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Tailor-made smart glove for robot teleoperation, using printed stretchable sensors

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***Abstract*—This article introduces a taylor-made smart glove that integrates resistive strain and pressure sensors. A home-made silver based stretchable ink is screen printed over textile to create a strain sensor that estimates finger bending for all fingers. Another piezo resistive ink was synthesized, and screen printed on fingertips, using a specific architecture for pressure sensing that can be used to determine the pressure applied on a fingertip. Using these two techniques, a full glove is printed and is used as a Human Machine Interface (HMI) by recognition of different hand gestures. Unlike previous gloves that are based on placement of external bending sensors, the developed glove in this work can be taylor-made based on user´s hand size and the desired resolution of the sensors. Furthermore, the e-textile based gesture recognition architecture is comfortable enough for long-term use. We demonstrate recognition of 10 gestures, that are used to tele-operate different gaits of a walking robot.**

***Index Terms*—Conformable Electronics; E-textile; Wearable devices; Human Machine Interface; Gesture Recognition; Epidermal electronics**

I. Introduction

TEXTILE, as the common and widely accepted "wearable" for the human being, has an outstanding potential to host electronic circuits for wearable bio-electronics both due to its light weight and flexibility, but also due to warmth and comfort when worn[1]. In contrast to polymeric e-skins, textile can be cut and easily tailor-made to the desired dimensions[2]

Having in mind the dynamic morphology of the human skin, wearables must conform to the human skin and must keep their functionality while being bent, folded, twisted and when subject to strains up to 30%, the normal stretchability of the human skin[3]–[5].

Current wearables in the market have limited applications due to mechanical restrictions imposed by rigid or semi-rigid components and bulky electrical wiring that lead to movement restriction[6]. Furthermore, this mismatch between rigid electronics and the dynamic characteristics of the human body lead to malfunction of the electronics after prolonged use.

Different techniques for fabrication of stretchable circuits and sensors have been proposed and developed in recent years[7], [8] including mask deposition[9]–[11], laser patterning[12], [13], and printing techniques[14]–[20].

Although, gesture recognition with EMG armbands[21]–[23] and smart gloves had been presented in some works[6], [24], [25] and has received attention for usage in rehabilitation systems[26]–[28] and wearable robotics[29], [30], as well as for sign language to text translation[31], none presents the possibility of creating taylor-made e-textile gloves with desired geometry and sizes of both the garment and the sensors, using simple, and scalable methods. In this work, we demonstrate a facile fabrication technique for an e-textile strain sensor, for decoding the finger bending, and as well a pressure sensor for measuring fingertip pressure. We use a carbon-based hyper-elastic ink as resistive sensing element and a silver-based highly conductive hyper-elastic ink used for the electrical interconnections. A taylor-made e-textile glove is then developed using these techniques. Custom electronic circuits boards are as well developed for signal acquisition, processing and communciation. As a case-study, we deomnstrate application of this device as a Human Machine Interface that is able to recognize 10 different hand gestures. We show an application of the device to teleoperate various gaits of a walking robot, including sitting, standing, "hand-shaking", dancing, and various walking gaits.

II. Materials and Methods

The wearable smart glove is composed of two main parts: The textile glove, which includes one strain resistive sensor and a resistive pressure sensor in each finger and a rigid electronic circuit board for sensor data acquisition and processing as well as communication with external hardware

A. E-textile Glove

A conductive paste that was previously described in [32] was used to fabricate the resistive sensors. In contrast to common Ag based conductive inks and pastes that demand for a post-baking (thermal sintering) step, this composite is surfactant-free and does not require a baking step. The whole printing process is performed at the room temperature, which is especially important for textile-based electronics, as most textiles cannot withstand high baking temperatures of over 100ºC. Furthermore, this stretchable polymer can withstand strains of more than 600%. It is highly conductive (7.02 × 105 S m–1)), and exhibits only a modest gauge factor (0.9). As well, it was previously shown that the electromechanical

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coupling of the inks remain
s constant, even after 1 year of exposure to the air without any encapsulation layer.

