# A low-cost, compliant, underactuated prosthetic hand with custom flex sensors for finger bending estimation

Luiza Amador Pozzobon[1], Rodrigo da Silva Guerra[2] and Giovani Rubert Librelotto[3]

***Abstract*— Access to quality prosthetics to aid in daily activities is a privilege of only 5% of those in need of such equipment. It is noted that the high cost of these, associated with the lack of skilled labor, are two of the factors that aggravate the situation. Thus, the need for cost-effective prosthetic technologies, targeting the population of developing countries, is observed. Inspired by this problem, this paper presents the process of conceptual study, design, and prototyping of a low-cost prosthetic hand that is compliant and underactuated. The hand has a wrist of two degrees of freedom, and five independently actuated fingers. One of the main contributions of this work is the design of a low-cost optoelectronic sensor for the finger's curvature estimation.**

## I. Introduction

The World Health Organization (WHO) estimated in 2017 that only one in ten people with disabilities has access to assistive technologies. Such technologies, among which the prostheses are cited as an example, are responsible for assisting in the daily life tasks of individuals. Prostheses are devices used to replace a totally or partially missing limb. Their usage enables a healthier, more productive, independent and dignified life, reducing the need for long-term support or caregivers [1].

The same organization reported that out of the 40 million amputees in the world, only 5% have access to any type of prosthetic [2]. This small number is mainly due to the high cost of prostheses and the lack of qualified personnel in this area. In developing countries, the scenario is even more complex, as even prosthesis that would usually be considered as low-cost in developed countries are prohibitively expensive for most of the population.

With these statistics in mind, this project aims to present a low-cost hand prosthesis design and its accompanying flex sensor for finger curvature estimation. In section II, are the related work that inspired this project, in section III, the hand and its manufacture process are presented, in section IV, the low-cost flex sensor is parameterized and in section V are movement and gripping tests the hand was subjected to.

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[1]Luiza Amador Pozzobon is an undergraduate student of Control and Automation Engineering at Federal University of Santa Maria, Santa Maria - RS, Brazil luiza.pozzobon@gmail.com

[2]Rodrigo da Silva Guerra is with the Department of Electrical Engineering at Federal University of Santa Maria, Santa Maria - RS, Brazil. At the time of development of this project, he was a visiting scholar at National Taiwan Normal University. rodrigo.guerra@ieee.org

[3]Giovani Rubert Librelotto is with the Department of Languages and Computer Systems at Federal University of Santa Maria, Santa Maria - RS, Brazil. librelotto@inf.ufsm.br

## II. Related Work

The human hand is one of the most demanded bodyparts for reproduction through prostheses. Its usability and needs are obvious, however, because of its high complexity, versatility and dexterity, it is extremely difficult to be faithfully replicated. Aiming at reproducing the sensory capacity of the hands, [3] researched the fabrication of a soft prosthesis with a wealth of sensations. The prosthetic limb in this work makes use of optoelectronic sensors in the form of expandable optical transmission lines capable of detecting the texture, shape and softness of objects.

In the matter of materials, 3D printing has been widely used in the creation of low-cost prosthetics [4]–[6]. In a previous work, the authors studied the effectiveness of a 3D printed prosthetic hand, triggered through its wearer's body, in everyday tasks, such as pushing buttons and turning a key [7]. Two hand sizes were tested and, although successful in some applications, still did not reach the dexterity of a human limb. Thus, besides the theoretical and constructive study, it is essential to examine the applicability of the hand to be built, as well as its aptitude to accomplish ordinary activities that the conventional limb would easily perform.

On another extreme of the spectrum, a prosthetic hand with the technological grade of that built by [3] would hardly be reproducible in underdeveloped countries due to the lack of access to these materials. In addition, 3D printing is still not disseminated - and relatively expensive - specially in less densely populated cities. Therefore, it is vital to return to the origins and review what is available in these environments, just as suggested by [8]. In that work, the solutions found by the low-income population in developing countries are presented, and it highlights the need of creation of specific technologies as well as the use of existing materials that are readily available in such regions. The aforementioned paper reports prostheses that are made of wood, bamboo, PVC, plastic, polymeric molding and some metal parts. In addition, they are activated through the movement of the user's body, not having, for the most part, electrical and electronic parts, although some are mentioned in the text.

