Sensorized Glove for Measuring Hand Finger Flexion for Rehabilitation Purposes

Michela Borghetti, Emilio Sardini, and Mauro Serpelloni

***Abstract*—Over the last 30 years, scientific and technological progress has boosted the development of medical devices that can assist patients and support medical staff. With regard to the rehabilitation of patients who have suffered from traumas, robotic systems can be an aid for rapid patient recovery. This paper focuses on studying and implementing a system for measuring the finger position of one hand with the aim of giving feedback to the rehabilitation system. It consists of a glove where sensors are mounted suitably configured and connected to an electronic conditioning and acquisition unit. The information regarding the position is then sent to a remote system. The objective of this paper is to provide a sensorized glove for monitoring the rehabilitation activities of the hand. The glove can have several other applications such as: 1) the recognition of sign language; 2) the diagnostic measurement of the finger movement at a distance; and 3) the interaction with virtual reality.**

***Index Terms*—Exoskeleton, finger flexion measure, low-power system, measurement of body motion, rehabilitation, resistive sensors, sensorized glove, wearable device, wireless communication.**

I. INTRODUCTION

EVERY year, millions of people worldwide experience problems because of traumatic brain injuries, degenerative diseases, and articulation traumas. For example, 60 million Americans have disabilities that affect their daily lives [1]. Among the different types of brain trauma, stroke is the major cause of disability in adulthood [2] and the incidence of this trauma is doubling every decade >55 years. In the United States of America, one American out of 100 have had a stroke, in the United Kingdom 700 000 cases occur annually [3], whereas in New Zealand there are 6000 cases of stroke and two-thirds of these are fatal [4]. Rehabilitation aims to restore patient's physical, sensory, and mental abilities affected by injuries, diseases, and disorders, and to support the patient to compensate the deficit that is not medically treatable. In addition to surgery, patients with stroke and muscular disorders need rehabilitation to regain mobility [5]. Recent evidence has demonstrated that intensive and repetitive practice is effective in the recovery of functional motor skills. The impact of cognitive, musculoskeletal, and perceptive disorders on motor activity increases with age. In 2030, it is expected that years in the United States the population over 65 will be 20% of the total population; in Europe and Japan it will reach 30% [1]. Under these conditions, the growing demand for rehabilitation treatments would increase public spending significantly. The adoption of robotic systems would reduce the healing time and, in the future, would allow the telerehabilitation management, giving the patient the ability to perform the exercises at home, thus reducing costs and difficulties of transport to a hospital. Regarding the specific rehabilitation of the hand, the robotic system needs a sensorized unit, like a glove with suitable sensors. Because of its lightness and portability, a sensorized glove allows to measure the position of each finger, but simultaneously, to perform the required movement.

An important aspect that the project design should consider is that different people have different hand sizes and shapes. Thus, a calibration procedure of the sensorized glove is necessary before use. Some commercial sensorized gloves are proposed in different sizes to cover the largest range of hand sizes.

Several commercial companies have developed sophisticated and general-purpose systems. Among commercial products, the first glove, the Power Glove, was developed for home entertainment, with variable resistances and an infrared sensor for the wrist position [6]. An example with multiple sensors is CyberGlove [7]. The most sophisticated version is a glove equipped by 22 resistive sensors, which measure the flexion extension and the finger and wrist adduction–abduction movements. The glove communicates with a personal computer (PC) either through wireless or USB. The battery power lasts 2/3 h at each charging [8]. This way, the glove can be used for remote handling, the interaction with virtual reality [9], recognition of sign language [10], and computer-aided design and recognition of motor skills. It, however, presents some disadvantages, in particular, the need of calibration for new users [11] and high cost. In [12], VPL DataGlove consists of optical fiber sensors for detecting the flexion-extension movements of the fingers and magnetic sensors for detecting the position and orientation of the palm. Communication with the PC is obtained through the serial port. The optical fiber sensors are affected by a nonlinear response and the magnetic sensors may not be compatible with the environment or the robotic device. In [13], Human Glove (manufactured by HumanWare) consists of 22 Hall Effect sensors, which measure the flexion-extension and the finger and wrist adduction–abduction movements. Communication takes place according to the Bluetooth standard with a PC.

Because of the limits of the commercial products reported above, in particular, regarding the cost and the high complexity, several prototypes have been developed lately.

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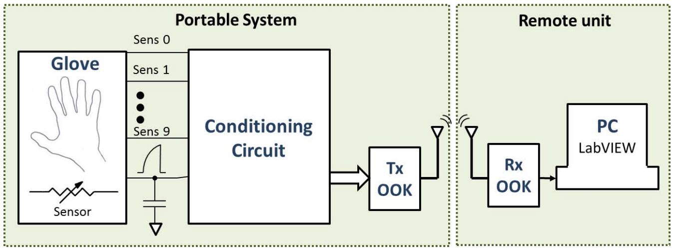


Fig. 1. Block diagram of the proposed system.