In parallel, a carbon-based ink was developed by mixing 9wt% carbon black (Alfa Aesar) in the same SIS-Toluene solution used in [32].

Fig. 1 and Fig. 2 summarize the process for fabrication of the printed sensors and their working principle: Using a CO_2 laser machine (Universal Laser Systems VLS 3.50) distinct

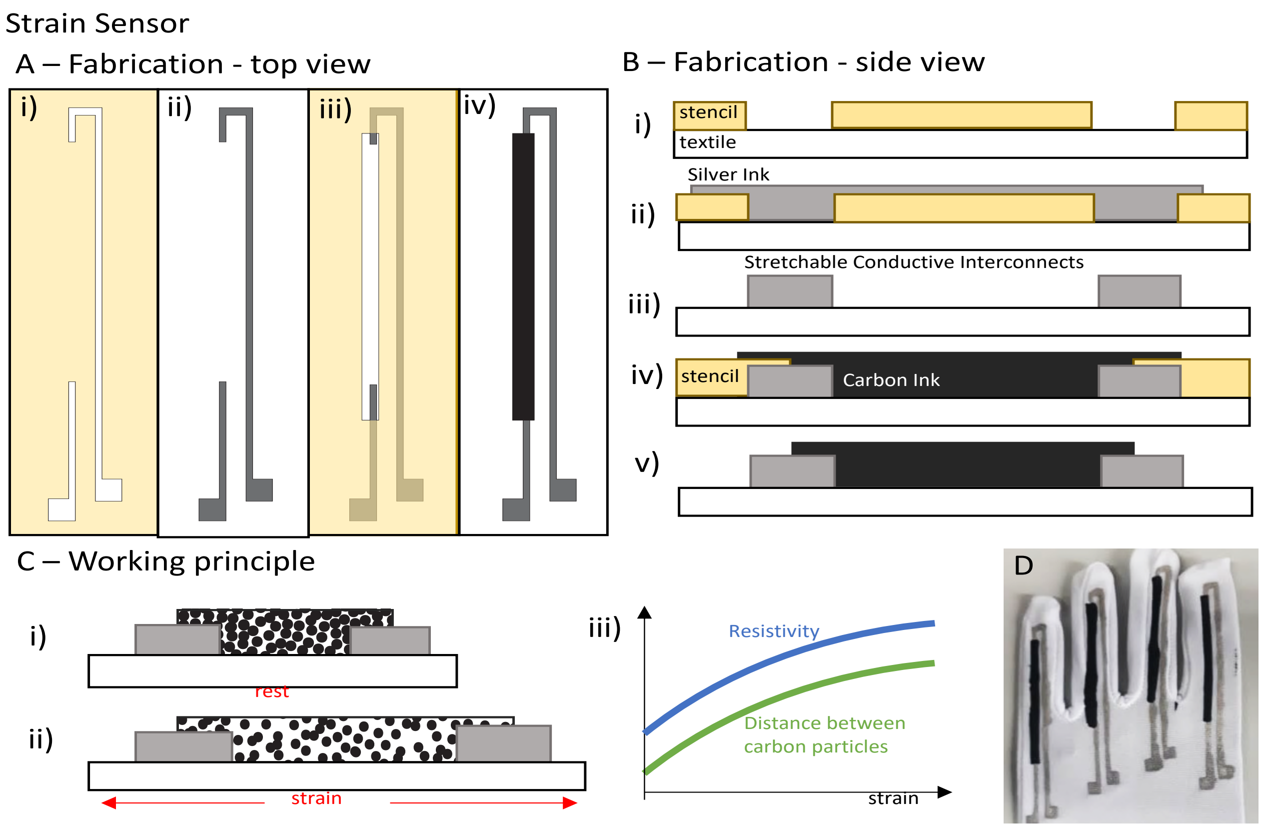

Fig. 1. Strain Sensor. A: Fabrication steps (top view); B: Fabrication steps (side view); C: Working principle based on the percolative effect; D: Strain sensors printed on a glove.

