Wireless Data Glove System developed for HMI

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***Abstract*—Human Machine Interfaces support users to interact or simply control any kind of devices founded on machinery basis. Very simple and common interfaces are represented by the mouse and keyboard tools by which a user interact with the personal computer "machine". It is however evident how these tools can be particularly "limited" since they "act" only in a 2D superficial environment and cannot provide an *immersive experience*. So in the latter years new kind of interfaces have been investigated in order to expand the user capabilities in a 3D space, then increasing the realism degree too. In this paper we deal with a new kind of these interfaces. In fact we developed a sensorized glove capable to measure all human hand Degree of Freedom (DoF), "translating" them into commands for personal computers.**

Keywords - Data Glove; Human Machine Interface

I. INTRODUCTION

Bend sensors have been endowed in a Lycra based glove so to furnish electrical signals when flexed by user hand. The overall system of sensors, glove, electronic interfaces and wireless part, form the so called data glove, which we referred with the term of HITEG-Glove since our group name (Health Involved Technical Engineering Group). In addition a virtual environment has been created so to give to the user a useful real-time visual feedback via ad-hoc avatar to his/her actions.

The measured movements of user hand furnish electrical signals that we converted into pc actions, such as movements of cursor in a virtual 3D space, open/close applications, play virtual instruments or even built or assemble virtual objects (see Fig. 1). For the latter case the hand avatar reproduce exactly all the user hand movements (flex-extension, abdu-adduction of finger movements, wrist angular positions).

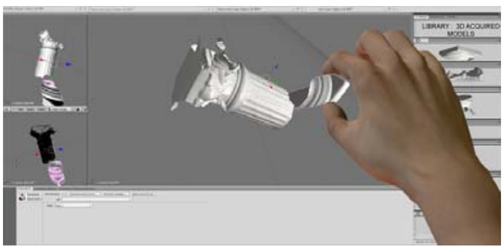

Figure 1. Hand movements recorded by the data glove are real-time reproduced via avatar. 3D interaction to assemble 3D virtual objects.

This paper describes the presented overall system in all its single parts, i.e. the sensors characterization and application, the designed and developed electronic circuitry for signal conditioning, the wireless adopted protocol and finally the realized very realistic avatar representation of recorded user movements.

II. SENSOR CHARACTERIZATION AND HITEG GLOVE

The HITEG-Glove here presented is mostly based on bend sensors capable of measuring bending angles thanks to the piezoresistive effect by means of which, to each angle they are submitted to, it corresponds a different resistance value.

We measured performances of several bend sensors, manufactured by Flexpoint Sensor System Inc. and Image S.I., different in lenghtness and encapsulation materials.

Sensors resistance variation vs. bending angle is measured thanks to an home-made set-up based on hinges where the sensors lay on, and a stepper motor which provides the rotation of one wing of the hinge (with respect to the other which is fix constrained) simulating a human finger joint rotation (Fig. 1).

The adopted motor, necessary for the movement imposed to the rotating wing, was a Trinamic PD-109 two phase hybrid stepper, microstepping optimized. It was provided with a Trinamic Motion Control Language (TMCL) which consists of an instruction set of motion control commands. On the basis of a host computer PC based software development environment, the TMCL-IDE, motion control commands were given to the motor. A rigid frame provides the necessary stability to the system. The motor is fixed on an optical bench by angular Newport EQ80-E shores. The motor motion was transmitted to the hinge's axis thanks to an universal rigid joint in order to obtain an excellent stability. For testing a sample, an hinge's wing was fixed on the structure, while the other wing was free to be moved by the motor.

With the described measurement set-up, each sensor can be characterized in a -90° to 180° (from inward to outward) range for programmable step value of bending angle, number of measurement repetitions and mechanical actuator speed. At known angles, the resistance values of the sensors are measured by an Agilent 34405A multimeter.

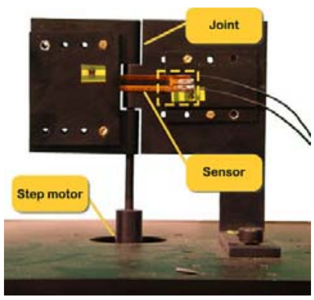

Figure 2. Experimental set-up for macroscopic bending measurements: it is designed to simulate the human finger joints kinematics.

