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Motion Algorithms for a Neuroprosthesis Equipped with Velostat Sensors

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Abstract. The objective of this extended version of our previous paper [1] is to present some new motion algorithms tested on a neural prosthesis prototype that is equipped with manually fabricated Velostat sensors used for providing tactile feedback to the patient. This neural prosthesis was developed as part of a larger research project that aims to capture biological signals with the help of implants at the level of the median nerve and ulnar nerve. These signals will later be processed with various techniques to be suitable for triggering the movement of the prosthesis. Such a prosthetic device is intended to help the large number of patients who suffer from upper limb amputation. The implemented motion algorithms are based on how the motors, that are part of the mechatronics structure, rotate in one direction or another, with a certain speed, to achieve a specific movement. The implemented algorithms are functional, they have been successfully tested on the experimental assembly containing the mechatronics structure and the command-and-control block. The signals received from the pressure sensors with Velostat can also be used for the stimulation of the implanted electrodes, wrapped around the remaining nerves of the patients' stump, and the user will perceive a tactile sensation. This way the bidirectional communication will be possible between the user and the prosthesis.

Key-words: Algorithms, microsystems, Velostat, actuators, neuroprosthesis.

1. Introduction and Preliminary Results

The hand is a powerful tool, and its loss triggers severe physical and psychological inconvenience; this gives us a strong grip, but also allows us to manipulate small objects with great precision. The results of the social statistics show that almost 3 million people worldwide have an arm amputation, most of them from developing countries [2]. The main causes of amputation in different countries are influenced by the degree of industrialization, the transport system, and the health care available in each country [3], but in general the reasons for amputation include cardiovascular diseases, traumatic accidents, infections, tumors, nerve damage (trophic ulceration) and congenital anomalies (4.1 per 10,000 births). The most common causes of upper limb amputation are trauma and cancer, followed by complications of vascular diseases affecting the right arm following workplace injuries [4]. Spectacular technological development in recent years has led to the commercialization of a wide range of forearm prostheses (the size of the global prosthetics and orthoses market is expected to reach $ 12.28 billion by 2025 [2]). The increased interest received internationally by the field of intelligent prosthetics has resulted in the recent years from the exponential increase in the number of research projects, doctoral theses, and commercial achievements (neural or myoelectric controlled artificial hands, software packages for simulation and testing) [5]. The attention is focused on creating of a device that best suits the needs of the user, having bidirectional communication, supported by a very rich sensor system. Consequently, it is of greatest interest to provide tactile feedback for a neural prosthesis. The pressure sensor with Velostat, also presented in our previous paper [1], will equip the prosthesis developed in the EEA Grant ARMIN (Arm Neuroprosthesis Equipped with Artificial Skin and Sensorial Feedback). The sensors were used for implementing motion algorithms that tested bidirectional communication between the user and the mechatronic structure.

2. Overview of Scientific Literature

The ability of an individual to move is necessary to perform the basic activities in everyday life. Movement disorders significantly reduce the quality of life of a patient and specifically limit the independence of the affected subjects. Although the field of artificial hands has made a rapid progress in the last 10–15 years, an intelligent artificial hand, performing movements like a healthy hand, under the direct neuronal control of the patient, still poses a challenge for scientific research [5, 6]. An upper limb prosthesis is an assembly of mechanical and electronic components that replaces a missing part of a person's hand. Over time, scientists have tried to make structures as light, resistant and controllable as possible, even seeking to produce the tactile, thermal sensation for patients so they enjoy life as they did before the amputation caused by accidents or trauma.

A recent study [7] shows a promising prototype based on similar principles we also use in our implementation. This presents an implementation of the neuroprosthetic hand as a portable and self-contained unit with real-time control of individual finger movements with embedded deep learning-based control. The neural decoder used was designed based on the *recurrent neural network* (RNN) architecture. The authors succeeded to demonstrate the system's robustness, high-accuracy (95–99%) and low-latency (50–120 ms) control of individual finger movements in various laboratory and real-world environments.

Another good implementation is the one found in [8] that describes the development of a prosthetic hand based on human hand anatomy, with 3D printed phalanges from Polylactic Acid material. The authors used EMG signals to control the prosthetic device; they applied advanced signal processing techniques (signal acquisition, filtering, classification, and training) on those signals so that they could correctly predict different hand movements.

