Wrist Angle Measurements using Soft Sensors

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Abstract— **With new technologies appearing, there are many opportunities to innovate in the field of human-machine interfaces. Motion tracking measurements done directly on the human body are an intuitive way to input data from a user, but existing technologies are either confined to an experimental room or must continuously fight against integration drift using sensor fusion. Bulkiness and comfort can also be issues. In this paper, a novel approach is shown enabling absolute wrist angle measurements using three hyperelastic strain sensors placed at specific locations around the wrist. Once calibrated, the device can successfully measure flexion, extension, radial deviation, ulnar deviation, pronation and supination while having a very small impact on the user. As a proof of concept, the wrist sensor is used to control remotely the roll, pitch and yaw of a quad copter.**

I. Introduction

Since the increased popularity of computers in the 1980s, commonly used human-machine interfaces have not changed significantly. Electronic devices have certainly become more powerful and portable, but the ways humans interact with them is often limited to keyboards, computer mice or joysticks.

Instead of pressing buttons or holding a device, a more intuitive way to input data would be to capture direct motion from a part of the body such as the hand or head. This would allow a runner to change track on his music player without taking it out of the pocket, or to change the TV channel without requiring a remote control.

Although many human motion tracking technologies exist, they suffer from serious limitations. For instance, cameras locating markers placed on the body (e.g. ©Vicon environment) offer fast and reliable positioning measurements [1]–[3] but are limited to the room where the cameras are installed. On the other hand, motion sensors involving Inertial Measurement Units (IMUs) [4]–[6] can bypass that limitation and be used outdoors, but can suffer from integration drift and the continuous need to re-adjust their absolute positioning. Finally, goniometers [7] offer absolute positioning but at the cost of wearing bulky and uncomfortable hard elements which do not conform to the complex human body shape and the skin's stretchiness.

A more recent device from Microsoft research [8] combines the benefits of vision and IMUs while keeping the device portable. This «portable Kinect» offers also the advantage of tracking movements from the fingers, and not only the wrist motion. Its main limitation, as for the goniometers, resides in its bulky form factor which is inconvenient to wear in everyday life.

To tackle these limitations, a more intuitive, comfortable, novel and low profile human-interface using hyperelastic strain sensors has been developed in the Harvard Microrobotics Lab. It consists of a sensing wrist band that allows easy interaction with electronic devices and in any kind of environment.

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II. Wrist Sensor Design

Soft sensors [9] are highly stretchable and compliant sensing skins which provide valuable joint angle information with minimal impact on the host system. They are made of a rubber containing microchannels filled with a liquid metal at room temperature (eutectic Gallium Indium, or eGaIn). Under strain or normal pressure, the soft sensor's electrical resistance changes which makes them easy to interface with common electronic circuitry. Previous studies have shown that soft sensors can be successfully used to do on-body data measurements such as on a suit for wearable leg motion tracking [10] or a tactile wearable keypad [11]. Furthermore, it has also been shown [12] that their behavior is barely affected by temperature change, which is important when placing them in direct contact with the human body.

In the case of wrist angle measurements (Fig. 1), a minimum of three sensors are required to capture its three degrees of freedom (DOF), namely Flexion/Extension (F/E), Radial/Ulnar deviations (R/U) and Pronation/Supination (P/S).

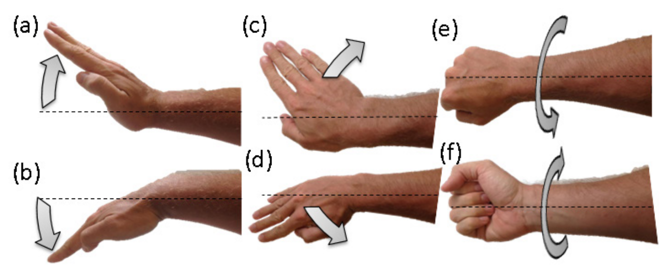

Fig. 1. (a) Extension (b) Flexion (c) Ulnar deviation (d) Radial deviation (e) Pronation (f) Supination

There are several locations around the wrist where strain sensors can be placed to sense these DOFs. In analogy with strain gauges placed on a rod, the obvious solution is to place them as shown in Fig. 2 (a) and (b).

