Long Term Measurement of Human Joint Movements for Health Care and Rehabilitation Purposes

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***Abstract*— This paper presents a novel human joint motion recording method, The recorded data are sent to the receiver, which is placed in the close proximity or in the same room with the patient, via a wireless short-range communications system that guarantees 3 days of battery life. This method exploits commercially available bend sensors to convert mechanical human joint movements into electric signals which are then acquired, pre-processed, wireless transmitted and post-processed. We propose a novel way of sensor's application, underlying advantages and drawbacks which could be drastically reduced by electronic circuitry anyway. The network configuration and the specific air interface are chosen to satisfy system requirements in terms of data rates, battery autonomy, and mobility.**

***Index Terms*— Biosensors, human joint, WBAN, Virtual reality.**

I. Introduction

For an efficient rehabilitation treatment is mandatory to rely on long term human movement values (regarding finger joints, wrist, knee joint, etc.) and/or physiological responses (heart rate, body pressure, etc.), continuously recorded during every day life, hopefully in home environment. As an example, from a medical point of view, it would be very useful to count on measured values of movements regarding sit or supine body posture on the chair or on the bed. Nevertheless, the state-of-the-art provides very few reliable systems that are enough inexpensive to be adoptable in a wide range of cases and that, at the same time, present the characteristics of; portability, so to record data also outside of clinics and hospitals; automaticity so to overcome the need of an operator; capability of providing continuous stream of data, and hence, effectively useful for researchers and operators in rehabilitation purposes.

II. Sensor System

A. Bend Sensors

In order to measure human motion, several systems can be developed based on different physical principles, such as optic [1]-[3], magnetic [4], pneumatic [5], mechanic [6], electric [7], and so on. All of them have advantages and disadvantages w.r.t. others. In this paper we consider the use of bend sensors because our aim was to realize long term measures taking into basic consideration the realization costs, and one bend sensor's commercial cost can be as low as few dollars. These sensors act as analog resistors since are made of carbon resistive elements printed on a thin flexible substrate. When the substrate is bent towards the printed side (outward bend) the resistive part increases its resistance value. With a backwards (inward) bend commercial sensors usually give no meaningful results since a really poor decreasing resistance variation is reported. In any case this latter undesirable (for some applications) result can be avoided if devices with piezoresistive sensor elements are smartly developed and adopted.

Fig. 1 shows two different and common bend sensor behavior for commercial devices. It can be noticed that one of the curve reports a common logarithmic behavior while the other a sort of step wise linear performance. With respect to the way we utilized the bend sensors (following described), it makes sense to take advantages from a step wise linear behavior. We recorded this from commercial sensors provided by Image SI, thanks to measures performed by an home-made ad-hoc set-up. Results are reported in Fig. 2 including the error as standard deviation.

The most important advantages we experienced for bend sensor are: low cost, so that a large number of subjects can adopt them and even disposable devices can be realized; lightweight, so that wearable devices can be equipped; versatility, since the same sensors can be applied for recording almost all the human movements; resistance variation value, which can be even hundreds times with bent sensor with respect to flat sensor position.

On the other side disadvantages are: aging behavior as the performance degrades within few months and no relevant

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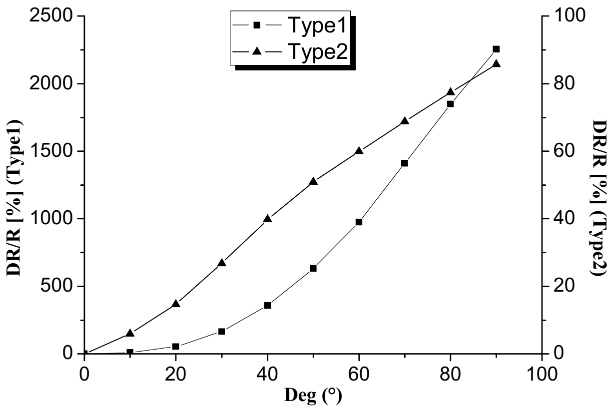