In [9] is presented an interesting surgical procedure called *targeted muscle reinnervation* (TMR) that is used to improve the control of upper limb prostheses. The technique transfers the residual nerves from the amputated limb to reinnervate new muscle targets that have otherwise lost their function. Another study [10] proposes an intelligent prosthetic hand using hybrid actuation and myoelectric control. A hybrid actuation system with a mechanism consisting of DC and *Shape Memory Alloy* (SMA) actuators was developed to increase the finger active degrees of freedom. Also, only two myoelectrodes channels were used for the input signal fed into the control system. Therefore, our paper aims to develop and implement algorithms for controlling a neural forearm prosthesis built using a 3D printer. It is also intended to test the functionality of the prosthesis as well as that of its mechanical limitations. The prosthesis is equipped with pressure and position sensors, and the movements are controlled by five DC motors. A modular design is carried out, to be able to adapt the algorithms to different constructive variants of sensors and actuators.

3. Experimental set-up for testing the motion algorithms

In the implementation of the neural prosthesis prototype analyzed in the current paper, it was tried to achieve a balance between size and mass, but it was also considered the ability to manipulate and adapt of the device. In particular, the following issues were addressed: additional psychological advantage can be obtained if the articulated hand resembles and moves like a natural hand; the artificial hand should be articulated and able to adapt to the shapes, textures of a variety of objects; the power supply must be small, portable, rechargeable, and secure (no such power supply was used at the test stage) [11].

To be able to adapt the created motion algorithms to different constructive variants of sensors and actuators in the future, a modular design (the components of the device can be easily separated) of the tested system was also carried out. Each component used in the hardware part of the project is independent of the others, so it can be replaced at any time if there is a need for higher performance. The mechanical structure follows kinematics and anthropomorphic appearance. The dimensions of the prototype are comparable to the dimensions of a natural hand; the thumb consists of two phalanges, and the rest of the fingers of three phalanges each. The actual construction of the prototype was carried out using a 3D printer based on the design made in SolidWorks, a computer program for designing mechatronic structures, which decreased not only the cost of development, but also the designing time. To obtain an anthropomorphic appearance, the patient's healthy hand was scanned and then mirrored, after which it was 3D printed. This mechanical structure is presented in Fig. 1.

More, this mechanical structure is an underactuated one in which a single actuator is used to drive multiple joints. The five DC motors, which determine the flexion or extension of the fingers, were placed so that the space inside the palm was used as efficiently as possible (Fig. 2). The motor that handles flexion or extension of the wrist is attached to the mechanical part that replaces the forearm. Some mechanisms with elastic cords, (replacing flexor and extensor tendons of the hand) wound on the motor shaft, were used to produce the movement of the prosthesis. The flexor and extensor tendons being connected to the same motor, basically they are connected to the same drive pulley. In this case the only independent joint is the metacarpophalangeal one, and the other two follow the direction given by this [12].

Fig. 1. The 3D-printed mechanical structure with anthropomorphic appearance.

The difference from other devices lies in the fact that in this prosthetic model, pulleys between phalanges are not used. The elastic threads pass through small channels of each phalanx and then stop on the distal phalanx [8].

