Pressure and Angle Sensors with Optical Fiber for Instrumentation of the PrHand Hand Prosthesis

Laura De Arco[1], María José Pontes[1], Marcelo Eduardo Viera Segatto[1], Maxwell E. Monteiro[2], Carlos A. Cifuentes[3,4], Camilo A. R. Díaz[1].

[1]Telecommunications Laboratory (LABTEL), Electrical Engineering Department, Federal University of Espírito Santo (UFES), Vitória, Brazil.
[2]Federal Institute of Espírito Santo (IFES), Serra, Brazil.
[3]Bristol Robotics Laboratory, the University of the West of England, Bristol, UK.
[4]School of Engineering, Science and Technology, Rosario University, Bogotá, Colombia.

E-mail: laura.barraza@edu.ufes.br

Abstract. The principal cause of upper limb amputations is due to traumatism. The prosthesis is an assistive device to help in the activities of daily for the amputee person. However, one of the latest reports shows that in developing countries there are around 30 million people without assistive devices. This work presents the development of two kinds of sensors for the PrHand, an upper limb prosthesis based on compliant mechanism and soft-robotics. The sensors are made with polymeric optical fiber (POF), due to their flexibility and low cost, and the working principle is based on intensity variation. The angle sensors are used for monitoring the interphalangeal joint of the fingers, and for the assessment were made cycles of closing and opening each finger. On the other hand, the force sensors are located at the tip of three fingers to track the force made over the objects. Before encoring the sensors were evaluated making five cycles of compressing and decompressing each sensor. The results show a linear behavior between the angle and the voltage variation, one most remarkable angle sensor result was with a sensibility of 0.0357 V/° and an R^2 of 99 % closing and 0.0483 V/° opening. In the case of the force sensor, a polynomial relation was found between the voltage changes and the pressure over the sensor; in some cases, the relation between voltage changes and pressure could be linear but that depends on the construction of the sensor. Regarding the obtained R^2 of 99 %, its sensibility was 0.0361 V/N compression and 0.0368 V/N decompression. In conclusion, was successfully developed two kinds of sensors for the instrumentation of PrHand prosthesis. It is expected to use angle and sensor variables as input in algorithms of Machine Learning to improve the detection of objects. One aspect to improve is to control in a better way the sensor construction parameters due to the considerable influence over the sensor behavior.

Keywords: Angle Sensor, Optical fiber, Pressure Sensor, PrHand Prosthesis

1. Introduction

The principal cause of upper limb amputations is related to traumatism (77.0 %), followed by congenital disorders (8.9 %), cancer (8.2 %), and vascular diseases (5.8 %); the last 0.1 % is by unknowledge causes

[1]. Around 59,000 amputations were performed in Brazil, by the year 2018 [2], and, the year later it was estimated that more than 528,000 people have some kind of disabilities in their hands and legs in Colombia [3]. Additionally, it was approximated that around 30 million people did not have assistive devices in developing countries. The robotics hand is one example of an assistive device, and for that reason, the interest in developing it has increased in the last years [4].

The main goal of robotic hands is to help psychological problems due to amputation, improve the user's self-esteem, and support activities of daily living [5]. These devices can be classified as humanoid hands, prosthetic hands, and research hands [6]. Humanoid hands aim to be as similar as possible to the limb they are replacing, regardless of cost and weight. Prosthetic hands line up for being as similar as possible to the human hand with respect to functionality. In the development of robotic hands, research prostheses take into account both aforementioned characteristics to develop robotic hands, which means seeking both the functional and aesthetic parts along with the best similarity to the human hand [7]. The most common materials used to develop prostheses are rigid and heavy, and are commonly used industrial mechanisms, increasing the device cost. Also, its performance is based on several motors and axes, which makes it a more complex system [8]. The prosthesis based on soft robotics is a new line of research prostheses that is growing up to face the disadvantage of the traditional ones. Their advantages include reducing the fabrication costs, decreasing weight, incrementing functionalities, making the elasticity module of the device more like the human body, among others [9].

