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A Low-cost, High-Performance, Soft Tri-axis Tactile Sensor based on Eddy-Current Effect

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Abstract—Tactile sensors are essential for robotic systems to interact safely and effectively with the external world. In particular, tri-axis tactile sensors are crucial for dexterous robotic manipulation by providing shear force information for features like slip and contact angle detection. In this paper, we present a soft tri-axis tactile sensor based on the eddy-current effect and composed from flexible coils and conductive films. Prototypes were developed, calibrated and evaluated, and achieved a force measurement resolution of 0.3 mN in each axis, with a bandwidth up to 1 kHz. The presented sensor is low-cost, robust, durable, and easily customizable for a variety of robotic and healthcare applications.

Keywords— Tactile sensors; eddy-current effect; inductance; flexible coils; elastomer

I. INTRODUCTION

Tactile sensors are essential for robotic systems to interact safely and effectively with the external world [1, 2], and also play a key role in providing tactile information for healthcare applications [3]. Recently, soft/flexible, thin tactile sensing skins have emerged based on a variety of transducer types (e.g. piezoelectric, piezoresistive, capacitive, triboelectric) [4-5]. However, tri-axis tactile sensors that measure both normal and shear force, thus emulating the human sense of touch, remain under-developed [1]. Recently, tri-axis tactile sensors based on capacitive sensors [6] have been investigated. They are highly sensitive, accurate, but typically require complex fabrication, and suffer from environmental interference. An alternative approach has used complex embedded micro-channels and liquid conductors, a tri-axis resistive tactile sensor has been developed [7], but is relatively large and expensive. Benefiting from the recent advances in integrated, compact magnetic field sensing chips, we developed a tri-axis tactile sensor (MagOne [8]) using a 3D hall-effect sensor and magnet embedded in elastomer. Such sensors are soft, low-cost and capable of high-performance, but inherently sensitive to static magnetic field interference from the environment or external objects, thus limiting their application. Therefore, we investigated alternative transducer mechanisms that could measure tri-axis force with accuracy and robustness. By transferring conventional eddy-current displacement sensors into a novel spatial configuration, a soft tri-axis tactile sensor using four inductive coils is proposed. Here, we describe the working principle, development, calibration and evaluation of a prototype system, which achieved a state-of-the-art resolution of 0.3 mN.

II. WORKING PRINCIPLE

Conventional eddy-current sensors (ECSs) [9] are used to measure the distance between a sensing coil and a conductive target. As shown in Fig. 1(a), when the coil carries AC current (typically at 0.1 MHz to 10 MHz), it generates an alternating magnetic field which induces eddy currents in the nearby conductive target. The eddy current in the target generates magnetic field opposite to that from the coil, thus reducing the magnetic flux in the coil and dissipating energy. The coupling between the coil and the target therefore acts to reduce the coil's inductance and increase its resistance [10]. Thus, the distance (d_z) between the coil and the target can be obtained by measuring the inductance of the coil. When the conductive target is relatively small or has a non-circular shape, moving it laterally from the coil's center changes the magnetic field coupling between the coil and target (Fig. 1(b)). Since the eddy-current intensity is highly dependent on the vertical distance, both vertical and lateral movement effects the magnetic field

