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A Prototype Force Sensing Unit for a Capacitive-type Force-Torque Sensor

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***Abstract* — Force sensing is a crucial task for robots, especially when the end effectors such as fingers and hands need to interact with an unknown environment, for example in a humanoid robot. In order to sense such forces, a force/torque sensor is an essential component. Many available force/torque sensors are based on strain gauges, but other sensing principles are also possible. In this paper we describe steps towards a capacitive type based sensor. Several MEMS capacitive sensors are described in the literature; however very few larger sensors are available, as capacitive sensors usually have disadvantages such as severe hysteresis and temperature sensitivity. On the other hand, capacitive sensors have the advantage of the availability of small sized chips for sensor readout and digitization. We employ copper beryllium for the transducer, which has been modified from the ones described in the literature to be able to be used in a small sized, robust force/torque sensor. Therefore, as the first step toward the goal of building such a sensor, in this study we have created a prototype sensing unit and have tested its sensitivity. No viscoelastic materials are used for the sensing unit, which usually introduce severe hysteresis in capacitive sensors. We have achieved a high signal-to-noise ratio, high sensitivity and a range of 10 Newton.**

I. INTRODUCTION

MEASURING the contact forces of a robot with its environment is crucial to ensure the safety and robust interaction, especially for human symbiotic robots that share their workspace with humans and which have to manipulate unknown objects.

In robotic humanoid hands often a combination of force/torque sensors in the fingertips and distributed force sensors in the skin is used, for example in [1]. Most force/torque sensors are based on strain gauges. In humanoid hands the available space is limited, and not only the space for the transducer, but also the space for the readout circuit and the wires needs to be taken into account. Capacitive sensors have the benefit of the availability of small sized chips for digitizing the signal. Yet, capacitive sensing is rarely used for macro scale force torque sensors, as capacitive sensors often have severe hysteresis and are sensitive to factors such as temperature.

In this paper, we use a capacitive force sensing unit that does not include viscoelastic materials, which usually lead to severe hysteresis in capacitive sensors. Compared to previous research, it has been modified to foster a parallel deformation, to achieve higher sensitivity and range. This change is also necessary so that the sensor unit can be used in the future for a force/torque sensor. Based on prior literature, we also include a temperature sensing pad, to compensate the influence of temperature changes on the measurements.

II. RELATED WORK

Many force/torque sensors for robotic hands are based on strain-gauges, for example [2][3]. Commercial off-the-shelf force/torque sensors are available such as ATI Nano17 [4], which is claimed to be the smallest commercially available sensor with the size of Ø17×14.5mm. However, the ATI Nano17 needs an additional readout circuit which can be difficult to fit inside a robotic hand. The sensor used in [2] is bigger, yet it includes the digitization electronics, which is beneficial as it reduces the numbers of wires that need to be connected, and digital signals are less noise sensitivity.

Capacitive-type sensors have been chosen as force or tactile sensor due to its advantage of its high sensitivity and resolution[1][5]–[8]. It is used as well in the human mimetic hand of the robot TWENDY-ONE [1][5]. The capacitive sensors in [5][6] use the AD7147 chip, which enables digitization of capacitive sensor measurements in very limited space. However, many capacitive sensors have used viscoelastic material as a deformable part of their sensor which result in introducing hysteresis to such systems [6]–[8]. A commercialized capacitive-type force/torque sensor from Wacoh-Tech Inc. also uses silicon rubber as a deformable element in their sensor [9]. MEMS capacitive sensors are another ongoing research area. They can detect force at a very tiny magnitude of 1 mN or less. However, the drawback of MEMS sensors are that they are fragile and easy to break if overload force is applied to them [10][11], which make them not suitable for integrating into a robotic fingertip or hand.

A capacitive sensor which uses copper beryllium as the deformable element was implemented in [10] and patented in [12]. Copper beryllium has high strength and low elastic modulus, as well as high electric conductivity. However, a

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hard ABS plastic (VeroWhite) knob is located on the top of the upper plate and is used to transfer the external force to the sensor, which introduces hysteresis to the sensor.