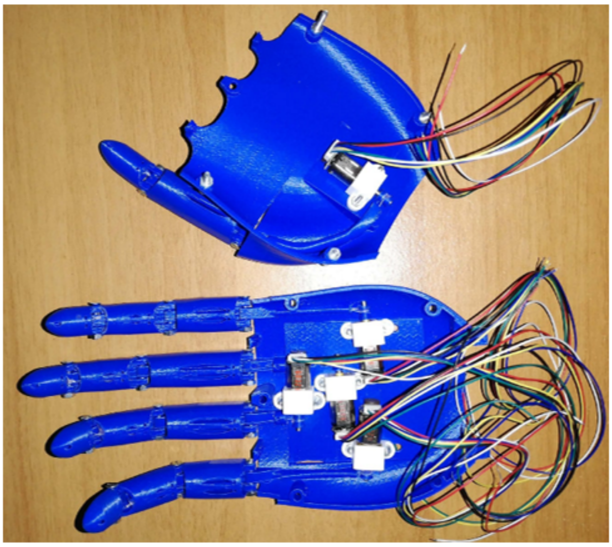
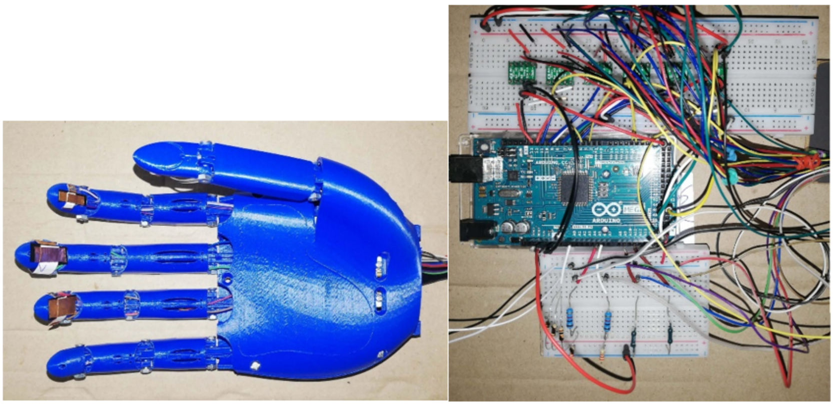


Fig. 2. The placement of the five DC motors inside the palm of the designed prototype.

Pressure sensors with Velostat are placed on the distal phalanges of the thumb, index finger, middle finger, and ring finger (Fig. 3.a). The control block consisting of the Arduino Mega2560 Development Board, which contains the Atmega2560 microcontroller, and the motor drivers, (Fig. 3.b), will be placed in the empty space inside the forearm of the neuroprosthesis. This block will transmit / receive data from neural interfaces, but also from the mechatronic structure (especially from pressure sensors and magnetic encoders). The command system processes the received data, analyzes them, and then performs appropriate actions based on the obtained results.



a. b.

Fig. 3. The pressure sensors with Velostat placed on the prosthesis's fingers (a); The control block consisting of the Arduino Mega2560 Development Board, including the Atmega2560 microcontroller, and the motor drivers (b).

4. Designing the Velostat pressure sensors

Another novelty introduced by this article is the using of sensors with Velostat to sense the pressure applied by the prosthesis on an object or to detect the contact of the prosthetic device with a surface. These sensors are used to stop grasping an object and to provide tactile feedback to the user. The signals received from the pressure sensors will also be sent to the intact remaining nerves in the amputated limb, generating a small sensation, which will allow the user to no longer rely on eye contact to perform a certain task [8].

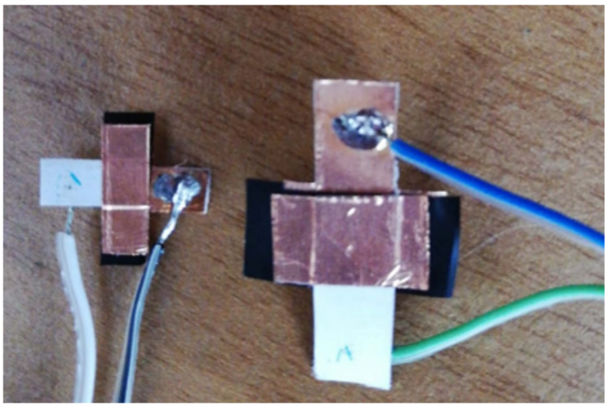


Fig. 4. The pressure sensors with Velostat manually fabricated with simple materials.

The Velostat, also known as Linqstat, is a polymeric composite material made of carbon impregnated polyethylene that belongs to the group of piezoresistive materials. It is suitable for use in various purposes, especially in the design of flexible sensors, which are highly sought after for biomedical and mechatronics applications. The main advantages of this material are the low manufacturing cost, the flexible range of dimensions, the simplicity of the interface circuits and the data acquisition process, the mechanical and chemical stability [10, 13]. But, the Velostat also has several disadvantages that limit its use to a wider range of applications, such as:

– it deforms over time and do not return to its original state like other piezoresistive materials, so its electrical properties change with aging and the exposure to the environmental conditions

– it has a non-homogeneous structure, and this affects the repeatability of the measurement data

– the use of this material for a sensor array is difficult because of the multi-directional conductivity, so the pressure applied to a certain point in the array influences the resistance of the neighboring points [6].