Given both the needs and the solutions of the population of developing countries presented, this project has as its general objective the manufacture of a low-cost, compliant and underactuated prosthetic hand. It is also aimed to manufacture a custom flex sensor with low-cost electronic components to promote ease of control and study of the prosthetic limb. The need to fabricate a device for this functionality is due not only to the high cost of commercially available devices, but also because they are not easily found in developing countries.

The specific objectives of the work are: (1) the construction of a low-cost prosthetic hand; (2) the construction of a wrist with two degrees of freedom; (3) the parameterization of the manufactured sensors; (4) the inclusion of finger and wrist actuators; and (5) general usage of the limb in the form of posing and gripping tests.

## III. The Prosthetic Hand

The materials used for the manufacture of the prosthetic hand are flexible PVC tubes for the fingers and MDF plates for the palm. In addition, the hand is anthropomorphic, with five fingers, triggered by one fishing line each, except the thumb, which can be triggered by two lines, in order to partially reproduce its complexity of movement in more than one dimension, crucial for certain grasping scenarios or more elaborate object handling.

The hand manufactured in this project uses principles of both compliant mechanisms and underactuated robotics. The first construction methodology is not only responsible for simplifying the fabrication process due the decrease of the number of parts of the mechanism, but it also increases its durability, portability and precision [9]. In the other hand, the second construction methodology, underactuated robotics, aims to use the natural machine's dynamics to achieve an efficient, precise and fast movement [10]. In this scope, when studying manipulation problems with underactuated robotics, such as the ones presented in this project, the goal is to build adaptable mechanisms, which have their control facilitated through a more complex design [11].

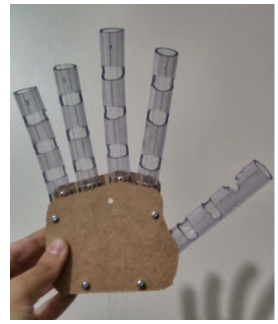
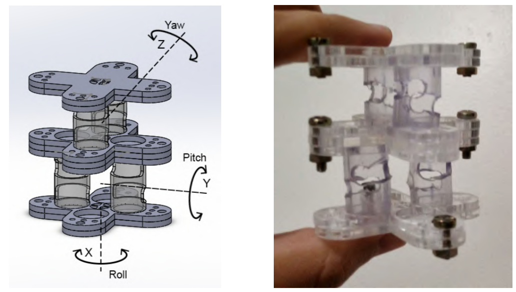


Fig. 1: Finished hand.




(a) Usual dimension of movements, pitch, yaw and roll applied to this project's wrist.

(b) Finished wrist.

Fig. 2: The wrist's rotation angles and the assembled piece.

### A. The Fingers

The fingers, made of a single piece of PVC tube, rely on the construction paradigms of compliant mechanism theory, as cited previously, which brings numerous benefits to this piece, including: the absence of friction between internal parts and the low constructive complexity. The amount of parts to construct these fingers is severely smaller than those that rely on separate phalanges. The choice of using the flexible PVC tubes is to enable the fingers to partially deform when gripping an object.

To enable the flexion of the fingers in a similar way to the human hand, we designed cuts along each PVC tube. These cuts act as joints, and are the flexing regions. Thus, the degree of bending for each joint depends on how convex, or "dug", is the cut of the region. Similarly, the strain required to flex the fingers through the lines decrease when more plastic is cut out.

The joints are produced in two stages: drilling and cutting. The drilling step is essential to ensure that there are no uneven edges in the bend region that could be deepened in unwanted directions with the repeatability of the movement, which in turn would shorten part's lifespan. With the starting hole made, the remaining part of PVC is cut from one side of the tube to finish the joint. Fig. 1 shows the finished hand. Unfortunately, no information regarding the PVC's resistance or similar specifications were found nor provided by the suppliers.