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The investigated piezoelectric sensors have a large measurement range for outward bendings from 0° to 120°, and correspondingly the resistance normally changes from 10 to 170 kΩ. The hysteresis they manifest is really negligible and repeatability is exceptional. Among all the performed measurements, some relevant results are showed in Fig. 3. It reports measurement results, resistance mean values and standard deviations, on 6 different 2 inches length polyimmide encapsulated Flexpoint sample sensors: each sensor is characterized repeating measurements 10 times, varying bending angle from 0° to 120° and return.

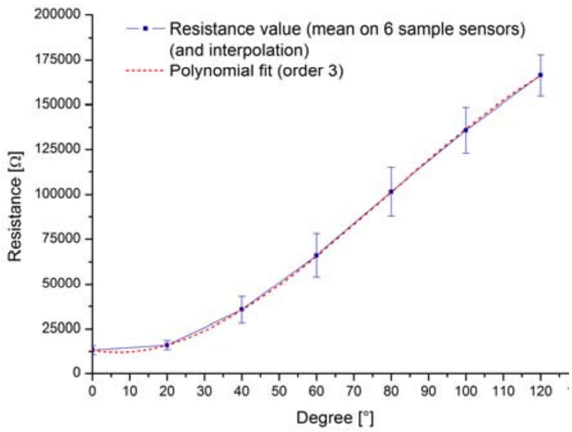

Figure 3. Resistance variation VS bending angle: mean on 6 sample sensors and standard deviation

After the characterization, the sensors are mounted on a Lycra based glove, each corresponding to a single finger joint (see Fig. 4).

Figure 4. HITEG Glove

The resistance variation vs. bending angle characteristic of each sensors was utilized to correctly convert the electric resistance value into the corresponding finger joint flexed angle.

III. Electronic Circuitry

The measured electric signals, coming from the sensors, were then conditioned, recorded and sent to a receiving location for further exploitation.

For the electronic interface and the signal conditioning circuitry it is generally convenient to have:

- a sufficiently large resistance variation for sensors;
- good "robustness" for the circuit, because there is more noise in wearable applications, consequently, direct resistive sensor-to-microcontroller interfaces are not strongly suggested;
- a simplified circuit structure for smaller size;
- an integrated and removable battery;
- a very low power consumption, to get a longer service time in which a continuous monitoring can be applied without battery replacement or recharge;
- comfort to wearers for user activities.

This is why we report here a solution we adopt as convenient for the previous requirements for a data glove system. A novel approach for analog signal conditioning before A/D conversion, which matches the requirements is presented. System configuration, accuracy and resolution have been analyzed in-depth and design rules have been defined.

Experimental results show that this electronic interface exhibits less than 1% error in a large measurement range for strain sensor rotation angle. It also shows a good stability to power supply interference. The interface has been successfully applied to a glove-based measurement system of hand gesture.

The optimized electronic interface for wearable sensors here concerned is based on a differential instrumentation amplifier. Fig. 5 schematizes the proposed electronic interface.

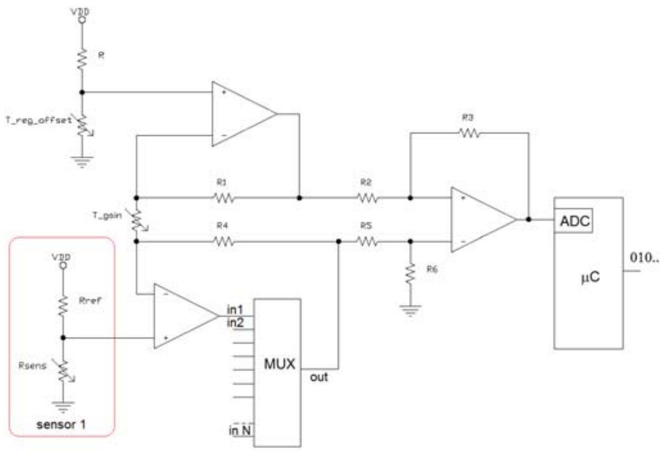

Figure 5. Signal conditioning electronic interface proposed

It consists of a group of voltage dividers for each resistive sensors, so to extract a voltage signal from sensor resistance variation using a first stage input buffer. Subsequently a second stage provides to properly shift/amplify the sensor signals with

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the possibility of finely adjusting both gain and offset level to make the levels of output voltage dividers fit the input range of a PIC microcontroller 12 bits A/D converter. In this way we can measure very little signal variation corresponding to very little joints bending.

