# A 10-17 DOF Sensory Gloves with Harvesting Capability for Smart Healthcare

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Original scientific paper

***Abstract*—We present a 10-17 Degrees of Freedom (DoF) sensory gloves for Smart Healthcare implementing an energy harvesting architecture, aimed at enhancing the battery lasting when powering the electronics of the two different types of gloves, used to sense fingers movements. In particular, we realized a comparison in terms of measurement repeatability and reliability, as well as power consumption and battery lasting, between two sensory gloves implemented by means of different technologies. The first is a 3D printed glove with 10 DoF, featuring low-cost, low-effort fabrication and low-power consumption. The second is a classical Lycra® glove with 14 DoF suitable for a more detailed assessment of the hand postures, featuring a relatively higher cost and power consumption. An electronic circuitry was designed to gather and elaborate data from both types of sensory gloves, equipped with flex sensors, differing for number of inputs only. Both gloves allow the control of hand virtual limbs or mechanical arts in surgical, military, space and civil applications. The proposed gloves were already individually evaluated in terms of repeatability, reproducibility and reliability, but in this work their performances are compared also in terms of power consumption, because a particular effort was devoted in this case to increase battery lasting for both systems, developing an Energy Harvesting (EH) system with the electronics relaying on Radio Frequency, Piezoelectric and Thermoelectric harvesters, and applying it to the gloves for the first time. The harvesting part was built and tested as a prototype discrete element board, that is interfaced with an external microcontroller and a radiofrequency transmitter board. Measurement results demonstrated a meaningful improvement in battery operation time up to 25%, considering different operating scenarios, for both glove systems, which exhibited not very different power consumption and therefore battery duration, in spite of different DoF measuring capabilities.**

***Index Terms*—Sensory glove, Energy harvesting, power management.**

## I. INTRODUCTION

The energy recovery from ambient power sources, the so-called energy harvesting, is an interesting way to capture and store energy for powering electrical devices, as those used in wearable electronics and remote wireless sensor network (WSN) [1-9]. Once the energy is recovered, the next step is to collect it in appropriate storage systems. With this aim, batteries are the most important storage block for autonomous devices, but they have a limited time duration that can be enlarged by the harvested free energy. Several efforts have been devoted to developing power harvesting techniques used to scavenge power either from the environment or from the human body [10]. Among the Energy Harvesting (EH) applications, in the last years a lot of interest has been devoted on sensory glove [11-13], both for healthcare and ludic application, in order to guarantee a long time operation [14,15]. The battery life time of the sensory glove can be harvested by means of different energy harvesters, operating all together such as electromagnetic, solar, thermal, acoustic, vibrational, etc.

In order to guarantee the glove comfort and portability we considered the development of an unwired, size- and weight-reduced system, which exploits multi-sources energy harvesting techniques in order to extend the battery lasting.

In this work we propose a couple of 10-17 degrees of freedom (DoF) sensory gloves for Smart Healthcare, implementing a multisource energy harvesting architecture, aimed at enhancing the battery lasting when powering the electronics of the two different types of gloves, used to sense fingers movements. The two gloves have different characteristic: the former is a 3D printed glove with 10 flex sensors on finger joints for 10 DoF hand motion assessment, the latter is a Lycra glove with 14 flex sensors on finger joints for 14 DoF hand motion assessment, requiring more power consumption. The performances of the presented gloves, which were already individually evaluated in terms of repeatability, reproducibility and reliability [16,17], are now compared also in terms of power consumption, testing them on six healthy subjects by mean of the Wise test [15]. The proposed multi-harvester system integrates Thermo-Electric Generators (TEGs) (that can be applied on the human forearm), stacked piezoelectric (PZT) disks, placed in the heel of a shoe, so to scavenge energy from the pressure generated by feet during walking or a running session, and RF dual band circuitry to capture energy from the available surrounding RF power. The harvesting part was built and tested as a prototype discrete element board, that is interfaced with an external microcontroller and a radiofrequency transmitter board. Measurement results demonstrated a meaningful improvement

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in battery operation time up to 25%, considering different operating scenarios.