In this paper, we use a copper beryllium plate like in [10], but modify it to foster a parallel deformation and achieve a higher sensitivity and range. This change is also necessary so that the sensor unit can be used in the future for a force/torque sensor. Furthermore, in this paper we use the AD7147 chip, as in [5][6], but we do not use a viscoelastic material for the transducer, which would introduce severe hysteresis. We also employ a temperature compensation pad like in [6].

The rest of the paper is organized as follows. The sensor and its major design features will be introduced in Section III. Section IV explains the experiments involved in testing the sensor performance and shows the results. The conclusion and future work will be presented in Section V.

III. Sensor Description

In this section, the explanation of the sensor will be provided. First, the sensor structure will be described and then the major design features of our design will be discussed.

A. Structure of the sensor

Three force sensing capacitor units and a capacitive-to-digital converter (CDC) chip, AD7147 [13], are on a four-layer printed circuit board (PCB), see Fig. 1. The transducer of the sensor is composed of a coated copper foil, which is part of the PCB itself, and a copper beryllium plate above the copper foil, to act as a pair of capacitor plates (see Fig.2). The technique of implementing a copper beryllium plate as a capacitor plate was inspired by the force sensing unit of a multimodal artificial skin presented in [10]. However, the implementation of the plate has been changed by having a knob as a part of the plate itself (further details will be discussed in the next section). When force is applied on the plate, a deformation occurs causing the relative distance between the plates to decrease, thereby resulting in a change in capacitance. The AD7147 is used to measure the change in capacitance, digitalize the measurement and send it to a microcontroller via an I2C bus. By using the I2C bus, up to four AD7147 chips can share the same data line, and each AD7147 can send up to 12 capacitance measurements, thereby drastically reducing the amount of necessary wires.

For the capacitive plates, to create a gap in their relative distance in the unloaded situation, only the solder mask layer is used, see Fig. 2. The solder mask can provide a sturdy flat support for the copper beryllium plate. The 4 corners surrounding the signal pad are used for soldering the top plate to the PCB, see Fig. 4. For the surface finish layer, a typical surface finishing found in PCB manufacturing called Electroless Nickel Immersion Gold (ENIG) is used to protect the copper foil from oxidation. ENIG was selected because of its smooth and very thin layer of coating of only approximately 5 micron. As a result, the gap between the capacitive plates can be maintained at around 10 micron according to the PCB manufacturer, which was confirmed with the measurement of Surfcoder SE-3400 of Kosaka Lab.

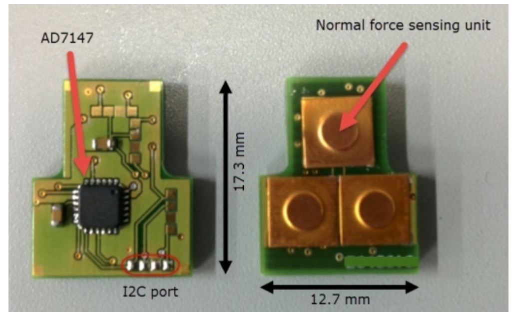

Figure 1. The bottom (component side) and the top side (force sensing side) of the PCB. The force sensing units, the AD7147 CDC chip and the I2C port can be seen.

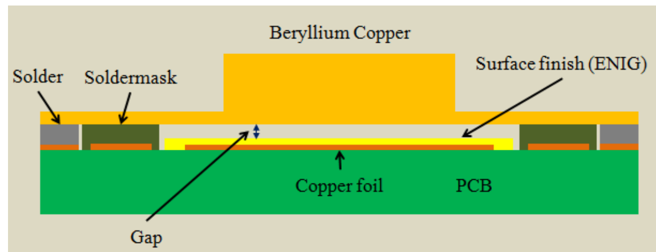

Figure 2. Side view of a single force sensing unit. The copper beryllium plate rests on the solder mask layer of the PCB. The gap is according to the difference in thickness between the solder mask and the surface finish (ENIG) layer.

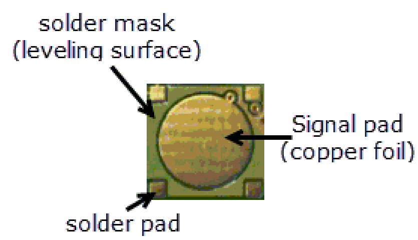

Figure 3. Top view of a single force sensing unit shows the shape of the solder mask layer that supports the copper beryllium plate. The copper beryllium plate is soldered to the four pads in the corners.