For example, in the case where only few hand gestures need be distinguished, the glove, in [14], is equipped with an electrode for each finger, forming capacitances that are measured. The combined sensor outputs make a pattern that corresponds to different finger flexion. The glove is very simple; it implements only three electrodes that are coupled with one electrode placed on the thumb. In [15], a data glove with force sensors is shown. The force sensors consist of a steel plate substrate where commercial strain gauges are attached. The sensors are glued to a rubber-coated glove. The glove is equipped with only five sensors, therefore it cannot measure each joint of the fingers. In [16], a wearable sensing glove based on heterocore fiber-optic nerves for monitoring finger flexion is shown. The heterocore sensor elements are embedded in the back of the glove, and the glove is able to detect the angles of the joints regardless of differences in interphalangeal length. As opposed to the conventional fiber sensor techniques, these sensors are both wearable and capable of unconstrained motion monitoring. The proposed solution requires a sophisticated system light source with high power consumption. Another instrumented glove implementing electromagnetic sensors is reported in [17] and [18]. The glove integrates 11 3-D electromagnetic sensors capable of measuring human hand movements including all the phalanges. The glove, however, requires a method of generating a reference magnetic field; three generator assemblies, each one comprising three coils, produce sequential magnetic fields forming a reference plane. When the glove is placed in the magnetic field, each sensor mounted on the glove measures the field component along its axis while an algorithm, implemented in a PC, converts the measurement data into a 3-D position and orientation.

The previous commercial products are very expensive, whereas other devices [19], [20], still under development, are low-cost alternatives, but low power consumption issues are not considered.

In this paper, to measure the finger flexion-extension movements, a new simple, low-power, low-cost, and wireless device is designed, made, and tested. The proposed sensorized glove permits to measure 10 joints of one hand. The proposed system includes a portable device, consisting in a sensorized glove and its conditioning circuit, which elaborates and sends the data to a remote unit (a PC), recording, and displaying the data. The design specifications of the portable system are such as: 1) independence from the remote unit; 2) low power consumption; 3) ease and comfort of wearing for people who have reduced hand motion; 4) lightweight; and 5) low cost. The portable system is powered by the battery, the data transmission from the portable device to the remote unit is wireless using a nonstandard protocol to reduce the power consumption. Because patients who wear this device may be suffering from muscle weakness and limited range of motion, the device should be light and easy to wear. The low cost makes it suitable for the rehabilitation at home, guaranteeing stability, and repeatability. The system description is reported in all the parts in Section II, whereas the experimental setup and the results are described in Sections III and IV.

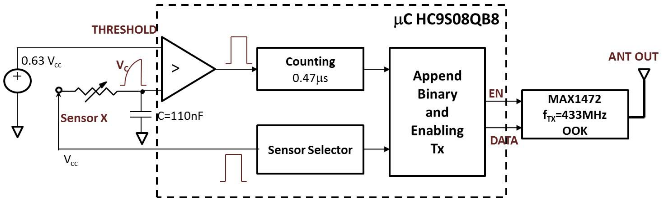


Fig. 2. Block diagram of the conditioning and transmitting electronics.

II. System Description

A block diagram of the system is shown in Fig. 1. The system is composed of a portable system and a remote unit. The portable device is the transduction system and consists of a glove comprising 10 resistors (two for each finger) connected to a microcontroller through front-end electronics, described below. The management of the sensor measurement is assigned to the microcontroller that performs several functions: interfacing and conditioning of signals from the sensor block and data transmission. During the operation, the remote unit, made up of a receiver and a PC, converts, records, and displays the received measures of each joint deflection.

In Fig. 2, the block diagram of the conditioning and transmitting electronics is shown.

The resistive value R of each sensor is calculated through the principle of charge and discharge of a capacitor with capacitance C, in series to R, according to the formula $R = \tau/C$, where τ is the time required to charge the capacitor at 63% of the voltage reference of the conditioning circuit.