Then the microcontroller can send the digital signals in serial form to a general purpose PC for post elaboration, reconverting them to the corresponding bending angles of the joints. Voltage dividers are used because of their simple structures and potential high dynamic measurement ranges they can furnish. In order to minimize the size of the electronic interface, a single conditioning circuit of the signal, which can be used by every sensor implementing a polling routine on a multiplexer, has been reasonably designed. It is important to notice that the voltage signal variation range varies from sensor to sensor; this is because the technological process of factory doesn't produce identical devices (as it results clear by observing the standard deviation reported on the 7 calibration points of the characteristic curve reported in Fig. 3). Another reason is that the maximum bending angle of each sensor depends on the joint it is applied to; for example the sensors of the proximal interphalangeal joints, which perform the maximum bending angle possible (typically 120° in a wholly able subject), react with the largest resistance variation.

Figure 6. Human finger joints

For such reasons it is necessary to choose, in designing the instrumented differential amplifier, a voltage gain (and a level shift) which have to be the best match in order to make the signals of all the sensors fit the input range of a PIC microcontroller 12 bits A/D converter. Considering a single voltage divider (represented in the box left below in fig. 4), a significant issue in the design is how to set R_{ref}.

The single element has the following voltage divider:

$$\frac{V_i}{V_{cc}} = \frac{R_{sens}}{R_{ref} + R_{sens}} \tag{1}$$

So, after a 120° bending:

$$\frac{\Delta V_i}{V_{cc}} = \frac{R_{sens\_max}}{R_{ref} + R_{sens\_max}} - \frac{R_{sens\_min}}{R_{ref} + R_{sens\_min}} \tag{2}$$

where R_{sens_min} corresponds to 0° bending, whereas R_{sens_max} to 120° bending, which is the maximum allowable flexion of a finger joint and ΔV_i to the consistent voltage variation.

In order to maximize the signal sweep for the maximum allowed flexure degrees, the voltage divider resistance R_{ref} can be yield nullifying the corresponding partial derivative:

$$\frac{\partial}{\partial R_{ref}} \frac{\Delta V_i}{V_{cc}} = \frac{R_{sens\_max}}{(R_{ref} + R_{sens\_max})^2} - \frac{R_{sens\_min}}{(R_{ref} + R_{sens\_min})^2} = 0 \tag{3}$$

to obtain:

$$R_{ref\_opt} = \sqrt{R_{sens\_max} R_{sens\_min}} \tag{4}$$

which corresponds to the geometric mean of the extreme sensor resistance values.

If the sensor bending sweep is not always the same, an optimized reference resistor for each sensor has to be chosen.

The normalized voltage signal variation coming from each sensor becomes:

$$\frac{\Delta V_i}{V_{cc}} = \frac{1}{{R_{ref}}/{R_{sens\_max}} + 1} - \frac{1}{{R_{ref}}/{R_{sens\_min}} + 1} \tag{5}$$

$$\frac{\Delta V_i}{V_{cc}} = \frac{1}{\sqrt{{R_{sens\_min}}/{R_{sens\_max}}} + 1} - \frac{1}{\sqrt{{R_{sens\_max}}/{R_{sens\_min}}} + 1} \tag{6}$$

$$\frac{\Delta V_i}{V_{cc}} = \frac{1}{q^{-1} + 1} - \frac{1}{q + 1} = \frac{q - 1}{q + 1} \tag{7}$$

where:

$$q = \sqrt{{R_{sens\_max}}/{R_{sens\_min}}} \tag{8}$$

The equation 7 provides the maximum voltage divider signal variation with the optimized value for $R_{ref\text{-}opt}$.

Furthermore it can be seen that a strain sensor exhibiting the largest sweep in resistance for a given bending angle is required, because $\Delta V_i/V_{cc} \rightarrow 1$ for $q \rightarrow \infty$, even if this sensitivity is smoothed from the root.