### B. The Wrist

In order to further explore the compliance capability of the material used for the fingers, the same was chosen for the wrist fabrication. It has two degrees of freedom: the pitch, rotation around the y axis; and the yaw, rotation around the z axis, as shown in Fig. 2. These two degrees of freedom simulate both flexion/extension, as well as abduction/adduction movements of the human wrist, respectively.

The structure of the wrist resembles that of a tower, so that each "floor", or stage, separated by a cross-shaped piece, is responsible for the rotation in one of the mentioned axes. On each stage there are two tubes with identical cuts but arranged perpendicular to those of the other stage. Both the mounting disparity and the use of a pair of tubes are due to the need of isolation of unwanted rotation axes. In addition, using the pair instead of a single tube acts as a reinforcement to the compression of the wrist when the tendons are pulled.

In this piece, not only are the PVC tube pairs coupled, but it is also where the actuation happens through the traction of fishing lines, similarly as for the fingers. The pair of lines, tied at each end, are connected to the motor horn in a differential manner, i.e. one is tied counterclockwise, while the other is clockwise. Thus, according to the direction of the motor's rotation, one of the lines will always be tensioned, putting the wrist in movement.

Due to the load applied to the ends of the cross-shaped parts of the wrist, a factor of concern was their rigidity. Thus, its manufacture in acrylic was chosen. It is noteworthy that although the piece is cited in the text as one, for the feasibility of connecting the PVC pipes, it was manufactured as two, one with cutouts for their connection. As presented in Fig. 2, cross-shaped pieces with cuts and no cuts are stacked together, by either pairs, in the extremities, or in trio, to create grooves where the tubes are inserted.

### C. *Actuators and their support structure*

The motors used for actuation of the fingers and the wrist are the ROBOTIS Dynamixel MX-28 in multi-turn mode. It's important to note that these were used due their prompt availability in the laboratory in which the hand was manufactured, and they should not be considered low-cost. The choice of low-cost actuators was left out of the scope of the present work. The employment of the chosen servomotors aims only to facilitate the validation of the construction methods applied to the limb itself (hand and wrist), since these actuators are robust, easy to use and allow the personalization of almost any configuration.

A supporting structure for a total of nine Dynamixels was built using metallic pieces, which guarantee a greater durability and robustness when compared to other materials and production methods, such as 3D printing. There is a central shaft where the "L" cross-section bars are connected, which, in turn, is where the motors are coupled. Each trio of such bars is separated by a triangular plate, which not only ensures greater stability to the actuators, but is also the path the prosthetic hand's traction wires pass through.

## IV. Sensor Parameterization

As mentioned previously, we opted to design and manufacture our own optoelectronic flex sensors, due to the high cost of commercially available ones. The constructed sensors are made of a coil extension spring with two electronic components at its terminations: a LDR sensor and a LED, as observed in Fig. 3's scheme. With this construction setting, the more the spring is bent, the less LED's light reaches the LDR sensor. However, the reflexion of the metal spring ensures that at least some light intensity reaches the LDR. The feeding circuit for the LDR is a simple voltage divider, and the sensor value is higher the more light it detects, acting as a "light sensor".

Parameterization tests of this custom assembly are necessary to ensure its quality, robustness and accuracy of readings. In this manner, two tests were performed: repetition and hysteresis. The tests were executed for three pairs of different length sensors: two with 3 cm; two with 3.5cm and two with 7cm springs. The choice for these two tests was based on similar studies already performed with flex sensors, such as those presented by [12] and [13]. Note that all tests were conducted in the same environment and under the same conditions.

To perform the tests, each sensor was coupled with one end attached to the side of a Dynamixel MX-28 servo actuator. The other end had partial movement in order for the rotation to be applied. In the next sections, sensors 0 and 1 correspond to the 3cm spring length, sensors 2 and 3 to 3.5cm, and sensors 4 and 5 to 7cm.

