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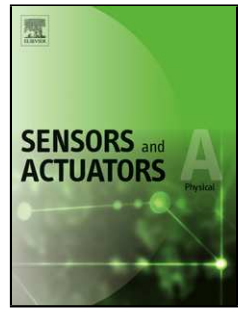

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Robust and High-Performance Soft Inductive Tactile Sensors based on the Eddy-Current Effect

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Highlights

- The first Soft Inductive Tactile Sensor (SITS) is proposed.
- Working principle and design methodology of SITS are discussed.
- A SITS prototype achieves a resolution of 0.82 mN in a range of over 15 N.
- The presented SITS can operate in water or other harsh environments.
- The SITS systems are low cost, durable, low hysteresis, and high performance.

Abstract

Tactile sensors are essential for robotic systems to interact safely and effectively with the external world, they also play a vital role in some smart healthcare systems. Despite advances in areas including materials/composites, electronics and fabrication techniques, it remains challenging to develop low cost, high performance, durable, robust, soft tactile sensors for real-world applications. This paper presents the first Soft Inductive Tactile Sensor (SITS) which exploits an inductance-transducer mechanism based on the eddy-current effect. SITSs measure the inductance variation caused by changes in AC magnetic field coupling between coils and conductive films. Design methodologies for SITSs are discussed by drawing on the underlying physics and computational models, which are used to develop a range of SITS prototypes. An exemplar prototype achieves a state-of-the-art resolution of 0.82 mN with a measurement range over 15 N. Further tests demonstrate that SITSs have low hysteresis, good repeatability, wide bandwidth, and an ability to operate in harsh environments. Moreover, they can be readily fabricated in a durable form and their design is inherently extensible as highlighted by a 4x4 SITS array prototype. These outcomes show the potential of SITS systems to further advance tactile sensing solutions for integration into demanding real-world applications.

Keywords

Tactile sensor, eddy-current effect, inductive sensor, planar coil, elastomer, conductive film

1. Introduction

Tactile sensors are essential components that enable robotic systems to interact safely and effectively with humans and the environment [1, 2]. They also offer significant potential for use in modern healthcare systems [3], including prosthetics [4], wearable health monitoring devices [5], and smart surgical instruments [6]. Compared to the visual and auditory senses, the tactile sensory capabilities provided by human skin [7, 8] are complex, combining large arrays of high performance, multi-modal sensory elements (receptors) within a mechanically compliant substrate (skin tissues) to extract information through deformation during interaction with objects [1, 9]. These attributes have provided a natural benchmark for those seeking to develop tactile sensors and achieve a comparable performance to biological systems such as human hand [10], notably in resolution, accuracy, bandwidth and mechanical compliance. To be effectively applied in real-world environments, it is advantageous that they are durable and robust to the repeated mechanical interaction inherent in tactile sensing. Research into tactile sensors which attempts to meet these challenging objectives has been catalysed by recent advances in enabling technologies, particularly printed organic electronics [11] and advanced materials [12]. Remarkable progress has been made in developing compliant sensory systems, with notable examples including an ultra-lightweight, tactile sensing array with integrated organic electronics [11], a printed flexible tactile sensing skin [13], self-powered sensors employing triboelectric effects [14] and systems using organic electronics that simulate the signalling outputs of the mechanoreceptors found in human skin [15]. Nevertheless, challenges remain in the ease with which tactile sensors can be fabricated, interfaced and integrated into robotic and healthcare systems. Researchers seeking innovations in tactile sensing have explored and exploited new materials, novel composites/structures, fabrication techniques and transducer mechanisms [16]. In this work we focus on the opportunity to use an alternative transducer mechanism to develop high-performance, robust and durable tactile sensors.

Tactile sensors are typically derived from modes of transducer sensitive to strain, stress, displacement or vibration. A wide variety of different transducer mechanisms have been exploited to date [17], with common modalities including piezoresistivity/resistance, piezoelectricity, triboelectricity, capacitance, optics/laser, and magnetic field [16]. Piezoresistive/resistive tactile sensors [18] are prevalent, and operate by measuring the resistance variations caused by changes in contact area between conductive materials, changes in conductive path in conductive elastic composites, or changes in the geometry of conductive liquids [19]. They are low-cost, and require simple readout electronics, but they also encounter low sensitivity, slow response, small dynamic range and large hysteresis. Recently, an ultra-sensitive resistive pressure sensor (1 Pa resolution) [12] has been developed by using an elastic hollow-sphere microstructured conductive polymer, however large hysteresis was observed. Piezoelectric sensors [20] generate electrical charges when force is applied. They are typically highly sensitive, but rigid, and only detect dynamic forces. Recently, novel piezoelectric composites and structures (e.g. PVDF [21] and piezoelectric nanowires [22]) have been developed for flexible tactile sensors. Capacitive tactile sensors [23] obtain force information by measuring the capacitance variations caused by the movement of one electrode toward another when force is applied to the elastic body. Flexible single-axis and three-axis forms of capacitive tactile sensors have been developed, for instance using conductive textile as electrodes [24]. Despite their high sensitivity and rapid response, capacitive tactile sensors require complex fabrication processes [25], and they are sensitive to environmental contaminants [26] (such as oil, dust, liquid and vaporous water etc.). Other research has exploited optical transducers for tactile sensing, typically using camera/photodetectors to monitor the deformation of soft skins [27]. This approach yields highly deformable systems, insensitive to electromagnetic interference and environmental contaminants. A notable example is a thin (<150 μm), transparent, flexible tactile sensor array based on a polymer-waveguide system [28]. However, it has relatively low sensitivity, poor repeatability, and large hysteresis in comparison to other sensing modalities. Magnetic field-based tactile sensors [29] have seen recent enhancements from the availability of integrated, compact, Hall-Effect sensing chips, providing sensors which are deformable, durable and low-cost [30]. This type of sensor has been integrated into fingertip of robotic hand to provide tactile sensing feedback [31]. However, they are directly affected by external magnetic sources or ferro-magnetic objects which change the local magnetic field distribution. These factors make such sensors prohibitive for applications involving objects made of ferro-magnetic materials (e.g. Iron, nickel, cobalt and their alloys).