Sensors A and B are aligned with the arm and separated by 90 degrees to capture most of the surface stretch due to rotation about X or Z (or flexion/extension and radial/ulnar deviations in the case of the wrist). The role of sensor C

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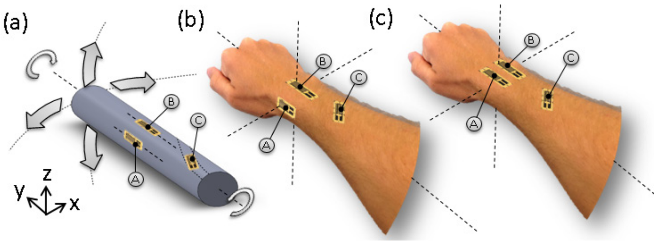

Fig. 2. (a) Similarity with applying strain gauges on a rod (b) Top and side application (c) Top application

is to sense torsion about Y (or pronation/supination on the wrist), and can be placed above or under the forearm.

Although there are many similarities between measuring deformation angles on a rod and on a wrist, the latter presents a number of additional difficulties. First, the skin can be highly stretchable (∼1.5x) which requires using strain sensors which can follow that stretchability. Then, at the transition from the forearm to the hand, there is a sharp increase in the wrist circumference, thus any sensor placed here is always bent. This would induce a lot of crosstalk on sensor A from Fig. 2 (b) when flexing or extending the wrist. Lastly, bones such as the head of the ulna create a bump that can interfere with the sensors. After taking these points under consideration, the sensor positioning shown on Fig. 2 (c) has been chosen. Fig. 3 shows a prototype of the wrist sensing band where the soft sensors are attached to rubber straps using Velcro. The two sensors covering the carpal row measure the flexion/extension (sum of the readings) as well as the lateral deviations (difference between the readings). The third sensor is placed laterally with a slight angle (∼10°) under the wrist to measure pronation and supination. It is important that its alignment stays away from the forearm's longitudinal axis to reduce crosstalk under flexion/extension.

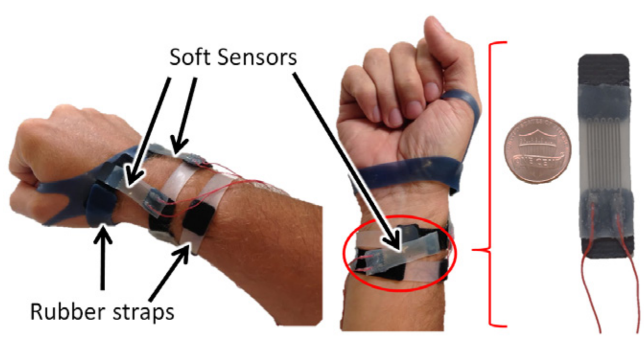

Fig. 3. Wrist sensor prototype using three soft sensors.

III. Fabrication

The soft sensors are fabricated in several steps. First the uncured rubber (EcoFlex 0030, Smooth-On Inc., Easton, PA 18042, USA) is poured on two molds created with a 3D printer (Objet 30, Stratasys, Eden Prairie, MN 55344, USA) as shown in Fig. 4 (a). While one layer is flat, the other contains the microchannels' pattern (300 x 300 μm). Both layers are then bonded by spin coating (2000 rpm, 50sec) the flat layer with a wet layer of the same rubber (Fig. 4 (b) and (c)). Liquid metal (eGaIn) is then injected using two syringes pierced in reservoirs at each microchannel extremity (Fig. 4 (d)). One syringe is used to inject the liquid metal and the other to remove the air to ease the injection. Copper wires are then anchored in the reservoirs (Fig. 4(e)) and are connected to a signal conditioning circuit composed of a Wheatstone bridge and an operational amplifier. The output can then be connected to a DAQ card (NI USB-6210, National Instruments, Austin, TX 78759, USA) to read data on Matlab (The MathWorks Inc., Natick, MA 01760, USA) or on an Arduino (Smart Projects, Turin, Italy).