### A. *Repetition Test*

The repetition test aims to investigate the degree of repeatability of the sensor, i.e. whether the readings for the same bending angles are consistent at different periods of time. Thus, the motor is rotated from 180° (extended and relaxed spring, see Fig. 4) to 60° (flexed spring) every ten degrees. For each angle, ten sensor readings are taken, and the test is performed ten times clockwise (from 180° to 60°) and ten times counterclockwise (from 60° to 180°). Between one test and another, there is a three second interval for system accommodation. Fig. 5 shows the standard deviation in terms of percentage for (a) a set of commercial flex sensors as presented by [13] and (b) the results obtained from the flex sensor presented in this paper for each of the bending angles.

Our flex sensors present competitive results when compared to commercially available ones, especially until the bending of 110°when observing sensor 0. It's probable that the light suffered from slight interruption in intense bending degrees, as indicated by the increase in the SD. variation from 110° to 120°.

### B. *Hysteresis Test*

From the data obtained for the clockwise and counterclockwise movements of the previous explained test, it is then possible to generate hysteresis graphs, which is the time dependence of the current outputs compared to the past outputs of a system [12].

Fig. 6 presents the normalized hysteresis results for the 3cm, 3.5cm and 7cm spring sensors respectively. The average

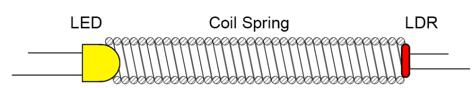
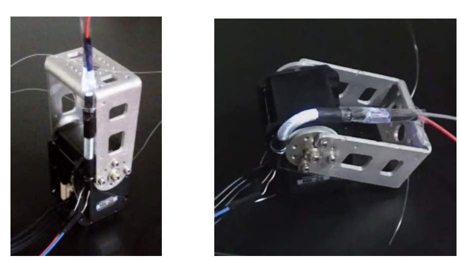


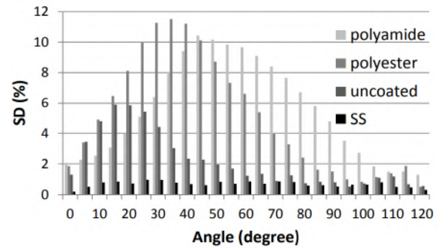

Fig. 3: Optoelectronic flex sensor's scheme.



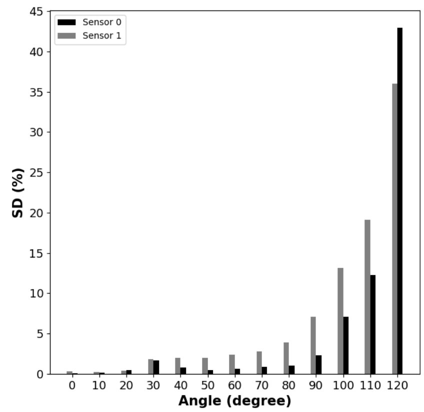
(a) Actuator at 180°. Sensor extended.

(b) Actuator at 60°. Sensor flexed.

Fig. 4: Actuator rotation degrees in the sensor's parameterization tests.




(a) Results obtained from commercially available sensors, as presented in [13]




(b) Results obtained for the flex sensors 0 and 1 presented in this paper.

Fig. 5: SD. (%) versus bending degree for commercial and our custom-made flex sensor.

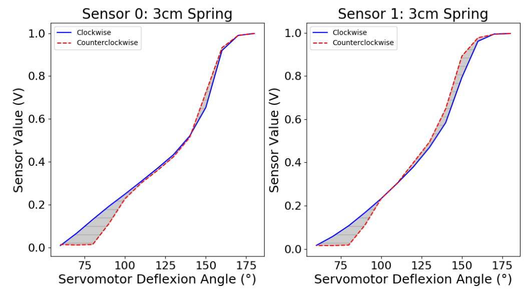
value of the ten readings of each angle is taken as the value read. Then, the values read are averaged for the ten test repetitions, both clockwise and counterclockwise. This last averaged value represents a point on the hysteresis graph.

