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Electronic skin based on flexible capacitor

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***Abstract*—The safety of human-machine interaction is very important in intelligent manufacturing, and the main purpose of ensuring safety is to enable the robot to receive information about the surrounding environment through proximity sensors, which can achieve good interaction between the machine and humans. In view of the current shortcomings of electronic skins, such as poor flexibility, lack of proximity sensing system, and the immeasurable magnitude of force after contact, we design a composite sensor that can realize proximity and small force haptics in this paper. We use flexible materials such as copper foil, polyimide, polyurethane and a new type of semiconductor material based on super capacitor and design a double-layer pressure-capacitance sensing structure based on the principle of human induced capacitance, variable dielectric constant and variable pitch capacitance. And we use STM32, FDC2214 chip to build a complete information acquisition and processing system.**

***Keywords*—flexibility, non-contact proximity sensing, small force measurement, super capacitor.**

I. Introduction

With the development of the technological society, the level of intelligence, informatization and integration of equipment is gradually improving. As a rapidly developing discipline, robot science is slowly expanding from traditional industry, agriculture, that is, the first and second industries to the emerging service industry and other tertiary industries. It integrates mechanical manufacturing and intelligent manufacturing, and includes sensing, control, information, calculation and other modules. it is gradually developing into a highly integrated technology and a comprehensive intelligent machinery field. However, in these complex industrial scenarios, such as human-machine interaction and multi-machine coordination, there are obviously certain safety hazards to humans, such as collisions between robots and humans, and other safety accidents often occur. So the robot safety issue was formed as an industry consensus [1]. Human-machine interaction requires the machine's own sensors and to realize the robot's reception of external information, most of the industry uses visual sensing and contact sensing.

But in practical applications, in order to ensure the normal working space of the robot and prevent accidental collisions, only visual and contact perception are not enough. Proximity sensing is also required to warn or make corresponding obstacle avoidance actions. Also feedback with proximity sensing information to adjust the way that robot contacts the outside world can achieve sensitive, intelligent, and safe human-machine interaction and more flexible robot movements. Besides, it can overcoming the problems of slow response, low sensitivity, and difficulty of flexible avoidance of traditional robots [2]..

In the context of increasingly close human-machine cooperation, the efficiency of communication and collaboration between humans and robots is crucial. But the complexity of the interactive scene and the uncertainty of the flow of people request higher requirements for the accuracy of human-machine interaction. Therefore, in addition to the necessary visual perception and tactile perception, the robot also needs to have strong proximity perception. At this stage, proximity sensing uses multi-capacitance sensors. Because the range of visual perception is in the range of tens of centimeters to several meters, and tactile perception is on the surface of the robot, capacitive proximity sensing can be sensitive from a few millimeters to a few centimeters, filling the gap in the perception distance, which can make up for the lack of visual perception and tactile perception in various scenarios. In the meanwhile, it has the following advantages in human-machine interaction:

(1) Low cost. In terms of distance measurement, the capacitive sensor is about one-fifth of the cost of the photoelectric sensor, and the photoelectric sensor is also susceptible to external vibration interference, which may require additional damping measures. Capacitive sensors have no harsh operating conditions, and the expected

working life is also long.

(2) The sensitivity is usually high.

(3) Good stability. Capacitive sensors work stably and are not easily disturbed by external factors. The metal plates and the inorganic medium between them are highly resistant to temperature and magnetic fields. They can work normally in scenarios where the temperature changes frequently, with less impact and high reliability.

Capacitive sensors are widely used. In terms of proximity perception, it is used in motion detection and obstacle avoidance. It can detect the displacement and motion at nanometer level, and has fast response and high sensitivity. It is widely used in the accurate measurement of vehicle speed. In composition detection, capacitive sensors are also widely used in liquid composition detection, such as the use of capacitive sensing technology in oil refineries to detect the oil-water mixing ratio of oil; in grain storage, it can also detect the water content of grains such as wheat and corn [3].