The sensors are labeled from 0 to 9. The capacitor is connected to the comparator of the microcontroller: its output is high or low depending on the level of the signal to measure with respect to the set threshold. At the beginning of the measurement, the comparator generates an internal rising edge that activates the timer. Once the charge of the capacitor reaches the threshold value, the comparator generates a falling edge and stops the timer and the counter value is associated to the specific sensor. After each measurement, the microcontroller sends the measured data to the transmitter, which uses an ON–OFF key (OOK) modulation. These data are a packet of 21 bits; one bit identifies the start of transmission, four identify the sensor, and 16 bits encode the timer value. In addition, the timers are reset, the capacitor is uncharged and the peripherals are reinitialized. After that, another sensor is selected for the measurement and the corresponding pin of the microcontroller is enabled as an output with high value, whereas the pins connected to the other sensors become inputs (this does not affect the measurement).

In Fig. 3(a), an image of the different parts composing the system is shown. The sensorized glove is connected to the

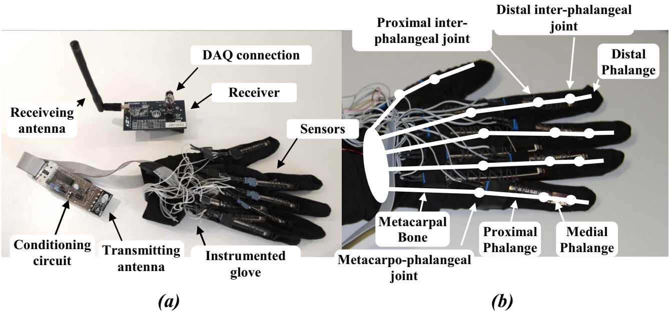


Fig. 3. (a) Image of the realized device and (b) sensors positioning.

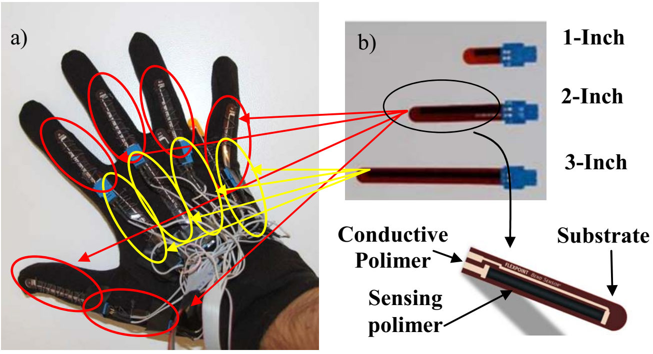


Fig. 4. Adopted bent sensors and positions. (a) Image of the sensorized glove and (b) adopted bent sensors.

conditioning circuit using a flat cable. The data are transmitted through a flat antenna to the receiving module, which can be connected to a data acquisition card (DAQ). Fig. 3(b) shows an image of the sensorized glove with a superimposed scheme of the bones and joints of a human hand. The bent sensors are placed for the measurement of the proximal interphalangeal joints (PIP) and for the metacarpophalangeal joints (MCP).

The sensors are mounted over an elasticized glove made up of 88% polyester and 12% elastane. This way, the freedom of movement and a stable support for the sensors are guaranteed simultaneously. The adopted transducers are thin film sensors, produced by Flexpoint Sensor Systems (FLXT) [21], whose weight is just a few grams. The sensors consist of two layers: 1) the sensing element, consisting of a silver-based material having piezoresistive properties and 2) a flexible substrate composed of polyamide, which protects the sensitive substrate. When the sensor is folded, the piezoresistive material undergoes a microstrain, which increases its electrical resistance because the conductive particles move away from each other, decreasing the conductance of the material and increasing its resistance. The resistance is a function of radius of curvature, if the radius of curvature is smaller the resistance is greater.

Flexpoint fabricates the sensor in three different lengths: 1–3 in Fig. 4(b).

Ten sensors are used, and they are positioned on the two proximal joints of each finger, as shown in Fig. 4(a). The sensors are positioned in the glove hence the finger joints are in the middle of the sensitive area; this way the sensor covers the finger joint area and follows its movement. In addition, each sensor is attached to the glove by stitched elastic; in fact the sensor is sensitive to the pressure at which it is subjected.

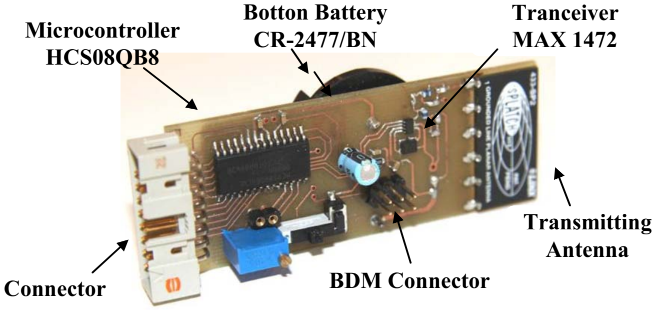


Fig. 5. Image of the conditioning and transmitting electronics.

