EMG Signals

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***Abstract*—This article presents a 3D-printable prototype design for a prosthetic arm that can be controlled by flexing any muscle in the user’s body through a sensor that collects electromyographic (EMG) signals from the muscle. The development of this type of prosthesis currently exists, but it is expensive; therefore, the aim of this project was to demonstrate the feasibility of using 3D printing technology for building a prototype of a controlled arm as a first step towards the development of lower cost prosthesis, and as a possible aid for low income people with disabilities.**

***Index Terms*—EMG, Prosthesis, Prosthetic Arm, 3D-printable, Bionic Arm, Low Cost Prosthesis, Myoelectric Sensor.**

I. INTRODUCTION

Although many types of prostheses have been developed over the years with great advances to try to solve the problem of a lost limb, progress in this technology is still limited and the costs are prohibitive because it takes a lot of work to produce and fit them to each amputation need. It is estimated that the cost of a body-powered prosthetic hand ranges from $\$4,000$ to $\$20,000$ [1]. The World Health Organization estimates that only 20% of people in a group of 30 million have prosthetic or other mobility devices to satisfy their needs [2].

This project made use of two types of technology mainly: three-dimensional (3D) printing and electromyography (EMG) signals. 3D printing is a relativity new technology that is based on computer aided design (CAD). This technology is revolutionizing different fields, including medicine, because the way to produce customized products is faster, easier and cheaper [2]. A printable prosthetic design can be build quickly depending on the size and quantity of parts, but the best part is that anyone can print them. In addition, they are easily modifiable, so that they can adapt to different amputations and people in constant growth.

In the area of biomedicine, EMG signals play a key role. An EMG sensor is used to detect the electrical potential of muscles when a contraction is generated. Although the use of these sensors has been widely used for medical research, its use in control systems has also been important and expanded in fields such as robotics and management of artificial limbs [3] [4].

Considering the current limitations of prosthetic cost and time required for construction, this preliminary project aims to develop a simple and low cost prototype of a 3D-printed robotic arm controlled by a micro-controller using a myoelectric sensor for hand control, as a first step towards the development of more complex low-cost prosthetics.

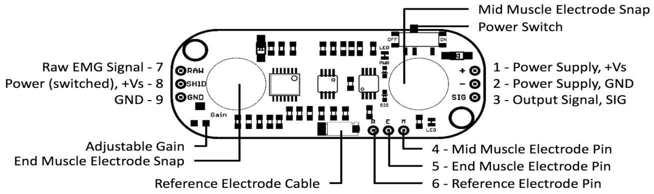


Fig. 1. MyoWare Muscle Sensor (AT-04-001) - Layout [5].

A. *MyoWare Muscle Sensor*

The MyoWare Muscle Sensor, shown in Fig. 1, is a commercially available electromyography sensor specially designed for microcontroller applications [5]. This sensor can be used to measure the electrical potential signals from three surface electrodes placed on the skin over any muscle. As shown in Fig. 2, one electrode should be placed at the middle of the muscle to be measured. The other one should be placed at the end of the muscle lined up the direction of its length. Finally, the reference node is placed on a bony or nonadjacent muscular part of the body near the targeted muscle [5].

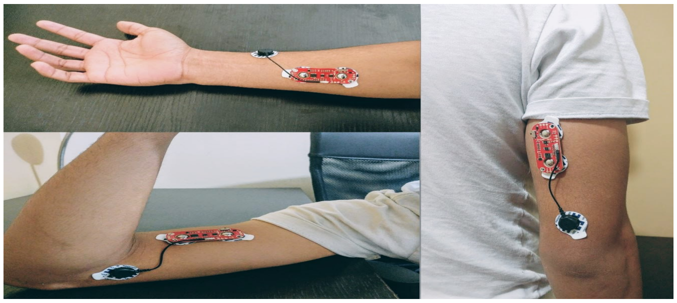


Fig. 2. Illustration of the Location of the Sensor in Different Muscles

The MyoWare Sensor has a dimension of 52.3 x 20.7 mm and can be powered by a voltage source between 2.9 - 5.7 V with a maximum current of 14 mA. The sensor has two output modes: EMG envelope and Raw EMG, where the maximum voltage output signal from the sensor depends on the voltage supplied.