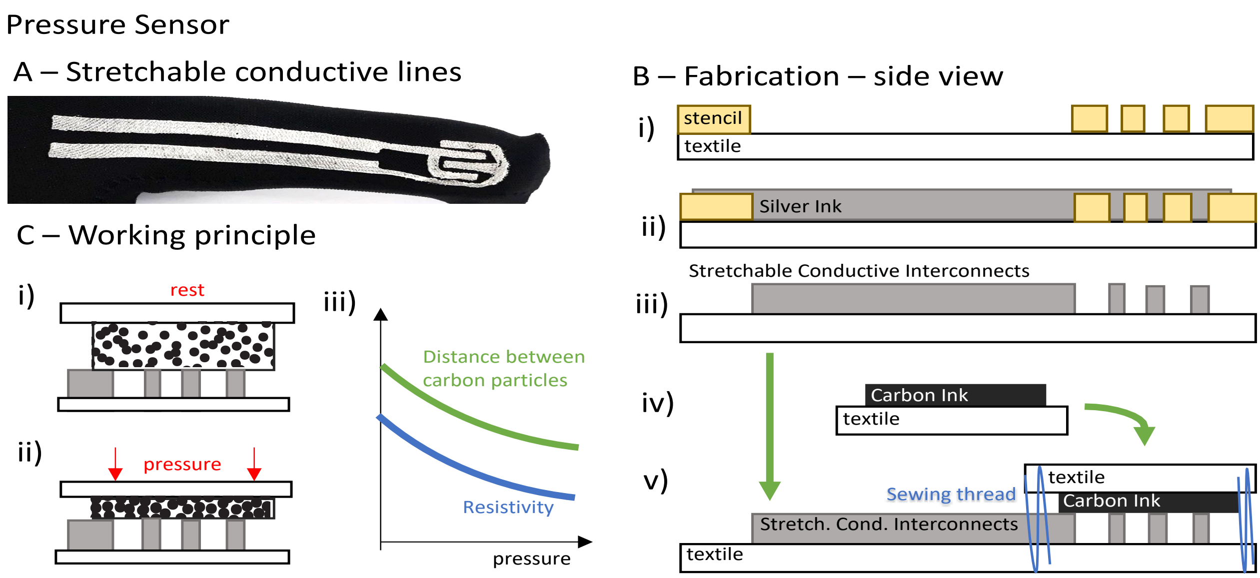

Fig. 2. Pressure Sensor. A: Interdigitated silver lines printed on a glove for the pressure sensor B: Fabrication steps (side view); C: Working principle based on the percolative effect.

stencils (LineafixAdhesive, Lineafix Hogar) are cut for the printing process. The used textile glove is made of 4-way spandex fabric that comes in different colours and the glove size is chosen to perfectly fit the users' hand. This is possible since different glove sizes are readily commercially available. The fabrication process of the strain sensors is as follows: The adhesive stencil with the shape of the conductive interconnects is fixated in the fabric glove (Fig. 1Ai, Bi). The silver-based ink is spread over the stencil (Fig. 1Bii) and the stencil is immediately removed, leaving the printed silver lines on the fabric (Fig. 1Aii, Biii), which are let to dry at room temperature for 30 minutes. A new stencil shaped like the sensing element is placed on top of the already-dry silver lines (Fig 1Aiii) and the carbon paste is spread on top (Fig. 1Biv). When removed, the stencil leaves behind a full strain sensor (Fig. 1Aiv, Bv), which is let to dry at room temperature for another 30 minutes. In Fig 1D 4 strain sensors printed on a glove are presented. The fabricated strain sensor increases its resistance with the increase of the applied strain, since the carbon particles get more separated from each other, as observed in Fig. 1C.
For fabricating the pressure sensor, a stencil is laser-cut and fixated in the textile (Fig. 2Bi)) and ink is spread on top (Fig. 2Bii)). This stencil is removed, revealing the stretchable conductive interconnects (Fig. 2Biii) which have an interdigitated shape as seen in Fig. 2A. These are let to dry for 30 minutes at room temperature. Another round stencil is placed on a separate piece of spandex and carbon ink is spread on top. This stencil is removed, and the carbon ink is let to dry at room temperature for 30 minutes (Fig. 2Biv). The spandex piece with the printed carbon element is placed on top of the interdigitate-shaped silver ink lines and sewn to the glove textile, as seen in Fig. 2Bv. The functioning of this sensor is as follows: when the applied pressure increases, the carbon particles are compressed together, decreasing the gaps between them. Consequently, the resistivity of the sensor decreases, as seen in Fig. 2C.
The behaviour of the carbon particles present in the ink, as explained previously, is explained by the theory of percolation of particles[33]. By making inks with different concentrations of carbon particles, one is able to create both pressure and strain sensors with different sensitivity and resolution. Also different shapes/lengths of the sensors could be Taylor-made to the size of the hand, allowing to fine-tune the sensor resolution and sensitivity. These tuneable characteristics of the developed carbon-based paste enable the creation of application-specific sensors that can be customized as intended, allied to the possibility of the sensors being directly printed in a glove (or other textile substrate) that perfectly fits the user physical and anatomical characteristics,
Although in Fig. 1 and 2 the height of the printed ink layers in the schematic is exaggerated, the final printed sensor is ultrathin and adds no relevant height to the textile.

