Compliant capacitive elastomer goniometer sensor for joint angle measurement

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***Abstract*— This paper presents a capacitive Goniometer Dielectric Elastomers Sensor (GDES), capable of measuring the movement of human joints. The model and fabrication steps of such an innovative compliant device are reported along with the results of a preliminary validation experimental campaign. Application for the measurement of human elbow flexion is also presented, showing the promises of the proposed GDES as an alternative solution to the standard option of Inertial Measurement Units (IMUs) to compute the relative orientation between two body segments.**

Keywords—Joint angle, IMU, dielectric elastomer sensor.

I. Introduction

A common strategy to reconstruct the attitude of the human body is the use of Inertial Measurement Units (IMUs), positioned on body segments. Considering a human body, these IMUs can be near the articulations of arm, limbs, head, and trunk segments, estimating their attitude by sensor-fusion strategies of the 3-axial sensors constituting the singular IMU, which are the accelerometer, the gyroscope, and the magnetometer [1], [2]. However, the accuracy of IMUs is severely affected by the environment, especially in a workspace with electromagnetic disturbances that cause a distorsion in the assessment of the tracked body [3]. In this context, this work proposes an alternative solution where the body joint angle is directly measured by a wearable sensor based on dielectric elastomers (DEs), [4]. Thanks to the symmetric assembly of two DE capacitive sensors placed on the two opposite faces of a flexible strip structure, a Goniometer DE Sensor (GDES) is realized that is capable of measuring its bending angle. In the following, the angle measurement models and the GDES fabrication steps are presented. Preliminary experimental results are also reported and discussed, comparing GDES functionality with that of IMUs. Finally, the conclusions summarize the state of such a research activity, introducing the next steps focused on the development of a hybrid body-tracking system integrating GDES and IMUs.

II. Joint angle measurement process

A. Joint angle measurement through IMUs

When an IMU is attached to a body, it is possible to assess its orientation by fusing the data of the accelerometer, gyroscope, and magnetometer sensors which compose the unit. The attitude output is represented by a quaternion $\boldsymbol{q}$. The angle between two connected IMUs is computed by comparing their quaternions. Fig. 1 shows the schematic representation of a flexible support with two IMUs attached. After a calibration step to orient the IMUs quaternions $\boldsymbol{q}_1$ and $\boldsymbol{q}_2$ to a common reference frame defined by the normal axis z, the angle ϑ is calculated as:

$$\vartheta = 2\arccos\left(\alpha_{q_\vartheta}\right). \tag{1}$$

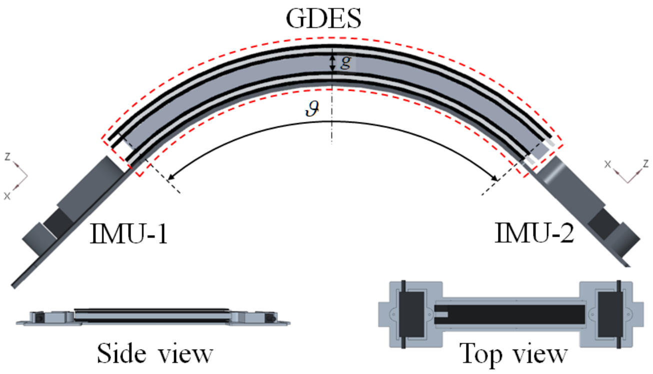

Fig. 1. The flexible support curvature angle schematic representation, with two IMU on the sides and a GDES in between.

where $\alpha_{q\vartheta}$ is the scalar part of the quaternion resulting from the Hamiltonian product defined as $\boldsymbol{q}_\vartheta = \boldsymbol{q}_1^T \odot \boldsymbol{q}_2$.

B. Capacitive GDES model and fabrication steps

The same angle can be measured through a singular compliant sensor, i.e., the GDES presented in this work, developed in analogy to resistive goniometer sensors [5], but with a completely different working principle. Indeed, the GDES is a capacitive sensor composed of two highly deformable parallel plate capacitors, $C^{(1)}$ and $C^{(2)}$, placed at the opposite faces of a flexible holding-structure, assembled through a straightforward manufacturing process, as shown in Fig. 2. As a result, the device differential capacitance $\Delta C = C^{(1)} - C^{(2)}$ is linearly proportional to the overall system bending angle ϑ, with $C^{(1)} = C^{(2)} = C_0$ when $\vartheta = 0$. The two deformable plate capacitors are realized by bonding via oxygen plasma two thin electrode layers, which are made of carbon black powder mixed in a Silpuran 6000/05 PDMS, on the opposite faces of a 20 µm PDMS film made of Elastosil Wacker 2030©. After realization, the deformable capacitors are attached symmetrically with the same process to the flexible holding structure. Finally, the GDES is obtained after deposing another Silpuran PDMS layer on the external electrodes to assure electrical isolation.

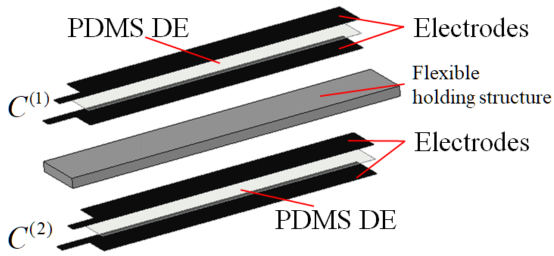

Fig. 2. Assembly of a GDES in its simplest form of components.