The sensor for touch detection designed in this paper is based on the excitation of the Velostat, which changes its electrical resistance parameter when it is bent or pressed. The sensor consists of a rectangular piece of Velostat placed between two conductive layers of copper that are glued to it to create a metal terminal. Two wires, that are inserted with an adjustable resistor to create a voltage divider type circuit, are glued on the copper strips (Fig. 4). As an operating principle, when a force is applied to the sensor, its resistance decreases because the resistance of the piezoresistive polymer between the conductive layers decreases. The sensor acts as a variable resistor, therefore the value of its voltage drop will be read and converted into a digital value by the analog-to-digital converter of the Arduino board.

5. The Electrical Characteristics of Velostat

Standard weights with a contact surface diameter of 10mm and 13mm were used to study the electrical characteristic of Velostat. Ten sets of measurements for the two types of supports were performed. A constant electrical voltage of E = 10V was applied and the average value of the current flowing through the sensor was calculated. The Velostat sensor resistance variation with pressure applied is presented in Fig. 5.

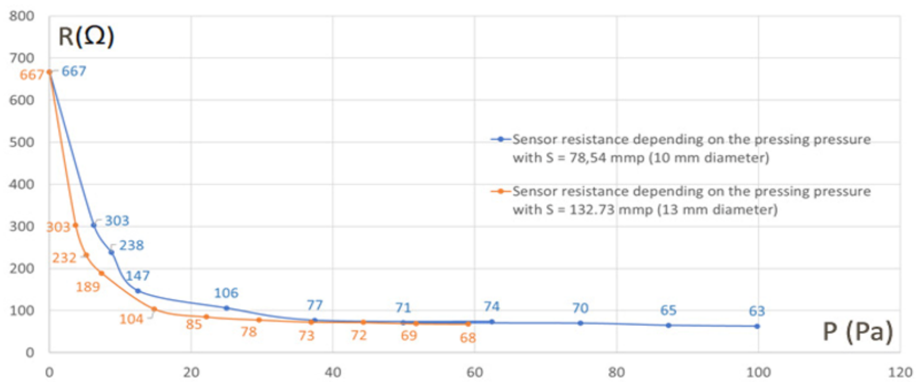


Fig. 5. The Velostat sensor resistance variation with pressure applied.

The pressure exerted on the Velostat material was calculated by the formula (1):

$$P = M^{*} g_n / S \ \ [Pa] \tag{1}$$

$m[g]$ – mass of the applied weight

$g_n = 9,8 m/s^2$ normal gravitational acceleration (lat.45°)

For a larger contact surface with the Velostat sensor, the curve of its resistance variation was slightly steeper. There were 3 behavior zones of the sensor depending on the value of the applied pressure. The first zone corresponds to sudden variations in resistance and was given by pressures in the range: 0 – 8 Pa. The second area corresponds to slow variations in resistance to pressures in the range of 8 – 24 Pa. The shape of the obtained curves confirms the results of the researchers of the study [14].

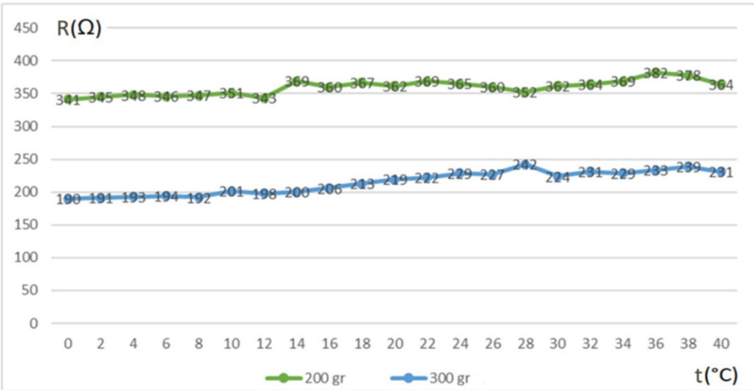


Fig. 6. Variation of the electrical resistance of the Velostat through the ambient temperature.

For the third zone, there are insignificant variations of the resistance for pressures included in the studied range: 24 – 100 Pa.

In order to determine the variation of the resistance of the Velostat according to the temperature, two sets of measurements were performed in a temperature-controlled enclosure (0°C–40°C). using weights of 200g and 300g.