In general, in the context of the increasingly frequent human-machine interaction in the robot field and the increasing demand and quality, combined with the advantages of capacitive sensing technology, it is important to give the robot a layer of "electronic skin" that enhances perception. It has a high practice significance and value.

There are more and more scenes of human-machine interaction, and the electronic skin of robots is getting more and more attention from academia. In the 1980s, scholars began to study proximity sensors, and achieved a series of results. At present, there are a wide variety of ultrasonic sensors, infrared sensors, laser sensors, and capacitive and inductive sensors for robot proximity sensing. Here are some typical capacitive sensors [4].

In an IEEE 2013 paper, Dirk Goger, Hosam Alagi and others designed a capacitive proximity sensor array in **Figure 1**. The measurement principle of this sensor is the fringe electric field effect. The capacitive sensing array is installed at the end of the robot hand, which can detect objects close to the end of the robot finger, and can also detect contact stress. According to the feedback action of the capacitive proximity sensor, the accuracy of actions such as grasping is improved, while avoiding collision with the operator. It is characterized by proximity-contact dual-mode perception, which can make some robots that require frequent human-computer interaction safer and more efficient [5].

In this article based on flexible capacitor we designed an electronic skin which can measure the spatial distance of objects close to the sensor in a non-contact way and measure tiny force less than 0.1N.

II. Proximity-pressure measurement system design

A. Measuring principle

(a) Structured sensor cover, silicone rubber (b) Integration of sensors in an anthropomorphic hand

Figure 1. Capacitive proximity sensor array

The measurement principle of the proximity sensor is the principle of human body induction capacitance in **Figure 2**: the human body can be regarded as a conductor, and there are many freely moving charges distributed on it. When the electric field is applied, these charges will move. And human hand can form human body’s inductive capacitance between the upper electrode plate of the parallel plate capacitance structure. The size of the human body’s inductive capacitance is related to the distance from the human hand to the electrode plate. Then we can calculate the distance from the human to the sensor by measuring the size of the human body's inductive capacitance to achieve non-contact proximity perception.

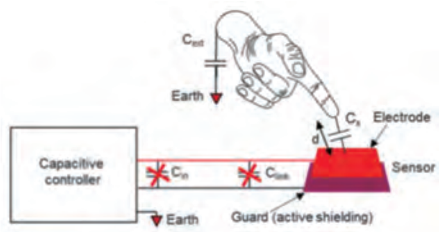

Figure 2**.** human body induction capacitance

The pressure sensor part can be simply considered as a parallel plate capacitor [6]. The formula of the parallel plate capacitor is:

$$C=(\varepsilon\cdot S)/\delta \qquad (1)$$

In the above formula, C is the capacitance; ε is the dielectric constant of the medium between the two plates; S is the relative effective area of the two plates; δ is the gap between the two plates [7].

From formula (1), we can see that the dielectric constant, effective relative area and the distance between the two plates can affect the capacitance value. As far as we know, most of the current research on flexible skin based on capacitive structure does not perform well on the perceptual sensitivity [8-9]. To overcome this shortcoming, we conducted a lot of comparative experiments in the early stage, and found that the pressure sensor based on the parallel plate capacitance structure would significantly improve the sensitivity after using microstructures and conductive materials to fill the dielectric layer.

Therefore, this paper uses super capacitor material filled with silica gel as a dielectric layer to improve the sensitivity of the piezoresistive sensor. When pressure is applied to the super capacitor dielectric layer, the dielectric layer deforms, and at the same time the porosity and conductivity of the super capacitor change. That is, the former will reduce the δ of formula (1), while the latter will increase ε. Therefore, theoretically ε/δ will increase significantly. Following this, we also carried out comparative experiment to verify. **Table 1** is the comparative test data using different sensor structures or materials. It can be found that the proposed super capacitor has a significant change in capacitance value under the same applied pressure compared to the sensing structure that only changes one parameter in the capacitance formula in other research literatures. And the use of super capacitor can greatly increase the initial capacitance value, as the thickness increases ε/δ increases, the initial capacitance also increases. It can enhance the ability of the sensor to resist interference. According to the sensitivity calculation formula, the use of super capacitor dielectric layer can improve the sensitivity of the sensor.