Fig. 1: typical resistance variation vs. bending angle for commercial sensors

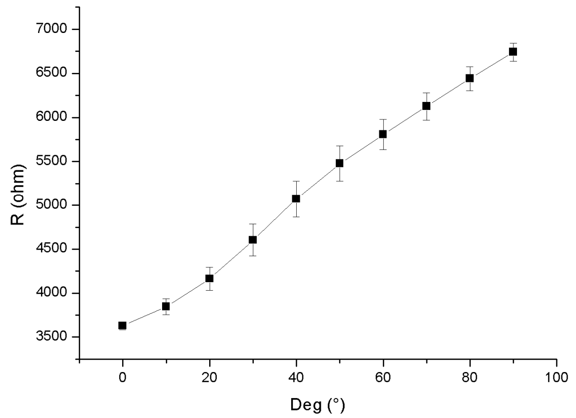


Fig. 2: values of resistance variation vs bending angle home-made measured

works can be found in literature so far to deal specifically with this aspect; precision, since the error on a measured angle is often above one degree; recovery time, since most bend sensors seem to take some time to revert back to the initial unbent resistance value; time-varying creep, since some sensors exhibit this unwanted behavior when held for a period of time in a fixed bent position [7]; donning way, since friction with skin can prevent the sensor from returning to the exact initial position so leading to drift in measurements; uninvestigated sensitivity to temperature changes.

B. Bend Sensor Application

In this paper we focus attention on a method to continuously record joint movements relative to human fingers, but taking into account how the same methodology is suitable for other human joints too. We adopted the previously discussed bend sensors taking into account both advantages than potential disadvantages. To measure all the joint finger movements of a human hand it is convenient to realize a sort of instrumented glove which is capable of recording each degree of freedom of fingers taking advantage of dedicated bend sensors. So the device consists of a plastic glove as support of such sensors mounted upon each finger joint to measure flexion / extension movements and between adjacent fingers to measure the adduction / abduction movements.

The novel way we decided to stick the sensors on the glove is taped them at both ends assuming a bump figure with flat finger (Arcuate 2 end Taped, A2T) and becoming perfectly adherent when the finger is bent, as schematically reported in fig. 3, where θ_i represents the measured angle values of the finger's flexion (fig. 3a,b) and abduction positions (fig. 3c,d). So, when user flexed his fingers the gloves stretched, meaning that we could not simply glue the sensor onto the gloves since the tension created when flexed would most definitely snap the sensor or unglue it. Of course, as a drawback, not all the resistance variation vs. bend angle was exploited but this limitation was drastically reduced thanks to the electronic surrounding circuitry.

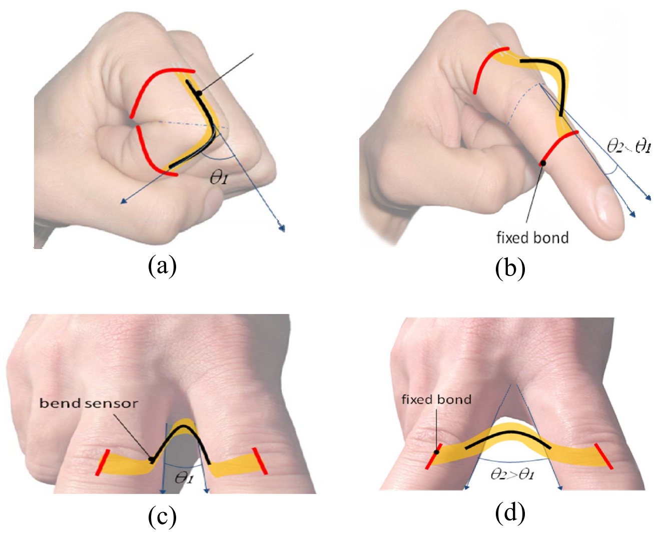


Fig. 3: A2T configuration

The sensors, provided by Image SI, are 10 cm long and present a nominal electrical resistance of about 3.5kOhm when unstressed. Sensors were cut with a length dependent both on finger joint (distal- proximal- metacarpo- phalangeal) and on the movement (flex-extension, addu-abduction) to be recorded. Sensor's contact were realized by a silver flexible paste and clamped by metallic pins while sensor's tip and bottom adhesions were obtained by an epoxy glue.