In order to minimize the noise and the stray capacitance, the PCB circuit was designed according to [14]. As a result, we use a 4-layered PCB and the AC shield function of the chip is used to shield all analog signals (capacitance measurement in this case) from all digital signals. In particular, the 3 signal pads on the top layer are all surrounded both at the side and at the second layer underneath by AC shield.

B. Temperature Compensation

In order to sense the influence of temperature on the sensor, a pair of copper foils is put in the third and bottom layer to create a capacitor called Temperature Compensation Pad (TCP). Its capacitance changes only according to temperature, and is insensitive to force. With the measurements from the TCP, the effect of temperature on the force measurement can be compensated, as it has been done in [6]: temperature compensation can be achieved by adding to the force measurement the change in TCP multiplied by a certain gain. The validity of this will be evaluated in Section IV-3.

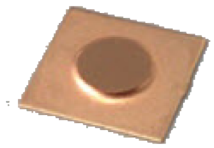

Figure 4. The copper beryllium plate is shown here; the knob on the top can be easily produced by lithographic etching process. The plate has an Ø3mm 0.33mm-height cylinder knob and a 0.08mm-thick 6×6mm flat base.

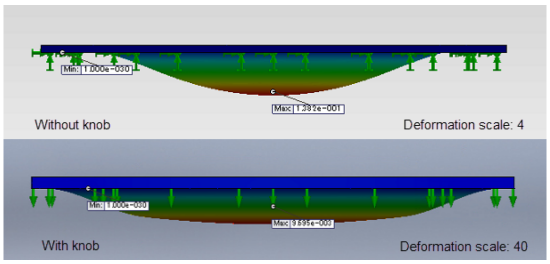

Figure 5. Comparison between the deformation of copper beryllium plates with and without the knob under 5N load; with the knob, the plate's deformation is almost parallel; less bending can be seen. The deformation is scaled for making the deformation more noticeable.

C. *Copper beryllium plate with knob*

Copper beryllium (CuBe2) is used as the top deformable capacitive plate due to its high strength, spring properties, and high electric conductivity. It is widely used for both industrial (e.g. spring, flexible hose) and electronics purposes (e.g. connector, contact bridge, switch parts) [15][16]. Moreover, it has also been used as a capacitive plate for a force sensing module in [10]. The variant of the copper beryllium used in this paper is CW101C R580 HV. The plate is produced by a lithographic etching process and it consists of an Ø3mm 0.33mm-height cylinder knob on the top of a 0.08mm-thick 6×6mm flat base.

The knob allows the sensing of external force easier without any addition components and it will be beneficial for our future development of a force/torque sensor as well. It also improves the performance of the sensor because the thick knob compared to the thin base will result in a more parallel and more homogenous deformation of the whole plate when the knob is pushed by an external force. The comparison of the deformation of a plate with and without knob can be seen in Fig. 5. The uniform deformation of the plate with a knob allows the capacitance to change more with the same deformation distance because not only the area where the force acts on will deform. Additionally, with the same magnitude of the normal force, the plate with knob will deform less so it can be placed closer to the signal pad of the PCB in order to gain more sensitivity.

The formula of capacitance of any 2 parallel plates is

$$C=\varepsilon_r\varepsilon_0\frac{A}{d} \tag{1}$$

Where

- C is the capacitance (F)
- ε_r is the relative static permittivity (unitless)
- ε_0 is the electric constant (F/m)
- A is the overlap area of the 2 plates (m^2)
- d is the separation distance between the 2 plates (m)

The thickness of the copper beryllium plate can be adjusted to achieve a certain sensitivity and range (by changing the spring constant). Counterintuitively, a smaller initial distance of the capacitive plates is beneficial for the sensitivity/range. For example, with half the initial distance, double the range with the same sensitivity can be achieved.

