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First Results of Tilted Capacitive Sensors to Detect Shear Force

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Abstract

This paper proposes a new soft capacitive-type 3-axis force sensor. The prototype version which can detect a multi-axis force vector is embedded inside 7mm-thick silicone skin, and provides digital output via an I2C bus. Tilted capacitive force transducers were used to measure the force vector; the transducers faced different directions to differentiate the tangential forces. Preliminary experiments were performed and the concept of the tilted force transducers has been proven to have the capability of differentiating the force vector acting on the sensor surface.

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Keywords: shear force detection; tactile sensing; tilted sensor; capacitive sensing; compliant sensor

1. Introduction

Robots are expected to share their workspace with humans in the future. Distributed tactile sensors in the robot skin are of utmost importance in such scenarios, as they provide direct information about the contacts with the environment. Many of the currently available distributed tactile sensors measure only normal forces, but shear forces are important as well. Furthermore, the robot skin should be soft, to weaken the peak forces from unwanted impacts. When soft material is used, it acts like a filter for the sensor measurements, and therefore the sensors should be as close as possible to the surface, without impeding the softness of the skin. Other requirements for distributed tactile sensors are distributed electronics to minimize the wiring, and flexibility in order to conform to the curved shapes of the robot body.

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The literature describes many ways to arrange normal force transducers so that they can sense shear forces. This paper introduces a novel way to arrange the transducers and provides preliminary results to prove that the different forces acting on the skin surface can indeed be differentiated. The other requirements for distributed sensors for robotic skin were taken into consideration as well, in particular the transducers are embedded in soft silicone and the sensor base is a flexible PCB. The sensor measurements are digitized locally to minimize the necessary wiring.

The rest of the paper is organized as follow. The related work is presented in Section 2. Section 3 covers the description of the sensor. The experimental setup is explained in Section 4, and its result are discussed in Section 5. Lastly, Section 6 will talk about the conclusion and the future work.

2. Related work

There are many sensing principles which can be employed for tactile sensing [1]. Piezoelectric sensors can detect changes in force, also shear force; they can measure high frequency signals, but cannot distinguish multidirectional forces [2]. Many optical sensors which can measure shear force are too big to be installed into thin skin because cameras are required to monitor the skin [3,4]. Some sensors have bumps on the skin surface to sense shear force [5,6]. A smooth skin surface, however, is preferable in many applications. Other sensors do not require bumps to be able to detect tri-axial force [7], yet they are based on strain gauges, and small-sized analog-to-digital converting chips for strain gauges are currently not available. More importantly, those sensors are difficult to combine with compliant skin.

Capacitive sensors have a high sensitivity, but also high hysteresis [1]. It is due to the fact that viscoelastic materials are usually needed so that the relative distance between two capacitive plates can be momentarily changed when being loaded with external force. Nevertheless, using a copper beryllium ($CuBe_2$) plate as a deformable element in capacitive-type force sensor which was first introduced by [8] can drastically reduce such hysteresis. Furthermore, the shape of the copper plate was modified by adding a bump to the top surface in order to strengthen the center part and provide more parallel and more homogenous deformation to the plate in [9] resulting in higher sensitivity. Due to the recent demand of capacitive touch-screen devices, capacitance-to-digital converter (CDC) chips, such as the AD7147 from Analog Devices, are available [10]. This chip enables the digitalization in very limited space and has been used previously for robotic skin sensing [11,12]. However, these capacitive sensors can measure only normal force, while the current paper aims to measure also the tangential forces.

3. Sensor's description

The concept of 3-axis force sensing of the sensor will be described and followed by the explanation of the design and the physical components which consist of the electronics circuit, the force transducer, and the silicone rubber to provide soft exterior to the whole sensor.

3.1. The concept of the sensor

The ability of detecting the force vector is accomplished by tilting 4 double-sided normal-force-sensing units up in 4 different directions (each unit composes of 2 transducers located on each side). Hence, the 2 units align themselves on the same axis but pointing on the opposite direction while the other two align on the axis perpendicular to the former two. The sensor is then embedded inside a soft material such as silicone rubber to not only provide a soft exterior but also to transmit the force that acting on the top surface to all transducers simultaneously (refer to Fig. 1(a)). As a result, these 2 pairs of the 4 units can sense the shear force acting on the upper surface; one pair responsible for the shear force acting in one direction and the other pair responsible for the perpendicular shear force. All the 4 units can sense the normal force acting on the sensor surface.