## II. THE PROPOSED LONG-LIFE BATTERY TIME GLOVES

For human body hands are fundamental to interact with the surroundings and to communicate too. A sensory glove allows to dynamically control the fingers and hand movements [14] in order to use the acquired data for several applications as among others: gaming, training or rehabilitation, evaluation of surgical gesture [12-20]. Generally, a sensory glove is made by an elastic glove with accelerometer or flex sensors embedded [13], generating electric signals according to fingers movements [14]. The hand movement capabilities are generally represented by 27 DoFs [20,21], so to take into account both flexion/extension and adduction/abduction of the finger joints as well as rotation/bending of the wrist. However, for usual applications, we can limit to a sub-set of DoFs. In particular, in the following we consider two gloves with different capabilities, a simple 3D printed glove with 10 DoFs, and a more sophisticated glove with a combination of 14 flex sensors and one inertial measurement unit (IMU), which are compared in terms of repeatability, reproducibility and reliability of the measures as well as power consumption.

### *A. From 10 to 14 DoF Gloves*

A 3D printed glove with 10 DoF was built as a single fabric without seams or welding or use of glues, according to the anatomy of the hand [17].

The glove design includes the housings for the flex sensors [14,26] (Flexpoint Sensor Systems Inc., South Draper UT, USA) on distal interphalangeal (DIP), proximal interphalangeal (PIP), and metacarpophalangeal (MCP) finger joints, which are pockets or two foils within which the sensor can slide during joint bending. As a future improvement, the sensor can be integrated into the glove during the printing process, in order to guarantee each sensor to be correctly fixed in its location.

Figure 1 shows a photo of the realized glove from the CAD design, and the wiring of the flex sensors, taken from a Lycra glove and applied to the printed glove without any modification.

Fig. 1. Flex sensors' wiring (left down) and 3D printed prototype (right up) of the CAD designed glove (left up) [17].

In order to measure the hand gestures, we developed also a sensory glove equipped with 14 flex sensors (Flexpoint Sensor Systems, Inc., Draper, UT) and a 3-axis accelerometer (ADXL335, by Analog Devices, Inc., Norwood, MA) able to measure the flex/ extension capabilities of the finger joints of a human hand, plus the wrist movements. Flex sensors were positioned on distal interphalangeal, proximal interphalangeal, and metacarpo- phalangeal finger joints, except for the thumb that has a proximal IP (PIP) sensor and distal IP sensor (DIP), as shown in Fig. 2. The accelerometer was positioned on back side of the hand. In total 17 signals were collected by means of a custom-made prototype board connected to a computer, so to take into account of both flexion/extension of the joints of the fingers and rotation/bending of the wrist. The complete wearable system can be seen in Fig. 3.

The selected resistive sensors are stable, low cost, with a thickness less than 5 mils, flexible, almost linear [21,26]. Different sensor sizes can be also selected depending on the application: sensors of 1, 2, 3-inches are available for the finger joints DIP, PIP, MCP, respectively. The influence of fabric composition on sliding and flexion of the sensor has been studied. The glove is made of 88% polyester and 12% Elastane, because it provides greater comfort for movement. For the present study, only one medium right-hand gloves were developed. because could be best worn by the largest number of participants. The used sensory glove covers all the hand, but it can be modified to let the palmar surface and the fingertips free to maintain the tactile sensitivity. The wiring connection of the sensors to the electronic board is flexible and with a diameter of 1.5 mm and a weight less than 1g/m. The sensory glove has a 50 g weight.