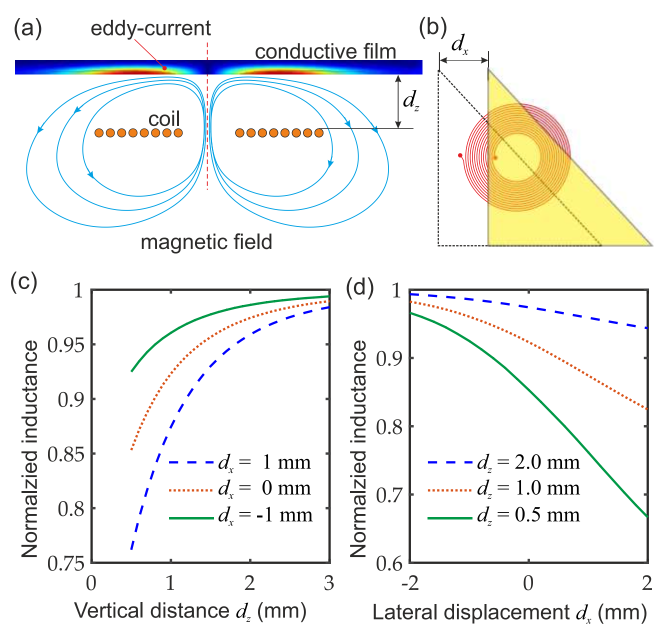

Fig. 1. (a) Operating principle of ECSs; (b) ECS for lateral displacement measurement; (c) Inductance to vertical distance response of an ECS; (d) Inductance to lateral displacement response of an ECS.

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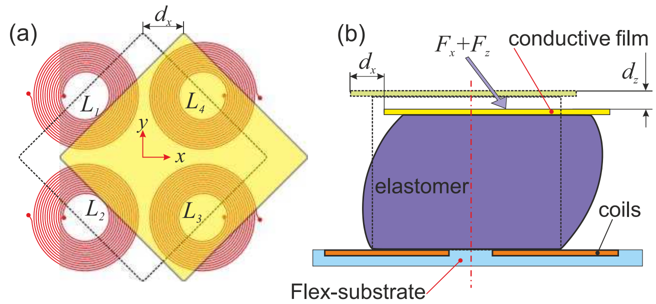

Fig. 2. Schematic showing a Tri-axis tactile sensor using four coils in (a) plan view (coil configuration) and (b) side view with elastomer layer

coupling and causes measurable inductance variation. As shown in Fig. 1(c, d), the inductance is more sensitive to lateral displacement when the vertical distance is small, and the target's lateral position also affects the inductance response to vertical distance.

Therefore, one coil is not adequate to detect the movement of the target in multiple axes. We propose a four-coil array to detect the tri-axis movement of a square conductive target. As shown in Fig. 2(a), when the target is moved along x axis, the target's magnetic field coupling with coil 3 and coil 4 increases, while the coupling with coil 1 and coil 2 decreases. The same principle applies in the y axis. When the vertical distance decreases, the coupling with all four coils increases. Using an elastomer to modulate applied force [8], a tri-axis tactile sensor can be formed. As shown in Fig. 2(b), this new sensor comprises a flex-substrate with four coils (sensing device), an elastomer (force-deformation transfer medium), and a conductive film (the target). When an external force is applied, the conductive film is moved vertically/laterally through deformation of the elastomer, which changes the inductance of all four coils. The relationship between L_x, L_y and L_z and the applied force F_x, F_y, and F_z is complex because of the highly nonlinear response of the ECSs and the strong cross-talk effect between axes. However, a decoupled output signal can be approximated by calculating differential inductance between coils (similar to balancing resistance in a Wheatstone bridge):

$$\begin{cases} L_x = L_3 + L_4 - L_1 - L_2 \\ L_y = L_1 - L_2 - L_3 + L_4 \\ L_z = L_1 + L_2 + L_3 + L_4 \end{cases} \tag{1}$$

III. Sensor Development

A 2×2 flexible coil array was used to develop a prototype tri-axis tactile sensor. Each coil has a diameter of 7 mm, and the distance between coils is 8 mm in both axis (Fig. 3(a)). There are two layers connected in series in each coil, 12 turns of loops in each layer. The loop trace has a width of 100 µm and pitch of 200 µm, and a thickness of 35 µm. A 2 mm thick, 10 mm diameter, cylindrical elastomer was made of silicone (Ecoflex 00-20, Smooth-on, USA). The sensing target was cut from 0.2 mm thick aluminium film in a 14 mm-square shape. The bottom surface of the elastomer is glued to the center of the coil array with a thin layer of silicone adhesive (ELASTOSIL® E 41, Wacker Chemie AG, Germany), then the aluminium film was glued to the top surface. The fabricated prototype was glued to an acrylic base to test and evaluate its performance (Fig. 3(b)).