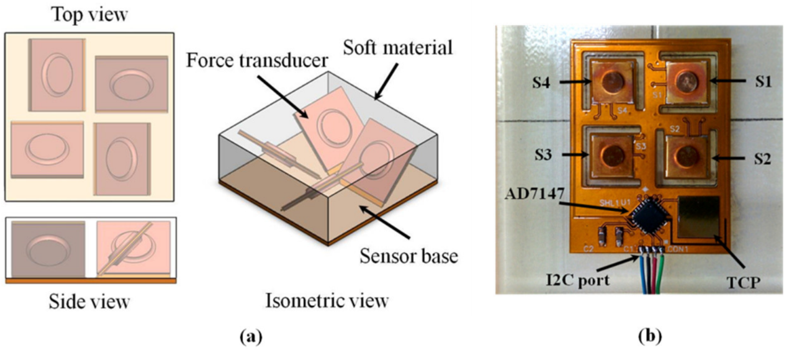


Fig. 1. The proposed sensor. (a) The conceptual design. (b) The circuitry of the sensor and its components.

3.2. Implementation of the sensor

3.2.1. The sensor's circuitry

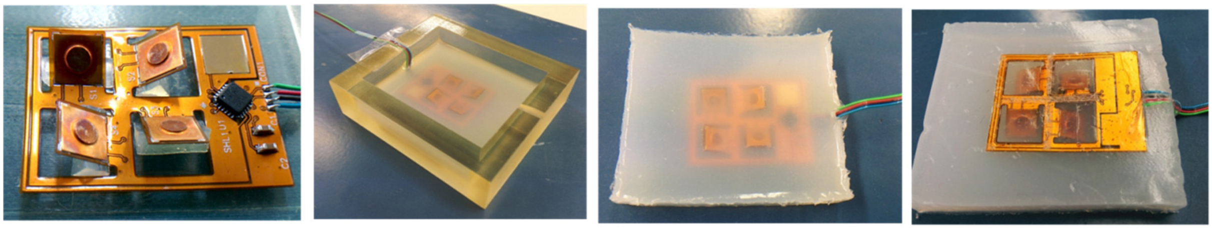
To accomplish the ability of sensing 3-axis force vector as mentioned earlier, a flexible PCB was used in order to allow capacitive-type force transducers to bend up. As can be seen from Fig. 1(b), one PCB consists of 8 transducers which each 2 of them were on the top and bottom sides of each force sensing unit (S1 - S4). Each force transducer consists of a signal pad which is made of typical copper foil used in flexible PCBs and a deformable copper beryllium ($CuBe_2$) plate which connects to ground; a force exerting on the copper plate can be sensed. The initial no-load distance of 24 µm exists due to the thickness of the non-conductive coverlay which separates the signal pad and the $CuBe_2$ plate (according to the specification of the manufacturer). The copper plate was mounted at its 4 corners to the ground of the PCB by a general reflow soldering method.

The $CuBe_2$ plate was chosen because of its high strength, spring properties, and high electric conductivity. The variant of the copper beryllium used in this paper was CW101C R580 HV. The plate was produced by a precise lithographic etching process and it consists of an Ø3mm 0.33mm-height cylindrical bump on the top of a 0.08mm-thick 6×6mm flat base.

To sense the capacitances in all transducers, the capacitive-to-digital converter (CDC) chip AD7147 (from Analog Devices) was used due to its compact size of 4x4 mm, and its ability to digitalize up to 12 measurements and send them over the I2C bus. With its small size, the chip could be easily fitted on the same PCB as where the transducers were; this reduced the chance that the analog signal would be interfered with noises. The AC shield feature of the chip prevents stray capacitance effect and improves the robustness of capacitance signal. Using I2C bus allowed 4 chips to share the same data line, and this could drastically reduce the required amount of wires and the space needed for contain those wires especially in the application of distributed tactile sensor where many individual sensors need to be installed together on a limited space. Furthermore, a pressure-insensitive capacitive sensor called Temperature Compensation Pad (TCP) located near the force sensors was designed to counterbalance the sensor's susceptibility to temperature change, as had been done previously [9,12].

3.2.2. The soft outer layer

After all the components were mounted onto the PCB, the sensor was molded inside soft silicone rubber in order to provide a soft exterior safe for human and to allow the sensor to measure multi-directional force. Since optimal material selection is not the focus of this paper, Ecoflex Supersoft 30 (from Smooth-On) was chosen due to its soft yet strong and high strain properties. The rubber has a shore hardness of 00-30 which is softer than human skin. Another, even softer option available is Ecoflex Supersoft 10 with shore hardness of 00-10 but this silicone left an oily layer on the surface even after it cured. Therefore, Ecoflex Supersoft 30 was selected to test how the sensor behaved in the soft silicone rubber.