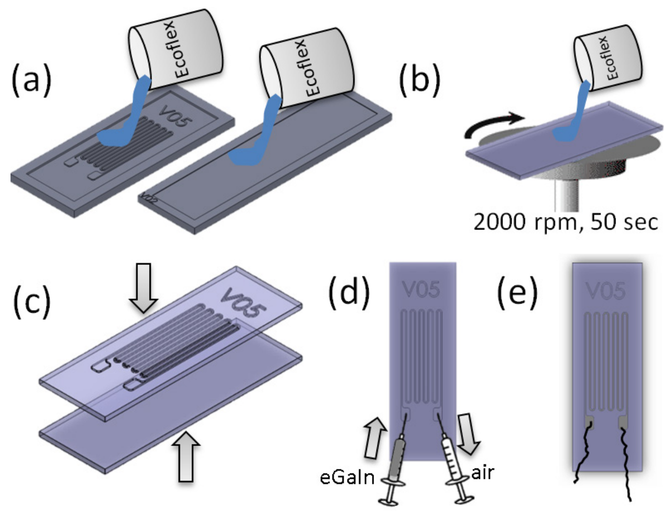

Fig. 4. (a) Rubber is poured in molds (b) The flat layer is spin coated (c) Bond layers together (d) eGaIn injection (e) Anchor wires

The rubber straps are made from the same rubber as the soft strain sensors and offer the advantage of not slipping on the skin. Uncured rubber is poured on a flat surface and a squeegee is used with an automatic film applicator (Elcometer 4340, Manchester, UK) to guarantee a controlled thickness (1mm). Once cured, a commercial CO_2 laser machining system (VLS 2.3, Universal Laser Systems) is used to cut the strap's contour.

On both soft sensors and straps, Velcro pads are glued with a silicone adhesive (Sil-Poxy, Smooth-On Inc., Easton, PA 18042, USA) to be easily attached or removed around the wrist.

IV. Characterization

Although the sensors have been placed to fit the wrist's complex 3D shape and minimize the crosstalk, they often present different sensitivity characteristics and can be positioned in slightly different ways from time to time or from user to user. Therefore, before each use, a calibration matrix [9,13] is be calculated to convert the reading from all sensors into the desired motion angles.

Although this method would require a way to measure externally the actual angles, a simplified approach is also tested to do a «blind calibration», with angles normalized to the maximum angle motion that the wrist can reach.

To be able to use calibration matrices, one first needs to ensure that the output signals are linear. Then, the different calibration methods can be applied. Previous studies [9] have already shown that pure elongation of the sensor results in a linear output. In the case of the sensors placed around the wrist, one needs to verify that this is still the case. Indeed, the complex shape of the wrist could induce localized normal pressure, which is also sensed by the soft sensor and can add some non-linearity to the measurement.

To compare the soft sensor outputs with the actual wrist angles, the latter can be measured by different means such as EM trackers or vision based measurement. Despite that, a custom-made calibration device has been built (Fig. 5). Compared to the other ways to track the wrist angles, this one has the advantage that each DOF can also be locked, allowing measurement of one DOF at the time. It consists of a handle which has three DOFs, each of which is being measured by a potentiometer integrated in the pivot joints.

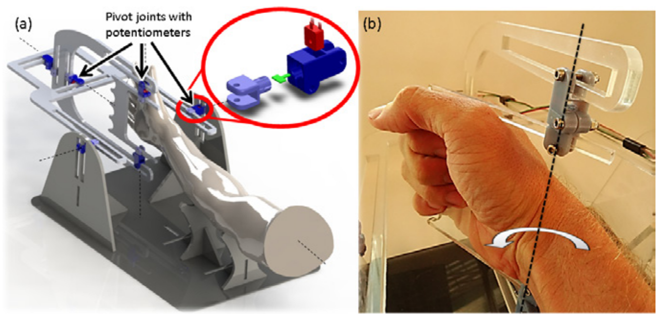

Fig. 5. (a) Calibration device used to measure the actual wrist angles. The pivot joints contain potentiometers to measure the angle, and can be locked. (b) For F/E measurement, the center of rotation is reported from the handle up to the level of the wrist.

For all wrist movement, at least four full strokes are done while data from the calibration device as well as the output values from the soft sensors are measured. The pace of the wrist movement is approximately 1Hz (a typical wrist movement speed). This data is then used to build the calibration matrix.