B. *Electronic Circuits*

Fig. 3A shows the block schematic for the developed acquisition and communication system. A voltage divider is integrated for each sensor, in which the value of the resistor is chosen, taking into the account the minimum and maximum resistance values of the printed sensors, in order to maximize the output range of the voltage divider fed to the microcontroller.
The chosen value for all resistors for the voltage divider in strain sensors was 2.5KΩ, and for the pressure sensors was 15KΩ. Each of the voltage dividers is connected to an analog port of an Arduino Nano Rev3(Arduino). This microcontroller was chosen due to the fact that it has 8 analog inputs, allowing for creating a glove with 5 strain sensors and 3 pressure sensors. This microcontroller feeds each of the analog inputs to a multiplexer and these are sequentially digitized by a 10bit successive-aproximation Analog to Digital converter (SAR ADC) with a sampling rate of 9.6KHz. It was observed that the developed sensors were quite imune to external noise, so no filtering circuitry was needed to further condition the acquired analog signals.
A HC-06 bluetooth modue (Guangzhou HC Information Technology Co., Ltd.) is connected to the arduino using TTL

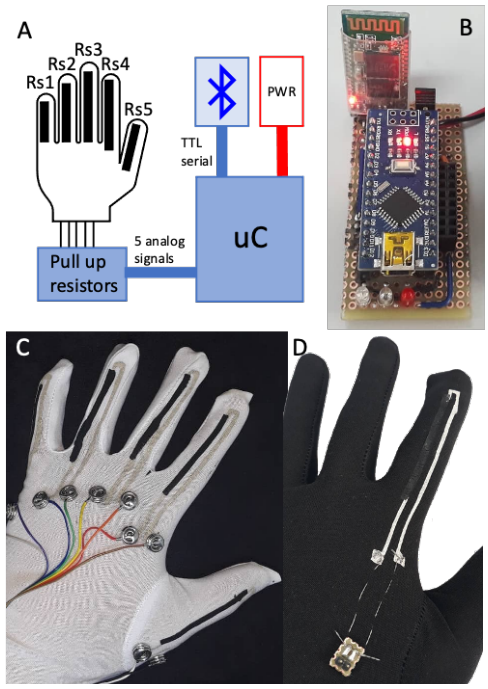

Fig. 3. A: Block diagram of the system. Each resistive sensor (Rs) is connected to the microcontroller through a voltage divider used to maximize the output range of the sensor; B: Custom-developed rigid circuit board where the microcontroller (Arduino Nano Rev3) and the Bluetooth communication module (HC-05) can be observed. C: Printed glove with snap buttons crimped in each strain sensor for connection to the rigid board; D: Connection between the printed strain sensor and the rigid electronic board using conductive thread

serial communication protocol, for data trasfer between the glove and other devices. 3 LEDs were also added in the board for visual feedback and debugging purposes.