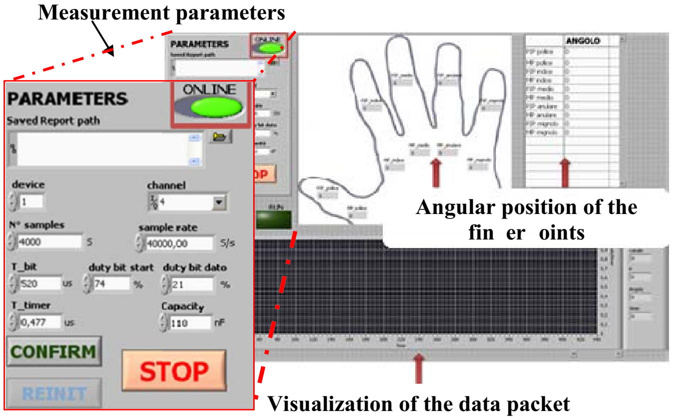
During the stretching hand movements, the elastic seems not to exert significant pressure on the sensitive area. For an average size hand the adopted sensor substrate is polyester (because the sensors on the glove are not subjected to abrasive agents) with these dimensions: for the MCP joints of the index, middle, ring, and little fingers, the mounted sensors are 3-in type and for the other joints, the sensors are 2 in. The choice of each sensor length depends on the hand and joint dimension, and by the available commercial dimensions of the sensors.

Thus, for the hand considered of average size, the 3-in sensors, being longer, were better suited for the MCP joints of the index, middle, ring, and little fingers, whereas the 2-in sensors were better for the other joints.

The microcontroller is the HC9S08QB8, commercialized by Freescale. This device is an 8-bit ultralow power microcontroller. In this case, the internal clock is used with a frequency of 32 kHz. The operating supply voltage is between 1.8 and 3.6 V. The transceiver is MAX1472; it has low-operating supply current depending on the output power and OOK modulation at 433 MHz. The operating supply voltage is between 2.1 and 3.6 V, with few milliampere of current absorption (maximum 9.6 mA, as reported in its datasheet). This device allows using a nonstandard protocol to reduce the complexity of the transmission and requires low power consumption (few megawatt) with respect to the others, which implement complex standard protocol like Bluetooth; the adopted unidirectional transmission is not encrypted and is asynchronous. Authentication and error detection are not implemented as well. The antenna is a planar antenna ANT-433-S produced by Lynx Technologies requiring little space, in fact, its dimensions are 28 × 13.72 × 1.57 cm. The receiver is the evaluation board 4312-DKEB1 of Silicon Labs. Its baud rate is 10 kbps and is suitable for a Sub-Miniature version A antenna. The sensors are connected across I/O pin and an analog-comparator input. When one sensor is supplied, I/O input connected to it becomes high and the other sensor pins are inputs.

The battery is the Panasonic CR-2477/BN, its characteristics are 3 V, 1000 mAh, and dimensions 24.5 × 24.5 × 7.7 mm, with 10.5 g of weight. It guarantees large autonomy as well. An image of the conditioning circuit is shown in Fig. 5. Its dimensions are 3 × 7.5 × 2 cm. The whole system weighs only 80 g.

The graphic user interface for the reading of the portable-system data is shown in Fig. 6. This program [called virtual



Saved Report path

device 1

channel 4

N° samples 4000 S

sample rate 40000,00 S/s

T_bit 520 us

duty bit start 74 %

duty bit dato 21 %

T_timer 0,477 us

Capacity 110 nF

Fig. 6. Image of the LabVIEW interface.

instruments (VI)] is implemented in LabVIEW environment and is executed on the remote PC. In the top-left panel, the user can set transmission parameters and sensor-calibration curves. Once the parameters are confirmed, the signal acquisition starts and the extent of each joint appears in the list on the upper right. In the interface, there is an image where the hand is represented with the indicators of the angular position joints.

An experimental setup was designed to calibrate the sensors. In this phase, the interface gives the information of the sensor resistance, whereas an optical system, described in Section III, measures the finger movements and calculates the joint angles. The angle measurement, obtained by the optical system, and the resistance values, from the transduction system, are reported in a graph and the curve obtained is mathematically fitted, finding the calibration curve, as reported in Section IV. This operation is repeated for all the finger joints.

After this procedure, for the validation of the portable system, a measurement session is executed. The calibration curve is loaded on the LabVIEW VI to convert the resistance measured by the conditioning circuit in an angular position relative to the extension of the joints. The angular positions of each finger joint obtained by the optical system and by the LabVIEW VI are compared, as shown in Fig. 13.