The use of sensors is necessary to monitor prosthesis activity and detect external stimuli. Among the most common sensors used in prostheses instrumentation, there are accelerometers, onboard sensing to evaluate the choice of grasp, and strain gauges [10, 11]. Most of the sensors aforementioned are made of rigid materials, which is not a problem for traditional prostheses. Notwithstanding, as the prostheses based on soft robotics manage different elasticity modules, their sensors should agree with that characteristic [10]. Therefore, a new type of sensors based on fiber optics are being developed to instrument soft robotics prostheses, due to advantages such as flexibility, insensitivity to electromagnetic interference, low cost, lightweight, and small dimensions [12].

The optical fiber could be defined as a medium where the light is propagated. Inside the fiber, the light is reflected to be transmitted from one side to the other. Optical fiber sensors have been included in several biomedical applications on the human body. For instance, as goniometers for the wrist, showing satisfactory results in the tracking of the wrist movement considering their degrees of freedom [12], in monitoring the angles of the fingers [13], the elbow and ankle, among others [14]. Regarding prosthetic applications, some works have focused on sensing pressure between the socket-user interface, measured the angle of the elbow [15], and mapped the strain of a below-knee prosthesis [16].

The PrHand is an upper-limb prosthesis based on soft robotics and complaint mechanisms, described in [17]. The computer-aided design (CAD) and the actual prototype are presented in Figure 1. The prosthesis has two actuation systems, the first one consists of a servomotor that oversees the fingers flexion with an inelastic tendon, as shown in green lines on Figure 1. Each tendon goes from the fingertip to the unifying slide system, which converts all fingers tendons, to a unified tendon that goes to the motor. The fingers extension is made by elastic joints that extend fingers with an internal flexible tendon. The other actuation system is a pump air responsible for the abduction movement by pneumatic actuators that are located between the fingers (red points on Figure 1). All the degrees of freedom of the fingers (flexion, extension, abduction, and adduction) are allowed because the fingers are based on a compliant mechanism. In total, the prosthesis has 15 degrees of freedom (DoF), as shown with the blue points on Figure 1, that are controlled by one motor and one pump air, for that reason is an underacted device. To improve the hand prosthetic grasping, the fingers have silicone coatings that increase the friction between the object and the fingers. The control is implemented using a Single Board Computer (SBC, Raspberry Pi 3) and performed in Robot Operating System (ROS).

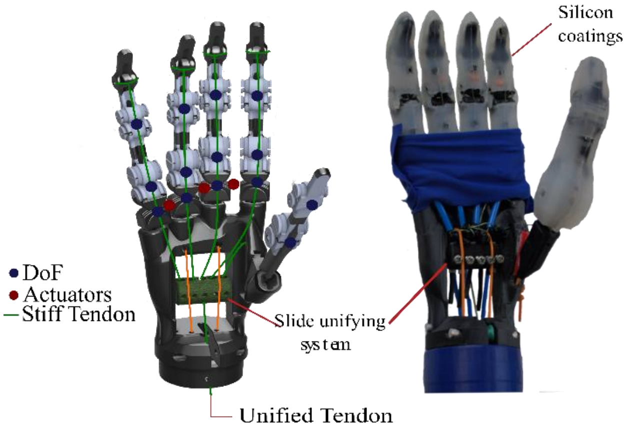

Figure 1. PrHand prosthesis based on soft-robotics.

The main goal of this work is to report the development of two sensors based on optical fiber, one for tracking the changes in the finger's angles and the other for measuring force over the fingertips. The working principle of both sensors is power variations, which implies monitoring voltage changes according to variations on angle or pressure. The paper is divided as follows: Section 2 describes the working principles of the sensors, how they were constructed, and evaluated. Section 3 shows the results and the discussion. Finally, Section 4 presents the conclusion achieved during the study.

2. Materials and methods

2.1. Angle sensor and benchmark

For the development of the sensor, a polymeric optical fiber (SH4001, Mitsubishi Chemical Co.) is used according to the proceeding described in [18]. The working principle is intensity variations, so the changes in the fiber curvature are measured as changes in the voltage. To increase the sensitivity of the sensor, a lateral cut is created where the power losses occur. Observe that the cut is performed in the fiber where the angle is measured. For the PrHand, the sensors measure the changes in the proximal interphalangeal joint angle of each finger (see Figure 2).