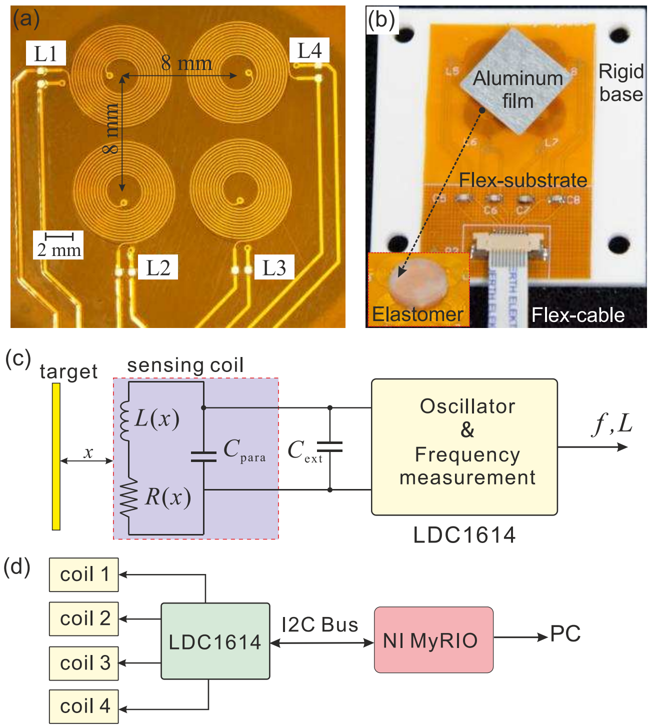

Fig. 3. (a) Magnified view of the flexible coils; (b) A tri-axis tactile sensor prototype; (c) The inductance measurement circuit; (d) The electronic interface for the sensor prototype.

As shown in Fig. 3(c), the electronic interface of this sensor is based on an LC oscillator, the oscillating frequency f of which varies with the coil's inductance:

$$f = \frac{1}{2\pi\sqrt{L\cdot(C_{para}+C_{ext})}} \tag{2}$$

A fully integrated, four-channel, digital inductance converter chip [11] (LDC1614, Texas Instruments, USA) is used to measure the inductance of the four sensing coils. The parasitic capacitance of the coil (C_{para}) is negligible, and a 220 pF NP0 capacitor is used as the external capacitance (C_{ext}) to form the oscillation network. The data is sent to a controller (NI MyRIO 1900, National Instruments, USA) via I^2C protocol. A LabVIEW program is developed to a) acquire and record data from the sensor and reference commercial force/torque sensor (Nano17-E, ATI industrial automation, USA), and b) to control the motorized micro-positioning stages.

IV. Evaluation

Firstly, the prototype was compressed by a rigid planar surface using the same experimental setup shown in [8]. Fig. 4(a) shows the inductance response with the applied normal force (0-13 N), which indicates that L_z is very sensitive to normal force, while some variation in L_x and L_y occurs due to imperfections in the sensor configuration. When the sensor is first preloaded with a normal force (8.4 N) the response alters, as shown in Fig. 4(b) with, L_x decreasing rapidly with shear force in the x axis but L_y and L_z have low variation. To obtain a calibrated force output from the measured inductances, a 2D scanning process (inset in Fig. 4(c)) was performed to collect a dataset of applied force and the corresponding inductance in z-x plane. Using the least-square-error fitting technique described in [8], a multi-parameter polynomial equation was calculated to