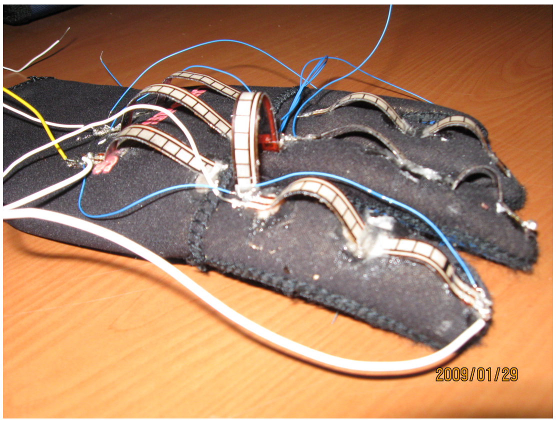
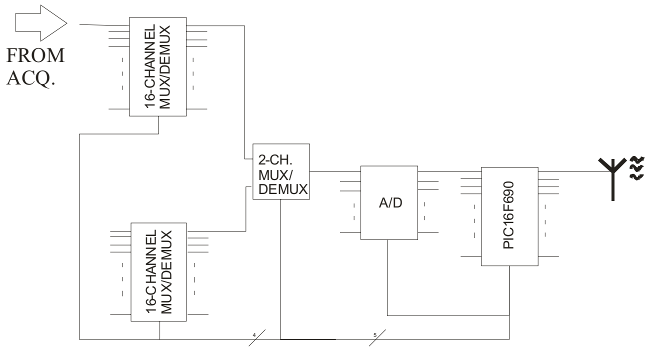


Fig. 4 : realized instrumented glove.

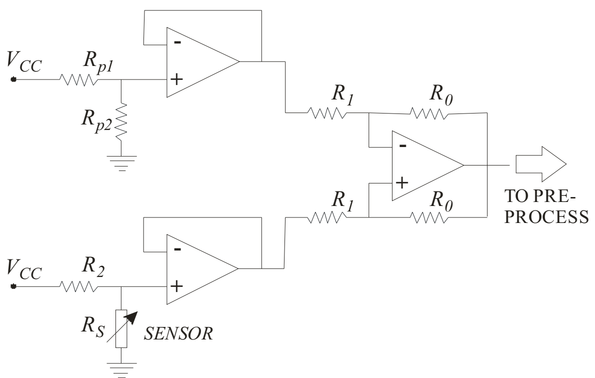


(b)

Fig. 5 : circuitry dedicated to (a) acquisition and (b) pre-process data signals.

C. *Bend Sensor's Data Acquisition*

The number of adopted bend sensors was 19 in order to record an equal numbers of finger's degree of freedom (DOF). Since the limited sensor's range of motion due to the proposed A2T configuration, the resultant resistance variation is between 5.2kOhm (flat joint) and 7.2kOhm (maximum bent joint). The sensors were inserted into a voltage divider configuration, so to obtain a corresponding voltage variation range within 2.3 and 2.6 V, followed by a buffer stage. Since we needed to furnish the measured data to an A/D converter, if the voltage variation range remained so limited, we couldn't exploit all the converter capabilities, so op amps in differential amplifier configurations were utilized as pointed out by fig. 5. In such a manner the previous minimum (2.3V) and maximum (2.6V) values were drove down to 0V and up to 5V respectively, taking advantage of the A/D converter capabilities. Signals were then feed into two 16 bit TI CD4067B multiplexers, followed by a Microchip MCP3202 A/D converter. A Microchip PIC16F690 microcontroller, receiving data from the A/D converter via SPI protocol, provided to address the multiplexers in order to determine which sensor's response accept and furnished data to a personal computer via RS232 interface.