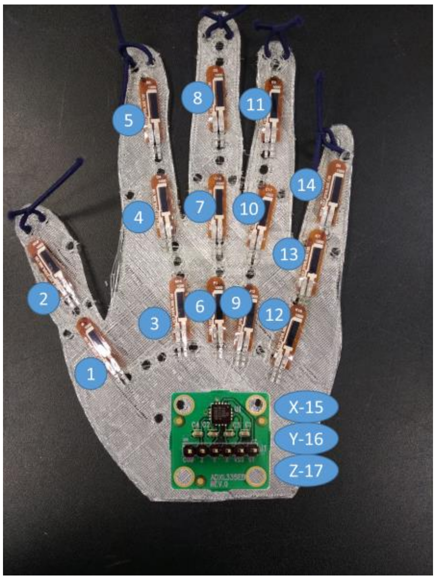

Fig. 2. Flex sensor position on the fin*ger joints of the 17 DoF glove, and IMU position on the back side of the hand.

### *B. Data Acquisition and Transmission Board*

The Arduino Leonardo electronic board allows the management of 14 analog inputs for the bend sensor signals, 2 digital pin for Bluetooth serial communication, and provides ground and voltage reference for operation of the bend sensors.

Fig. 3. The Lycra glove system: the glove with 14 flex sensors on the DIP, IP and MCP joint and the IMU device, and the acquisition and transmission box

The transduction takes place via a voltage divider between 0 and 5 V with a fixed 18 kΩ resistance, selected because it is the geometric mean between the maximum and minimum sensor resistance, to provide the widest voltage range [25]. The sensor readout circuit is followed by a 10-bit ADC module with a sampling frequency set to 1 kHz and the transmission frequency set to 50 Hz, to handle up to 20 multiplexed channels. Once the data are acquired, they are redirected to an RN42 Bluetooth module and sequentially to the receiving antenna connected to a PC. The current draw is about 100 mA for the 3D printed glove with 10 flex sensor, and 110 mA for the Lycra glove with 14 flex sensors and the IMU device, but is largely due to the acquisition and transmission board, since the bending sensor circuit has resistances of hundreds of Kohms and the IMU unit only absorbs 350 μA.

### C. Energy Harvesting System Architecture

Evidently, practical reasons impose a wireless transmission system of the sensory gloves. The glove data transmission block scheme trough wireless connectivity is represented in Fig. 4. The system is composed by a RF commercial transmitting block driven by a microcontroller and a remote receiving block connected to a data server. In order to guarantee a system battery long life time, the overall system includes a multi-harvester block, so as to scavenge free available energy directly from the surrounding environment, as demonstrated in [29-33]. The real case scenario is shown in Fig. 5. The transmitting and receiving blocks have been implemented with market components.

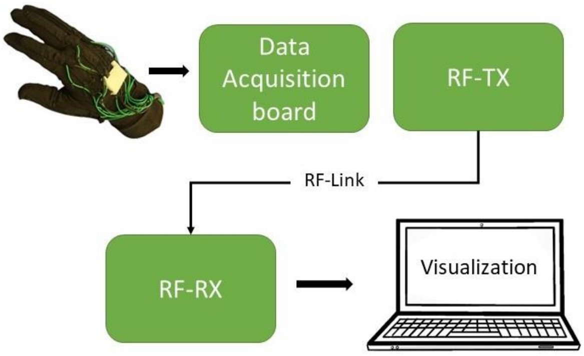

Fig. 4. Data glove acquisition and visualization process.