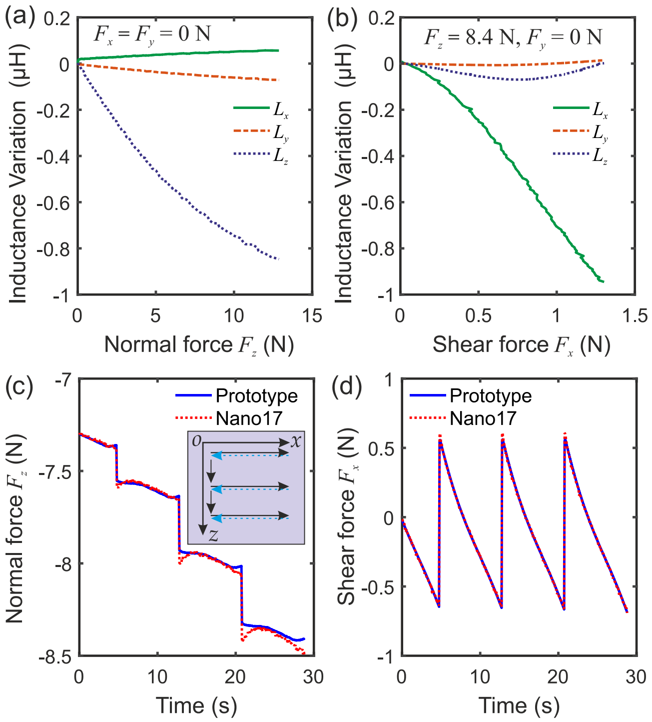

Fig. 4. Inductance to force response of the tri-axis tactile sensor prototype (a) Normal force (0-13 N); (b) Shear force (0-1.4 N with 8.4 N preload normal force); Calibrated force output of the prototype compare with the reference force from Nano17 (c) Normal force, scanning path (inset); (d) shear force.

describe the correlation between applied force and measured inductance. Thus, the real-time calibrated force output can be obtained from the measured inductance values. Fig. 4(c, d) shows the calibrated normal force (F_z) and shear force (F_x) output respectively when the sensor's top surface is moved lateral to apply shear force and the normal force is increased progressively. The results indicate a good match between the calibrated tactile sensor and the commercial reference sensor (Nano17, ATI). Noise testing results show that the sensor has a resolution (minimum detectable force) of approximately 0.3 mN (DC to 50 Hz) in all axes. By reducing the measurement time in the chip configuration, the sampling rate can be as high as up to 1 kHz.

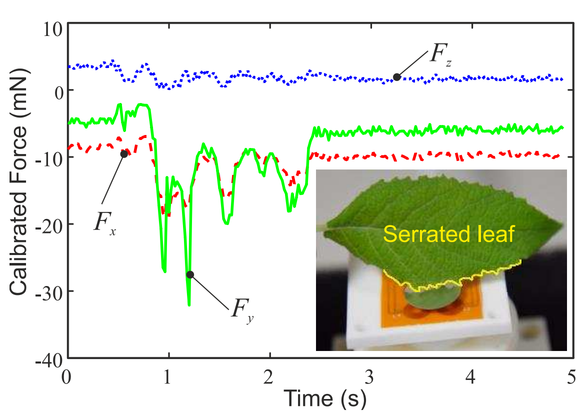

Fig. 5. The calibrated force output of the sensor prototype when a serrated leaf was moved across the sensor surface; the serrated leaf and the sensor prototype used for demonstration (inset).

To further demonstrate the sensor's capability, a new sensor prototype with a 14 mm circular target was developed and calibrated. A leaf with serrated edge was moved across the sensor's top surface, and the force output in all three axes was recorded and shown in Fig. 5. The serrated edges of the leaf result in shear force pulses (10 to 30 mN), which were clearly measured. A normal force as small as a few mN was also observed due to the light mass of the leaf.

V. Conclusion

In conclusion, we presented a new type of tri-axis tactile sensor, which is low-cost, robust, easy to fabricate and demonstrated high performance (0.3 mN resolution). Using a least-squares fitting technique for calibration, nonlinearity and cross-talk effects were minimized. The calibrated sensor shows comparable performance to an equivalent commercial force/torque sensor for multi-axis force measurements, but in a low-cost, flexible form.

In our ongoing work, more comprehensive characterization and calibration techniques (Soft Sensing Toolbox [12]) are being explored to more accurately and efficiently calculate force output from the directly measured inductances. We are also using computational models to optimize the geometry of the conductive target to achieve desired sensitivity in shear and/or normal force measurements. A miniaturized array version of this technology is being developed for a range of applications in robotics and healthcare. Furthermore, new materials and fabrication techniques offer the opportunity to produce a 'fully soft' tri-axis tactile sensor and improve durability to repeated physical contact.

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