Analysis of a Soft Haptic Device with Integrated Tactile Sensor and Actuator for Optimal Design

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Abstract—This paper presents the analysis of a soft haptic device comprising of tightly integrated touch sensor and actuator (SensAct). The integrated SensAct device comprises a piezoresistive touch sensor fabricated on the top of a flexible micro coil based electromagnetic actuator. The effect of the Joule heating from the coil was studied using the fabricated device and the design parameters such as magnetic force, actuator displacement for different currents were determined through a finite element simulation. The Joule heating is seen to occur only for current values from ~90mA and above and below this value, the actuator/sensor pair works well. From the steady-state analysis using the finite element simulation, the possible thickness-mode displacement was observed to be around ~200µm with ~20 mN magnetic force produced by the coil. These results show the potential of SensAct devices for vibrotactile feedback and with programmable thickness mode movements they could lead to intelligent interactive surfaces.

Keywords—e-Skin, Electromagnetic Coil, Flexible Actuator, Soft robotics, soft sensor; Touch Sensor; Interactive Surface

I. INTRODUCTION

Efforts to develop biomimetic electronic skin (e-Skin) [1]–[3] have significantly driven the research towards touch sensory feedback through development of a wide variety of soft, flexible and stretchable tactile sensors [4], [5]. Among the transduction mechanisms explored for tactile sensing, the capacitive [6]–[8] resistive [9], [10], piezoelectric [11]–[13] and optical [14] mechanisms are most popular. Despite the huge progress related to the development of tactile sensors, the e-Skin still lacks many key capabilities needed to respond like the human skin. For example, the mechanoreceptors in human skin are tightly coupled with muscles, as a result of which the stiffness of skin can be tuned. In this regard, an interesting engineering approach is to realize e-Skin with both tactile sensing and actuation [15]. By simultaneously controlling the actuator via the output of the sensor or controlling it separately, the granularity of the information extracted from e-Skin could be enhanced. This has a significant impact in applications such as, intelligent interactive surfaces [16], soft robotics [17], [18], wearable systems [19], virtual reality [20] and rehabilitation [1]. The actuators can be systematically programmed to move the interactive e-Skin in a chosen fashion.

Different mechanisms have been explored for the realization of both flexible and soft actuators including electromagnetic [21], electrostatic [22] etc. Skin-like actuation has also been explored by using various artificial muscles technologies such as liquid crystal networks, shape memory alloy, dielectric elastomers, carbon yarns, piezoelectric polymers, ferromagnetic elastomers, and conductive polymers etc.[23]–[25]. However, these solutions still lack the sensing capability as in humans. In this regard, we recently developed the SensAct devices having a touch sensor integrated on a flexible micco coil based electromagnetic actuator [15]. Although the fabricated SensAct device showed good performance, the development of an array of such seamlessly integrated sensors in tandem with the actuators require adequate analysis and optimization of the sensor/actuator pair – to understand their working as well as to improve the overall performance.

This paper presents the analysis of SensAct [15] through further characterization of the fabricated device and simulation using COMSOL Multiphysics [26]. The presented device comprises an electromagnetic actuator integrated with a piezoresistive pressure sensor as shown in Fig. 1. Sensing takes place through the change in resistance that occurs when pressure is applied on the piezoresistive sensing layer. The actuation layer leverages the magnetic interaction between the flexible coil and the embedded tiny permanent magnet to produce repulsion or expansion depending on the direction of current. This study aims to understand and establish design parameters (e.g. current requirements, displacement, actuation force, sensor-actuator separation distance) necessary for improving the device’s performance for application in eSkin.

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Fig. 1. Structure of the Integrated sensing and actuating (SensAct) device and application in the interactive surfaces.
interactive surfaces etc. as exemplified in Fig.1. In particular we have carried out: 1) Characterization of the fabricated device to understand the effect of joule heating from the coil on the integrated sensing layer for current ranging from 90mA to 180mA, below which heating is negligible; 2) a finite element analysis of SensAct using COMSOL Multiphysics to understand the interaction of the magnetic force from the coil and that of the magnet and the optimum distance of separation, between coil and magnet, as well as possible displacement using higher current values (1A up to 10A). This is necessary for the redesign of SensAct for future applications.

This paper is organised as follows: the design, fabrication and simulation of SensAct devices are described in Section II. The results are discussed in Section III and a summary of key outcomes is presented in Section IV.

II. DESIGN, FABRICATION AND SIMULATION

A. Fabrication

The fabrication involves two main modules, the sensing module and the actuation module, both of which were fabricated as detailed in [15]. The sensing layer was fabricated on a 12mm diameter × 1mm thin NdFeB disc magnet (Grade N42, 0.73kg pull) using graphite paste, and Sil-Poxy™ as the encapsulant, while the main element of the actuating layer, 15μm-thick spiral coil was fabricated following the LIGA process. Details of the fabrication steps for both sensing and actuation as well as their integration are described in [15].