According to the images, both 7cm and 3.5cm sensors have similar behaviors: a high variance (indicated by the steep slope of the curve) for a given reading range, and a low variance for the remaining readings. For 7cm sensors, the high variance can be observed from the test angles of 130° to 180°, while for 3.5cm sensors this behavior is observed from 150° to 180°.

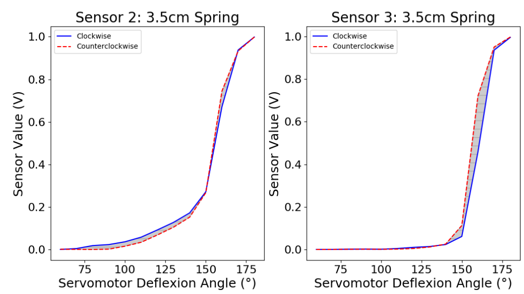
In addition, the testing instability of these sensor lengths is observed. For both, one of the tested elements has significantly lower quality than the other. Sensors 3 and 4, of 3.5cm and 7cm, respectively, for example, have nearly stagnant readings of 60° to 120° when compared to their pairs, sensors 2 and 5, which still do not have a good variation rate.

A good amount of the problems mentioned are minimized by reducing the length of the spring. Both 3cm sensors tested have higher reading linearity and substantially more stable behavior: there are no major behavioral discrepancies between the two elements, in contrast to what was found with the 3.5cm and 7cm pairs.

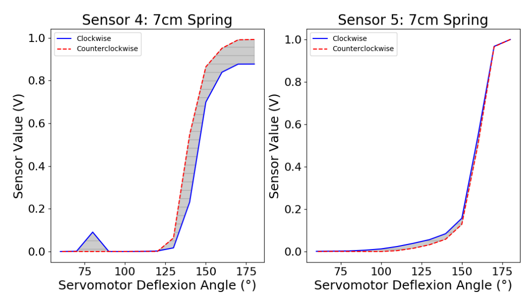
Both the larger hysteresis area, between 60° and 100°, and the stabilization of the 170° to 180° readings, are probably due to the difficulty of their coupling to the test system. Because they were smaller in size, their fixation was quite complex, so that there was a looseness in the movement of 170° to 180° (although the actuator moved, the sensor only rotated in position without being bent).




(a) Sensors 0 and 1: 3cm spring




(b) Sensors 2 and 3: 3.5cm spring




(c) Sensors 4 and 5: 7cm spring

Fig. 6: Hysteresis graphs for the pairs of 3cm, 3.5cm and 7cm sensors. Solid blue curve represents the clockwise movement, while the dashed red curve is the counterclockwise.

With given hysteresis and repetition testings results, it was decided to proceed to the prosthetic limb's evaluation with the 3cm sensors. As explained before, they appeared to be more stable and present a decent reading linearity, when compared with the other, longer, tested pairs.

## V. Results

Fig. 7 shows the finished and ready-to-use limb fixed on a horizontal surface with the palm down. In order to verify its usability as a prosthetic hand, two simple practical experiments were performed: (1) limb poses and movement of all engines; (2) grabbing of objects of daily use. These tests are presented below, along with the reading of five custom flex sensors internally coupled to each finger.

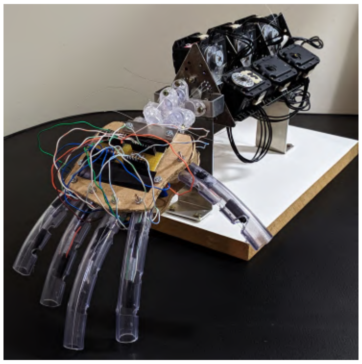
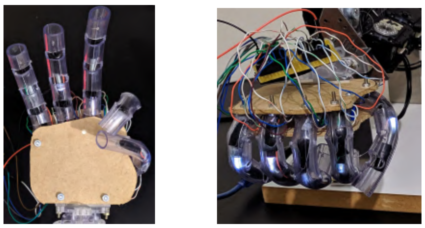


Fig. 7: Fully constructed hand with sensors attached.



(a) Precision Grip (b) Power Grip

Fig. 8: Hand's usual gripping patterns.