For both types of applied weights there were a slight increasing of the sensor resistance values for the selected range of usual ambient temperatures and there were no significant changes in the normal operation of the touch sensor due to variations of the ambient temperature.

6. Optimal Positioning of the Velostat Pressure Sensors

In everyday life, in every activity involving grasping an object, the brain continuously monitors the information received from the tactile and pressure receptors in the hand. For example, when writing, the force with which we act on the pen to correctly form the letters on the paper is important. Therefore, in the case of prostheses, the placement of sensors is extremely important because they must be positioned in those areas of the device where the captured information is useful and relevant to the control system. The most important sensors for a prosthesis are those of position and force or pressure that contribute to giving the user the feeling of proprioception. This sensation refers to the body's ability to perceive its own position in space, the movement and action of body parts [15]. In the case of magnetic encoders, we do not have flexibility for their positioning, they must be attached to each shaft of the motors to accurately detect the position of the finger. So, our attention was focused on the positioning of the pressure sensors.

The pressure sensor was strategically placed on the phalanx and palm to capture useful information related to the contact of the prosthesis with various surfaces or related to the pressure exerted by it on an object. To determine the optimal areas for placing the pressure sensors with Velostat on the prosthetic device, a series of tests were carried out in which the prosthesis was supposed to grab some objects of various sizes: a cylindrical object (diameter 4.5 cm), a ball (diameter 7 cm), a pen (diameter 1 cm). In the case of the cylindrical object, contact was detected at the level of the palm at the base of the fingers, but also at the level of the distal phalanges. The contact for ball, but also for pen, was detected around the tips of the distal phalanges. Thus, the pressure sensors should cover the distal phalanges starting from their base until they reach the nail area, so the prosthesis can handle small objects (diameter up to one centimeter) to larger ones (diameter of several centimeters). For those applications requiring better control of the grabbed object is preferable to have pressure sensors on the palm at the base of the fingers. The optimal positioning of the pressure sensors on the available mechatronic structure is shown in Fig. 3.a. When contact with an object is detected an enable signal is generated with the help of the microcontroller in the control block. That signal is used to coordinate the movement algorithms, but also to stimulate the implanted electrodes, wrapped around the remaining nerves in the amputated limb of the patient, so he can perceive a tactile sensation. In this approach, bidirectional communication is possible between the user and the prosthesis.

Figure 7 gives the different voltage levels that can be obtained depending on the pressure applied on the sensor. The response time of the sensor is around 1ms. The higher pressure (as observed between 190 ms and 235 ms), the smaller variations appear in the read values. In the case of applications where we use these sensors, these variations do not bother us because we are only interested in lowering values below a certain level, once this decrease is detected we are no longer interested in future values, only if we have applications that require several levels of pressure.

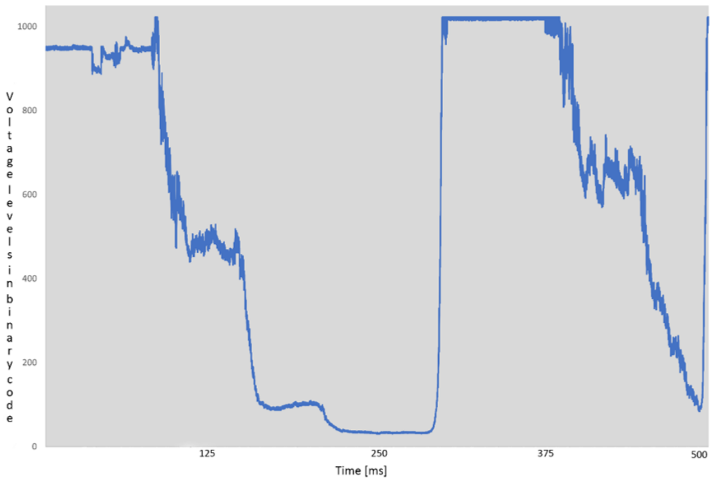


Fig. 7. Voltage levels read on the sensor with Velostat depending on the pressure applied on it.

