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A low-cost, simple, conductive rubber-based haptic sensor for kinesthetic human-robot interaction

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1 Introduction

Kinesthetic human-robot interaction (HRI) is the physical interaction between a human and a robot where the robot can perceive and react to the human's motions in a natural manner [1,2]. This form of HRI can be applied for programming or teaching new robot skills by kinesthetic demonstration. A typical approach to achieving kinesthetic HRI is through haptic feedback by using a force/torque sensor installed at the end effector of the robot [1,2]. The sensor can measure the feedback information introduced by the human, and the robot can respond to it in a coordinated and safe manner. While such a sensor (based on strain gauges) [1,2] is accurate and effective, it still requires a complicated housing structure and electronic circuit design. It is also labor-intensive to build, resulting in a high cost.

From this point of view, we propose here an alternative low-cost, simple haptic sensor for kinesthetic human-robot interaction (Fig. 1). The sensor is based on low-cost, commercially available, conductive rubber, which is a carbon filled rubber material with good electrical conductivity. The sensor housing structure design is simple (Fig. 2(a)) and the sensor circuit is based on a simple voltage divider concept. In fact, the sensor functions as a soft and flexible strain sensor (SFS) [3] that can be deformed; thereby changing its electrical resistance in response to an applied force. Thus, using the two conductive rubber-based SFSs (CSFSs) with our simple structure design leads to a simple and cheap sensor solution that can sense the magnitude and direction of applied forces in two axes. As a demonstration, we show how the proposed sensor can be used for haptic sensing in human-robot interaction with kinesthetic guidance.

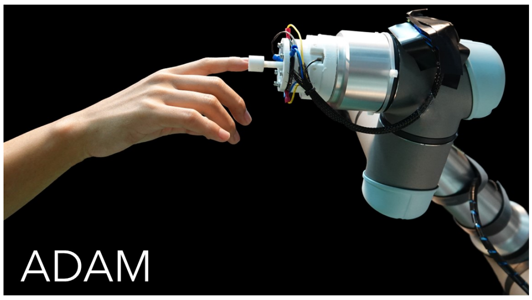

Figure 1: Articulated robot arm with conDuctive rubber-based hAptic sensor for kinesthetic huMan-robot interaction (ADAM).

2 Materials and Methods

Our haptic sensor consists of a flexible layer, a main housing, a ring, and a lever. The housing, ring, and lever are made of 3D printed PLA material. The housing is the main sensor body, while the ring clamps the flexible layer to the body and the lever is the sensor component that receives force/load. The flexible layer is the sensing component that converts applied force to electrical signals. It is composed of two pieces of small synthetic conductive rubbers (EP-T5074, NEO Plastomer CO. LTD., Thailand), each of which has a size of 5x40 mm (Fig. 2(a)). They are positioned in a cross, with one for sensing force or deformation in the x-axis and the other in the y-axis. A flexible 3D printed non-conductive layer (NinjaFlex 85A flexible TPU filament) is used to separate them and at the same time provide necessary elasticity to return the lever to its initial (vertical) position when the applied force is removed.

The electrical sensor output signals (describing the deformations of CSFSs) are measured through a voltage divider circuit. The measured signals are transmitted to a computer via an Arduino-Mega 2560 board with a USB interface with an update frequency of 50 Hz. A simple moving average filter is applied to filter sensory noise. The final preprocessed signals are used to control a robot arm to follow human guidance during kinesthetic human-robot interaction.

3 Experiments and Results

To assess sensor performance, we utilized the UR5 robot arm to accurately push the sensor lever to different positions from 0 to 360 degrees at 8-degree intervals (Fig. 2(b)). Each position was repeated eight times. Figures 2(d) and 2(e) show the results as heat maps of the top CSFS and bottom CSFS, respectively. The warm colors represent positive sensor values while the cold colors represent negative sensor values. The significant changes of the sensor signals