One notable physical phenomenon which remains undeveloped in soft tactile sensing is the eddy-current effect, despite its ubiquity in industry [32] in the form of eddy current sensors (ECSs), which enable non-contact displacement sensing with high sensitivity, wide bandwidth and robustness to environmental contaminants [33, 34]. ECSs operate by monitoring the distance between an AC current excited coil and an electrically isolated conductor (sensing target) [34], a configuration which minimises the need to expose potentially vulnerable electronic elements near the external environment. Based on this principle, Texas Instruments developed a demonstration system to detect touch/force on metal buttons [35] by monitoring the inductance change of a coil situated underneath. We sought to exploit the advantages brought by ECSs and translate this technology into a form-factor that can be readily designed, fabricated and optimised toward soft tactile sensing for robotic and medical applications. Thus, in this work, we present the first Soft Inductive Tactile Sensor (SITS) which exploits an inductance-transducer mechanism based on the eddy-current effect. We explain the operating principle and discuss design methodology, and develop physical exemplars to evaluate their performance and illustrate their potential for real-world applications.

2. Working Principle

The key components of a SITS comprise three layered elements; a planar coil (the sensing element), a deformable middle layer (elastomer) and an uppermost conductive film (the sensing target), as shown in Fig. 1(a). The operating principle of a SITS is based on the eddy-current effect (a form of electromagnetic induction) [36]. The coil excited by an AC current (typically 0.1—10 MHz) generates alternating magnetic fields which induce eddy currents in the nearby conductive film. The induced eddy currents in the film simultaneously generate magnetic fields which oppose those emitted from the coil, thus reducing the flux in the coil and dissipating energy [34]. This magnetic field coupling between the coil and the conductive film therefore acts to reduce the coil's effective inductance and increase its resistance. Applying an external force to the SITS displaces the conductive film toward the sensing coil (through deformation of the elastomer), which increases the induced eddy-currents and in turn decreases the coupled inductance of the coil. The SITS can thus be calibrated to relate the force applied to the sensor with the resultant inductance of the sensing coil. These principles can be extended from the single node SITS described above to an array version as illustrated in Fig. 1(b).

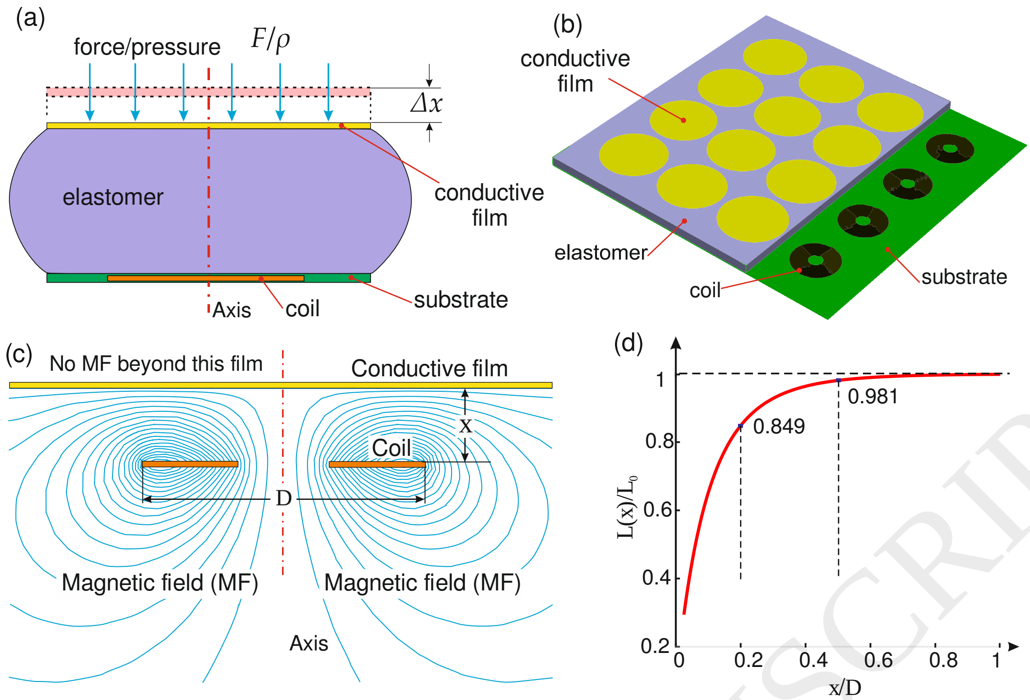

Figure 1 Schematic diagram of a soft inductive tactile sensor (SITS) and its working principle (a) A single node SITS; (b) A 4 × 4 array of SITS; (c) Magnetic field coupling between the coil and the conductive film in the SITS; (d) Normalized inductance to distance response of a SITS.

A key requirement for effective operation of the SITS is that the conductive film acts as an effective sensing target (to achieve appropriate measurement sensitivity) and an electromagnetic shielding layer (to avoid interference during interaction with conductive or ferromagnetic objects) as shown in Fig. 1(c). These aspects are governed by the geometry, excitation frequency, and electrical properties of the conductive film. A design guideline was derived through existing theories [36] and computational models [37], that the conductive film should have a diameter greater than the excitation coil and a thickness larger than the eddy-current penetration depth δ [36] (29.2 μm for copper at 5 MHz). The normalized response of a SITS, shown in Fig. 1(d), was determined through parametric analysis of a Finite Element (FE) model (using AC/DC module in COMSOL Multiphysics, Sweden). This indicates that the maximum distance between the coil and the conductive film is approximately 50% of the coil's diameter, whereby the closer the target, the higher the sensitivity. Similarly, decreasing coil size will increase the sensitivity, but lower the maximum coil-film distance [38]. Another attractive feature of SITSs is the ease with which their measurement performance can be designed and optimised for the requirements of a particular task. This is because the magnetic field coupling between the coil and the conductive film is independent of the mechanical properties of the elastomer. Thus the force measurement range, resolution and dynamic response can be adjusted through design of the elastomer (e.g. changing geometry, structure or materials property). For example, in SITSs with the same elastomer geometry, increasing material compliance will increase sensitivity (better resolution) but reduce measurement range.