7. Developing the Motion Algorithms

The command-and-control block permanently monitors the signals received from the sensors on the prosthesis, and on their basis were developed motion algorithms. Because we're talking about a neural prosthesis, which is a new concept, and the algorithms must rise to that complexity. Especially the intelligence of algorithms must come from the adaptability of the prosthesis to any stimuli and tasks. This adaptation must appear to be an involuntary mechanism that allows dexterity when maneuvering objects of a diverse range of masses, shapes, and textures. Such adaptation can be achieved on a hand prosthesis by adjusting the sensitivity of position and force feedback loops [11]. Based on all the information received by the prosthesis through the sensors with which it is equipped, the command-and-control block must be able to adjust whenever necessary. The control system must constantly monitor the positions of the fingers or the position of the palm in space (proprioception), the force exerted and the levels of signals coming from the sensors, then this block makes the appropriate changes so that the motors produce the desired movement at the level of the fingers and palm.

These motion algorithms depend on the control system, the DC motors and the sensors used to capture various information regarding the state of the prosthesis. The simplest step in designing the algorithms was to understand the operation mode of a single DC motor and its command to perform basic functions such as clockwise rotation, counterclockwise rotation, and stop (lock in a fixed position). For writing these basic functions, no special libraries were used, but the truth tables from the data sheet of the type of DC motor we used (Pololu 6V High-Power Carbon Brush). Later, these basic functions helped to write the motion algorithms. An equally important aspect as writing these functions was reading the data received from the magnetic encoders attached to the shaft of each DC motor and from the pressure sensors with Velostat. The Class concept in Object-Oriented Programming was used to set the characteristics (attributes) of DC motors and their behavior (methods). Also, using this basic concept is useful for reducing lines of code, so reducing the memory used, but especially for a more intuitive understanding of the variables and functions corresponding to each finger.

The Finger class was implemented for the control of each DC motor responsible for the movement of a particular finger of the prosthesis. This class contains the following characteristics (attributes):

- pin used to change the direction for the rotation of the motor (dirPin)
- pin used to set the motor's speed (pwmPin)
- interrupt pin used to read the number of pulses from the magnetic encoder (interruptPin)
- speed of each motor (mSpeed)
- the maximum number of pulses read from the magnetic encoder so that the fingers of the prosthesis do not deteriorate (maxPulses)
- a counter for the number of pulses read from the magnetic encoder (volatile type encoder-cnt because this variable is updated during an interrupt)
- the motor's position (pos)
- the value read from the pressure sensor with Velostat (velostat)

- a flag for detecting the contact of the finger with a certain surface (contactDetected)
- a flag for the current state of the motor (flag = 0 - initial state, 1 - flexion, 2 - extension, 3 - stop)
- the last moment of time when the DC motor has changed its state (previousTime)

One of the major challenges in designing the algorithms was to simulate several components moving in parallel. Perfect synchronization will never be achieved because the microcontroller we use has a sequential architecture, but because the board is very fast, we can take small, frequent actions, one after another, so that the feeling of synchronization is created. A common mistake in such applications, in which one wants to achieve the feeling of simultaneousness with an Arduino board, is the use of the delay() function. This function has a blocker character, it interrupts the microcontroller for a certain time, and the rest of the program remains on standby. To overcome this limitation, we used two approaches: using interrupts and using the millis() function. An interrupt is a function attached to a digital pin (not all the PINs can be used for interrupts - the Arduino Mega2560 board has only 6 such pins) that goes into execution, interrupting the main program, whenever external changes occur very quickly at the pin level. Once the interruption function is finished, the program continues from where it left off before the execution. It is preferable that the function is very short to not stop the main program from running for too long. Interrupts are usually used to monitor the status of a button or data received through serial communication. The second method is using the millis() function with which we can write a program that follows the concept of automaton or finite state machine in which actions are timed. The notion of "state" arises when for a certain task we retain the value of the current state with the help of variables, but also the last update, and the notion of "machine" consists in monitoring the variables and deciding whether the task needs to be updated. The millis() function returns how many milliseconds have passed since the current code was loaded into the microcontroller's memory. Millis() works thanks to a Timer integrated into the Arduino board, which starts running by itself after loading the program, without us having any intervention; also, this function is independent of the number of iterations of the main loop.