This is the reason which led us to prefer in this project the Flexpoint bend sensors (q^2=14) over those from Image (q^2=6), as it is represented in Fig. 7, where the voltage divider sweep is

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plotted against the choice of the reference resistance for different q values.

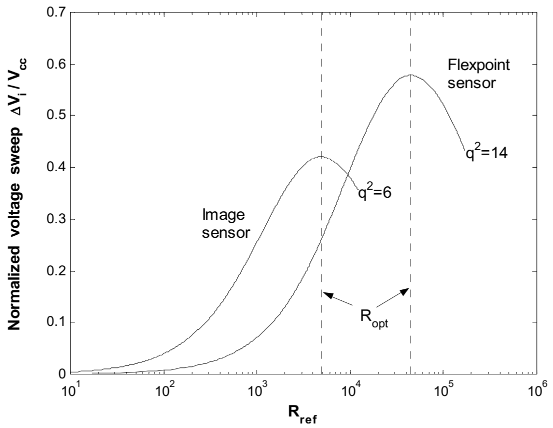

Figure 7. Normalized voltage divider output sweep VS reference resistor value

Further investigation is required to set the appropriate resolution for the A/D converter inside the microcontroller. Naming V_n the noise coming from the signal conditioning circuits and V_{nq} the quantization noise, where:

$$V_{nq} = \frac{1}{\sqrt{12}} \frac{V_{cc}}{2^N} \tag{9}$$

It can be seen that the resolution N can be chosen from the following inequality:

$$V_{ntot} = \sqrt{V_n^2 + V_{nq}^2} < V_{LSB} \tag{10}$$

$$V_n^2 + \frac{11}{12} \frac{V_{cc}^2}{2^{2N}} < \frac{V_{cc}^2}{2^{2N}} \tag{11}$$

$$V_n^2 < \frac{11}{12} \frac{V_{cc}^2}{2^{2N}} \tag{12}$$

$$N < log_2 \left(\sqrt{\frac{11}{12}} \frac{V_{cc}}{V_n} \right) \tag{13}$$

Since the rms noise measured at the output of the signal conditioning circuits is V_n=2mV, the above equation yields N<11. On the other hand, to guarantee a one degree resolution for finger joints bending measurements, supposing a linear sensor resistance variation VS bending angle, the required number of bits is given by:

$$log_2 \frac{V_{cc}}{\Delta V_i / 120} = log_2 \left(120 \frac{q+1}{q-1} \right) \approx 7.1 \tag{14}$$

Since the embedded A/D converter has 12 bit, the above mentioned conclusions allow to calculate how many LSBs must be set to zero by the PIC.

IV. Wireless Connectivity

For the data glove wireless connectivity, some requirements are mandatory:

- It must guarantee human safety;
- It has to assure a reasonable data rate;
- It has to cover a reasonable distance (range of transmission);
- It has to have low power consumption (for long life battery powered devices) and low transmission power (to reduce effects of radio signals to the body);

Some other requirements are preferable but less stringent:

- It is convenient to adopt an international standard
- It is preferable to be self configurable for more data gloves (or other dresses provided with sensors) at time

For all these reasons the connection between the micro controller and the computer for elaboration is realized using a MRF24J40MA transceiver (see Fig. 8) which support the ZigBee protocol for Wireless Personal Area Network (WPAN) development.

Figure 8. The adopted MRF24J40MA transceiver used for HITEG Glove wireless comunication

ZigBee is a low-cost, low-power, wireless mesh networking standard based on IEEE 802.15.4 definitions of Physical and Medium Access Control layers (PHY / MAC).

By using the information provided by the datasheet of the Chipcon CC2420/ZigBee, we computed the power P_d dissipated by a single Tx/Rx device. Assuming the utilisation of a battery PP3 (9V), with a capacity C_b of 500 mAh (equivalent to 16200 J) and a constant discharge, assuming a continuous monitoring, the expected battery lifetime is 3 days (see Ref. 1 for details), which can be considered a suitable value for our purposes.

V. Avatar Representation

Here it is described the avatar representation we realized via video based framework of recorded hand movements.