The final rigid board, which can be seen in Fig. 3B, is powered by a 6V battery.

C. Connection Between Rigid and Flexible Modules

One of the main problems when creating flexible electronic devices is that often they must be interfaced with rigid components, which can be difficult regarding the different mechanical responses of different textile and rigid materials when subjected to deformation. Most of the times, this mechanical mismatch leads to faulty electrical contacts or loose electrical connections after prolonged use.

Two solutions to this problem were exploited in this work, being them the use of snap buttons and the use of conductive thread to create interfaces between the textile sensors and the rigid board.

1) Snap Buttons

The use of snap buttons (Fig. 3C) enables the creation of washable e-textiles due to the ease of connection and disconnection. Furthermore, these are inexpensive and are easily clamped on textile in an extremely fast manner and can be as well clamped or soldered to rigid copper wires for connection with conventional electronic connectors such as the 0.1" spacing female headers used in this work.

2) Conductive Thread

Using conductive thread (*Stainless Thin Conductive Thread - 2 ply, Adafruit*) it is easy to create a reliable interface between the printed sensor and the rigid hardware board (Fig. 3D). To do this, the conductive thread was passed through the ink pads of the sensor using a needle and was then sewed through the textile glove to create the desired path. To interface the conductive wire to the rigid board, it was only needed to pass the wire through the board's holes tying a knot and dispensing some solder above it to keep the connection in place.

Since the conductivity of this conductive thread is only 1.3Ω/inch, and the sewed paths are so short, the thread's resistance was not considered to the calculation of the sensor's resistance.

D. Software

The software, which is fully run in the microcontroller sequentially reads each sensor's analog inputs and determines if the finger is bent or not (and to which extent) or if the fingertip is touched or not. An averaging filter could have been implemented for each analog channel, but this was not necessary since the sensors proved to be immune to external noise which means that, as explored further in the applications section, no false positives (i.e. wrong detections of finger bending or fingertip press) were ever detected when using the developed glove for teleoperation of a mobile robot.

Initially each sensors was calibrated by measuring its resistance values in the loaded/strained and unloaded/unstrained states.

For the application that we show later, each strain sensor is sequentially read and the combination of all 5 sensors is compared against a table of preset hand poses. In this application, both the sensors are treated as digital sensors (we only considered if the finger was straight or bent, above a certain threshold). When a recognized hand gesture is found, the corresponding value is sent via Bluetooth for visualization or integration in an external application. This process is close to instantaneous thanks to reduced amounts of data generated by the sensors and since all the software is run in the microcontroller.