2. Prototypes development

2.1 Sensor design

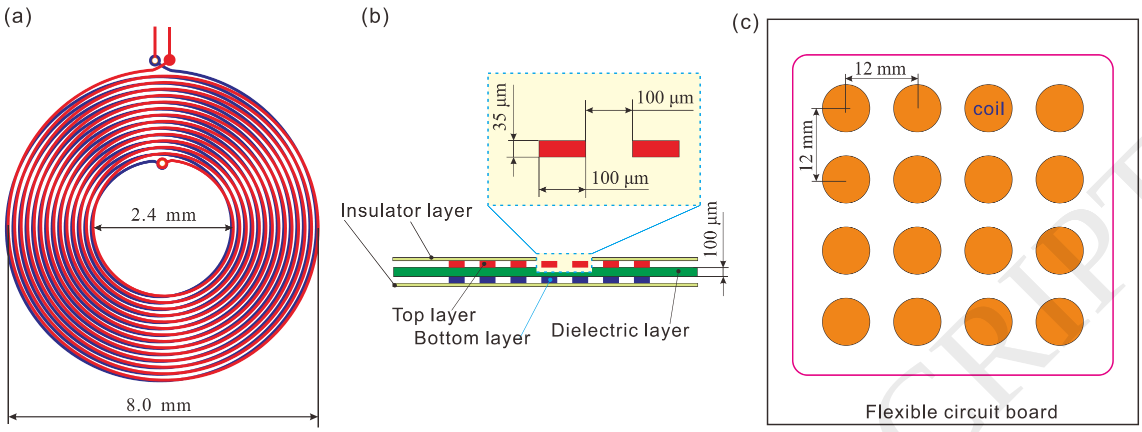

Figure 2 (a) Schematic of the double layer spiral coil; (b) Cross-section structure and dimension of the coil loops; (c) The configuration of the 4×4 coil array.

Double-layer spiral coils were designed to be fabricated by standard flexible printed circuit (FPC) manufacturer for SITS systems. As shown in Fig. 2, each coil has an outer diameter of 8.0 mm, and inner diameter of 2.4 mm, comprises 14 turns in both top layer and bottom layer. Both the width and space of the loop trace are 100 µm, and the thickness of the trace is 35 µm. The total thickness of the flexible coil is 0.2 mm. The minimum width and space of loop trace is determined by the fabrication capability of the FPC manufacturer (FS technology co., ltd, Shenzhen, China). The inductance of planar coil can be estimated by using empirical equations or numerical methods [39]. Here, we used FE models in COMSOL to calculate the inductance and predict the sensor's response to conductive film. The coil diameter is chosen to achieve a relatively large inductance (e.g. 5 µH) to realize a high resolution of inductance measurement using commercial available chips. The 4 × 4 coil array and conductive films have a distance of 12 mm in both axes (Fig. 2(c)). The conductive target is a circular copper film (35 µm thick) with a laminated polyimide substrate (75 µm thick), which has a diameter of 11 mm. Both the single element target and the target array were designed and fabricated by the same methods as the flexible coils.

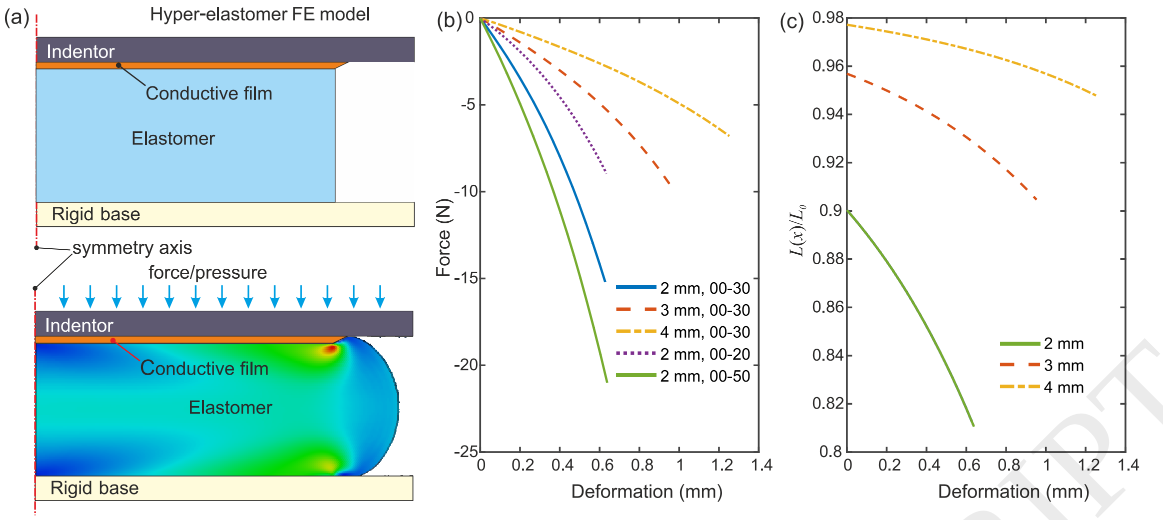

Figure 3 (a) FE model of a SITS elastomer structure in Abaqus (top) and von Mises stress of the deformed elastomer (bottom); (b) The force to deformation relationship of elastomers with different thicknesses and materials; (c) The inductance response to SITSs with different elastomer thicknesses.