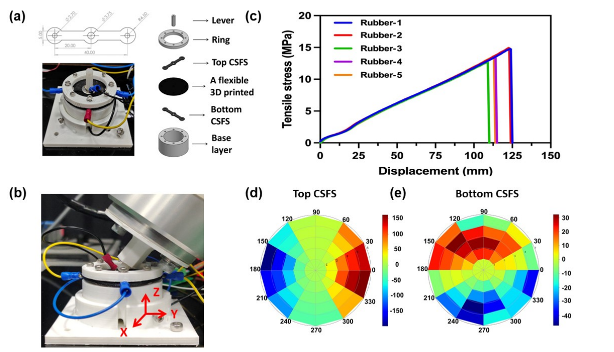

Figure 2: (a) The proposed sensor and its components. (b) The experiment setup with the robot arm UR5 and an example of pushing the lever around the x-axis. (c) Tensile stress and displacement of the used synthetic conductive rubber from five repeated tests. (d), (e) Heat maps of sensor output signals when pushing the sensor lever to different angles.

around the x and y axes can be obtained from the top and bottom CSFS components, respectively. Thus, one can use the sensor information for detecting 2D human-robot interaction force where the top component is for mainly detecting a left/right applied force, while the bottom one is for mainly detecting an upward/downward applied force, and their combination is for a diagonal applied force.

To investigate the maximum force that can be applied to our CSFS, we measured tensile stress and displacement with stretching rates of 60 mm/min at room temperature for five times. A sensor thickness of 0.485 mm was employed for the test. The results in Fig. 2(c) show that our CSFS has maximum tensile stress and displacement of approximately 14 $\pm$ 1 MPa and 117 $\pm$ 6 mm, respectively. According to this mechanical property data, a proper sensor size can be designed with respect to an applied load.

Finally, we implemented the conductive rubber-based haptic sensor on the robot arm for kinesthetic human-robot interaction (ADAM) as shown in Figs. 1 and 3. In this demonstration, the user inserted an index finger in the lever slot (Fig. 1) to interface to the robot and then moved the finger to guide the robot (finger-based robot guidance). At around 21-28 s, the user moved the finger or pushed the sensor to the left, as such the sensor output of the top CSFS strongly decreased to a negative value below a threshold (see red dashed line in Fig. 3(a)) while the one of the bottom CSFS slightly decreased (still above the threshold). This information was sufficient to guide the robot to move its arm to the left of the user. At around 33-40 s, the user guided the robot to the right where the sensor output of the top CSFS turned to a positive value above a threshold (see green dashed line in Fig. 3(a)). At around 43-52 s, the user guided the robot to move upward where the sensor output of the bottom CSFS significantly increased while the top CSFS output was still high since the sensor was not fully returned to its initial position. At around 59-65 s, the user guided the robot to move downward where the sensor output of the bottom CSFS significantly decreased to a negative value and below a threshold (see red dashed line in Fig. 3(a)). At around 72-79 s and 82-89 s, the user guided the robot to move to the top right and the bottom left where the outputs of the top and bottom CSFSs became both high positive values and high negative values, respectively.

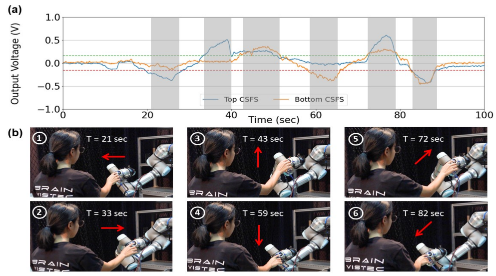

Figure 3: Demonstration of ADAM. (a), (b) Sensor output signals and snapshots during the kinesthetic human-robot interaction, respectively, (see also www.manoonpong.com/ADAM/video.mp4).

4 Conclusions

In this study, we introduce a low-cost, simple, conductive rubber-based haptic sensor. Due to the use of a commercially available cheap carbon filled rubber sheet[1] and simple 3D printed parts, the total hardware cost of the sensor is approximately 5 USD. The sensor can detect an applied force in x-axis, y-axis, and their combination. Consequently, the sensor can be utilized as a joystick for manual control or as a simple 2D haptic sensor for guiding or instructing a robot arm via kinesthetic human-robot interaction. However, the sensor is still limited to a small applied force and cannot distinguish the changes in the positive and negative z-directions. In the future, we will investigate the mechanical properties of soft/flexible sensor materials for scalability, as well as extend the sensor setup for 3D haptic sensing.

5 Acknowledgments

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[1] The carbon filled rubber sheet (A4), which has an area of approximately 623 cm2, costs 20.24 USD. The total area of two CSFS pieces used for the sensor is approximately 6 cm2. Thus, the CSFS costs approximately 0.2 USD.