Motion algorithms work like an automaton, they start in a standby state, in which all DC motors are turned off. In this state, the start command is expected to come by entering from the keyboard the number corresponding to the desired algorithm. This serial communication is achieved by connecting the USB of the computer used to the Arduino board. When the start command is issued, the movement begins. The motors are independently controlled to allow objects of different shapes to be grabbed. The movement stops when voltage levels exceeding the required threshold are read from the pressure sensors. The positions of the motors are saved in memory and used for the release phase. After a time in which the grasp of the object has ended and the grip has become stable, it is necessary to extend the fingers involved in the specific movement, the hand thus switches to its original position and waits for the new command [8]. The release command of the object is given by pressing on a sensor with Velostat, separate from the pressure sensors used for tactile feedback.

Different from the algorithm presented in [1], for this article the following algorithms were tested: grasping an object with two fingers, holding a spherical object grasping an object with three fingers.

At first, the hand is in the initial position (maximum extension of the fingers, all the flags are 0). We send the command to start the movement then the index finger and thumb flex. When the voltage levels read from the Velostat pressure sensors located on both fingers exceed the set threshold value, a flag (contactDetected) for each finger is activated. Through the contactDetected indicator, the motor drivers receive the command to change the direction of rotation for the motors, thus achieving the extension of the fingers. With the help of the variables pos, the positions of the motors at the time of contact with the surface of the object are memorized. The position is expressed in the number of pulses received from the magnetic encoder, so the extension will be made the same number of pulses to reach the initial position in which the choice of a new movement is expected (flags become 3). In Fig. 8 is presented an organigram of this algorithm and Fig. 9. shows algorithm tested on our prototype.

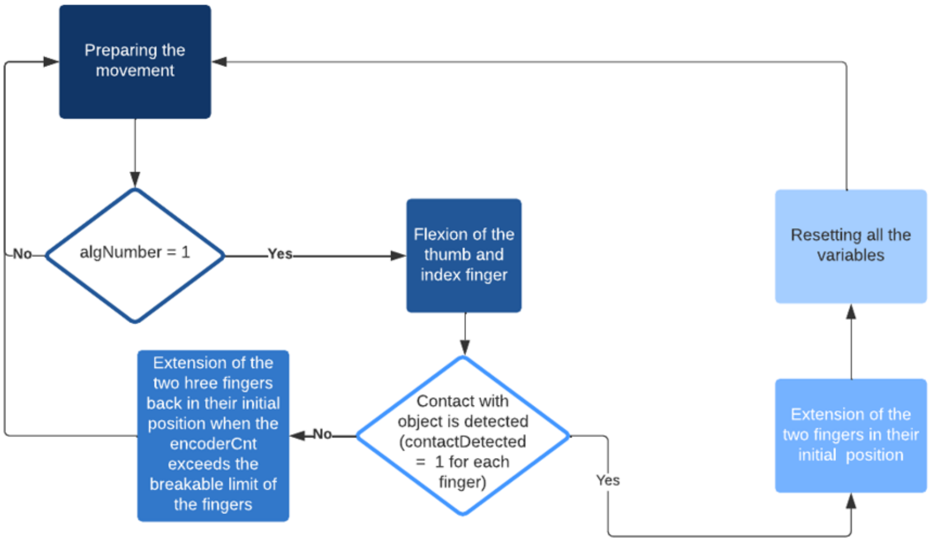


Fig. 8. Organigram for the algorithm of grasping an object with two fingers.

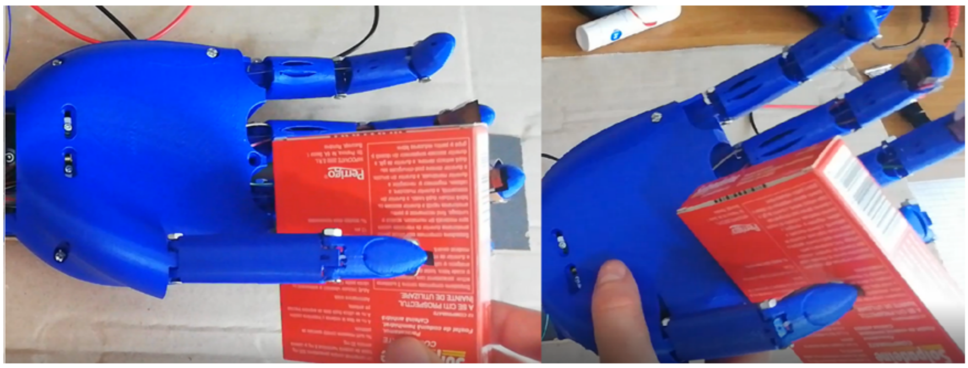


Fig. 9. Testing the algorithm of grasping an object with two fingers.