The envelope signal is a RAW signal that is amplified, rectified, and integrated within the sensor transducer. An illustrative example of the difference between these signals can be seen in Fig. 3. This signal can be directly used for the analogue to digital converter of a micro-controller.

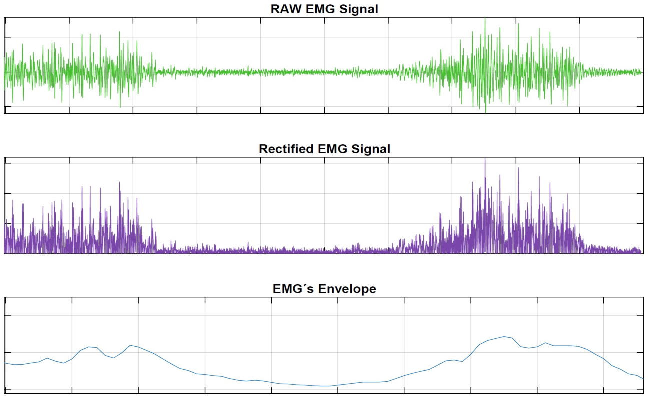


Fig. 3. Representative Difference Between RAW and Envelope Signal [3].

II. Methodology

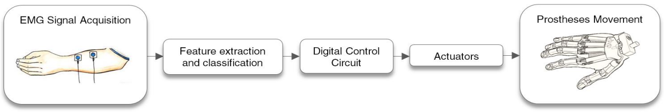


Fig. 4. Flow Chart for Prosthesis Control.

For the control of the prosthesis, the general scheme shown in Fig. 4 was used. The RAW and the envelope signal from the EMG sensor were collected and used to characterize the digital control circuit. This control was made in LabVIEW software where an interface (GUI) was also developed to graph the signal features.

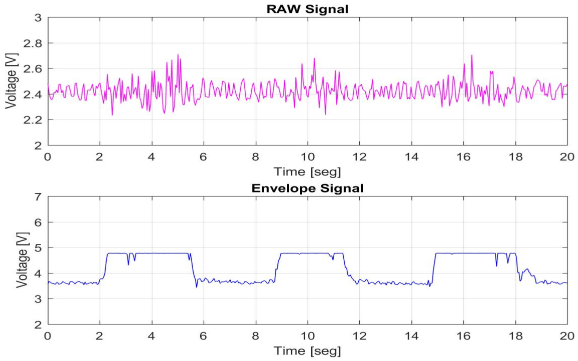


Fig. 5. RAW Signal and its Envelope in Flexing Cycles Tests

A. *EMG Signal Acquisition*

For signal acquisition, once the muscle to be measured is known, the area above it is cleaned before the sensor is used. The MyoWare sensor is placed as described; the envelope and RAW EMG signals are amplified and sent through an arduino microcontroller board, used as DAQ device, to LabVIEW software. To communicate LabVIEW with the Arduino board, LINX toolkit was downloaded into the LabVIEW. An example of the collected signals is shown in Fig. 5.

B. *Feature Extraction and Classification*

The signal was used in the range of 0 to 1024 of the microcontroller instead of its voltage value in volts because on a larger scale, it is easier to extract the required characteristics. Using different acquired signal tests, it was decided to program the movement of the prosthesis by proportional control because of the force applied instead of a movement solely due to a specific threshold value.

A control due to a threshold value is a good and quick way to control the movement; however, this method requires specific measures for each muscle and for each person to be calculated, in addition to not having the ability to gradually control the prosthesis. Proportional control has the advantage that it is automatically scaling the input signal to the values required by the actuators. Thus, the movement of the prosthesis is gradual as the muscle flexes.