(a) (b) (c) (d)

Fig. 2. The molding of the sensor. (a) the sensing units were supported by triangular silicone rubber. (b) the liquid silicone rubber was poured into the molding block to cover all the sensor's circuit. (c) the top view of the molded sensor. (d) the bottom view of the molded sensor.

The manufacturing of the sensor started by fixing the PCB in a molding block with double-sided tape sticking under the PCB. 45-degree triangular silicone rubber was then inserted under each force sensing unit to maintain the angle of bending (Fig. 2(a)). This 45-degree angle was preferred so that a good balance of sensitivity to shear and normal force can be achieved. However, due to the springback of the PCB, the bending angle became 30 degrees instead as measured by a protractor. After all the triangular supports were in place, liquid silicone rubber was poured into the mold with the height of 7mm from the bottom of the mold (Fig. 2(b)). This 7mm thickness was selected so that the tilted force sensing units are approximately 2mm under the top surface to prevent the transducers from being exposed and maintain the softness of the sensor. The silicone was left to cure for 4 hours after degassing for 2 minutes. After the curing finished, the sensor was taken out of the molding block (Fig. 2(c) and (d)).

4. Experimental setup

This experiment was performed to verify the ability to detect and distinguish 2D shear forces of the proposed soft sensor. The setup as shown in Fig. 3(a) consists of a manually-operated 3-axis stage, a 6-axis force-torque sensor (Nano1.5/1.5 from BL Autotech) which was mounted to the z-axis of the stage, and an aluminum 30x30x10mm^2 pushing block which connects to the tool side (the force sensing part) of the Nano1.5/1.5 sensor to monitor the actual force exerted on the sensor.

During the experiment, the actual force-torque data from the force-torque and the readout of the sensor including environment parameters (temperature and humidity) were recorded by the Arduino Uno (slave) and Arduino Due (master) with a synchronized sampling rate of 40 Hz. Two microcontrollers were used because of the different voltage level of the sensor (3.3V) and the 6-axis force-torque sensor (5V). The synchronization of the two sensor readings was verified with an oscilloscope.

5. Experimental result

The experiment was conducted by first manually moving the z-axis stage down until the block pushed the sensor's surface with the magnitude of approximately 800g as measured by the force-torque sensor. After that, the x-y stage was moved one axis at a time with the displacement of 2mm while the z-axis was locked in place to generate both normal and shear force at the sensor surface. Figure 3(b) shows the relationship between the direction of shear force and the corresponding capacitive sensor units. For example, a force created by moving the x-y stage in +Y direction should increase the sensor readout of S1 but decrease that of S3.

The result of this experiment is shown in Fig. 4. It can be seen that the direction of the applied shear force can be identified by the readouts of the proposed sensor. For example, when there was a force acting in +Y direction, the readout of the transducers S1 increased while that of S3 decreased as seen in Figure 4(c), while S2 and S3 increased slightly corresponding to the increment of the force in Z-axis. When there was a force acting in –X direction, the force sensed by S2 increased while that of S4 decreased. The response of S1 and S3 were constant since the force in Z direction was left unchanged.

Nevertheless, the sensor measurements resulting from the shear force in +X direction did not correspond to our expectations, and this phenomenon has to be further investigated.

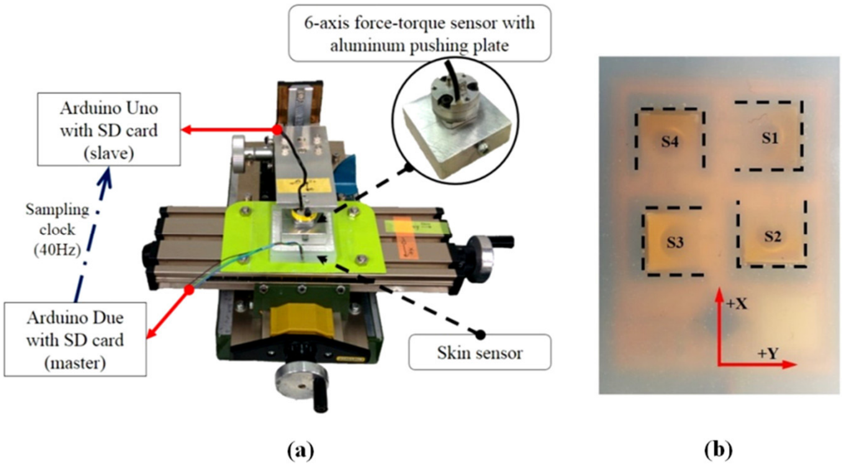


Fig. 3. (a) The experimental setup. (b) The 4 transducers and the axis of the 6-axis force-torque are shown. For example, +Y force will increase S1 readout, but decrease S3 readout.