Figure 2. Angle sensor anchored in the PrHand prosthetic finger.

For the benchmark, the relationship of the angles with the voltage changes of opening and closing cycles of the prosthesis fingers is used. The servomotor angle changes around 30° every 20 seconds until the cycle is completed. Six repetitions per finger are made. A microcontroller (Teensy, PJRC, USA) is used to measure the voltage in the photodetector. The test is recorded with a digital camera to make the tacking of the angle with the software Kinovea.

2.2. Force sensor and benchmark

The force sensor is also developed with polymeric optical fiber (POF), and the working principle is power variation. However, for this sensor, the intensity is induced differently. A lateral cut is performed to place the led, enabling monitoring the signal intensity. It means, when the distance between the led and the fiber changes, the measured voltage in the fiber extremes also alter. To construct the sensor, the cutout is placed parallel to the LED, maintaining a small gap between them. The LED and the fiber are placed in a 3D printed mold with cylinder shape, where they are covered with a transparent polydimethylsiloxane (PMDS) silicone. Once the resin has dried, the pressure sensor head is fabricated. Hence, when pressure is applied to the silicone, the distance between the LED and the fiber is reduced and when it is removed, all the elements return to their initial position.

For the assessment, a compression structure was used, as is shown in Figure 3. It allows to make a controlled pressure over the sensor. A micrometric positioner allows controlling a constant pressure over the sensor. The structure was 3D-printed and anchored to an optical breadboard to provide stability to the system characterization. To know the applying force, a strain gauge is used, and the data was collected with an Arduino Uno (Arduino, Italy). For the characterization, five cycles of compressing and decompressing are made from 0 N to 29.4 N. The maximum value of the applied force was defined, taking into account a previous study where the maximum force that the prosthesis can make over an object was 30 N. The sensor voltage variations are measured with the same microcontroller used to measure angle variations. Three sensors are developed and located in the fingertips of the little finger, middle finger, and thumb.

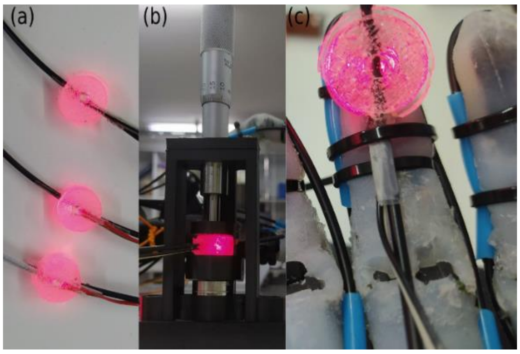

Figure 3. (a) Force sensors with polymeric optic fiber. (b) Characterization setup of the force sensor. (c) Force sensor anchored in a finger.

2.3. *Sensor Testing*

In [17], the prosthesis functionally was assessed for which grip types the prosthesis better performs, comparing to the grasp types the human hand performs during activities of daily life, namely: hook, spherical grip, tripod pinch, and spherical grip. In [19] the angle sensors information was used for grasp types recognition with machine learning (ML) algorithms, taking into account the grasp types aforementioned. Thus, in this study the same four objects that were used in [19] by grip type are used. However, at this time both the angle and the pressure sensors are analyzed under grasping tasks. The objects used are: a jar for the hook grasp (H), a ball for the spherical grip (SG), a tuna can for the tripod pinch (TP), and a tuna can for the cylindrical grip (CG). Figure 4 is shown both sensors grasping the SG object.

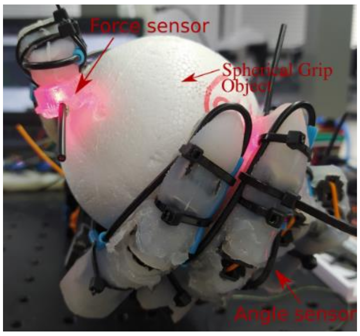

Figure 4. Force and angle sensors anchored in the prosthesis with the prosthesis grasping one object used for testing the response of the sensor to the prosthesis.

3. **Results and Discussion**

3.1. Angle sensor

Considering that the prosthesis is based on soft robotics, the fiber is a good candidate for the measurement of the parameters that allow controlling the prosthesis behavior. Its advantages including resistance to electromagnetic interference, flexibility, and low cost are very important, particularly because one of the main goals of the prosthesis research is their low-cost production. The sensors are uncomplicated to implement and allow for replication, which is a significant feature for this type of development.