Table 1. Performance of different materials

Name	Polyurethane	Super capacitor	Polyurethane	Super capacitor
Size	3cm 3cm 3mm	3cm 3cm 3mm	3cm 3cm 4mm	3cm 3cm 4mm
Initial C	7.6pf	32.5pf	5.6pf	38.3pf
C change under 0.1N	<0.1pf	8pf	<0.1pf	13.7pf

B. Overall Design

The flexible capacitive sensor uses a double-layer sandwich structure, consisting of a total of five capacitors. One capacitor is responsible for proximity perception, and four are used as pressure sensor arrays. The shielding layer is used for shielding in the middle to ensure that the two capacitors work independently without interfering with each other.

The advantage of this design is ensuring that the capacitance fluctuation of the pressure sensor does not affect the measurement of proximity perception. Generally, when using a working capacitor to measure proximity perception and force, due to the limitation of materials, even if a flexible material such as a silicone layer with rapid rebound is used, there is still a phenomenon that the capacitance value cannot be recovered quickly. After being stressed, the capacitance value of the capacitive sensor can quickly return to the original capacitance value, the error is generally 1pF, and then slowly change until it is stable. For the pressure sensor, the 1pF error does not affect the measurement accuracy, but the proximity signal is usually small, with a range of 0.1pF-10pF. The slowly changing capacitance value will directly affect the accuracy and measurement distance of non-contact measurement, and most flexible materials have this problem. Therefore, we have adopted this double-layer sandwich structure so that they do not interfere with each other. The overall structure is shown in **Figure 3**.

C. Fabrication of proximity and pressure sensor

Copper foil is selected as the electrode material of proximity sensing capacitance sensor. Because of its good flexibility, it can be used as a flexible electrode, and its resistivity is low, which makes the basic capacitance larger, thus suppressing the influence of parasitic capacitance and environmental interference. Polyimide is selected as the dielectric layer, which has the characteristics of high dielectric constant and flexibility. The shielding layer is made of copper plated nickel polyester fiber cloth, separated from the lower plate by polyimide, which can well shield the interference of capacitance below. The upper plate adopts the equipotential loop as the shielding layer. The overall effect is shown in **Figure 4**.

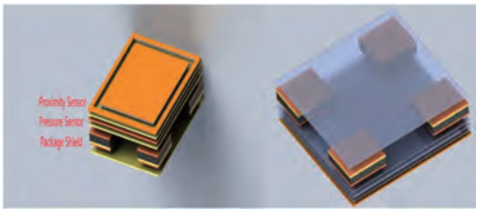

Figure 3. Overall Design

Figure 4. Top view of proximity capacitance sensor

In addition, the main purpose of using the equipotential loop is to eliminate and reduce the influence of edge capacitance effect, so that the capacitance change is only the human induced capacitance. The accuracy of measurement is improved in **Figure 5**.

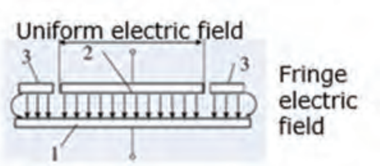

Figure 5. The principle of eliminating edge effect by equipotential ring

The upper plate of the sensor is connected with the excitation electrode, and the lower plate and the shielding layer are grounded in **Figure 6**. Because the human body is approximately grounded, the inductive capacitance of human body is paralleled with the working capacitance, and the measured capacitance change is the change of human inductive capacitance.