(a)

III. Wireless Network

To implement a wearable and comfortable instrumented glove that can provide a continuous stream of data for several hours during ordinary every day life, it is mandatory to have a wireless connection between the sensors of the glove and a receiver apparatus that is located in the close proximity or in the same room of the person who wear the glove.

The wireless system was required to assure at least 24 hours of battery autonomy. Therefore, short-range and low power consumption transmission system must be considered in the design of the wireless connection.

Table 1 shows the main commercial products that are available for the deployment of a Wireless Personal Area Network, which means short range (till about 10 meters) and low consumption ad-hoc wireless network in the Industrial Scientific Medical (ISM) band for data transmission [9], [10]. In the same Table I, we have also included a new air interface that is currently proposed as a solution for Wireless Body Area Networks (WBANs) and it is not commercially available. This air interface is based on the combination of Frequency Modulation Ultra WideBand (FM-UWB) at the physical layer and IEEE 802.15.4 at the medium access control layer [11].

In the following, we derive the main requirements (data rates and energy consumption) that will drive the choice of the air interface for the wireless connection and also the network configuration and topology that are more appropriate for the specific application.

First of all, let us recall some of the main characteristics of the prototype of glove that will be implemented:

- The glove is monitored by using a minimum of 19 sensors.
- Because of the natural constraints on the movement of the fingers, a number of N_1=5 sensors per glove (large range sensors) can provide a maximum angle measurement of α_1=120^0, while a number of N_2=14 sensors per glove (small range sensors) can provide a maximum angle measurement of α_2=90^0. Furthermore, the maximum rate of movement of a hand (from opening to closure) is R_{max}=6 Hz.

- The measure of the angle of each sensor must be converted to digital format with a maximum quantization error which we imposed of at most $\alpha_R=1^0$.

We optimized the design of the wireless system separately for the large range and small range sensors.

Taking into account the requirements on the quantization error, the analog signal provided by the large range sensors must be converted to a digital data expressed with n_1 bits, while the analog signal provided by the small range sensors must be converted to a digital data expressed with n_2 bits, where:

$$n_1=\left\lceil \log_2\frac{\alpha_1}{\alpha_R}\right\rceil=7, \qquad n_2=\left\lceil \log_2\frac{\alpha_2}{\alpha_R}\right\rceil=7 \qquad (1)$$

The sampling rate R_1 of the data provided by each large range sensor and the sampling rate R_2 of the data provided by each small range sensor, can be computed on the basis of the maximum rate of movement of a hand:

$$R_1=\frac{\alpha_1}{\alpha_R}R_{\max}=720\text{ Hz}, \qquad R_2=\frac{\alpha_2}{\alpha_R}R_{\max}=540\text{ Hz} \qquad (2)$$

and, hence, the data rate B_1 provided by each large range sensor and the data rate B_2 provided by each small range sensor, are given by:

$$B_1=R_1n_1=5{,}040\text{ bit/s}, \qquad B_2=R_2n_2=3{,}780\text{ bit/s} \qquad (3)$$

The aggregated data rate B_{tot} provided by one glove and which must be delivered to a server via wireless links was:

$$B_{tot}=B_1N_1+B_2N_2=78{,}120\text{ bit/s} \qquad (4)$$

It is worth noting that this data rate was computed for a single glove. To choose the proper topology of the sensor networks, we have to recall that the final objective of the prototype was to monitor simultaneously two or more gloves in the same area. The wireless network should only support the transmission from the sensors to the monitoring server (uplinks) and there was no need for data exchange between sensors. Therefore, the chosen air interface should only support a star topology. Furthermore, the allocation of the channel resources was very easy since the service request from each sensor is known a priori and was constant during the provision of the service.