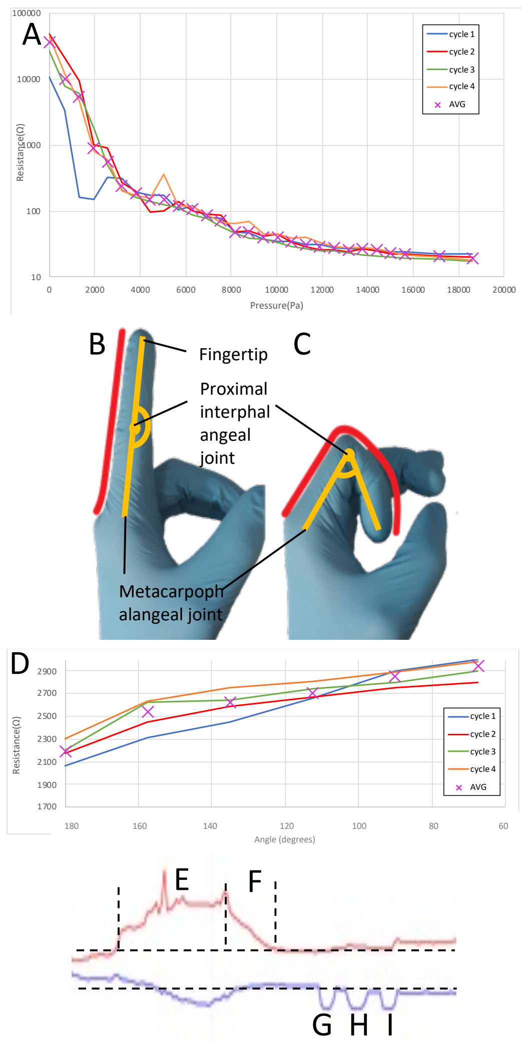

Fig. 4: A: Relation between the pressure sensor's resistance and the applied pressure. B: Length of finger skin in resting position – 8cm - (in red) and angle of finger bending (in yellow). C: Length of finger skin in bent (stretched) position – 10.5cm - (in red) and angle of finger bending (in yellow). D: Relation between the strain-sensor's resistance and the bending angle of the user's finger. E,F,G,H,I: Output visualization for one strain sensor (Red) and one pressure sensor (Blue), printed on a glove. E: Bending finger. F: Relaxing finger. G, H, I: Fingertip touches.

Also, there is no delay in transmitting the information to the robot since only one byte (corresponding to the required preset pose) is sent via Bluetooth.

III. Results and Discussion

A. Sensors Evaluation

1) Strain Sensor

A simple experiment was performed in order to evaluate which stretch displacement would a textile placed in a finger joint be subjected to.

Following the procedure shown in Fig. 4B and C, in red, the length of the upper part of the finger was measured in the resting position (Fig. 4B) and in the maximum bent position (Fig. 4C). The obtained values were respectively 8cm and 10.5cm, corresponding to a strain of 31.25%. Fig. 4D shows the relation between the sensor's resistance output (acquired with a *Gw Instek GDM-8351*) and the degree to which a finger is bent. This angle of finger bending was defined, as the angle formed by the fingertip, the proximal interphalangeal joint and the metacarpophalangeal joint, as observed in Fig 4B and C, in yellow. Since the developed printed strain sensors were printed below the distal interphalangeal joint, the contribution of this joint for bending the finger was disregarded and thus the finger movement leads to the almost-linear behaviour of the strain sensor observed in Fig. 4D.

The average hysthetesis shown by this sensor is 220Ω (min 150Ω and max 320Ω).

2) Pressure Sensor

One pressure sensor was connected to a Multimeter (*Gw Instek GDM-8351*) in order to read its output resistance when the applied pressure varied. To vary the pressure, the weight placed on top of the pressure sensor (1cm^2 contact area) was sequentially increased, leading to the results in the plot depicted in Fig. 4A. It is observable that the pressure sensor's response is consistent and repeatable over sequential cycles. Although when the fingertip is not pressed and at lower pressures (below 2000Pa) the data shows some hysteresis, this this can be overcome by considering that a fingertip touch happens only above 2000Pa, which is enough for most teleoperation, human-machine interface, and rehabilitation applications.

The average hysthetesis shown by this sensor is 15.5Ω.

3) The Glove

In Fig. 4E, F, G, H, I, the output of one strain sensor and one pressure sensor printed on a glove can be observed in the form of a graph. The results of this output visualization show that fingertip touches are easily recognized as "valleys" in the blue signal (Fig. 4G, H, I). On the other hand, finger bending leads to a rise in the red signal that is proportional to the bending degree of the finger (Fig. 4E), while relaxing the finger decreases the output value (Fig. 4F). It can also be observed that the recovery of the sensor is very fast: looking at Fig. 4E, F , one can see that, as soon as the finger in fully straightened (final portion of the red signal in Fig 7F), the signal rapidly stabilizes in the same value as before bending the finger. Regarding the touch sensor, one can also observe in the blue signal from Fig. 4G, H, I that when the fingertip stops applying pressure, the signal returns almost immediately to the resting plateau (to be noticed the close-to-vertical slope of the signal between the full pressure and the resting points).