III. EXPERIMENTAL SYSTEM

In this section, the experimental system (Fig. 7) used to calibrate the sensors and test the conditioning circuit is shown.

The sensorized glove is worn by a person and the conditioning circuit is connected to the glove and fed using the battery. The multimeter used for measuring the power supply and the resistance of the sensors is the model of Hewlett–Packard HP34401. The used oscilloscope is TDS 1001B with a bandwidth of 40 MHz and a frequency acquisition of maximum 500 MS/s. The receiver is connected to a DAQ card (6024E) and a LabVIEW program is developed.

The function of the PC is to convert the received signal from the transmitter into angular information associated with the correct channel and displays it on the screen. During the calibration phase, it is important to record the resistance measure of the sensors, obtained by the transduction system.

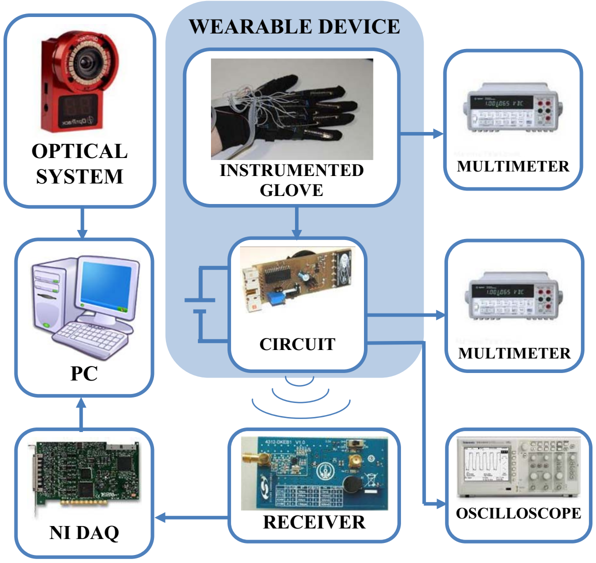


Fig. 7. Block diagram of the adopted experimental system.

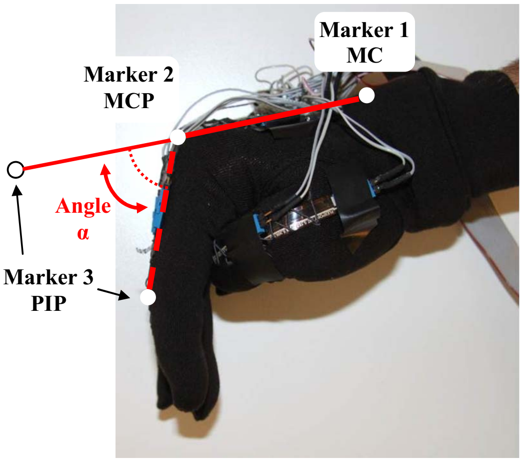


Fig. 8. Marker positions.

The optical system adopted is commercialized by OptiTrack. It is composed by three cameras (V100:R2) with a resolution of 640 × 480 video graphics array and a submillimeter accuracy. All the cameras are connected with an USB to a PC. The software adopted for the optical system calibration and image analysis are Arena commercialized by OptiTrack. The cameras are located at 60° from one another over three tripods to properly track the motion of the markers on the patient's back. An example for the measure of the position of a single joint with the optical system is shown in Fig. 8: three optical markers are placed: 1) on the PIP; 2) on the MCP; and 3) on the metacarpal bone. The two segments formed by the three points are monitored and the rotation of one segment with respect to the other is calculated. The markers are reflective and with a diameter of 7/16.

IV. EXPERIMENTAL RESULTS

In this section, the experimental results are presented. One of the challenges of this paper is to have a long working time obtained by reducing power consumption. To measure

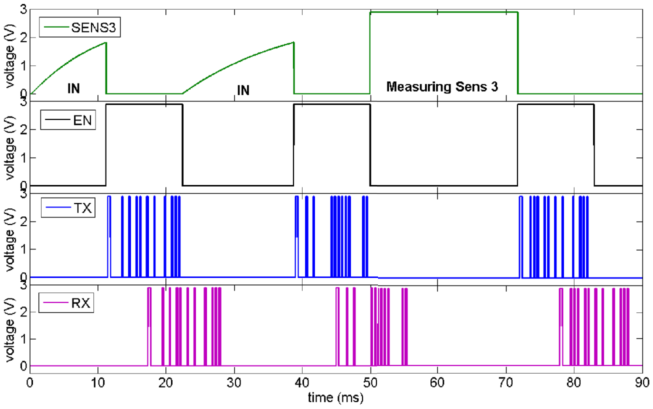


Fig. 9. Transmission and measuring signals.