In general, all the fibers showed a high-powered variation (2 VCC) with respect to the angle, which allows the hand angles to be tracked during movement. However, each sensor has its own response and must be calibrated independently. Two main reasons are associated with the fact not all sensors varying their intensity in the same ranges. First, although the lateral cut on the fibers is performed with a CNC machine, the POF has eccentricities of the core/cladding and the jacket, leading to different remotion of the material and affecting the sensitivity. Second, misalignments between the sensors and the joints cause different sensitivity too.

The R^2 of the fingers angle voltage equation per finger, of all fingers, showed that there is a linear relationship between voltages and angle since all are higher than 87 %, as is shown in Table 1. There are two sensor responses, one when the hand is closing and the other when it is opening. Due to the flexible feature of both the fiber and the fingers, it is hard to ensure that the opening movement follows the same path of closing, leading to some hysteresis, which in the worst case is 4 %. In [20], a technique to reduce hysteresis was discussed.

Table 1. Angle voltage equations per finger.

Finger	**Close Hand**	**R^2 (%)**	**Open Hand**	**R^2 (%)**
Little	V_c= -0.0042A_c+4.8808	90.68	V_o= -0.0045A_o+4.9131	96.66
Ring	V_c= -0.00194A_c+2.3561	89.05	V_o= -0.0217A_o+2.5834	97.99
Middle	V_c= -0.006A_c+2.3778	92.52	V_o= -0.0061A_o+2.4054	96.87
Index	V_c= -0.0054A_c+4.6702	87.95	V_o= -0.0043A_o+4.5757	93.73
Thumb	V_c= -0.00357A_c+8.1344	99.09	V_o= -0.0483A_o+9.9173	99.73

3.2. Force sensor

In general, the sensor is easy to fabricate, however, the behavior of the sensor response is highly influenced by the position of the led with respect to the fiber lateral cut. For the first sensor (middle finger sensor), a good linear relationship with a R^2 higher than 95 % was found. However, for the second sensor (thumb finger sensor) the response was not so linear, as it shown in Table 2. Therefore, another type of relationship between voltage and pressure is evaluated, with improvements in the R^2 values that represents the relationship between the variables evaluated. Here, a polynomial relationship showed better results, with all the R^2 values higher than 89 %, see Table 3. As the sensor information will be used in machine learning algorithms, the fact of having a polynomial response there is not a problem.

Table 2. Force voltage equations per finger. Linear relation.

Finger	**Compression**	**R^2 (%)**	**Decompression**	**R^2 (%)**
Middle	V_c= -0.0361F_c+4.5599	95.56	V_d= -0.0368F_d+4.5047	98.58
Thumb	V_c= -0.0242F_c+1.8626	78.37	V_d= -0.0085F_d+1.4774	72.57

Table 3. Force voltage equations per finger. Polynomial relation.

Finger	**Close Hand**	**R^2 (%)**	**Open Hand**	**R^2 (%)**
Little	$V_c=0.0006F_c^2-0.0425F_c+4.059$	98.24	$V_d=0.0036F_d^2-0.1366F_d+3.2478$	89.04
Middle	$V_c=0.0004F_c^2-0.0264F_c+4.4621$	99.24	$V_d=0.0009F_d^2-0.0107F_d+4.4563$	99.49
Thumb	$V_c=0.0012F_c^2-0.0608F_c+2.0121$	93.43	$V_d=0.0006F_d^2-0.0257F_d+1.5477$	97.56

The construction variables that can affect the sensor behavior are identified in two main groups. The first group is related to the lateral cut and the characteristics aforementioned that can change the sensor response. The second group is related to the sensitive zone of the led position. So, one variable is the distance between the two elements that makes the sensor working zone bigger or smaller, and, the other is the led position concerning the cut being exactly parallel to the input of light.

3.3. *Sensor Testing*

The experiments show evident variations between the different objects, hence, the use of these data for machine learning algorithms is good. The angle sensors were already tested in a KNN classifier, showing a good algorithm response with an accuracy of around 93 % [19]. This is confirmed by the signals response shown in Figure 5, where the difference between the objects is observed. For the force sensor, the response for each object is different and it is concluded that the information could be a good complement for the angle information (see Figure 6).