Initially, prior to the manufacturing of the sensor, a finite element simulation of copper beryllium plate was done in Abaqus/CAE software in order to determine the desired dimension of the plate and understand the expected value of force that the plate can withstand and the expected deformation to achieve the high sensitivity yet high force range capacitive sensor.

According to the distance between the capacitive plates of a sensor unit that can be manufactured as mentioned in Section III-A, the 10-micron deformation is the desired goal to achieve with a certain force. For the current study, we aimed that each sensing unit could measure the force up to 0.510kg (5N). Furthermore, by considering about the accuracy that can be achieved in the production of the copper beryllium plate, we designed the plate so that, with the force of 0.510kg (5N), the plate will deform around 6.4 micron with the dimension of the plate as described in Fig.4; the rest of the 10-micron gap is for the manufacturing uncertainty of the plate and the PCB.

IV. Experiments

A. *Experimental Setup*

A simple test setup is used to test the sensor measurements resulting from different weights that push against the sensor. The setup consists of a set of calibration weights ranging from 1g to 500g, a weight placement plate with a Ø6mm shaft for pushing on the Ø3mm sensor's knob, a stand with a linear ball bearing bushing that allow only the vertical movement of the shaft, and a digital scale with a resolution of 1g and the range of 2000g for monitoring the actual force pushing on the sensor. The sensor PCB is placed on a 3D printed plastic base providing a steady placement for testing and the whole unit is placed on the scale. The microcontroller used for reading data from the sensor is Arduino Due with a SD card module for recording CDC data at a sampling rate of 15ms. For this configuration of 3 capacitive sensors, the CDC process of AD7147 is completed every 12.288ms [13]. The communication between the microcontroller and the sensor is done via an I2C bus.

B. *Sensor characteristic tests*

1) *Signal-to-Noise Ratio (SNR) test*

This experiment is done with 2 sizes of load; 0.254kg and 1.044kg. Each load is manually put on the weight placement plate which will transfer the force to one of the three sensors (S1) for a period of approximately 5 seconds, and the response of the sensor is recorded. The result is shown in Fig. 7 and Fig. 8. The SNR is then calculated according to [17],

$$\mathrm{SNR} = \frac{|\mu_U-\mu_P|}{\sigma_u} \tag{2}$$

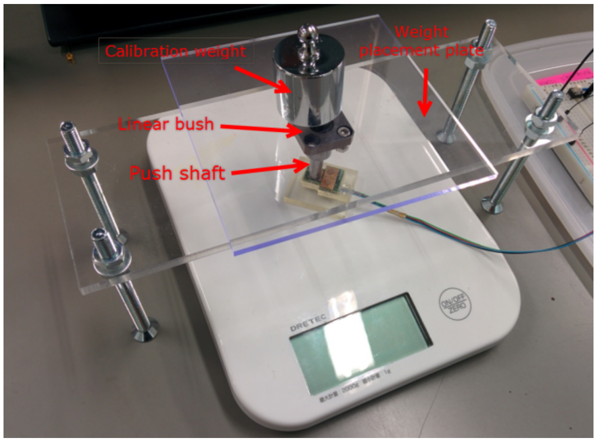

Figure 6. Overview of the experimental setup; the setup consists of a digital scale, a linear ball bearing bushing with its support structure, a sliding shaft with weight placement plate.

Where:

μ_U = mean value of sensor when not loaded
μ_P = mean value of sensor when loaded
σ_u = standard deviation of value when not loaded

For the load of 0.254kg, μ_U= 3744.17, μ_P = 6400.95, σ_u = 0.75, and for the load of 1.044kg, μ_U = 3849.40, μ_P = 16415.07, σ_u = 0.61. As a result, the SNR of the 0.254kg load is 3534.6, and that of the 1.044kg load is 20638.7 which can be considered as very high ratios for the sensor.

2) Accumulated load/unload test

The purpose of this test is to examine the response of a sensor unit (S1) to a load change. The test was done by putting weight on manually one after another on the weight placement plate of the test stand to increase the load to the sensor, and then taken out one by one to decrease the load. The load range used here is varied from 0.046kg to 1.144kg by using a set of calibration weights which consists of 0.001kg to 0.500kg weights. The load sensed by the sensor also includes the weight of the push shaft and the weight placement plate of the test stand which is 0.046kg in weight). The time in between loading and unloading each weight is approximately 5 seconds, and the overall time of the whole loading/unloading experiment is around 2 minutes 30 seconds.