Simple circular elastomers were used to develop the SITS systems as illustrated in Fig. 1(a). To investigate the force-deformation relationship of circular elastomers, a symmetric FE model of the SITS elastomeric structure was developed in Abaqus (Dassault Systèmes, France). The material properties were approximated using a hyper-elastic neo-Hookean model with shear moduli of 6077 Pa, 12350 Pa, and 20010 Pa for Ecoflex 00-20, 00-30, and 00-50 respectively. The elastomer was assumed to be axisymmetric and bounded by two rigid plates. The upper plate also contained a rigid layer representing the conductive film. The top plate was displaced and the reaction force exerted by the elastomer was recorded. The von Mises stress of a deformed elastomer is shown in Fig. 3(a) (bottom). Using this FE model, the force-deformation relationship of five circular elastomers (12 mm diameter, 2 mm, 3 mm, and 4 mm thickness using Ecoflex 00-30, 2 mm using Ecoflex 00-20 and 00-50) were calculated and plotted in Fig. 3(b). This indicates that thick elastomers are softer than thin ones, and have larger maximum deformation. Figure 3(c) shows that a SITS with thick elastomer has less inductance variation even though the deformation is larger. Thus, thick elastomer results in softer structure, but lower inductance to distance sensitivity. SITS systems with 2 mm elastomers made of different materials will have exactly the same inductance to deformation response. Thus, the one with softer material will have higher sensitivity (better resolution), but lower force range.

2.2 Fabrication and assembly

Uniform silicone sheets (Ecoflex 00-20, 00-30, and 00-50) with the required thickness (2 mm, 3 mm, and 4 mm) were cast using standard mould-casting procedures [29]. Two parts of the liquids were mixed by 1:1 weight and de-gassed, then poured into the mould to cure at room temperature. All circular silicone elastomers were cut by a laser cutter (VLS 3.50, Universal laser systems) from these uniform silicone sheets. Finally, these elastomer were cleaned by ultrasonic in isopropanol bath for 2 minutes to remove ashes generated by the laser cutting process. Figure 4(a, b) shows the three components of a SITS and the magnified view of a flexible coil for SITS prototypes. To assemble the SITS prototypes, the flexible coils were first glued to the rigid acrylic base with double sided tape (3M, USA). Then, conductive films were glued to elastomers with a thin layer of silicone adhesive (ELASTOSIL® E 41, Wacker Chemie AG, Germany). Lastly, the elastomers with conductive films were glued to the flexible coils with the same methods. An assembled SITS prototype is shown in Fig. 4(c).

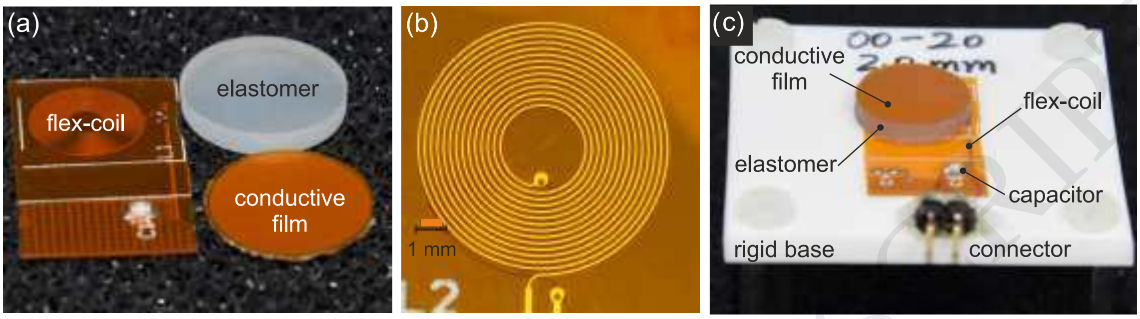

Figure 4 (a) The three components of a SITS; (b) Magnified view of a flex-coil for SITS prototypes; (c) An assembled SITS prototype;

2.3 Electronic interface

To obtain the force applied to the elastomer, the coil's inductance at the working frequency needs to be monitored in real-time. As shown in Fig. 5(a), the inductance measurement circuit used for SITS systems is an LC oscillator that comprises the inductive coil and an external capacitor in parallel. The oscillating frequency of this *L*-*C* network varies with the inductance:

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

where C_{para} is the parasitic capacitance of the coil and the cable, C_{ext} is the capacitance of the external capacitor. A fully integrated, four channel, digital inductance converter chip [40] (LDC1614, Texas Instruments, USA) is used to drive the inductor-capacitor network and measure its oscillating frequency, thereby the inductance of the coil. The coil (including a 10 cm coaxial cable) has an inductance of 4.9 μH. As discussed in section 2, to achieve both good measurement sensitivity and an effective shielding effect, the penetration depth of the eddy-currents should be less than the conductive film thickness (35 μm in the presented prototypes), requiring an operation frequency above 3.47 MHz. If the chip operates at its maximum frequency of 10 MHz, the LC network requires a minimum external capacitance of 51 pF for stable measurement. However, in this configuration the measured inductance would be easily affected by parasitic capacitance (comparable in magnitude to the external capacitor). Therefore, a larger 220 pF NP0 capacitor is used to form the oscillator, operating at a lower frequency of approximately 5 MHz in our design. The coil is driven by an AC current of 0.5 to 0.8 mA at the oscillating frequency of the LC network. The digital output of each LDC1614 is sent to a microcontroller (myRIO, National Instruments, USA) via I2C protocol. The maximum sampling rate of the system is determined by the conversion time of the LDC1614 chip, representing the number of reference clock cycles used to measure the sensor frequency. Therefore, higher sampling rates (of up to 4.08 kHz as limited by the I2C communication) can be achieved by configuring shorter conversion time at the expense of increasing noise. For the 4×4 sensing array, four LDC1614 chips are used to measure the inductance of the 16 coils. Each chip provides 4 channels, each channel can operate up to 1.02 kHz sequentially. For the 16 nodes sensing array, the theoretical max speed is 1.02 kHz since four LDC1614 chips can work in parallel. Texas Instruments also provides another single-channel, high-speed LDC chip (LDC1101) which can reach a maximum sampling rate of 183.8 kSPS using a SPI communication bus. A double channels, 1-of-4 multiplexer (SN74CBTLV3253, TI, USA) was used to switch the I2C bus sequentially from one LDC1614 chip to another (Fig. 5(b)). The PCB including LDC1614 chips, 40 MHz external crystal oscillators (clock), a Multiplexer, and connectors were designed, fabricated and assembled for single-node and array version of SITS prototypes.