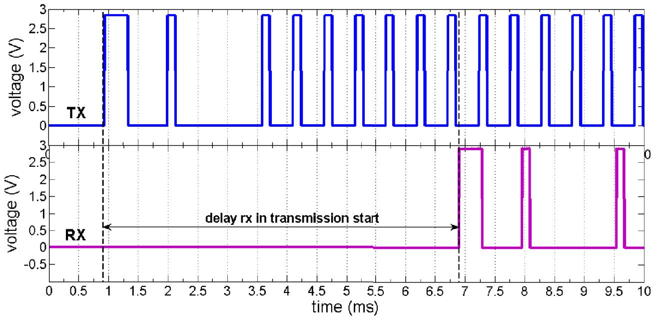


Fig. 10. Transmitting (TX) and receiving (RX) signals.

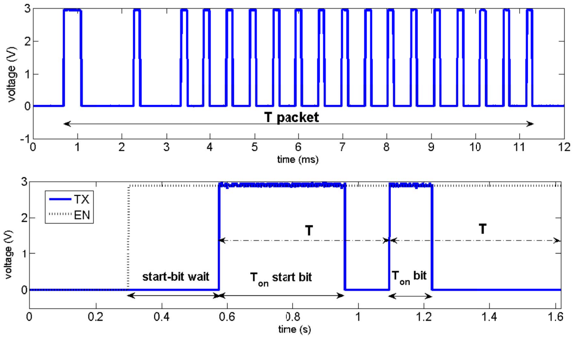


Fig. 11. Packet data timing (above) and time of the start bit of the transmitting signal (below).

supply voltage range and power consumption, the battery is replaced with a variable voltage generator and the multimeter HP34410 is connected in series to measure the device current consumption. The minimum voltage supply under that the system does not work is 1.9 V, whereas the maximum current request is 3.6 mA.

Experimentally, keeping active the device powered by the battery, the working time exceeds a week.

Three reference resistors (100 kΩ, 150 kΩ and 200 kΩ), used to emulate the sensors, are used to validate the conditioning and transmitting electronics. In Fig. 9, a measure example is reported: the green line (Sens3) is the supply voltage of a resistor (in this case that with 200 kΩ of resistance), the black line (EN) is the enable signal of transmission, the blue (TX) is the transmission data output to the transmitter, whereas the magenta (RX) is the received data.

TABLE I

TIME MEASURES OF DATA PACKET IN TRANSMISSION AND IN RECEPTION TO VALIDATE THE SYSTEM

DESCRIPTION	**TIME**
start-bit wait	276 μs
T	520 μs
T_{on} start bit	388 ± 6 μs
T_{on} bit	128 ± 6 μs
T packet	10.45 ms
Delay rx in transmission start	5.920 ms

TABLE II

RESISTANCE VALUES OF 10 RESISTORS MEASURED WITH THE PROPOSED CONDITIONING CIRCUIT REPEATED FIVE TIMES EACH

		Test1	**Test2**	**Test3**	**Test4**	**Test5**
Sens	R_{rif}[Ω]	R[Ω]	R[Ω]	R[Ω]	R[Ω]	R[Ω]
0	181860	181592	181597	181605	181597	181541
1	150605	150253	150228	150197	150180	150154
2	119860	118729	118725	118733	118725	118707
3	55980	55783	55775	55766	55745	55736
4	47069	46815	46815	46823	46810	46819
5	22065	21900	21905	21909	21900	21905
6	38840	38600	38592	38600	38596	38587
7	32996	32779	32779	32771	32771	32762
8	6793	6744	6744	6744	6744	6744
9	26926	26730	26730	26738	26721	26725

In Fig. 10, the start of the transmitted and the received data packet are reported; there is a delay between the two signals of 5.92 ms. An example of data packet and its focus at the beginning of transmission are shown (Fig. 11) to define the nomenclature in Table I.

In Table I, the measures relative to the data packet are reported. At the transmission start, the enable signal becomes high, whereas the data packet is transmitted after start-bit wait. Repeating the time measures of T_{ON} start bit and T_{ON} bit, they have not fixed values, due to the resolution of counter which manages the transmission.

While operating, it was verified that there were not lost data bit and the VI decodes received data in the correct timer value. Using the conditioning circuit and resistors with measured resistance value (reference), the correct capacitance value of the capacitor was calculated (108.3 nF) and it was verified that was similar to its nominal value of 110 nF, permitting a maximum measurement time of 20 ms.

Finally, the resistance of 10 different resistors was measured with the multimeter HP34401. The resistors were connected to the conditioning circuit and the resistance measures were repeated five times. The results are reported in Table II. Comparing the measured values, the system commits a percentage error $<0.7\%$ relative to each reference.

