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High-Stiffness Capacitive Torque Sensor based on a Hybrid Scott-Russell and Parallelogram Mechanism

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***Abstract*—While joint torque sensors enable precise robot interactions, insufficient structural stiffness significantly limits control bandwidth and accuracy by reducing overall system rigidity. This study proposes a high-stiffness torque sensor based on a hybrid Scott-Russell (SR) and parallelogram (PL) flexure mechanism. The SR structure performs mechanical displacement amplification, ensuring high sensitivity even within a rigid design. By integrating the PL mechanism, the inherent parasitic rotation typically observed in conventional SR structures is effectively suppressed, ensuring pure translational motion between the capacitive electrodes. This hybrid flexure maximizes the capacitance change and achieves high sensing sensitivity while maintaining the high structural stiffness required for robust robotic joints. The proposed mechanism is validated through simulation, demonstrating its potential to ensure both system-level rigidity and high-resolution torque sensing.**

***Index Terms*—Force and Tactile Sensing, Cooperating Robots**

I. INTRODUCTION

As Physical AI advances, robots require precise sensing to interact with unstructured environments. Joint torque sensors are essential for this, enabling high-fidelity torque control and collision detection. Extensive research has focused on developing joint torque sensors based on various sensing principles, such as resistive, optical, and capacitive types. [1]–[4] While these designs offer excellent sensing performance, simultaneously ensuring high structural stiffness remains a challenging trade-off for high-performance robotics. Insufficient sensor stiffness significantly degrades the overall control bandwidth and positioning accuracy of the robotic system, potentially leading to unwanted oscillations during high-speed or high-load tasks.

To address this, we propose a high-stiffness capacitive torque sensor based on a hybrid Scott-Russell (SR) and parallelogram (PL) flexure mechanism. The SR structure performs displacement amplification to ensure high sensitivity within a rigid design. Simultaneously, the PL mechanism constrains the electrodes to pure translational motion, maintaining a uniform gap across the entire sensing surface to maximize the capacitance signal change. By integrating these mechanisms, the sensor achieves high sensing resolution while preserving the structural robustness for robotic joint application.

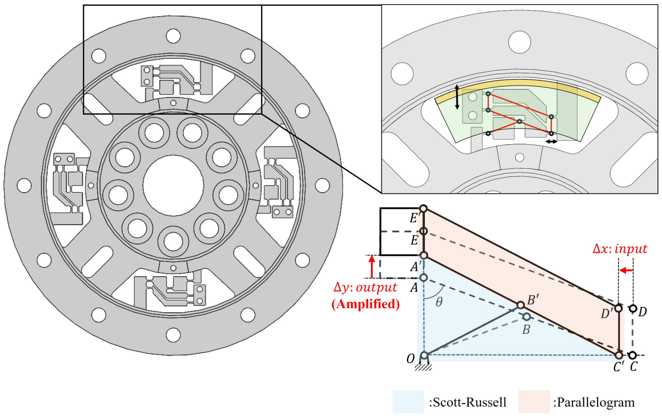

Fig. 1. Design of the high-stiffness capacitive torque sensor: (Left) overall torque sensor model, (Top-right) magnified view of the hybrid mechanism and electrodes, and (Bottom-right) kinematic schematic of the displacement amplification.

II. PROPOSED HYBRID FLEXURE MECHANISM

A. Scott-Russell Displacement Amplification

The SR mechanism serves as a displacement amplification stage. In high-stiffness sensors, structural deformation under torque is inherently minute, limiting the achievable signal change. To overcome this, the SR flexure amplifies small tangential deformations into larger radial displacements at the electrodes, enhancing sensitivity without compromising structural rigidity.

As shown in Fig. 1, the mechanism consists of links OB and AC joined at B, where $OB = AB = BC$. The tangential displacement Δx is magnified into a radial displacement Δy at point A, with the amplification ratio governed by [5]:

$$\frac{|\Delta y|}{|\Delta x|} \approx \tan\theta, \tag{1}$$

where θ is the initial angle $\angle OAB$.