C. *Digital Control Circuit and Actuators*

For actuators, servo motors were used. The chosen servo motor was the MG996R model because of its torque of 11 kgf·cm when it is powered by a voltage of 6 V [6]. To give greater strength to the hand and avoid overheating, a motor was used for each finger.

A pulse width modulated signal was used to control the servo motors. Proportional control allows that pulse widths of the PWM servo signals increases linearly with the EMG signal magnitude. PWM is a squared signal switched between a high logic state to a low logic sate. The output voltage of the PWM signal can be chosen by changing the width of the square signal with respect to its period [7].

The design of the prosthesis was made in a way so that a 90° movement was sufficient to close the entire hand. Since the PWM was chosen with a period of 20 ms, a pulse width ratio of 0.5 ms over 20 ms was the maximum extension of the hand, placing the servo motors to 0°. A pulse width ratio of approximately 1.5 ms over 20 ms was the maximum contraction of the hand, placing the servo motors to 90°.

Because of this, the proportional control was made by changing the input signal, in the range of 0 to 1024, in order to obtain a signal in the range needed as input for servo motors with a pulse width of 0.5 ms to 1.5 ms.

D. *Circuit Design*

The circuit implemented in this project is shown in Fig. 7. As can be seen, power regulators (AMS1117) have been used. These regulators prevent servo motors from drawing

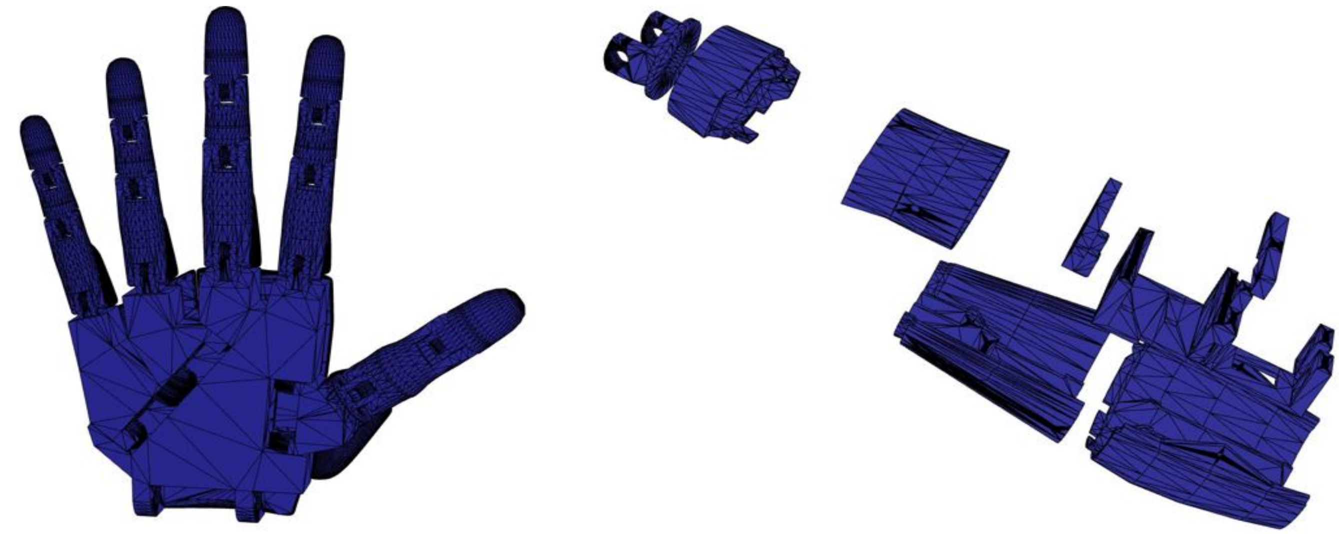


Fig. 6. Design of Prosthetic 3D Printable Parts

a large amount of current from the battery, a situation that can damage used electronic components. To achieve this, the regulators limit the power and voltage supplied to the servo motors, delivering a maximum current of 800 mAh.