Table 1: characteristics of current standards for WPANs.

wireless technology	ZigBee	Bluetooth	WiMedia	FM-UWB/802.15.4
topology	star, peer-	star (piconet), interconnected	peer-to-peer (or	star, peer-to-peer (or mesh)
	to-peer (or mesh)	stars (scatternet)	mesh)	
maximum number of nodes	255	8 (in a piconet)		255
maximum link data rate	250 kbps	723 kbps	480 Mbps	100 kbps
Energy consumption	very low	low	medium	very low

Taking into account the previous discussion about the requirements of the wireless network in terms of energy consumption, topology, data rate and number of nodes, we selected the ZigBee network as the most suitable choice. In fact, ZigBee can effectively satisfy the requirements on the data rate and the maximum number of nodes while assuring a very low energy consumption.

By using the information provided by the datasheet of the Chipcon CC2420/ZigBee, we can compute the power P_d dissipated by a single Tx/Rx device, that is:

$$P_d=V_oI_t=3.6\times17.4\times10^{-3}=0.062\text{ W} \qquad (5)$$

where I_t is the current consumption in the Tx mode and V_o is the operating voltage. Assuming the utilisation of a battery PP3 (9V) battery with a capacity C_b of 500 mAh (equivalent to 16200 J) and a constant discharge, the maximum duration T_l of the battery charge is:

$$T_l=C_b/P_d=16200/0.062=72\text{ h} \qquad (6)$$

Therefore, assuming a continuous monitoring, the expected battery lifetime is 3 days, which can be considered a suitable value for our purposes.

IV. VIRTUAL REALITY

Acquired, conditioned and wireless transmitted data can finally be recorded for a real-time and/or for a post process implementation of virtual reality. To this aim we developed a computer graphic scenario which accurately replicates every DOFs in finger movements. As an example fig. 6 represents index finger closing gesture. The graphical part was based on Blender which is an open source, cross platform suite of tools for 3D creation. A pointed mesh represents the hand exoskeleton and all the movements are performed through a mesh accurate disposition. The obtained graphical result shows a very good likeness with a real human hand. Finger movements were performed via C++ software language and the program interface presents standard control buttons: save/open, play/pause, zoom in/out. Error or warning messages occur in the case of senseless received data.

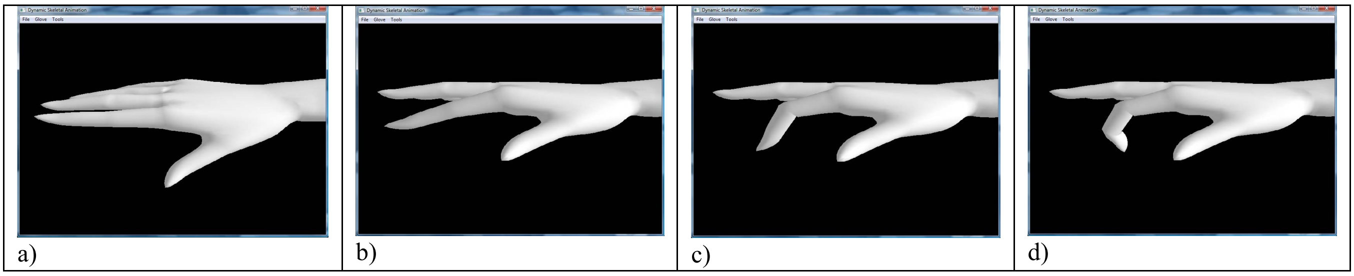


Fig. 6 index finger gesture from a) to d)

V. Conclusion

An instrumented glove has been presented. Bend sensors have been adopted and circuitry of pre-post processing electric signals has been designed. Recorded data were wireless transmitted to one receiver (computer) in the close proximity or in the same roon of the patient by using a short-range wireless system based on ZigBee technology. An approximate evaluation of the power consumption needed to transmit those data shows that this technology guarantees 3 days of battery life, which is suitable for the considered application. Virtual environment was realized with 3D model of the human hand, which is easily changeable, reconfigurable and adaptable to different kind of data inputs.

Rehabilitation treatment, tremor care, functional use of body segment, disabilities, deviation in joint movement patterns would greatly take advantage of this system.

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