The resulting output of the sensors shows both good precision and repeatability over the tested cycles, with typical values of the strain sensor being Rmin=2KΩ (rest), and Rmax=2.8KΩ (maximum finger bending), while the pressure sensor's resistivity lays between Rmin=20Ω (full finger pressure) and Rmax=30KΩ (rest).

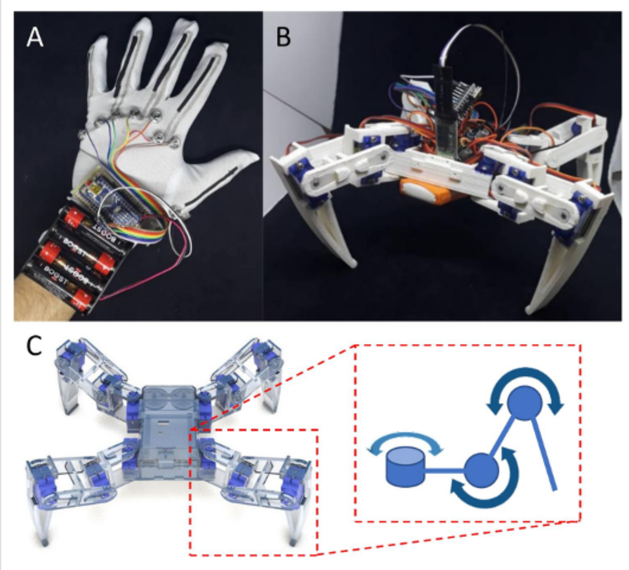

Fig. 5. A: the final prototype of the fully printed glove, which is used to control a B: robot. C: 3D model of the robot and detail of the 3 degrees of freedom that compose one of the legs. In total, the robot has 12 DOFs

B. Human Machine Interface

In order to show a possible application for the developed system, a full glove system with 5 printed strain sensors (Fig. 5A) was used to control an Arduino based quadruped robot (Fig. 5B). This glove was fully customized and adapted to the hand shape and size of the intended user. Furthermore, the size of each strain sensor was adapted to the length of the user's fingers.

The used robot is a very common walking robot topology, composed of 12 rotational Degrees of Freedom (3 per leg), as evidenced in Fig. 5C.

A set of 10 different hand gestures, depicted in Fig. 6, are recognized by the control unit of the glove and transmitted to the robot via Bluetooth – using a HC-05 bluetooth module (Guangzhou HC Information Technology Co., Ltd.) in the robot end. Each gesture corresponds to a different movement or action as depicted in Fig. 6. The results of this application can be seen in Multimedia Extension 1.

A “Lock” gesture was created in order to stop the robot from moving. When the “Lock” – gesture 10 – is activated, the robot stops reacting to any other hand gestures, until a new “Lock” is received.

When the robot is unlocked, the microcontroller sequentially reads the input from each finger sensor and stores them in a “current position array”. When all 5 fingers are read, the “current position array” is compared to the “table of stored positions” (Fig. 6), looking for a matching hand gesture. To reduce the appearance of false positives, 3 consecutive matches (sampled at 10Hz) with the same gesture are needed to consider that the user is performing the detected gesture, thus increasing the system’s reliability.

Although no significant drift of the sensors was observed, thanks to the good recoverability of the polymers, the glove was calibrated for each the user at the beginning of each round of tests that was performed. For this an automatic calibration step was used where the user simply performs the gesture prompted by the program, so it is recorded in memory.

More than 100 tests were performed with different gestures and a 100% success rate was achieved by this HMI.

IV. Conclusion

In this work we present the fabrication of a fully printed glove for finger bend and fingertip pressing recognition. Both the developed strain sensor and the pressure sensor are composed of a resistive printed sensing element and printed conductive interconnects based on the percolative theory[25]. The strain sensors have shown to withstand strains similar to the normal human skin stretchability, being thus ideal for wearable applications. Furthermore, the pressure sensors show good recovery from pressure. Also, the strain sensors showed both sensitivity and rapid recovery rate after bending cycle. Due to the use of SIS as a binder in the developed inks, the sensor doesn’t present any cracks or lack of adhesion to the textile substrate after repeated usage.