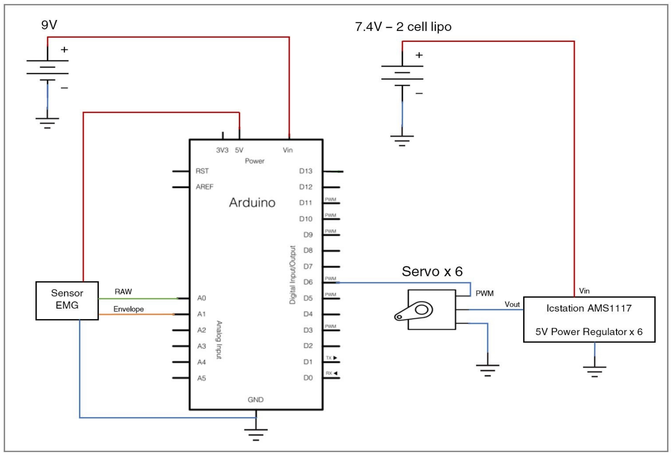


Fig. 7. Circuit Schematic.

E. Prosthesis Design

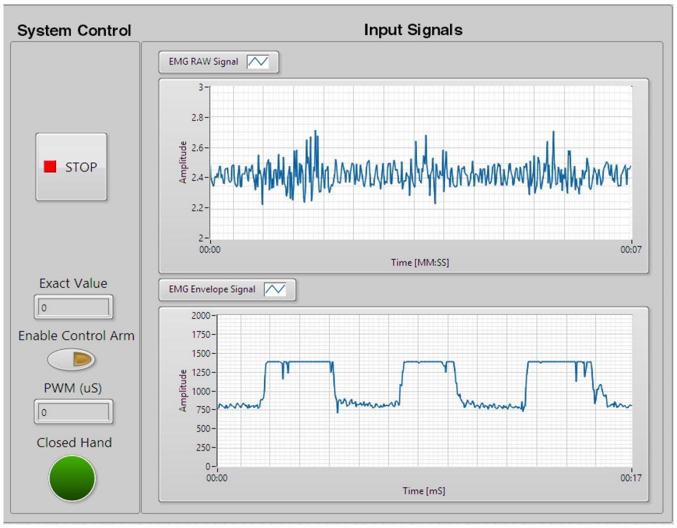
To select the most efficient prosthesis design, a search was made on different articles and researches comparing the possibilities. InMoov is an open source 3D printed robot that is conceived as a development platform for Universities and other educational and hobby purposes [8]. The structure of the robotic parts of the body have a great mechanical design. Because of this, the design of the prosthesis in this project is based on the robotic arm of InMoov project. The design, which can be seen in Fig. 7, was printed with PLA material, and it has dimensions of about 49 cm in length and 10.5 cm in width in the widest part of the forearm. Each finger has a single degree of freedom; while this may be a limitation, it allows the prosthesis to remain at a low cost as well as being easily printable and buildable.

The maximum theoretical force that can be applied to the fingers, when fully extended, was calculated based on the torque on the axis of rotation at the knuckles of each finger, because it is the furthest away from a force applied to the tip of the fingers. This force was averaged at about 0.71N which means it can withstand a mass of about 72g.

However, when the fingers contract, they can provide greater force because the applied force is closer to the torque in the knuckles. This force was averaged at about 1.67N which means that the hand as a whole has a holding capacity of approximately 682g.

The servo motors have a speed limitation in their turning movement. It was estimated that for a complete opening and closing movement of the hand, it takes approximately 0.5s from the time the servos begin to move.

F. Graphical User Interface



Exact Value: 0

PWM (uS): 0

Fig. 8. Graphical User Interface (GUI).

The graphical user interface developed, which can be seen in Fig. 8, allowed for a better control experience. The behavior of both signals, RAW and Envelope, can be viewed in real time on the interface. The interface was developed in such a way that allows the control of the prosthesis and the graphing of the signals independently; thus, it was possible to see the behavior of the signals and whether or not the muscle flexion was sufficient to pass to the control of the prosthesis.