The response of one of the 3 sensor units (S1) to both load and unloading are shown in Fig. 9. In the figure, it can be seen that loads of approximately 0.046kg to 0.150kg are located very close to the linear approximation line. However, the loads of around 0.200kg and above gradually drop under the line, but the response of the final weight of 1.144kg goes beyond the line. We expect that the resulting response is sufficient for many tasks with humanoid robots.

Additionally, the maximum standard deviation of the test is 81.16 units, which is found at the unloading of the heaviest weight of 0.500kg. However, the average value of all standard deviation of the whole test is 13.79 units and the lowest standard deviation is 1.74 units.

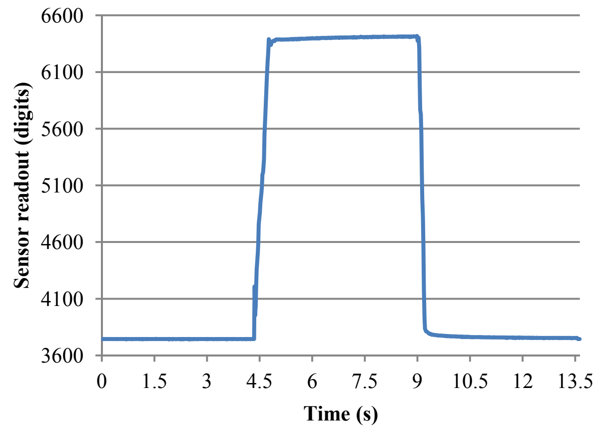

Figure 7. Response of the single force sensing unit to the load of 0.254kg.

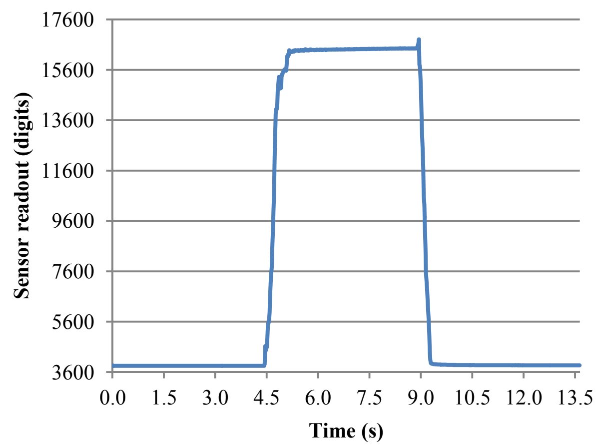

Figure 8. Response of the single force sensing unit to the load of 1.044kg.

Moreover, in terms of hysteresis that can be found in the sensor due to the difference in readout value of the same weight during loading and unloading period, the maximum drift that can be found is 636.77 units which is approximately 0.042kg, and the average drift is around 212 units or 0.014kg which can be considered as a low level of hysteresis providing that a unit can measure the force up to 1.144kg.

3) Temperature drift test

This test is aimed for study the feasibility of using the TCP to counteract the thermal drift in the sensor measurements. The test is done by monitoring the drift in sensor readout signals due to the change in temperature. The setup for this experiment consists of an Expanded Polystyrene (EPS) box that is covered with aluminum sheets inside in order to maintain temperature, and a closed PET bottle filled with hot water. The sensor is put inside the box together with Sparkfun TMP102 – an I2C temperature sensor with the resolution of 0.01˚C for measuring the actual temperature during the experiment. The wires of the sensors connect to the microcontroller through a small hole which is covered with aluminum sheet to minimize temperature leakage.