It is noted that the values read by the sensors are not normalized as those presented in the previous chapter, in some of the parameterization tests. In this section, the results obtained by them are raw, ranging from 0 to 5V, although none actually reaches the maximum 5V. In addition, the tests were performed under ambient light of less than 100 lux of intensity. The influence of ambient light to the sensor's readings was tested, although not presented in this paper, and we found no significant influence of luminous intensities of up to 600 lux. The poses and grips presented in this chapter are achieved by driving the motors individually using the keyboard keys. The feedback of the flex sensors' values was not used in the control loop, which is open (servo actuators moved in closed loop using actuator's own angle feedback, but the finger bending measurement was not used in these experiments).

### A. Poses and Movement

In this experiment, all motors attached to the fingers or wrists were moved to confirm the functionality of the construction. In addition to general movement, the hand was put into basic poses such as precision grip, power grip, peace sign, hang loose and thumbs up, as shown in Fig. 8 and Fig. 9. Table I shows not only the values captured by the 3cm flex sensors internal to each finger for the above poses, but also their values in the relaxed position before any tensioning (labeled as "Rest").

### B. Objects Gripping

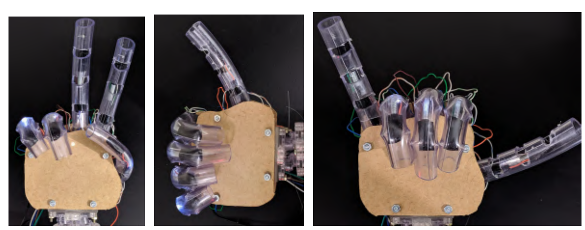
After the movement testing, the prototype was submitted to more expressive usability tests. Four objects were tested for distinct grabs by the prosthetic hand: (1) a 3cm diameter Styrofoam ball; (2) another ball, slightly larger, of 4.5cm of diameter; (3) a 200ml full soda bottle; and (4) a thin, slippery wallet. All of the objects were placed in front of the hand for it to grab.

For the first object evaluated, the 3cm diameter ball, it was intended to test the ability to grasp small objects. The object was suspended exclusively by the ring finger, as observed in Fig. 10. This grasping was successful with the prosthesis, lifting the object firmly and safely.

Both the second ball and the soda bottle were tested for power grip style simulations. In Fig. 10 it is possible to observe the result for the first element, which was naturally grasped by the hand, even with no thumb usage. Fig. 11 shows the second object's grip, the 200ml soda bottle, significantly heavier than the previous ones.

By suspending this item, the wrist was briefly bent downward due to the object's weight, which was easily corrected with the pitch control (y-axis rotation). However, in the same trial, the ring finger tensioning line broke so as to make it impossible to use it in the grip. This is due to the fact that the edges of the holes in the triangular piece, through which the wires circulate between the motors, have not been smoothed, causing the wire to be cut due to friction in the segments. Surprisingly, even with this adversity, the limb was successful in suspending the object in question, mainly making use of the thumb, index and middle fingers. This is confirmed by the sensor readings, as shown in Table II, where all values of the grip tests are displayed.

In the last test, the limb suspended a wallet of approximately 42g and 8mm of thickness. The material of this object is slightly slippery, which made it difficult to initially adjust the grip. However, the hand was still successful in suspending it, as shown in Fig. 11. The index and thumb fingers create

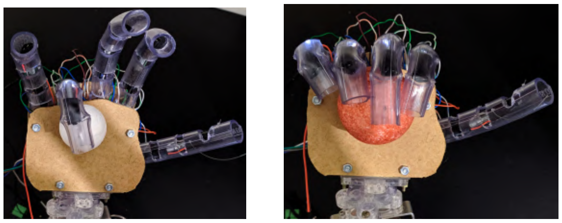


(a) Peace Sign (b) Thumbs Up (c) Hang Loose

Fig. 9: Varied hand poses.