In this way, the graphical user interface has a button to activate and deactivate the control of the arm when necessary as well as an indicator light that would confirm that the hand is closed or open. In addition, there is an indicator of the PWM value in μseg delivered to the servomotors to verify the existence or not of errors.

III. RESULTS AND EXPERIMENTATION

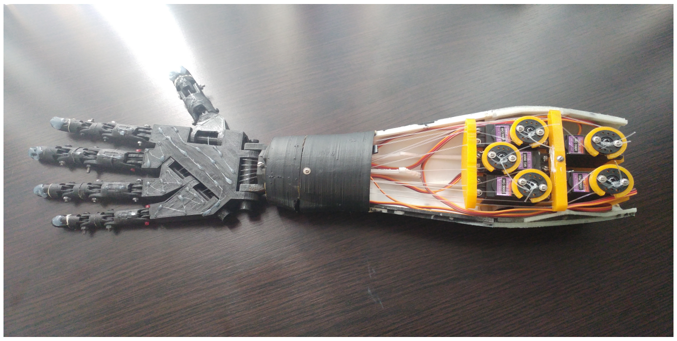


Fig. 9. Fully Assembled Prosthesis

The final result of the prosthesis construction can be seen in Fig. 9; the prosthesis has a weight of approximately 960g. The material used by 3D printing was PCL, the pieces were smoothed and re-drilled to ensure their adaptation and to improve the overall movement of the prosthesis. Silicone coating was used both on the fingers, especially the tip, and on the palm of the hand to ensure a better grip of objects.

The design was made in such a way that servo motors are located in the lower part of the forearm. As shown in Fig. 10, different threads made of fishing line, are used as tendons and pass from the fingertips to a piece located on the shaft of each motor, where the tendons are connected and allow the simultaneous and coordinated movement of each finger with its respective motor.

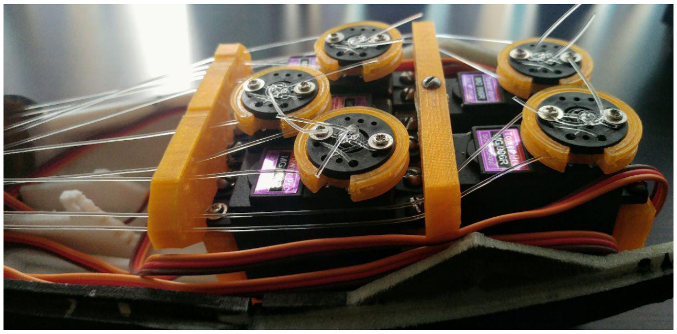


Fig. 10. How Artificial Tendons Work

Two different tests were performed to observe the behavior of the prosthesis with different users and in different arm locations; Fig. 11 shows the prosthesis connected one of the users who underwent the tests. The first test consisted of opening and closing the hand 10 times with intervals of about 2 seconds for each action to test the capacity and speed of response of the prosthesis was checked. Table I, presented below, shows the results obtained in this test.

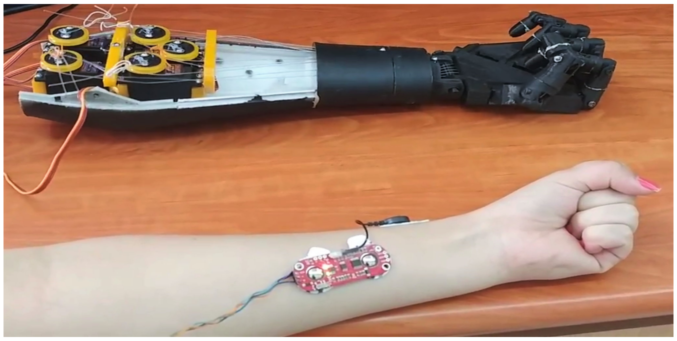


Fig. 11. Prosthesis connected to a user for testing

TABLE I
RESULTS AND ACCURACY FOR THE OPENING/CLOSING TEST - 10 TIMES

	Sensor Location		
Subject A	**Forearm**	**Biceps**	**Triceps**
Correct	9	8	9
Wrong	1	2	1
Accuracy %	90	80	90
Subject B			
Correct	10	10	9
Wrong	0	0	1
Accuracy %	100	100	90
Subject C			
Correct	10	10	9
Wrong	0	0	1
Accuracy %	100	100	90

The second test consisted of closing the hand completely as tightly as possible and holding it in this position for about 7 seconds. This checked the ability of the user to control the hand by carrying the muscle near fatigue to observe if the hand opened earlier than desired. Table II, presented below, shows the results obtained in this test.