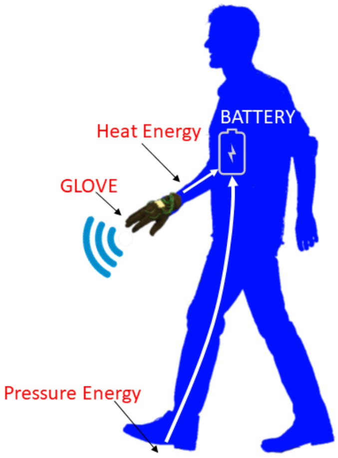

Fig. 5. The complete system block scheme

The harvesting block architecture is shown in Fig. 6. Three different harvesters terminated with a Schottky diode so to avoid reverse current flow operate in parallel. Details of the hardware implementation have been already reported in [33]. The energy coming from the human heat is collected by means of a set of 6 standard 2 cm × 2 cm Peltier cells. The cells were arranged in series connection as depicted in Fig. 7a, in order to achieve a higher output voltage. The cell surface is 55% smaller than the one employed in previous works. This reduces the harvested power per cell, but increases the power per area, since a smaller surface helps to achieve a better adhesion with the human forearm skin. Concerning the piezo harvesting branch (Fig. 7b), we adopted a parallel configuration of multiple stacked piezoelectric disks. Finally, for the RF harvester, a multichannel harvester operating at 936 MHz and 2.4 GHz with a dual band commercial antenna (Fig. 7c) and power selected incoming path as in [8].

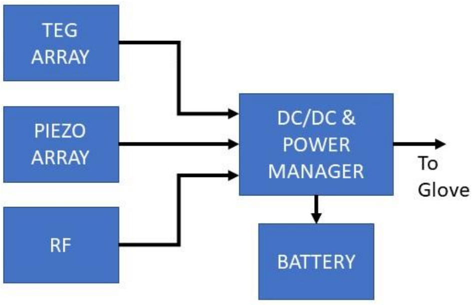

Fig. 6. Blocks representing the multi-harvesting system. It includes a thermal, pressure and RF energy harvesting paths, connected to a power management block.

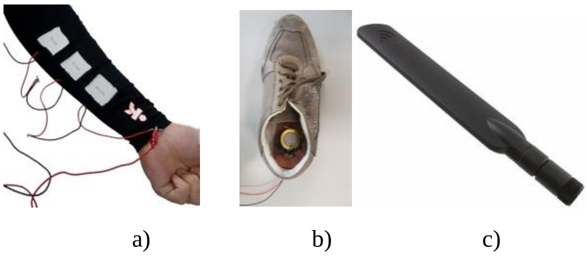

Fig. 7. a) TEG Harvester; b) PZT Harvester; c) RF Antenna

## III. MEASUREMENTS METHOD

To compare the glove performances, the Wise test was conducted on the developed gloves [16,19]. Six healthy subjects were involved, 4 males and 2 females, all right-handed, 40 years mean age with SD=±20 years. The measurement protocol was approved by the local ethics committee. The glove was worn by the right hand and the electronic board was attached to the forearm. The measuring setup consisted of 4 areas: the area where to place the open hand at rest, the large mold area, the small mold area and the closed hand area. The hand postures during the Wise test are shown in Fig. 8.

The large mold is a 3D printed cylinder of 63 mm diameter, and the small mold of 53 mm. These two sizes have been selected because they are between open and closed hand: the mean values, measured with a 3D printed goniometer with 1-degree sensitivity, are 30 degrees for MCP and PIP with large mold, whereas they are 45 degrees for MCP and PIP for small mold.

The Wise test provides a mold gripping task A (Fig. 8 postures 2, 3 or 4) and a resting hand task C (posture 1). At this stage, the unit was never removed to study the repeatability of the sensors. A second stage with B in the same position of A and D in the same position of C, the sensor unit was removed and worn again to study the reproducibility of the sensors. A time slot of 10 seconds for recording each position was selected from which the 6 central seconds were extracted for the analysis. The test was repeated for 10 iterations, then for 10 blocks (with a break of at least 3 minutes between two consecutive blocks for doffing and donning the glove). A first code deals with the organization of data, whereas a second code is used to calculate the Range and standard deviation (SD) values, intra-correlation coefficients (ICCs), and correlation between Range and SD for all subjects. The bending angles of the hand joints were measured without wearing the data gloves, using a manual goniometer with 1-degree resolution; the obtained values were used in calibration for mapping the digital values into angular values.