V. Results and Discussion

For each wrist movements, the soft sensor values are compared to the angles from the calibration device. One sees clearly in Fig. 6(a) and (b) that Sensors A and B react in a similar manner for F/E and oppositely for R/U while Sensor C doesn't sense a lot of activity. On the other hand, when doing P/S, Sensor C measures most of the movement.

For each movement, a linear regression is calculated for every sensor's output (S_A, S_B and S_C). The slopes m are then reported in a matrix C:

$$C = \begin{bmatrix} m_{F/E,S_A} & m_{R/U,S_A} & m_{P/S,S_A} \\ m_{F/E,S_B} & m_{R/U,S_B} & m_{P/S,S_B} \\ m_{F/E,S_C} & m_{R/U,S_C} & m_{P/S,S_C} \end{bmatrix} \quad (1)$$

The matrix is then inverted using the Moore-Penrose pseudo inverse method, and the wrist angles (α) can then be measured using the following equation:

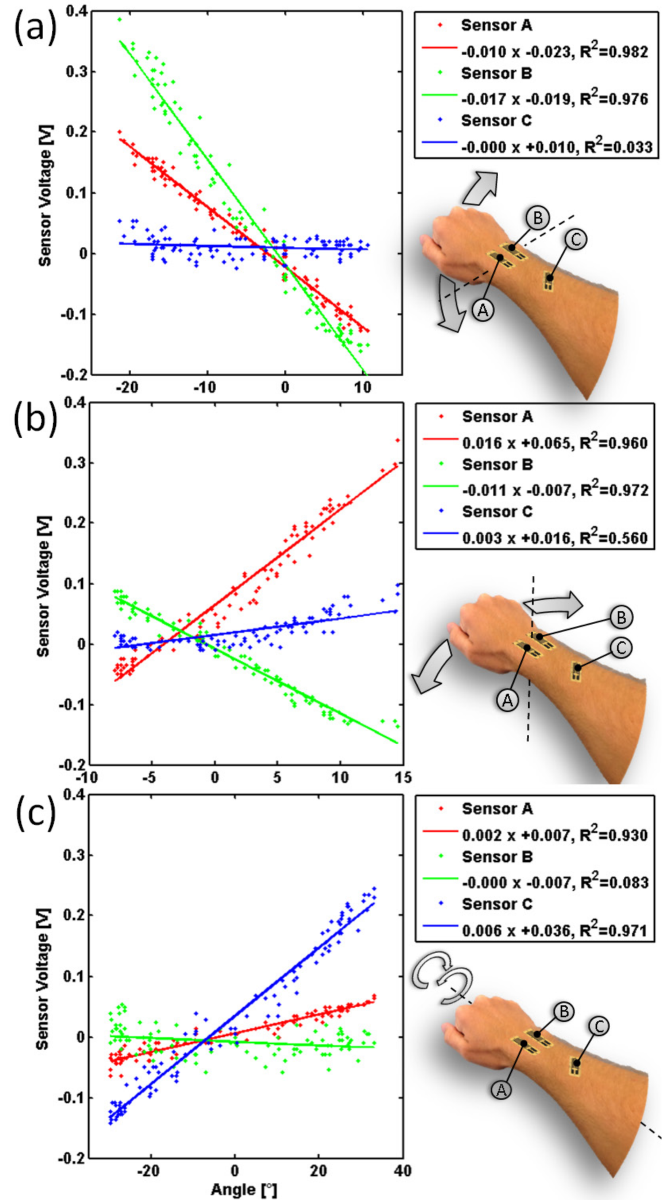

Fig. 6. Sensor output Vs. wrist angle given by the calibration device for (a) Flexion/Extension, (b) Radial/Ulnar Deviations and (c) Pronation/Supination

$$\begin{bmatrix} \alpha_{F/E} \\ \alpha_{R/U} \\ \alpha_{P/S} \end{bmatrix} = C^{-1} \cdot \begin{bmatrix} S_A \\ S_B \\ S_C \end{bmatrix} \quad (2)$$

In the case of this experiment, the following calibration matrix is obtained which has a condition number of 3.85.

$$C^{-1} = \begin{bmatrix} -28.9 & -41.2 & 5.72 \\ 47.4 & -26.8 & -14.5 \\ -24.7 & 10.7 & 185.6 \end{bmatrix} \quad (3)$$

Fig. 7 shows a comparison between the sensing wrist band and the calibration device. The root mean square (RMS) errors for F/E, R/U and P/S are 1.98°, 3.2° and 7.46° respectively.