TABLE II
RESULTS AND ACCURACY FOR THE RETENTION TEST - 7 SECONDS

	Sensor Location		
Subject A	**Forearm**	**Biceps**	**Triceps**
Correct [seg]	6.27	5.35	7
Wrong [seg]	0.73	1.65	0
Accuracy %	89.57	76.43	100
Subject B			
Correct [seg]	6.78	6.4	7
Wrong [seg]	0.22	0.6	0
Accuracy %	96.86	91.43	100
Subject C			
Correct [seg]	6.53	7	7
Wrong [seg]	0.47	0	0
Accuracy %	93.29	100	100

Correct and wrong actions as well as accuracy are shown based on the ratio of the number of correct guesses over the total number of events. The results obtained show a great degree of accuracy and control of the prosthesis. Users were asked how they felt about performing the tests, and everyone found it easy to control; however they noticed that they required more effort in the second test. This is expected, as it requires that the muscle to generate greater pressure, which causes some fatigue.

IV. CONCLUSION

In this work it was shown that it is possible to perform an arm prosthesis with relatively little effort, low cost, and with a very acceptable operation. Proportional control worked properly and it was sufficient for the control of the prosthesis.

The mechanical design of the prosthesis was very successful and met expectations. It should be stressed that the best thing about this 3D printing prosthesis is that anyone can print it, and it also has modularity, so it can be adapted to different patients by easily modifying the size and shape.

There are always some changes that can be made for a better result. These changes can begin with the use of different motors; although the servo motors used can be easily obtained and worked quite well, these are too large and their weight is something to be taken into account. To replace them, DC motors may be used with custom gears to reduce the weight and size of the internal structure. In this way, the use of artificial tendons made of threads can be avoided and instead, the motors can be placed so that they work directly on the fingers.

The use of an EMG sensor provided the necessary capabilities to read the electrical signals of the muscle fibers, allowing a correct control of the prosthesis. However, there are different techniques that can be used to acquire the signals. For example, techniques such as the use of several EMG sensors could provide control to each finger separately. Targeted Muscle Re-innervation (TMR) is also a way to obtain better control. Although this technique becomes invasive because it requires a surgical procedure, it can be taken into account depending on the objectives required in the development of a better prosthetic control.