The size of proximity sensing capacitance sensor is 10x10cm. If the size of the sensor is too small, the basic capacitance will be too little, which will increase the interference, and at the same time, the change of the human induced capacitance is also related to the size of the sensor. If the sensor size is too small, the change will be too small to measure. If the sensor size is too large, the influence of the environment on the sensor will increase, and the effective signal will not be submerged. However, with the increase of sensor size, the change of human inductive capacitance will not always increase. Therefore, we select the best size sensor through the comparative test of different sizes of sensors. The experimental results are shown in **Figure 7.** In the experimental results we can come to the conclusion that when the size of proximity sensing capacitance sensor is 10cm x10cm, it works best for detecting close objects.

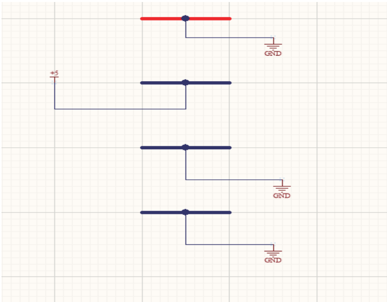

Figure 6. Sensor plate connection diagram

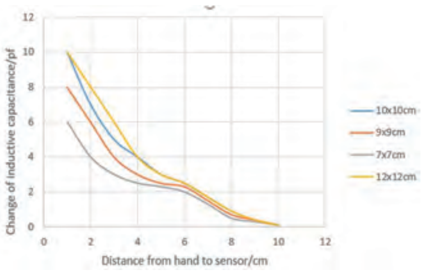

Figure 7. Comparison of different sizes of sensors

The electrode material of flexible pressure capacitance sensor is copper foil. Super capacitor material and silica gel are selected as the dielectric layer materials. Through a number of comparative tests, the final material proportion is coke particle carbon (24%) + acetylene black (6%) + 15 hardness silica gel (70%). Firstly, the mixed super capacitor material was added into anhydrous ethanol, and then let it fully dispersed in 15 degree silica gel. With sufficient stirring, the super capacitor was evenly dispersed into the silica gel. When the ethanol is completely volatilized, the silica gel curing agent is added for stirring, and the mixture is poured into the mold and solidified at room temperature for 24 hours to form a 3cm x 3cm x 3mm structure. After molding, copper foils were added on the upper and lower sides as electrode plates, and polyimide was added between the lower plate and the dielectric layer as the insulating layer, and then pressed with heavy weight for 24 hours. Super capacitor materials can effectively improve the basic capacitance of the sensor and the resolution of micro force. Last, we set up four sensor nodes on the area of 10cm × 10cm as a 2x2 array. As an axial shielding layer, copper nickel plated polyester fiber cloth can shield the influence of installation environment, such as mechanical arm.

D.Sensor performance test

We connect the non-contact approaching sensor to the capacitance meter for reading, and parallel move the hand to the upper plate of the sensor from a distance. Starting from the change of indication, record the indication of capacitance meter when there is every 1cm drop, and take the average value after several experiments. The curve between the change of induced capacitance and the interval distance is shown in **Figure 8**. It can be seen that the relationship between the distance and the changing capacitance is approximately exponential. The variation at 10cm is 0.1pf, and the variation at infinite approach is about 10pf. After being given force, it can recover really fast. The recovery time is less than 2s, and the error is generally less than 0.5pf.

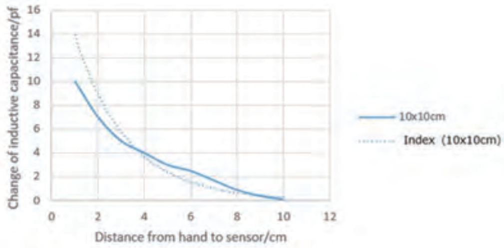

Figure 8. Distance-capacitance variation curve

The relationship between the force and capacitance is shown in **Figure 9**. It can be seen that the capacitance changes rapidly when the force is in the range of 0 ~ 0.7N, and the change is slow between 0.7 ~ 20N. The overall sensitivity is gradually reduced. We divide the study into two sections, for linear fitting respectively.