The results of the algorithm exposed in Fig. 10 are similar to those presented in Fig. 9. The difference is that a spherical object will be grasped with three fingers, from the initial state the thumb, index finger and middle finger flex to form a kind of tripod for the targeted object. The DC motors stop when the three pressure sensors fixed on the tip of each finger detect the contact with the surface of the target object. The tension limits, at which the detection is made by the pressure sensors, have been properly chosen so that the pressure applied by the prosthesis on the target object is sufficient that it does not destroy the object, but does not escape it either. After a lapse of time, we generate a signal to release the object by pressing the pressure sensor with Velostat, specially made for this task. All three fingers extend to their initial state determined with the help of pos variable that memorized the positions of each motor.

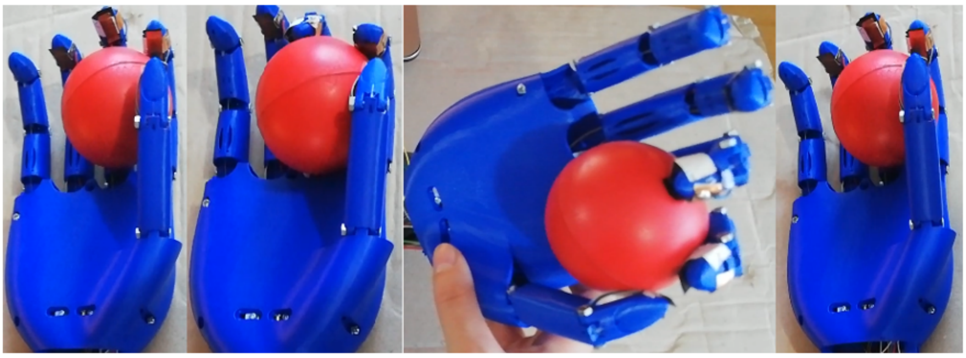


Fig. 10. Testing the algorithm of grasping a spherical object with three fingers.

8. Results and Conclusions

This extended version of [1] provides detailed information on the implementation of some motion algorithms. The experiments carried out with the prosthetic hand were aimed to check the correct functionality of the device, but also to test the mechanical structure. These tests have shown that the entire device created, including the command-and-control block, mechanical structure, and sensors system, is feasible. It was achieved tactile feedback from prosthesis to the control block and this is the reason why our prosthetic device differentiates itself from existing commercial devices that do not offer this functionality. The placement of the pressure sensors played an essential role for the proper functioning of the algorithms, so we had to ensure that they do not change their position and that the sensitive area of the sensors can touch the surface of the object. We observed the following aspects as mechanical limitations: - the length of the phalanges influences the movement, so a proportionality ratio should be kept to the lengths of some real phalanges (the proximal phalanx of the thumb is much longer than the distal one, contrary to a natural hand)
– the thumb has a small stretch compared to the other fingers (1300 compared to 2500 pulses read from the magnetic encoder) which restricts the possible movements
– the direction of movement of the thumb intersects the direction of movement of the index finger, and the two fingers lock each other in applications of clamping cylindrical objects of small diameters.

The device tested in the present work is quite versatile and sophisticated. It allows the realization of various types of movements starting from those that involve the use of a computer, to those in which we can use objects of various shapes and sizes for daily activities or even in recreational activities. Also, with the signals received from pressure sensors with Velostat, algorithms such as grabbing an object with two fingers, grasping a spherical object with three fingers. The designed algorithms are functional, they have been successfully tested on the experimental assembly containing the mechatronics structure and the command-and-control block. A modular design of the tested system was made to adapt the algorithms to different constructive variants of sensors and actuators. Each component used in the hardware part of the project is independent of the others, so it can be replaced at any time by another component with different specifications. Although the work has achieved its intended objectives, there are still aspects that can be improved, such as rethinking the use of the motors and their placement to allow a greater range of motion, enriching the sensor system to transmit various information to the user, modifying the mechanical structure.

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