Due to the incompressibility of the employed materials and by considering homogeneous deformation of the deformable capacitors, the capacitance difference ΔC of the GDES is linearly related to the bending angle and the thickness g of the flexible holding structure as

$$\frac{\Delta C}{C_0} = (K_1 g)\vartheta + K_2, \qquad (2)$$

where K_1 and K_2 are two constants, to be determined via experiments, representing the sensitivity and the offset of the GDES, with the offset arising due to misalignments while assembling the device.

III. Experimental Tests

A. GDES experimental validation

The GDES calibration is performed by measuring differential capacitances in static conditions under different bending angles. The capacitances are measured with an LCR meter (Rohde & Schwarz HM8118), and the bending angle is maintained fixed with a customized testbench shown in Fig. 3. The extremities of a support, which is made with a Formlabs Form 2 printer using the Flexible 80A Resin, where the GDES is attached, are constrained to two rigid plates connected by a revolute joint. The angle between the two plates is measured by a commercial digital protractor (Lux-Tools). Two GDES with different flexible holding-structure have been tested at different bending angles: a GDES-1 with $g \cong 4$ mm, and a GDES-2 with $g \cong 1$ mm. The obtained results are shown in Fig. 4. The straight lines are the fitted results based on the model (2), and the narrow shaded areas represent their 95% confidence interval, showing a high level of accuracy. The unknown parameter for GDES-1 are $K_1 = 0.1875$ and $K_2 = -14.6$, whereas for GDES-2 are $K_1 = 0.16$ and $K_2 = 0.31$. As expected, K_1 parameters are almost similar, demonstrating the linear dependency between ΔC and the thickness g of the flexible holding structure.

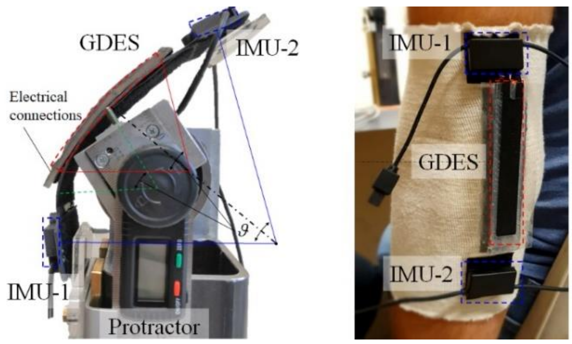

Fig. 3. Left, testbench; right, IMUs and GDES attached on human elbow.

With the same procedure, the accuracy of the angles measured by two IMUs has been validated on the same testbench. The IMUs are firstly calibrated and then tested measuring angles in the range of 0° - 100°, resulting in a root mean square error between the computed angle of equation (1) and the one read via the protractor of 0.8° with a high accuracy fitness index $R^2 = 0.9994$.

B. Human joint angle measurement with GDES and IMUs

As a preliminary test for the experimental evaluation of GDES in the measurement of human joint motion, two IMUs and GDES-1 have been fixed to an elastic band located on the human elbow, as shown in Fig. 3 on the right. The elbow is maintained at three different fixed angles, estimated thanks to the IMUs relationship (1), while the GDES-1 differential capacitance is measured at the same time. The three results are reported as cross markers in Fig. 4, showing a promising performance of the capacitive sensor, although with less accuracy for small bending angles since a measured angle lays outside the confidence interval.

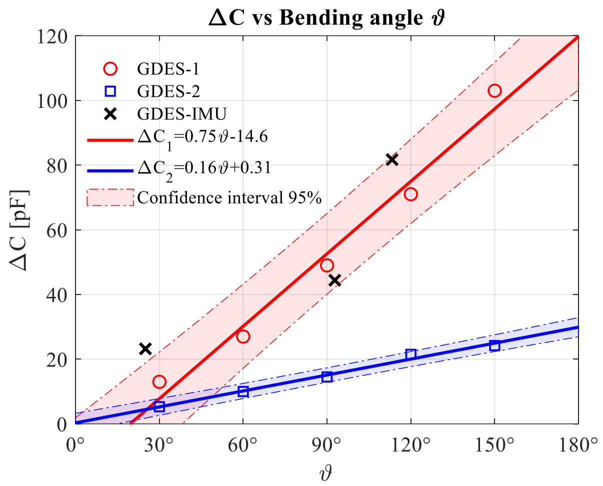

Fig. 4. Experimental results for GDES-1 and GDES-2 differential capacitance compared with the protractor angle measurements as well as compared to IMU measurement.

IV. Conclusion and Future Steps

This work reports on the conception, characterization and preliminary experimental validation of a goniometer made of two capacitive dielectric elastomer sensors (GDES) for the measurement of human joint movement. As predicted by a simple model, the acquired angle measurements are linearly proportional to the differential capacitance of the GDES. Furthermore, an experimental test is also performed for the measurement of human elbow flexion, demonstrating the feasibility of the GDES to be used as a wearable goniometer sensor. Compared to IMUs, a GDES is characterized by a simpler working principle and structure, is low-cost and is rather immune to electromagnetic disturbances. Thanks to these features, integration of GDES within IMUs can potentially lead to very robust and accurate human motion tracking systems. However, the proposed GDES still requires significant improvements for what concerns design, manufacturing and processing of measurement signals.

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