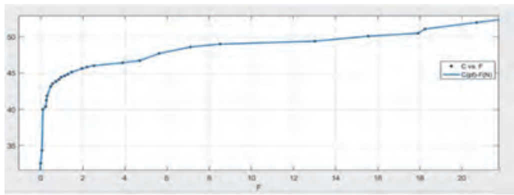

Figure 9. Force-capacitance variation curve

The linear fitting results are as shown in **Figure 10**.

The first period data point is marked by "+", and the sensitivity is 28.6 pf / N. According to the measurement data, the minimum resolution is 0.04N at the accurate measurement equipment level.

The sensitivity of the second segment is 0.68 pf / N and the minimum resolution is 0.1N.

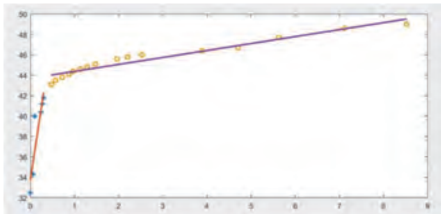

Figure 10. Linear fitting results

The first segment is dominated by variable dielectric constant, with high sensitivity and resolution, while the second segment is dominated by variable spacing, with relatively low sensitivity and resolution, but it can also meet the needs of most application scenarios. Compared with the nonlinear curves of most capacitive sensors, the two linear working areas of the sensor are more convenient for control. The results show that when the effective area of the flexible capacitor is about $0.5cm^2$, and 0.10N force is applied, the change of capacitance can reach 5.4pf. It can withstand large force without damage and return to the original capacitance value. In addition to the indexes of recovery and sensitivity, the repeatability test of the sensor is also carried out. The repeatability is good and can take 500N force without damage.

III. CONTROL SYSTEM

A. Hardware design

We select FDC2214 of Texas Instruments as the capacitance digital sensor for the system. The capacitor has high resolution (28 bits), large capacitance detection range (10kHz frequency, 1mH inductance, the maximum input capacitance is 250nF), multi-channel measurement function (4 channels), anti electromagnetic interference architecture, and can work normally in high noise environment. FDC2214 is often used in proximity sensor, gesture recognition, liquid level sensor and so on. Because of its high resolution and stable output, it is selected as the capacitance sensor of the system. The design of capacitance measurement circuit is shown in **Figure 11**. There are four measurement channels in total, which can meet the requirements of dual channel measurement of sensor. The external crystal oscillator is used to replace the internal RC oscillation of the chip to eliminate the influence of temperature drift.

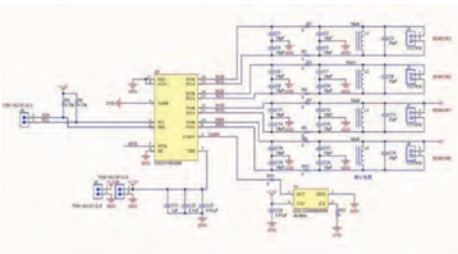

Figure 11. Measurement circuit diagram

Because the main control board of the system need to use IIC communication and serial communication, so we select stm32f407 MCU as the main unit in the control part. The main frequency of STM32F407ZET6 chip is 168M, which has rich peripheral resources. It can use STLINK online debugging programmer to burn and debug, which is convenient for debugging in the development process.

B. IIC communication design

The IIC communication sequence diagram of FDC2214 is shown in **Figure 12**.

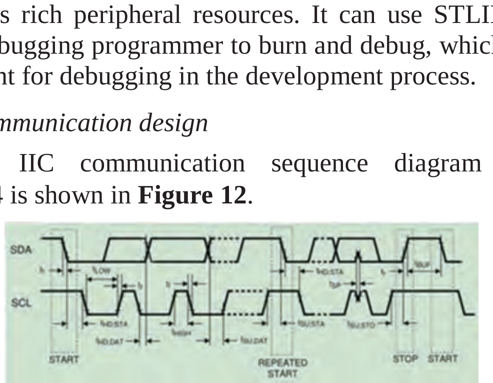

Figure 12. Communication sequence diagram

The main control chip STM32F4 comes with hardware IIC, but for the sake of code portability, this study uses IO to simulate IIC timing to carry out IIC communication, and the effect is basically the same as that of hardware IIC. After initializing IIC related IO ports, write configuration information to FDC2214 registers according to actual usage. Then, the values of the result registers corresponding to each channel of fdc2214 are read periodically. Then, the capacitance value of each channel is calculated by using the correction value of precision instrument calibration, and the accurate capacitance value can be obtained, and then the distance measurement can be carried out by using the correlation curve.