B. Characterization

Considering that the sensing and actuation layer are integrated, the effect of joule heating from 15μm-thick spiral coil on the integrated piezoresistive sensing layer was studied. This is because the actuator uses the electromagnetic coil, and joule heating is bound to occur when current runs through the 15μm-thick coil over some period. We studied this effect for coil current ranging from ~90mA up to 180mA. Below 90mA, the heating is negligible and the integrated actuator/sensor works well as reported in [15]. To do this we first characterized the sensing layer without any current through the coil to calibrate the output of the sensor. This was carried out by attaching the device firmly to a stable 1004 glass probe attached to a controllable linear stage, forces from 0 to ~3.5N were systematically applied on the sensor. The output of the sensor was logged using an E4980AL LCR meter (Keysight Technologies, Santa Clara, CA, USA) by measuring the change in their resistance. In order to drive the actuator and measure the heating effect on the sensor, the actuator was connected to a signal generator, power supply and a simple constant current source, while the output of the sensing layer was connected to the LCR as described previously. By driving the integrated actuator on and off with different currents (~90mA to 180mA), for equal number of time (34 s) the output of the sensing layer was logged simultaneously using the LCR meter.

C. Simulation

The AC/DC module of COMSOL Multiphysics was used to analyze the device. In order to improve the simulation time and computational complexity of such a device, the spiral coil was approximated as a homogeneous toroidal coil, and its 3D model was represented as a simple cylinder with the same dimensions as the initial coil. The coil was assumed to be 45 turns of a thin wire (AWG 40 with the same electrical properties as the SensAct device. The neodymium magnet was placed on top of a coil and was defined as a N42 NdFeB magnet (Chinese magnet standard), with a magnetization of 1000 kA/m (Fig. 2). The neodymium magnet was simulated using a magnetization model and the coil was simulated with a relative permeability. These 2 components were then embedded into an Ecoflex elastomeric material and integrated fully into an air domain with a normal atmospheric pressure of 1 atm, ambient temperature of 293.15K and a gravitational acceleration of 9.81 m/s². Two main steady state analyses were carried out during the simulation: 1) using small current (1mA to 48mA) as in our original fabricated SensAct [15]; and 2) using higher current values (1A to 10A) to explore further the effect of current on the displacement of the magnet so as to optimize it for future application. The steady-state analyses were carried out and the force at various displacements (100μm to 800μm) was measured. To find out the thickness mode displacement of the magnet when the spiral coil was excited, the distance between the coil and the magnet was parametrized, along with the excitation current excitation current. The simulation was solved using the Flexible Generalized Minimal Residual Method (FGMRES) Solver with a critical maximum convergence parameter of 10⁻⁴, and the magnetic fields and solid physics were solved in parallel, to ensure that the simulation accounts for the solid properties of the Ecoflex encapsulation.

III. RESULTS AND DISCUSSION

Fig. 3a shows the result of characterizing the sensing layer using different applied forces with no current flowing through the coil. This shows that as the force on the sensing layer increases, there is a decrease in the resistance of the layer which is as a result of the graphite particles coming closer to form a conducting matrix. It shows a relative change is resistance (AR/R₀) of ~20% for a range of 0.5 to 3.5N.

The effect of the heat produced by coupling the coil and the sensing layer was studied by examining the drift in the sensor’s resistance. It was observed that the resistance of the sensor increases as the current increases (Fig. 3b). This is because joule heating increases with coil current, and this heat is transferred to the coupled sensing layer causing its resistance to change over time. Points A, B, C, and D shown in the inset at the bottom of Fig. 3b represents the time when
the actuator was turned on for 180mA, 160mA, 130mA and 90mA respectively. This shows that after the actuation was turned on, there was no significant drift in the resistance of the sensor for at least ~2 seconds. The drift occurs from supply current of ~90mA which is also the coil’s safe current limit. After a current of 90mA, the temperature of the coil starts to rise significantly. The inset in Fig. 3b shows the drift caused by this current, and this ranges from ~0.005Ω/s to ~0.04Ω/s for coil current ranging from 90mA to 180mA respectively.

The magnetic flux density and the interaction between the coil and the magnet can be observed in Fig. 4a with a maximum magnetic flux of ~50 mT. Fig. 4b and Fig. 4c show the resultant magnetic force, for small currents (1mA to 48mA) and larger currents (1A to 10A) respectively. In both cases the resultant force is zero at ~200µm. At this distance the magnetic force equals the other opposing forces such as the weight of the magnet (~5.89x10^-7 kg), gravity (9.8m/s^2), and Ecoflex encapsulation. After this point, the magnetic force becomes too low to displace the magnet. It can be safely assumed that the magnet’s possible displacement lies somewhere in this range. The insets in both Fig. 4b and 4c show an increase in force with increasing current, which will be a guide for choosing operating current during fabrication and characterization stage. Fig. 4b and Fig. 4c also give an insight to the possible force acting on the magnet at different coil-magnet separation distances. This is useful for choosing the separation distance during the fabrication of the actual device.

IV. CONCLUSIONS

This paper presented the analysis of an integrated sensor and actuator device (SensAct) for optimal design. The fabricated device was characterized to understand the effect of joule heating from the coil on the integrated sensor. Through a finite element simulation, the steady-state analysis was carried out to understand the interaction of the magnetic force from the coil and the magnet and the optimum distance of separation between them as well as possible displacement for lower and higher current values (up to 10A). These results serve as a good starting point for several future improvements of SensAct device to open up interesting opportunities for soft robotics, e-Skin, and interactive surfaces.
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