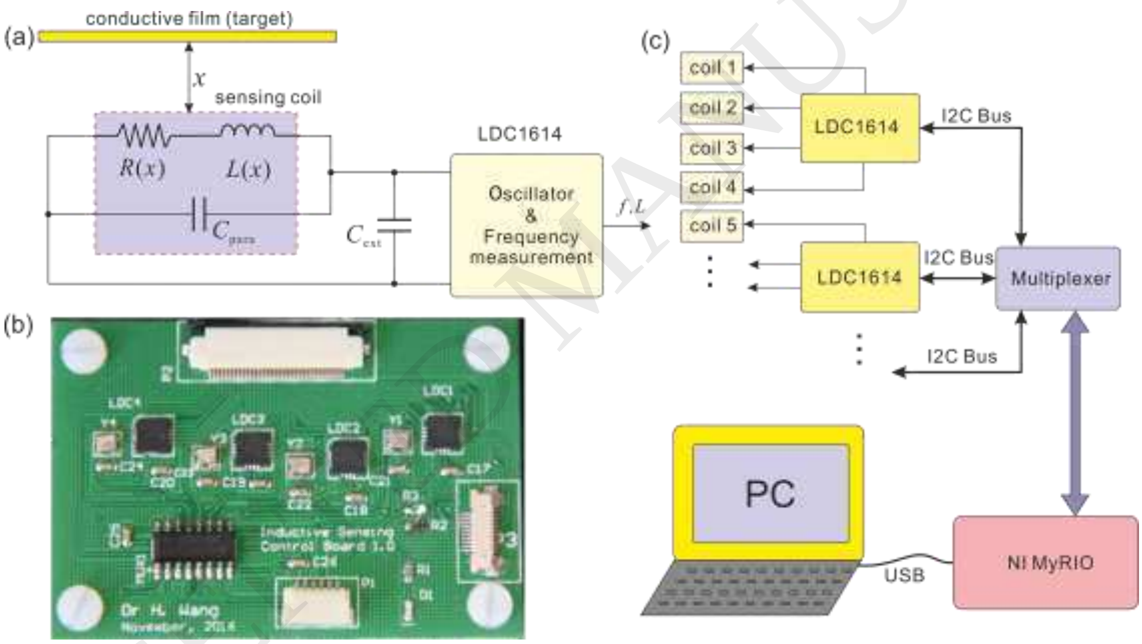

Figure 5 (a) Schematic diagram of the inductance measurement circuit for SITSs; (b) The PCB used for SITS prototypes; (c) Schematic diagram of the electronic interface for the 4×4 SITS array.

3. Experiments and Results

3.1 Experimental Setup

To characterize and evaluate the SITS prototypes, an experimental testing setup (Fig. 6) was built, which comprises a motorized micro-positioning stage (T-LSR75B, Zaber Technologies Inc, Canada) to move the SITS prototypes in z axis, two manual positioning stages to move the indenter in x and y axes, and a 6-axis force/torque sensor (Nano17-E, ATI industrial automation, Apex, NC, USA) to monitor the force. The motorized stage has a minimum step of 0.5 μm, a travel range of 75 mm and repeatability of 2.5 μm. The force/torque sensor has a measuring range of ±35 N in the *z* axis, and in *x*/*y* axis, with a resolution of ±6.25 mN. A custom program was developed for the microcontroller system (using LabVIEW, National Instruments) to acquire and record data from the force sensor and SITS systems simultaneously, and to control the positioning stage through the test procedures. As illustrated in Figure 6, the z-axis motorized stage carries the sensor prototype to move down against a flat rigid surface fixed on the load cell to apply load. The sensor's deformation increases/decreases incrementally with 10 μm step size through the movement of the motorized stage, until it reaches a pre-set final position (or critical force). In each step, the stage move 10 μm and pause for a few milliseconds. Immediately after the stage finish its 10 μm movement, the program acquire a dataset of inductance measurement and reference force (from load cell), and write this dataset into local file for post processing.