C. Control system programming

The program framework is shown in **Figure 13**.

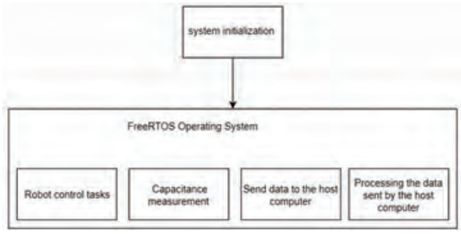

Figure 13. Measurement circuit diagram

The control program uses FreeRTOS operation system, and the corresponding tasks are set up in each part of the frame diagram. Although the single-chip microcomputer can only run one task at the same time, there is no difference between fast switching between tasks and running multiple tasks at the same time. The use of real-time operating system can also improve the system's responsiveness to the change of human hand distance.

D. Manipulator motion control

PCA9685 is used to drive the rudder. PCA9685 steering gear drive board is a device that sets the duty cycle of PWM wave of each channel according to the corresponding register value of each channel. IIC bus is also used for communication. The IIC bus has been introduced before and will not be repeated here. By adjusting the duty cycle of PWM wave, the SG90 steering gear connected with the corresponding channel can be rotated to the corresponding angle. The operating frequency of the control task of the manipulator is the same as that of the measurement task, both of which are 50 Hz. When it is detected that the distance between hands is greater than the minimum safe distance, the manipulator will move back and forth between 30 ° and 150 ° at the speed of 12.5 ° / s. When it is detected that the distance between the hands is less than the minimum safe distance, the manipulator stops at the current position, and the main control adjusts the brightness of the distance indicator according to the distance between the hands. The smaller the distance, the greater the brightness of the indicator. When it is detected that the human hand has touched the sensor, the master control touch indicator lights up, and the manipulator starts to move in reverse immediately. It turns off when no touch is detected. When the hand distance is greater than the minimum safe distance again, the manipulator will resume movement.

E. System construction and experimental verification

In this paper, the flexible electronic skin capacitive sensor measuring circuit control system is built. For the outlet line of sensor, the principle of line alignment should be as short as possible. The conductor is perpendicular to each other, and the parallel wire is shielded by coaxial barrier wire. It is connected to the measuring circuit and communicates with the control unit STM32. The whole system is built as shown in **Figure 14**.

Figure 14**.** System construction

The system has certain flexibility and can be attached to the surface of the general manipulator. For example, the system is the attached to the arm shown in **Figure 15**.

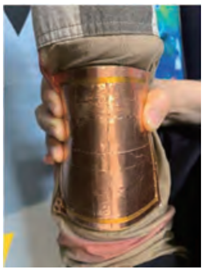

Figure 15. Flexibility display

In order to verify the proximity performance, we will gradually approach the sensor from a distance, and read the capacitance value returned by the measurement circuit. The value change curve is similar to the change curve measured by the capacitance meter, and the maximum distance it can sense an object is 10 cm. The manipulator stops moving when the hand approaches the sensor, and the proximity indicator is on. As the distance between the hand and the sensor is reduced, the brightness of the proximity indicator light gradually turns on. When the hand contacts the sensor, that is, when 0.1N force is applied, the contact indicator light turns on.

IV. CONCLUSION

In this paper, an electronic skin based on capacitive sensor is designed and tested in the laboratory environment, which can be used in human-computer interaction scenarios. Compared with similar sensors, it has the advantages of compound perception and high sensitivity. The next step is to optimize the performance and manufacturing process of the super capacitor sensor, and install it into the real industrial manipulator and production environment for experiment.

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