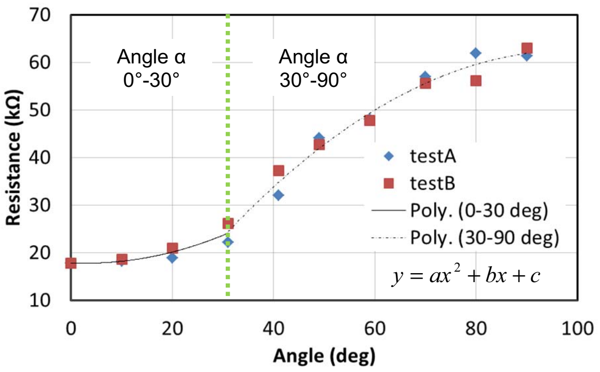


Fig. 12. Measurement data obtained wearing the sensorized glove and using the optical system for angle measurement.

Bending tests of the fingers, consisting of the bending of every single joint of 0°–90°, were executed wearing the sensorized glove and using the optical system reported in the experimental system paragraph. In these tests, to simplify the amount of measurement data, only one flex sensor at a time was considered; however, identical procedures were made for all sensors of the whole hand. In particular, the experimental data shown in Fig. 12 regards the sensor on MCP joint of index, the behavior is similar for the other sensors.

Thus, the optical system is simplified, because only three markers are necessary (Fig. 8). The bend data acquired by the optical system and by the sensorized glove system were collected. This test was repeated two times. Fitting the measures with polynomial approximation, the calibration curve is approximated with two polynomial curves of the second order, one for angles >30° and one for angles under 30°, as shown in Fig. 12. The obtained polynomial coefficients (a, b, and c) for the 0°–30° curve are +7.9, −45.3, and 17 833, and for the 30°–90° are −8.2, +1628, and 18 156, respectively. The same procedure is repeated for the other joints and the coefficients are different. This type of calibration is required for the first time. The calibration curves are inverted and loaded in the VI for the conversion of the resistance measure regarding information of the angle.

The calculated coefficients, describing the calibration curve of each sensor, are included in the LabVIEW program for the conversion resistance angle. Furthermore, bending tests of the fingers were performed for four consecutive times to evaluate the performance. In Fig. 13, the experimental results obtained with the sensorized glove are reported. The average values are shown with dots, whereas the dashes represent the limits of the confidence interval of 95.4%. The graph shows the best fit line as well. Therefore, the measurements for the characterization and calibration of the system composed of the sensorized glove and the conditioning electronics have a good agreement with what was previously designed.

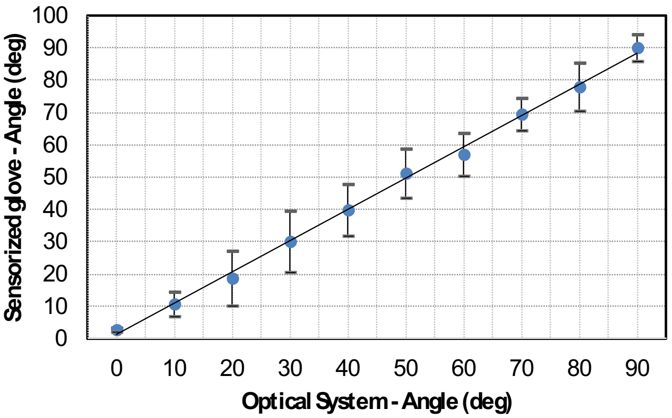


Fig. 13. Comparison of the data obtained with the sensorized glove respect those with the optical system.

V. CONCLUSION

In this paper, a new device to measure the position of the fingers is proposed. With respect to commercial solutions, this system reduces power consumption. The battery lifetime covers over a week. Furthermore, the proposed glove is lighter than commercial devices in fact, it weighs only 80 g. The use of flex resistive sensors and of the OOK modulation for the transmission, instead of Bluetooth standards, for example, makes the device simple, light, portable low power, and low cost. The experimental results acquired with the sensorized glove show a good correspondence with the values obtained with an optical system used as a reference. For new users, the system must be calibrated, as for all the types of sensorized gloves. In the future, the focus will be paid on the experimental validation arranging different tests on different subjects.

REFERENCES

[1] R. A. Cooper, B. E. Dicianno, B. Brewer, E. LoPresti, D. Ding, R. S. G. Grindle, and H. Wang, "A perspective on intelligent devices and environments in medical rehabilitation," *Med. Eng. Phys.*, vol. 30, no. 10, pp. 1387–1398, Dec. 2008.