B. Parasitic Motion Suppression via Parallelogram Flexure

While the SR mechanism effectively amplifies displacement, a conventional single-link SR structure inherently suffers from parasitic rotations at its output terminal. To ensure

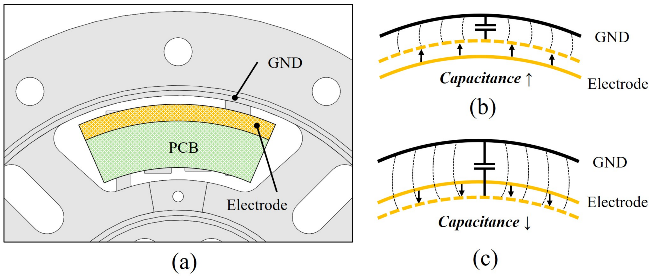

Fig. 2. Capacitive sensing implementation: (a) integration of PCB electrodes, (b) increasing capacitance due to a reduced gap, and (c) decreasing capacitance due to an enlarged gap.

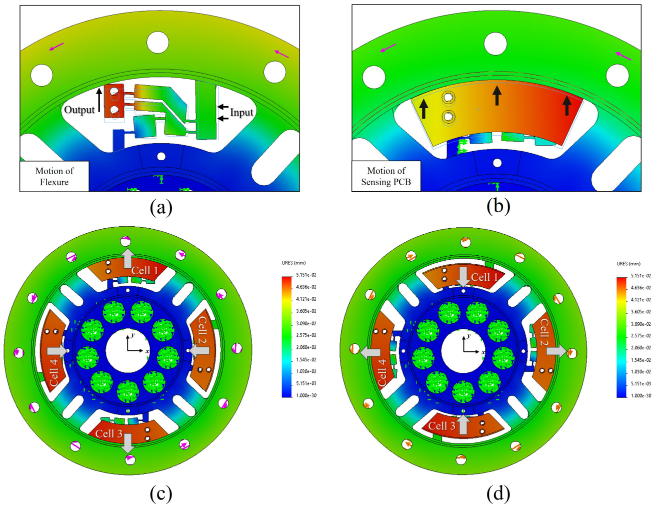

Fig. 3. Finite element analysis (FEA) results: (a) deformation of the hybrid flexure mechanism, (b) parallel translation of the sensing PCB, (c) overall sensor deformation under $+T_z$ torque, and (d) overall sensor deformation under $-T_z$ torque.

a large effective sensing area and maintain signal linearity, a PL flexure mechanism is integrated to act as a precision linear guide. This flexure structure constrains the rotational degrees of freedom, ensuring that the magnified displacement Δy results in pure translational motion of the electrodes. By suppressing parasitic tilting, the mechanism maintains a uniform air gap across the entire electrode surface, thereby maximizing the usable capacitance change.

C. Implementation of Capacitive Torque Sensing

As shown in Fig. 2, torque is measured by detecting capacitance changes between the arc-shaped GND surfaces of the sensor body and the arc-shaped electrodes. The hybrid mechanism converts the input torque into a magnified radial displacement, which alters the air gap and induces a change in capacitance. The parallel guidance ensures this displacement occurs uniformly across the electrodes, maximizing the effective sensing area and sensitivity.

III. SIMULATION AND ANALYSIS

The mechanical behavior of the proposed hybrid flexure was validated through FEA to confirm its dual-functional role: displacement amplification and parallel guidance. As shown in Fig. 3(a) and (b), the SR mechanism successfully converts the input tangential displacement into a radial output. The analysis confirms a mechanical amplification ratio of 2.2, which validates the kinematic design intended to enhance sensing sensitivity. Furthermore, the PL mechanism ensures that the sensing PCB undergoes pure translational motion, maintaining a uniform gap across the electrodes without parasitic tilting.

Fig. 4. Prototype of the developed high-stiffness joint torque sensor.

Figures 3(c) and (d) illustrate the overall structural response under $\pm T_z$ torque. The flexure units are designed with alternating orientations such that two opposing cells exhibit identical capacitance trends. This symmetrical configuration ensures that when a torque is applied, the capacitance changes in a differential manner across the cells.

IV. CONCLUSION

The final implementation of the developed high-stiffness joint torque sensor is presented in Fig. 4. This study proposed a high-stiffness capacitive torque sensor based on a hybrid SR and PL flexure mechanism. The design successfully overcomes the sensitivity-rigidity trade-off by achieving a 2.2-fold mechanical displacement amplification while maintaining a high torsional stiffness of $408\,\mathrm{kNm/rad}$. Through FEA, it was confirmed that the hybrid flexure effectively contributes to maximizing the capacitance signal by providing both displacement amplification and precise electrode alignment. This mechanism offers a promising solution for high-performance robotic joints requiring both high control bandwidth and precise torque feedback.

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