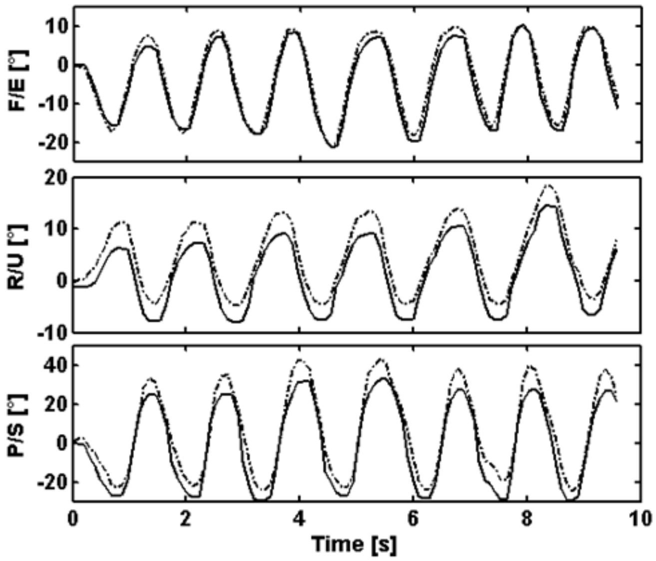

Fig. 7. Output comparison between the sensing wrist band (dashed) and the calibration device (solid line)

A «blind calibration» can be useful in cases where it is inconvenient to use the calibration device to build the calibration matrix (e.g. outdoors). This simplified calibration process consists of asking the user to move sequentially his/her wrist to the maximum deflections. Each sensor value is measured and the slopes are determined with only two points (e.g. between the maximum flexion and extension) and the output corresponds to an angle normalized to the wrist's maximum deflections. From there, the utilization of the rotation matrix remains the same as described above.

VI. Application

As an example of an application for the sensing wrist band, it is used to control the roll, pitch and yaw of a small quad-copter (Fig. 8). This is usually done using a commercial remote control with which the pilot interacts using his fingers on two sticks with two degrees of freedom each.

After a «blind calibration» and some tuning on the input voltages, the sensing wrist band offers an intuitive piloting approach, as if the pilot is controlling the copter holding a virtual control stick in his hand.

To send signals to the quad copter, its original remote control is modified to accept analog input voltages from an external source instead of the on-board potentiometers. Because the sensing wrist band offers three DOFs, the fourth channel (throttle to control the vertical speed) is still done using the original remote control.

VII. Conclusion and Future Work

Due to their high compliance and sensitivity, soft strain sensors allow novel ways to do motion tracking on the human body. This paper describes how it can be successfully done on a part of the body which would be one of the most suitable for an intuitive human-machine interface: the wrist.

Compared to other methods to do motion tracking on the body, this way is probably the least bulky and the most

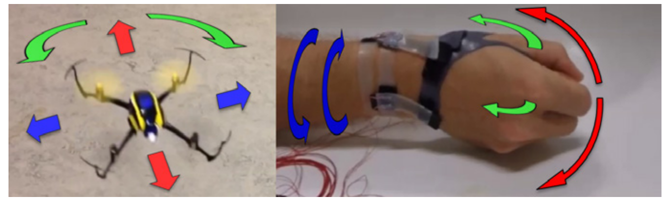

Fig. 8. Sensing wrist band used to control a remote controlled quad-copter.

comfortable to wear as it is composed mostly of soft or liquid phase materials.

Future work will include a more in depth study of the skin's stretchability around the wrist while doing different movements. This will allow optimizing the sensor placement.

To bring more portability to the device, the sensing wrist band will also be integrated with a watch which will serve as a power source, signal conditioning unit and wireless transmitter. Finally, wrist control of other kinds of devices such as surgical robots will be studied.

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