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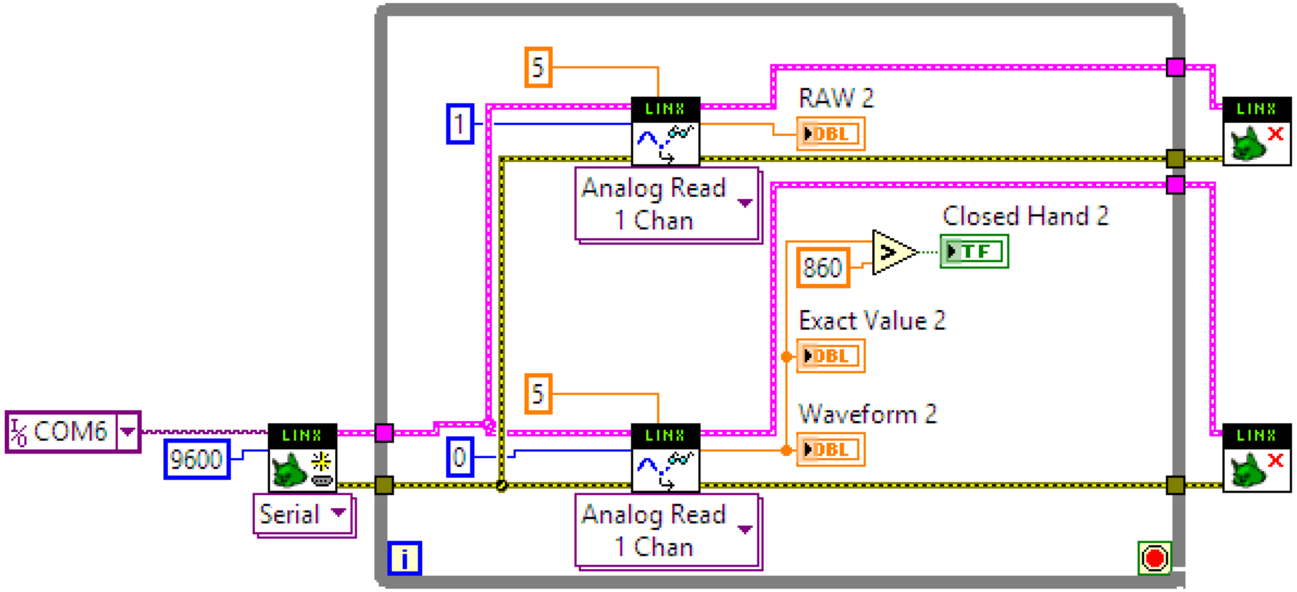
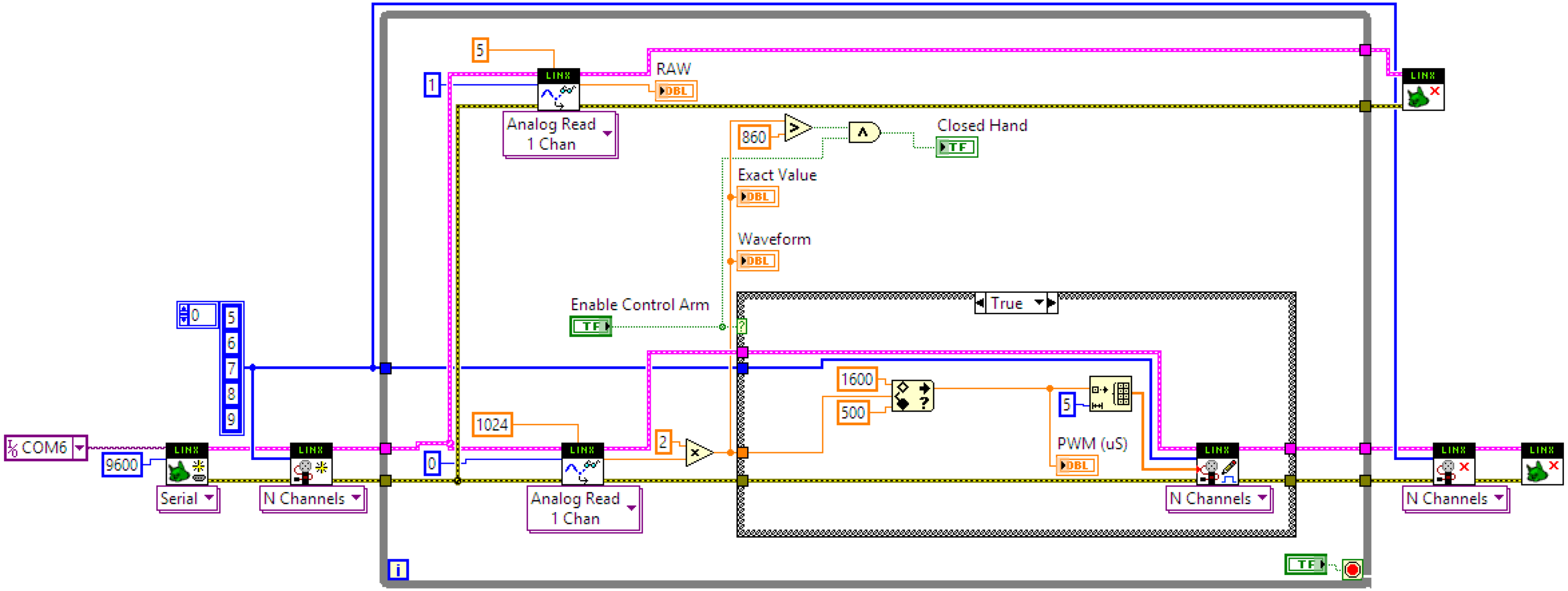
ANEXOS