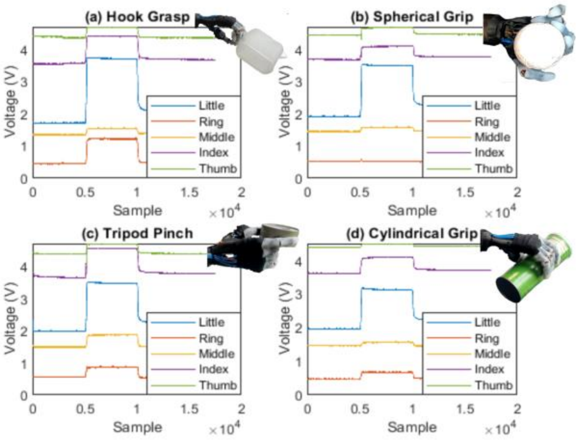

Figure 5. Angle sensors response to the PrHand prosthesis making different grasp kinds. (a) Hook. (b) Spherical Grip. (c) Tripod Pinch. (d) Cylindrical Grip.

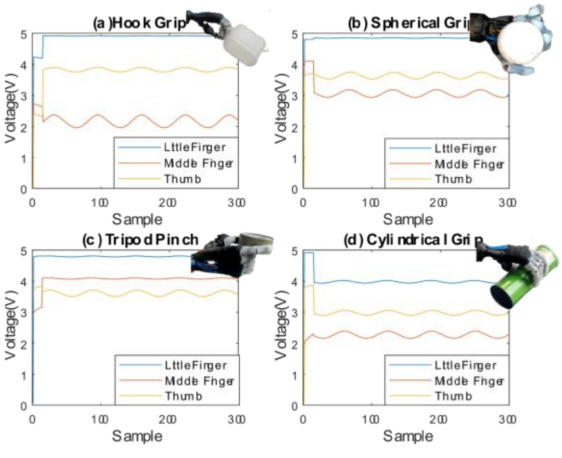

Figure 6. Force sensors response to the PrHand prosthesis making different grasp kinds. (a) Hook. (b) Spherical Grip. (c) Tripod Pinch. (d) Cylindrical Grip.

For the Hook grasp, it is required that all fingers are almost close, and, for that reason, there is a big angle variation in the graph (See Figure 5a). In the case of the force sensors, as the contact occurs with the jar handle, the fingertip that makes major contact with the object is the thumb (See Figure 6a). For the spherical grip, the objects are balls and, depending on their size, all fingers can be used or not. In this case, it just needs the thumb, the ring, the middle, and the index finger. As the little finger is not in touch with the object, the angle variations are going to be higher, and the others are going to take the object form (See Figure 5b). As was mentioned before, the little finger does not make contact with the object, so the force sensors that change are the ones in the middle and thumb fingers (See Figure 6b).

The fingers mostly used in the tripod pinch are the thumb and the index finger. So, the higher difference is observed in the other fingers, as those fingers make the support for the object and, for that, the response is different concerning the other grasp types (See Figure 5c). Taking the fingers involved in the grasp, the finger with the higher voltage difference is the thumb (See Figure 6c). In the cylindrical grip, all fingers are needed for grasping the object, hence, the angle sensors do not present many variations (See Figure 5d). In contrast, the force sensors showed greater variations when compared with other grips, since all fingertips are in contact with the object (See Figure 6d).

4. Conclusions

This paper reports the development of two sensors based on optical fiber, one for tracking the changes in the fingers angles and the other for measuring force over the fingertips. The angle and force sensors are effortless to fabricate, and their characteristics agree with the prosthesis soft robotics attributes due to the optical fiber flexibility. A linear relationship was found between voltage and finger angles, greater than 87.0%. For the force sensor it was found that a polynomial equation describes best the relationship between voltage and applied force. However, depending on the sensor fabrication that relationship could be linear, better described by polynomial equations. The pressure sensor could be a good complement for angle information in algorithms for recognition of grip types, considering that difference was found between the evaluated objects.

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