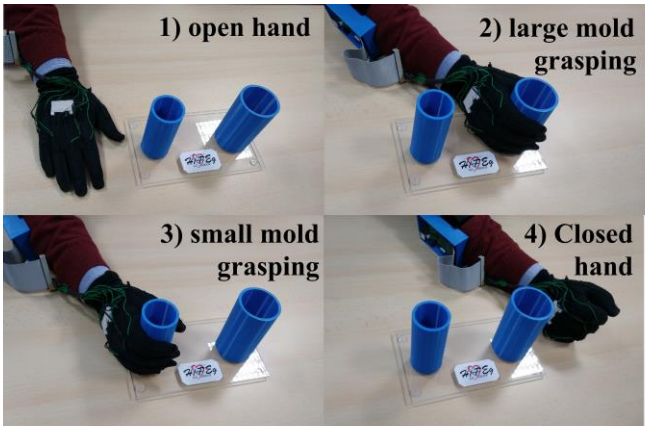

Fig. 8. Hand postures during Wise test: 1) open hand, 2) large mold grasping 3) small mold grasping, 4) hand completely closed.

## IV. MEASUREMENT RESULTS

### A. Glove performance comparison

Measurements performed by the 3D printed glove and the Lycra glove were saved in the Matlab workspace as two 5-dimensional matrices indexed by the trial number (10), block number (10), joint or sensor number (10), position number (4) and subject (6). The Range and SD values were computed among the trials, and the mean across blocks, joints, positions and subjects is presented in Table I to evaluate repeatability (task A and C) and reproducibility (task B and D) in comparison with the results obtained by Simone [19], who applied only 5 flex sensors on the MCP joints, but did not considered the thumb, and Gentner [15], who applied 10 flex sensors on MCP and PIP joints like our 3D printed glove.

TABLE I
MEASUREMENT RESULTS OF THE 3D PRINTED AND LYCRA GLOVE IN TERMS OF REPEATABILITY (TASK A-C) AND REPRODUCIBILITY (TASK B-D) COMPARED WITH OTHER GLOVES FROM LITERATURE.

| Glove | DoF | Task A | | Task B | | Task C | | Task D | | Mean | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Range | SD | Range | SD | Range | SD | Range | SD | Range | SD |
| Printed | 10 | 5.94 | 2.03 | 9.04 | 3.67 | 2.44 | 1.2 | 5.77 | 1.95 | 5.80 | 2.21 |
| Lycra | 17 | 6.67 | 2.12 | 6.85 | 2.16 | 3.47 | 1.11 | 4.45 | 1.44 | 5.36 | 1.71 |
| Gentner | 10 | 6.09 | 1.94 | 7.16 | 2.26 | 2.61 | 0.86 | 3.98 | 1.28 | 4.96 | 1.59 |
| Simone | 5 | 5.22 | 1.61 | | | 1 | 0.5 | | | 3.36 | 1.05 |

The reliability between measures in each task was assessed by intraclass correlation coefficients (ICCs) [16]. The ICC calculation was based on within-subject variance, which reflects measurement errors. If within-subject variance is low, the ICC approaches 1 and the measurements are considered as reliable. Conversely, if the ICC approaches 0, a large fraction of variance is explained by measurement errors (indicating a low reliability). The mean out of 20 ICC calculations for each joint was used as a measure of joint sensor reliability. Thus, for each joint, four ICC values (one for each task) existed. The mean ICC for each joint across tasks served as a measure of reliability for a specific joint.

ICC values are reported in Table II, which are comparable to gloves evaluated by Gentner [15] and Simone [19]. Consequently, the repeatability and reliability of the 3D printed, and the Lycra gloves are similar to other evaluated gloves and also lies within the measurement reliability of manual goniometry (0.7) [15].

TABLE II
COMPARISON OF RELIABILITY, EXPRESSED AS INTRACLASS CORRELATION COEFFICIENTS (ICCS) RESULTING FROM THE WISE TEST, BETWEEN THE 3D PRINTED GLOVE WITH 10 DOF, THE LYCRA GLOVE WITH 17 DOF AND OTHER GLOVES FROM THE LITERATURE

| Glove | DoF | ICC | | |
|---|---|---|---|---|
| | | Min | Max | Mean |
| Printed | 10 | 0.69 | 0.83 | 0.73 |
| Lycra | 17 | 0.71 | 0.90 | 0.75 |
| Gentner | 14 | 0.87 | 0.98 | 0.93 |
| Simone | 4 | 0.79 | 1 | 0.95 |

### B. Energy Harvesting Results

With respect to previous published papers [33,34] the multi harvester block has been optimized in terms of working efficiency. Table III summarizes the achieved results in terms of conversion efficiency and harvested power.