The studied approaches to connect soft sensors to rigid electronic boards (snap buttons and conductive threads) showed reliable, being that the conductive thread has the advantage of being more visually attractive and reducing the number of rigid elements in the final design.

This glove proved to work reliably as a human machine interface, by detecting different hand gestures to control a robot, as shown in the previously presented applications. Considering the quite distinct signal amplitude between the bent and the extended finger, all gestures could be recognized with 100% success rate, during over 100 tests, and no confusion ever happened.

The easy, fast and inexpensive fabrication method of these printed resistive strain and pressure sensors is ideal for the creation of customized wearable sensors which are taylor-made both in terms of user size, and as well in terms of the sensor range and resolution, by adjusting the sensors’ geometry or the carbon particle loading in the conductive composite. Future work includes direct integration of electronics microchips into the textile, using methods previously presented by our group[34].

As well, the quality of the printed sensors is linked to the quality of the printing. To address these issues and increase reliability and repeatability, novel high resolution printing methods over textiles will be addressed in further works

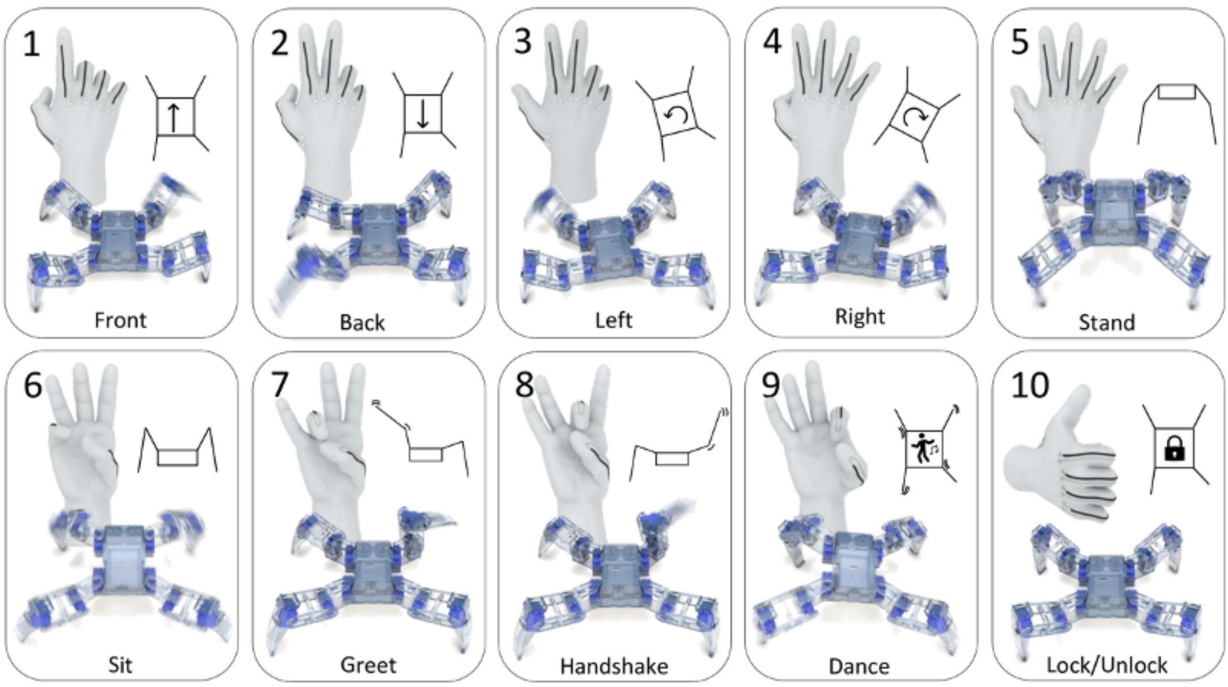

Fig. 6. Recognized hand gestures and their correspondence to the robot's movements

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CONFLICT OF INTERESTS

The authors declare no conflict of interest.

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