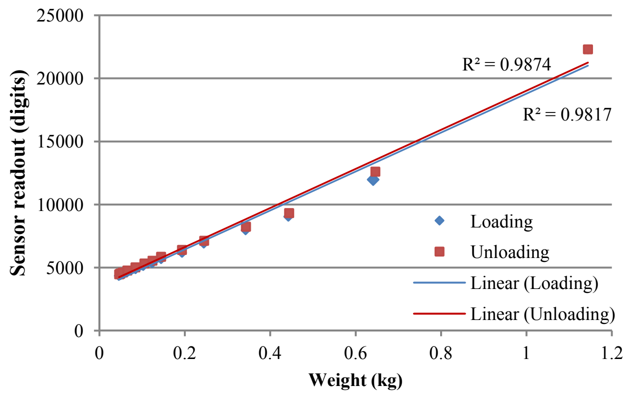

Figure 9. Loading/unloading test plot of the average of the sensor readout; the load is range from 0.045kg to 1.144kg.

The experiment starts by using the room air conditioner to cool down the sensors, as well as the overall temperature of the room where the experiment is performed, until the temperature drops to around 20˚C. After that, the bottle is put inside the box and the box is closed to allow the temperature inside to rise to 40˚C. The box is then opened to allow the temperature to gradually drop to around 25˚C while the bottle is still kept inside the box to achieve a slow drop in temperature.

As the result of the experiment as shown in Fig. 10, it can be seen that the drift of both a force sensing unit (S1, in green) and TCP (in blue) responded to the thermal variation in almost the same fashion but at a different magnitude. The S1 is more responsive to the change than the TCP. A simple compensation trial has been done in order to test the feasibility of temperature compensation by subtracting the drift in S1 with the drift in TCP times with a fixed gain (5 in this case) in a similar fashion as can be found in [6]. The result of compensation is not perfect but drift in S1 is reduced from the maximum value of around 140 units to 20 units and the rest of the drift almost stay in a band of ±20 units which can be roughly translated into ±0.002kg misread.

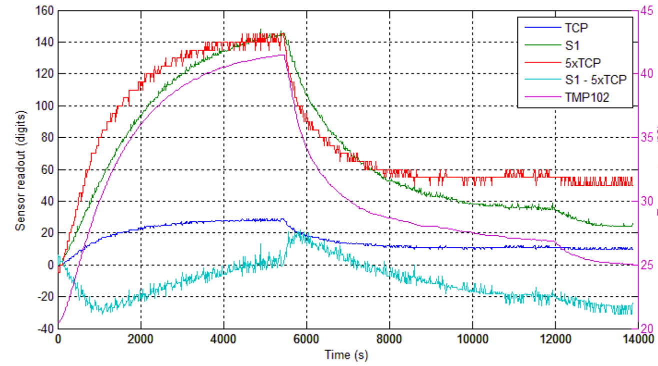

Figure 10. The effect of temperature change on the sensor is shown together with an attempt of compensation of sensor readout (S1, green) readout (cyan). The compensation value comes from the drift in TCP (blue, red (5-time scaled)) and the actual temperature is sensed by TMP102 (magenta).

V. Conclusion and Future Work

A. Conclusion

The paper presented the prototype of a capacitive-type force sensing unit in order to examine the performance of the sensor. In this study, the finite element simulation of the copper beryllium plate is done prior to the manufacturing of the actual plate to finalize the dimension of the plate and, more importantly, to confirm the benefit of the knob in allowing a more parallel deformation; more sensitivity and range of measurement can be achieved. The experiment for investigating the performance of the actual sensor is then performed. It included the test for determining the signal-to-noise ratio of the sensor, the loading/unloading test to see how linear the response of the unit can achieve and what level of hysteresis occur in the implementing of copper beryllium as the deformable transducer, and the test of thermal variation's influence on the sensor. The result of the experiments shown that with the implementation of copper beryllium plate, the AD7147 chip and the careful design of the sensor PCB, very high SNR, low hysteresis sensor with a high sensitivity is obtained and also an ability to compensate the effect of thermal change.

B. Future Work

Tests for the further characteristic of the sensor will be done in order to acquire more detail of the sensor before the manufacturing of the future force/torque sensor, especially, the dynamics test with a more reliable load cell with a force-controlled pushing unit that can receive the frequency command in order to gain a more consistent input signal when comparing to the manual loading/unloading method used in this paper. A temperature and humidity controllable oven would be also preferable for a proper temperature and humidity variation test. Furthermore, a quantitative measurement will be conducted and the result will be compared with a widely used sensor in order to evaluate the performance of the proposed sensor.

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