[2] G. A. Donnan, M. F. M. Macleod, and S. M. Davis, "Stroke," *Lancet*, vol. 371, no. 3, pp. 1612–23, 2008.

[3] C. T. Freeman, A.-M. Hughes, J. H. Burridge, P. H. Chappel, P. L. Lewis, and E. Rogers, "A robotic workstation for stroke rehabilitation of the upper extremity using FES," *Med. Eng. Phys.*, vol. 31, no. 3, pp. 364–373, Apr. 2009.

[4] H. S. Lo and S. Q. Xie, "Exoskeleton robots for upper-limb rehabilitation: State of the art and future prospects," *Med. Eng. Phys.*, vol. 34, no. 3, pp. 364–373, Apr. 2012.

[5] E. Akdogan and M. A. Adli, "The design and control of a therapeutic exercise robot for lower limb rehabilitation: Physiotherabot," *Mechatronics*, vol. 21, no. 3, pp. 509–522, Apr. 2011.

[6] D. L. Gardner, "The power glove," *Des. News*, vol. 45, pp. 63–68, Dec. 1989

[7] L. Dipietro, A. M. Sabatini, and P. Dario, "A survey of glove-based systems and their applications," *IEEE Trans. Syst., Man Cybern. Part C, Appl. Rev.*, vol. 4, no. 4, pp. 461–482, Apr. 2008.

[8] (2009). *CyberGlove II Wireless Glove* [Online]. Available: http://www.cyberglovesystems.com/

[9] A. Alamri, M. Eid, R. Iglesias, S. Shirmohammadi, and A. El Saddik, "Haptic virtual rehabilitation exercises for poststroke diagnosis," *IEEE Trans. Instrum. Meas.*, vol. 57, no. 9, pp. 1876–1884, Sep. 2008.

[10] C. Oz and M. C. Leu, "Linguistic properties based on american sign language isolated word recognition with artificial neural networks using a sensory glove and motion tracker," *Neurocomputing*, vol. 70, nos. 16–18, pp. 2891–2901, Oct. 2007.

[11] J. Zhou, F. Malric, and S. Shirmohammadi, "A new hand-measurement method to simplify calibration in CyberGlove-based virtual rehabilitation," *IEEE Trans. Instrum. Meas.*, vol. 59, no. 10, pp. 2496–2504, Oct. 2010.

[12] D. J. Sturman and D. Zeltzer, "A survey of glove-based input," *IEEE Comput. Graph. Appl.*, vol. 14, no. 1, pp. 30–39, Jan. 1994.

[13] (2011). *Human Glove Reproducing Hand Posture* [Online]. Available: http://www.hmw.it/hmw_i.html

[14] N. Karlsson, B. Karlsson, and P. Wide, "A glove equipped with finger flexion sensors as a command generator used in a fuzzy control system," *IEEE Trans. Instrum. Meas.*, vol. 47, no. 5, pp. 1330–1334, Oct. 1998.

[15] K. N. Tarchanidis and J. N. Lygouras, "Data glove with a force sensor," *IEEE Trans. Instrum. Meas.*, vol. 52, no. 3, pp. 984–989, Jun. 2003.

[16] M. Nishiyama and K. Watanabe, "Wearable sensing glove with embedded hetero-core fiber-optic nerves for unconstrained hand motion capture," *IEEE Trans. Instrum. Meas.*, vol. 58, no. 12, pp. 3995–4000, Dec. 2009.

[17] Y. Su, C. R. Allen, D. Geng, D. Burn, U. Brechany, G. D. Bell, and R. Rowland, "3-D motion system ('data-gloves'): Application for parkinson's disease," *IEEE Trans. Instrum. Meas.*, vol. 52, no. 3, pp. 662–674, Jun. 2003.

[18] Y. Su, M. H. Fisher, A. Wolczowski, G. D. Bell, D. J. Burn, and R. X. Gao, "Towards an EMG-controlled prosthetic hand using a 3-D electromagnetic positioning system," *IEEE Trans. Instrum. Meas.*, vol. 56, no. 1, pp. 178–186, Feb. 2007.

[19] L. K. Simone and D. G. Kamper, "Design considerations for a wearable monitor to measure finger posture," *J. Neuro Eng. Rehabil.*, vol. 2, no. 1, p. 5, 2005.

[20] R. Gentner and J. Classen, "Development and evaluation of a low-cost sensor glove for assessment of human finger movements in neurophysiological settings," *J. Neurosci. Methods*, vol. 178, no. 1, pp. 138–147, 2009.

[21] (1997). *Bend Sensors Technology Mechanical Application Design Guide* [Online]. Available: http://www.flexpoint.com/

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