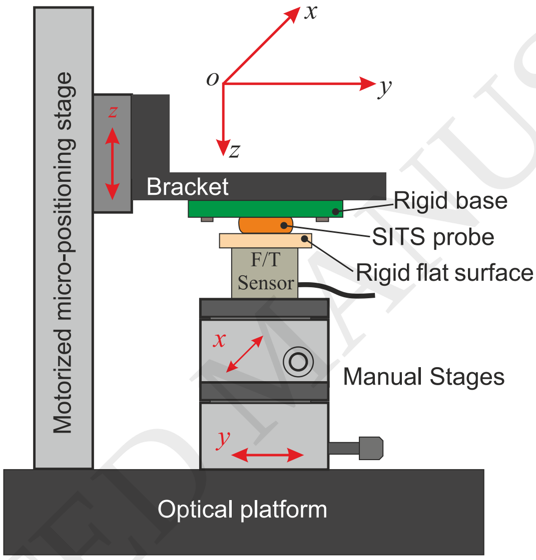

Figure 6 Experimental setup

3.2 Characterization

To characterize the SITS prototypes and validate the design, five prototypes with different elastomer thickness and materials (2 mm, 3 mm, and 4 mm using Ecoflex 00-30, 2 mm using Ecoflex 00-20 and Ecoflex 00-50) were fabricated and tested. As shown in Fig 7(a, b), the thin-elastomer prototype yields a stiffer sensor structure than that of the thick-elastomer prototype, and has a larger inductance variation per unit deformation (because the conductive film is closer to the coil). Overall, this results in similar inductance to force sensitivity (Fig. 7(c)) and force measurement resolution (Fig. 7(d)). Figure 7 (c, d) also illustrated that these prototypes become less sensitive (lower resolution) at high force due to much higher stiffness of the elastomers when they were deformed. It is a desirable feature that these sensors can detect smaller force variation at low force. The 2 mm prototype with a softer elastomer material achieved a higher resolution than the stiffer one at the expense of a lower force measurement range. The resolution (minimum detectable force for a given bandwidth) is calculated by $Res=N_L/S_{dL/dF}$, where N_L is the RMS noise of inductance measurement at a sampling rate of 100 Hz, S is the sensitivity of inductance to force. The key attributes and performance determined for all five prototypes are summarized in Table 1. It should be noted that the "Characterized Range (N)" stated is the range over which we tested the sensor, but the ultimate upper limit will be significantly higher, limited only by material strength of the elastomer and adhesive. The resolution values listed in Table 1 are the zero force resolution for each prototype, which increases to approximately 2 times at high force (Figure 7(d)). As detailed in the last row of Table 1, these prototypes have a similar dynamic range of approximately 14 measurement bits within their characterized range.

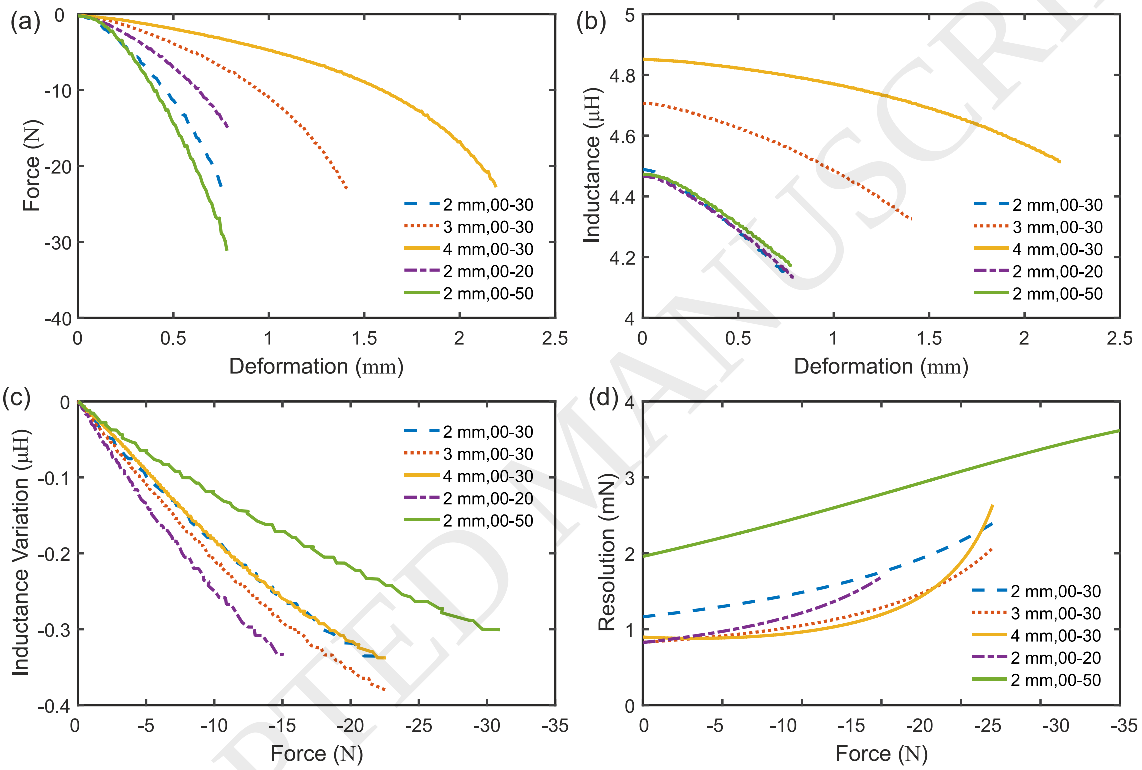

Figure 7 (a) The compression force to deformation of the five SITS prototypes with different elastomer thicknesses (2 mm, 3 mm, and 4 mm) and materials (Ecoflex 00-20, 00-30, and 00-50); (b) The inductance to deformation of these prototypes; (c) The inductance variation to applied force of these prototypes; (d) The force measurement resolution of these prototypes with applied force (at DC to 100 Hz).

Table 1 Parameters and performance of the five SITS prototypes

Prototypes	#1	#2	#3	#4	#5
Elastomer Thickness h	2 mm	2 mm	2 mm	3 mm	4 mm
Elastomer Materials (Ecoflex)	00-20	00-30	00-50	00-30	00-30
Unloaded Inductance (μH)	4.47	4.49	4.47	4.71	4.85
Noise N_L ($\times 10^{-5}$ μH)	2.43	2.39	2.67	1.90	1.65

Resolution *Res* (mN)	0.82	1.16	1.96	0.83	0.90
Characterized Range (N)	15	22	30	22	22
Dynamic Range (bits)	14.16	14.21	13.91	14.69	14.58