Regarding the TEG harvested power, considering an average ambient temperature of 22°C, a conversion efficiency peak of about 60% was achieved for an equivalent 10 kΩ load. For the PZT harvester measuring procedure, we employed an equivalent resistive load and a 75kg human walking at 1Hz speed on average. Measures showed in Table III demonstrate how the conversion efficiency peak, thus the maximum harvested power was achieved at lower loads, around 1 kΩ. To conclude, Figure 9 shows the overall multichannel RF path conversion efficiency, which is the combination of both low-power and medium-power harvesting channels, covering a -20 to 5 dBm window of incoming power. The combination of the two RF harvesting channels allows to obtain a good conversion efficiency for an extended input power range, as demonstrated in [33-38].

The capabilities of the presented harvesting system where tested by implementing a low-power acquisition and transmission board as a benchmark platform. The system involves a microcontroller ARM Cortex M0 (by Microchip) and a Si4463 transceiver (by Silicon Labs) whose output transmission power was set to 0 dBm. The overall current is about 4 mA in idle mode, and as-low-as 10 mA in transmission mode. According to [9], by exploiting a power saving transmission algorithm, it is possible to achieve a power consumption of 13 mA on average, regardless of the chosen transmission baud rate (19200 or 38400), which in combination with the average harvested power, can extend the battery lasting of about 25%.

TABLE III
SUMMARY OF THE ACHIEVED EFFICIENCY AND HARVESTED POWER FOR THE TEG ARRAY AND PIEZOELECTRIC HARVESTER, RESPECTIVELY, WITH RESPECT TO THE EQUIVALENT OUTPUT LOAD.

| Equivalent Load [kΩ] | TEG Conversion Efficiency [%] | Piezo Harvested Power [mW] |
|---|---|---|
| 1 | 32 | 0.8 |
| 2 | 37 | 0.55 |
| 5 | 47 | 0.3 |
| 10 | 58 | 0.26 |
| 20 | 49 | 0.22 |
| 50 | 29 | 0.2 |
| 100 | 38 | 0.3 |

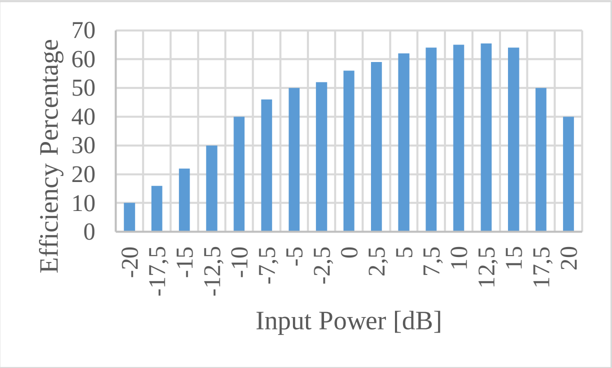

Fig. 9. RF path conversion efficiency [8].

## V. CONCLUSION

We have presented a 10-17 degrees of freedom sensory gloves for Smart Healthcare, realized by means of different technologies, implementing an energy harvesting architecture. The harvesting circuitry, able to scavenge energy from RF, Thermo-Electric Generators and piezoelectric disks, was tested, demonstrating the feasibility towards low supply-powered IC applications.

The Wise test with six healthy subjects was conducted on the selected gloves to make a comparison in terms of measurement repeatability, reproducibility and reliability, as well as power consumption and battery lasting. It can be shown that the repeatability, reproducibility and reliability of the 3D printed and the Lycra gloves with energy harvesting capability are similar to other evaluated gloves and also lies within the measurement reliability of manual goniometry, but the battery duration is increased by 25%.

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