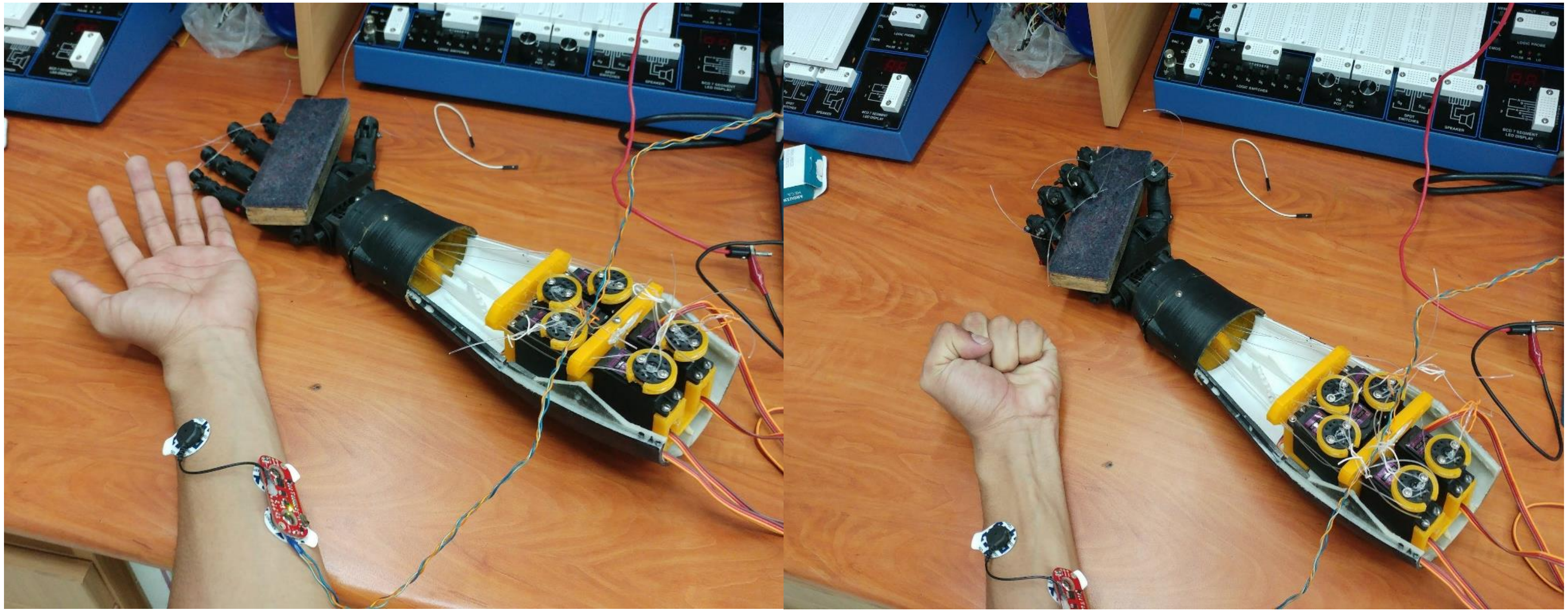
Anexo 1: Diagrama de bloques para la adquisición de la señal.



Anexo 2: Diagrama de Bloques para el Control de la Prótesis

Anexo 3: Prueba de Agarre de la Prótesis

Anexo 4: Prueba de Agarre de la Prótesis



Anexo 5: Prueba de Agarre de la Prótesis