3.3 Evaluation & demonstrations

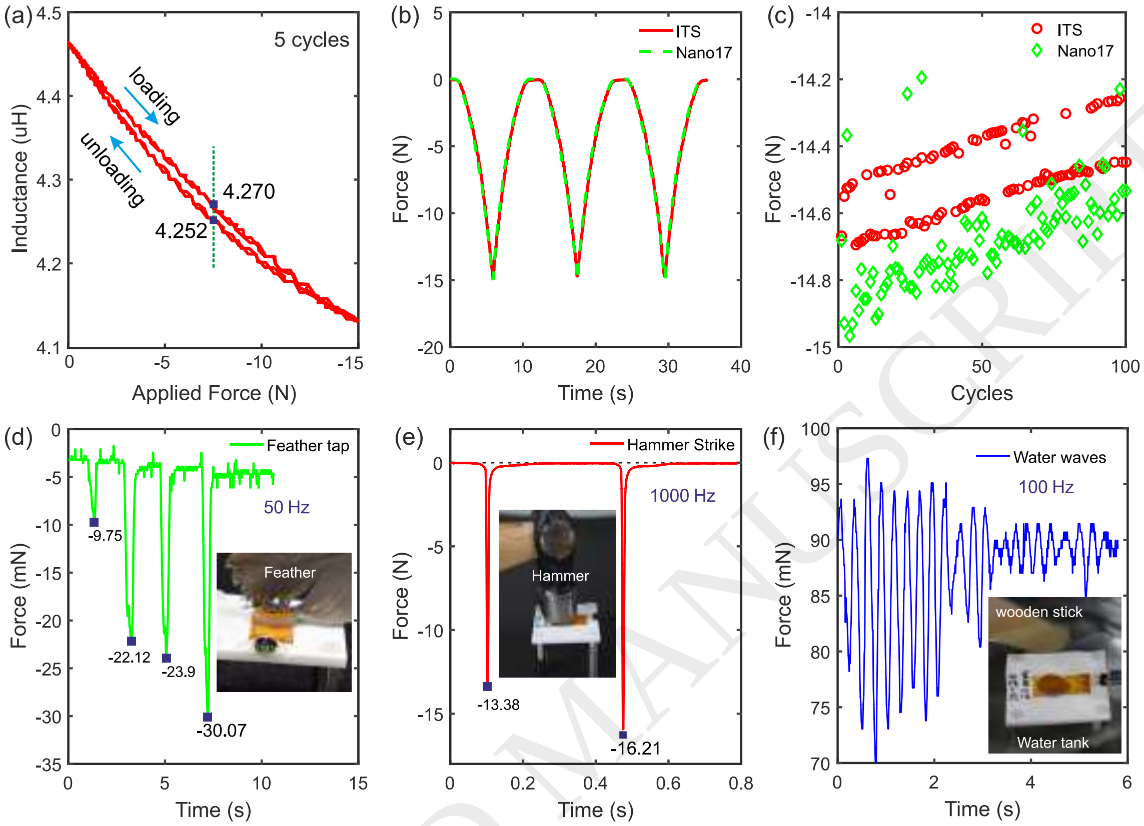

Figure 8 (a) Inductance variation of a SITS prototype during 5 cycles of loading and unloading process (0- 15N, velocity: 1 mm/s); (b) The calibrated output of a SITS in a cyclic indentation test compared to the reference sensor Nano17; (c) The loaded output of a SITS and Nano17 during 100 indentation cycles; (d) The output of a SITS when gently tapped by a feather; (e) The output of the same SITS when hit by a hammer; (f) The output of the same SITS when it is submerged with ripples on the surface.

To further evaluate the performance of SITS systems, we conducted additional tests using prototype #1 (Ecoflex 00-20, 2 mm elastomer). Inspecting the inductance variation to compression force during cyclic loading, reveals a maximum hysteresis of 5.4% for 15 N load at a velocity of 1 mm/s (Fig. 8(a)) attributed to the viscoelastic properties of the elastomer. The SITS prototype was calibrated using these data with polynomial curve fitting, then this was used to determine force output from the measured inductance data. Figure 8(b) shows the calibrated force output from the SITS prototype during a repeated indentation process with respect to a commercial reference sensor (Nano17). The standard deviation of the SITS prototype's force output is only 0.75% of the applied force (15 N) during 100 cycles of indentation in approximately 20 minutes (Fig. 8(c)), in comparison to 0.96% for the reference sensor Nano17.

A series of demonstrations were then conducted to illustrate the capability of SITSs for real-world applications. Firstly, a SITS prototype was gently tapped by a feather, and small forces (10 mN to 30 mN) were clearly measured (Fig. 3(d)). Secondly, the same ITS prototype was then hit with a hammer and the force output was recorded at 1000 Hz (Fig. 3(e)), which demonstrates that the SITS prototype is capable of reliably capturing the impact with 16 N peaks occurring in less than 5 ms during a hammer strike. We limited the strikes in this paper to avoid test to failure as they were intended to demonstrate that a wide range is possible, rather than define absolute limits. Finally, the SITS prototype was placed in a tank and it continued to operate while submerged under 20 mm of water, with the sensitivity to detect the pressure variation from ripples induced on the surface (Fig. 3(f)). A video clip shows the action and the corresponding results of the above demonstrations (SITS Demo Video_SNA.mp4). In summary, SITS systems can be used in applications to detect rapid phenomena, operate across a large dynamic range, with high resolution and robustness in harsh environments.