Once data has been correctly acquired and converted into digital form, all values are sent to PC with a specific protocol useful to disambiguate and recognize the exact sensor under investigation (among all the 15 adopted, one at time) and its value. So the data are tidily stored in a specific database, one record for each sensor, one field for each recording time. In such a way data can be useful re-called and utilized in simple numerical format or, more effectively, utilized to replicate the real hand movement by a virtual avatar on a PC screen. With this aim, it has been realized a Graphic User Interface (GUI), programmed in C++ language, by means of Windows Application Program Interfaces (API) and DirectX 9.0c. The overall software converts digital values into bending degree values for each finger joint and it represents all postures on a graphical body model. A complete 3D body model was realized starting from Blender, which is an open source multiplatform software. In order to animate the model mesh and make it move, translating real human actions to virtual actions in the simulated environment, we defined an armature which is made of a series of invisible bones connected to each other via parenting or constraints, that allow us to pose and deform the geometry that surrounds it, in this case the mesh.

The armature is used for building skeletal systems to animate the postures of characters and anything else which needs to be animated (see Fig.8, A and B).

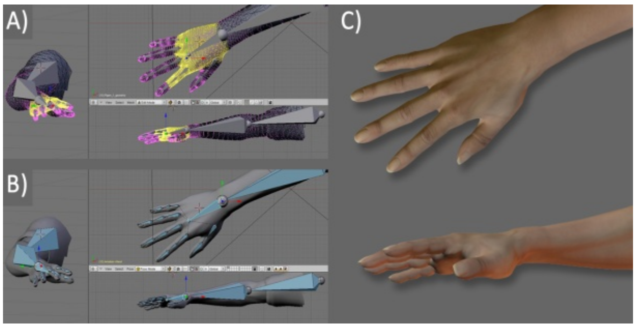

Figure 9. A 3D human hand model: A) Mesh with vertex group (yellow selection); B) Armature: hidden hand bones; C) Final rendering of the rigged model with textures and lights.

The armature modifier allows objects to be deformed by bones: as a bone moves, it deforms or moves the vertices (single points of a mesh) associated with it. The mesh surface is analogous to the skin of the human body. The armature is also called Skeleton. There are various great advantages from the utilization of 3D virtual model of the hand.

During the pre-processing data phase, the model has been utilized as a support tool to qualitatively verify the measurement repeatability. During the real-time visualization phase, the model allowed the hand visualization from different points of view, a continuous monitoring of the coherence of data streams and a rapid re-calibration if necessary.

During the post-processing data phase, thanks to the model, it was possible to replay all the fingers movements in slow / rapid / frame-by-frame motion and to isolate even just one finger at a time, removing the others from the view, in order to focus the operator's attention only on some important details.

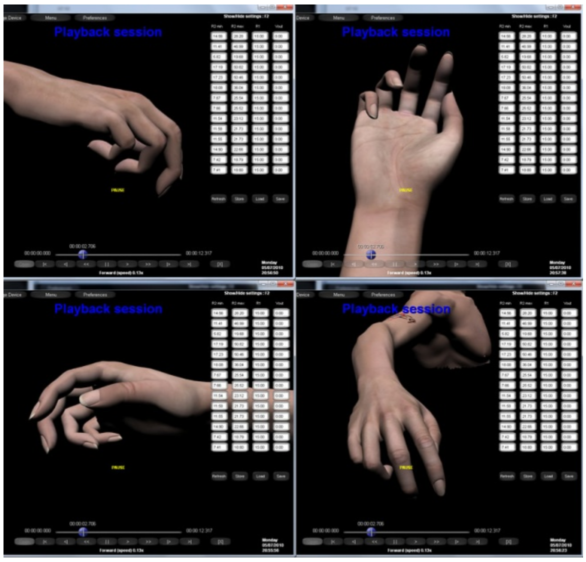

Figure 10. A reproduction session: software allows user to see an acquisition session off-line, and by rotating 3D model in any direction, it is possible to analyze reproduction from different viewpoints.

CONCLUSIONS

We designed, realized and tested a complete data glove system for realizing Human Machine Interface not limited to 2D dimensions as the common pc interfaces are. The system has been detailed in all its parts i.e. sensors, glove, circuitry, virtual representation. We believe this work can greatly improve new interaction possibilities with real machines.

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