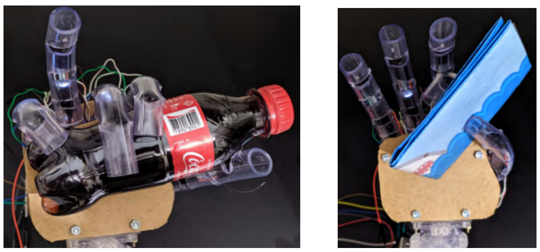
TABLE I: Sensor values obtained by each finger, in volts, for each pose presented and for resting position.

| Pose/Finger | Thumb | Index | Middle | Ring | Little |
|---|---|---|---|---|---|
| **Rest** | 4,38 | 4,49 | 4,61 | 4,42 | 3,74 |
| **Precision Grip** | 1,53 | 1,22 | 4,59 | 4,40 | 3,55 |
| **Power Grip** | 1,75 | 0,93 | 1,75 | 0,37 | 1,33 |
| **Hang Loose** | 4,41 | 0,77 | 1,77 | 0,27 | 3,83 |
| **Peace Sign** | 1,58 | 4,48 | 4,61 | 0,40 | 1,37 |
| **Thumbs up** | 4,38 | 0,87 | 2,32 | 0,44 | 1,38 |



(a) 3cm ball (b) 4.5cm ball

Fig. 10: Gripping balls of different sizes.



(a) 200ml soda bottle (b) Slippery wallet

Fig. 11: Gripping of a heavy and a slippery object.

orthogonal planes, making the prosthetic hand able to pick up objects of reduced thickness based on the precision grip.

The estimated cost (in USD) of the prosthesis, minus the actuators and their supporting structure, is presented in Table III. The costs were quoted in Brazilian reais with the quotation from july/2019.

## VI. Conclusion

This paper presented the fabrication of a low-cost prosthetic hand, composed by the hand itself and a wrist with two degrees of freedom. Both of these components were idealized with construction methodologies such as underactuated robotics and compliant mechanisms, which tend to improve not only the durability of a piece, but also it's precision and ease of control. Each finger is composed of a single PVC tube piece with cuts that simulates separate phalanges. The low number of parts is also a benefit that the theory of compliant mechanisms presents. The limb was able to simulate traditional hand poses, such as the power and the precision grips, as well as successfully grip objects of daily usage, such as a wallet and a filled soda bottle.

A custom, low-cost, flex sensor was also built and evaluated in this project. It was noted that the 3cm length helicoidal spring sensor brought the more stable and linear results, when compared to the other tested lengths. This sensor is not limited to the usage presented in this paper, and may be applied to any scenario in which there is the need of bending evaluation.

Future projects include the application of Reinforcement Learning algorithms in order to further verify the aptitude of the limb in daily usage, such as the opening of a valve or in-hand object manipulation. Repairs to the motor's support structure are to be made in order to avoid rupturing of the tensioning wires, as well as further wrist's reinforcement

TABLE II: Sensor values obtained from each of the gripping patterns, in volts.

| Grip/Finger | Thumb | Index | Middle | Ring | Little |
|---|---|---|---|---|---|
| **3cm Ball** | 4,40 | 4,47 | 4,57 | 0,40 | 3,14 |
| **4.5cm Ball** | 4,36 | 1,63 | 2,90 | 0,65 | 1,63 |
| **Soda** | 3,15 | 2,11 | 3,56 | 4,39 | 1,75 |
| **Wallet** | 1,98 | 4,40 | 4,51 | 4,34 | 3,55 |

TABLE III: Estimated cost of this project's prosthetic hand and accompanying flex sensor, in USD.

| Item | Amount | Value (USD) |
|---|---|---|
| **PVC 18mm** | 1m | 0.66 |
| **MDF** | 2 plates | 1.59 |
| **32kg fishing line** | 1 roll | 8.46 |
| **LDR sensor** | 5 | 4.55 |
| **LED** | 5 | 1.32 |
| **Coil spring** | 5 | 4.55 |
| **Arduino Uno** | 1 | 22.00 |
| | **Total** | 43.13 |

structures are to be added. Also, in order to enable the usage of the limb in an actual low-cost manner by those in need, other actuation possibilities should be studied to replace the Dynamixel servomotors.

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