4.4 Multi-node SITS Demonstration

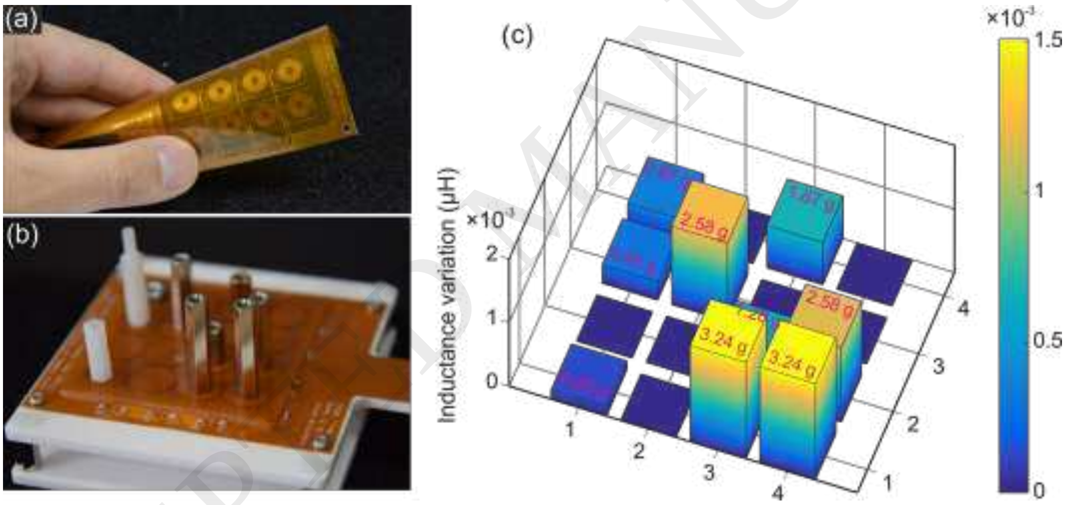

Figure 9 (a) A 4×4 flexible coil array; (b) An assembled 4×4 array SITS loaded with brass and plastic hex nuts; (c) The resultant measurement from the 4x4 SITS array under loading.

A 4×4 coil array was fabricated (Figure 9(a)) to produce a multi-node SITS. By laminating a sensing coil array film, a 54 mm × 54 mm × 2 mm silicone sheet (Ecoflex 00-20) and the circular conductive film array, a 4×4 SITS array was assembled and fixed to a rigid plastic base for testing (Fig. 9(b)). A series of plastic/brass hex nuts (weighing from 0.25 g to 3.24 g) were placed on different locations of the sensing array, the corresponding coils' inductance variation were recorded and plotted in Figure 9(c). The results clearly show the presence of these hex nuts and their different weights. It is illustrated that the SITS design can be extended from a single node into a multi-node form.

5. Discussion and Conclusion

This paper presents the first soft inductive tactile sensor (SITS), which exploits an inductance-based transducer mechanism based on eddy-current effect. The working principle of the sensors and the associated design methodology were discussed with reference to theoretical and computational models, and prototypes were developed and evaluated. It is demonstrated that SITSs can achieve high performance (sensitivity, bandwidth, dynamic range etc.), and they are robust to operate in harsh environments. An exemplar prototype achieved a state-of-the-art resolution of 0.82 mN (7.3 Pa) across a large dynamic range (14 bits) with low hysteresis and good repeatability. The same sensor was able to operate while submerged in water and to detect pressure variation from ripples on the water surface. A 4 × 4 SITS array demonstrates that the sensing principle can be extend to an array form to cover a large surface for force mapping. Furthermore, tri-axis force sensing based on the same concept can be developed by using multiple coils with single conductive film [41].

In this work, our testing has been limited to planar surfaces, although the operating principles indicate that SITS will also operate on curved surfaces. However, recalibration would be required to achieve accurate results as self-inductance and sensitivity would change. Crucially, the modular and flexible design of SITSs makes it easy to customize their performance and form to facilitate integration into different robotic and healthcare systems. While the presented prototypes have a relative large coil size of 8 mm diameter, the design of SITS is inherently scalable, coil size could range from 50 mm to 2 mm with the current configuration of LDC measurement chip and a proportionally scaled elastomer. As coil size decreases further, the system requires higher driving frequencies to ensure an appropriate large inductive reactance ($2\pi fL$) for high resolution measurement of inductance. For instance: a micro-coil (1 mm diameter) could also be used to develop inductive displacement/tactile sensors by exploiting high frequency electronics (e.g. 60~90 MHz [42]). In this case, a customized integrated circuit should be placed near the coil to achieve a robust system as electromagnetic interference from these lead wires could affect the results and the inductance of lead wires would be comparable to the coil's inductance.

As a deformation/displacement-based tactile sensing technology, SITS have similar features as capacitive tactile sensors, but with the addition of insensitivity to environmental contaminants (liquid, dust, non-magnetic medium, etc.). Furthermore, SITS do not require wire connection to the upper conductive film, enabling fabrication in a durable form for real-world applications. Benefiting from the working principle of AC magnetic field coupling, SITS are superior to Hall sensor-based systems (e.g. sensors like MagOne [29]) due to two key factors. Firstly, SITS are inherently insensitive to external magnetic field interference as the effective inductance of the coupled coil-conductive film structure is measured at a single frequency. Secondly, measurements won't be affected by conductive and/or ferromagnetic objects as the conductive film acts as a shielding layer for the sensor. Hall-effect based-tactile sensors must be placed in-site and are directly affected by external magnetic sources or ferro-magnetic objects which change the local magnetic field distribution. These factors make such sensors prohibitive for applications involving objects made of ferro-magnetic materials (e.g. Iron, nickel, cobalt and their alloys). Hall-effect based-tactile sensors are easy to scale up or down and can achieve three-axis force measurement with a compact chip, which can be an advantage for some applications. It should be acknowledged that SITS do have a notable drawback in their reliance on complex signal conditioning electronics. Integrated circuits (ICs) for inductance measurement are more complex and less mature in comparison to ICs for resistance and capacitance measurement. To the authors' knowledge, the LDC series from Texas Instruments are the only commercially available Inductance to Digital Converter chips. However, with continued developments on inductance measurement ICs in this area [43], fully integrated SITS with embedded electronics are achievable in the near future.

Our ongoing work is focused on enhancing the capabilities of SITS systems. In particular, we are optimizing multi-axis SITS and increasing measurement capabilities by measuring both the inductance and resistance of the coil to determine force and temperature simultaneously. In parallel, we are exploring innovations enabled through new materials (e.g. conductive textile, metal liquids, or conductive inks) and fabrication techniques (e.g. 3D printing of soft materials, Ink-jet printing, direct-ink writing), to enable stretchable and increasingly durable sensors to address the rapidly expanding needs of the robotic and bioengineering sectors.

Supporting Information

A video clip shows the action and the corresponding results of the demonstration tests in Section 4.3 is available (SITS Demo Video_SNA.mp4).

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