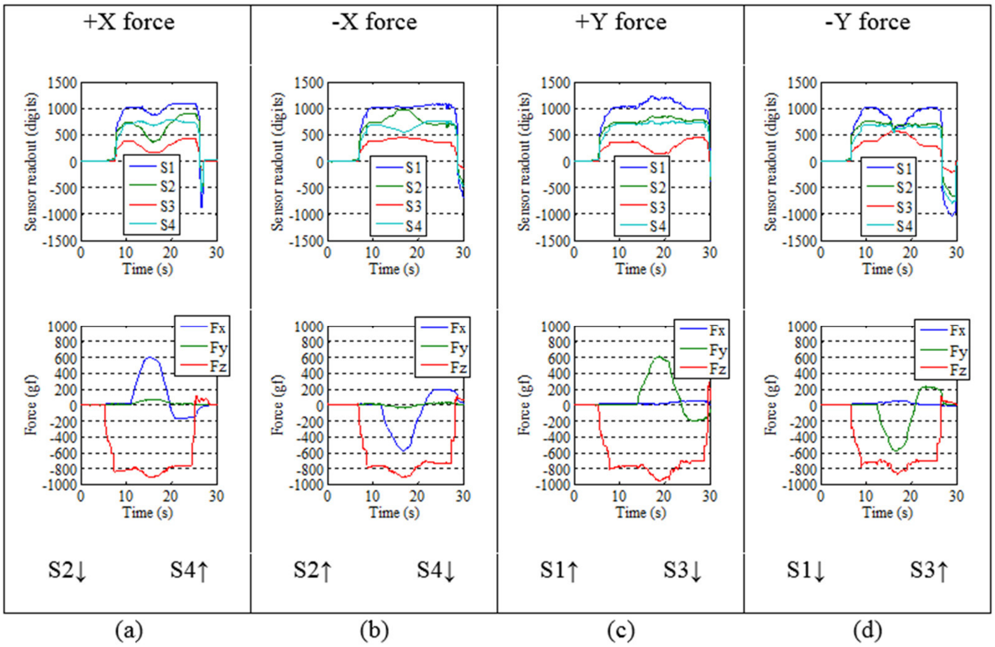


Fig. 4. The sensor readouts when applying a shear force in different directions. S1, S2, S3 and S4 are the 4 sensor units of the capacitive sensor. Fx, Fy and Fz are measured with the 6-axis force-torque sensor.

6. Conclusion and future work

This paper presented the concept design and a prototype of a tilted force sensor. A first implementation has been done, and preliminary test was performed to evaluate the ability of the sensor of detecting shear force. The main contribution is the tilted capacitive transducers with copper beryllium plate that should enable to measure the tangential forces acting on the sensor's upper surface. The first result showed that the proposed sensor can sense multidirectional shear and normal forces simultaneously. The included digitization of the sensor signals reduces the amount of necessary wiring, which is important for the installation on a robot.

Further experimental evaluation is necessary. Experiments about the characteristic of the sensor such as signal-to-noise ratio, and linearity need to be done. The evaluation of TCP in counterbalancing the thermal drift needs to be performed. More importantly, an improved version of the experimental setup will make it possible to better test the sensor response to shear forces and acquire the calibration matrix. A voice coil motor will be used to enable testing with consistent force input and also for frequency response testing. Several instances of the same sensor will be produced and tested, to obtain more comparative results.

The production procedure should be improved. Currently, the components are soldered manually, the amount of solder was not controlled, and the size of the solder pads for the copper beryllium plates might be too small, so slight excess of solder could affect the sensor characteristics. Using an improved PCB or a metal stencil could help distribute the solder equally. Furthermore, a more reliable method is needed to ensure the bending of the sensing units to a 45-degree angle. In general, the production process currently involves a lot of manual work, and should be further automatized to make the production cheaper and more reliable.

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