Perspective of Proximity Sensors on Robots Using Cross-Thought

Chenghao Xing

Leicester International Institute, Dalian University of Technology, Liaoning, China

* Corresponding Author Email: 1810363347@mail.dlut.edu.cn

Abstract. Robots play a significantly important role in the area of industry manufacture. In recent years, with the development of intelligence robots, collaborative robots and human-robot interactive robots, proximity sensors applied on robots become increasingly important and popular, since proximity sensors can assure safety during collaboration process between human and robots and help to complete difficult tasks such as objects grasping, objects handover, etc. This article gives the lasted development of proximity sensors and provides an introduction on proximity sensors which are used on robots by their categories. then some concrete applications of the proximity sensors on robots are introduced, such as collision prevention, objects grasping and handover, landing process control of robot legs and so on. In addition, this article also provides some possible future development directions of proximity sensors, such as mixture usage of different proximity sensors, more application scenarios, improvement of data processing method, etc., which can help future researchers to find research directions quickly.

Keywords: Proximity sensors; Robots; Collision avoidance; Object grasping.

1. Introduction

Nowadays, robots are increasingly important in industry. According to the data report of International Federation of Robotics (IFR), the industrial robot's market is enlarging at an average annual rate of 12%. [1]. Meanwhile, with the rapid development of intelligence robots, collaborative robots and human-robot interactive robots, the demands for robots to observe surroundings are increasing and sensors become growingly essential [2]. Among these sensors, the proximity sensors are very important sensors that can detect the distance between the sensor and the object, the movement of the approaching object, and even roughly determine the surface shape of the approaching object. Thus, proximity sensors are very useful in the fields of robot collision prevention and object grasping. In light of their great significance, it is particularly important to review the existing robot proximity sensors.

In this article [3], The authors provide an introduction to sensors commonly used in industrial robots, with a preliminary summary of proximity sensors, but there is no article that provides a systematic review of robotic proximity sensors. This paper will fill this gap by introducing the current mainstream robotic proximity sensors by category, presenting related applications and making predictions for the future development of proximity sensors.

This article will be arranged as follows: Different types of proximity sensors used on robots, their basic principles and latest development. Concrete applications of these proximity sensors. Some possible future development direction of proximity sensors.

2. Proximity sensors based on different principles

2.1. Overview

Proximity sensors are the sensors that can detect the approaching of objects [3]. According to the different operating principles of proximity sensors, proximity sensors can be classified as capacitive proximity sensors, ultrasonic proximity sensors, inductive proximity sensors, optical proximity sensors and other sensors. These proximity sensors are frequently used in human-robot collaboration and objects taking.

2.2. Capacitive proximity sensors

The principles of capacitive proximity sensor are as follows: capacitive proximity sensors comprise capacitors outside circuits. At the beginning, the object is far away and the electric field is undisturbed, as the object approaches, the electric field is disturbed and its shape changes, thus leading to the change of the capacitance, which can be detected by outside circuits. Then, using computer analysis, we can infer the distance of approaching object by the size of its capacitance. The change of electric field is shown in Figure 1.

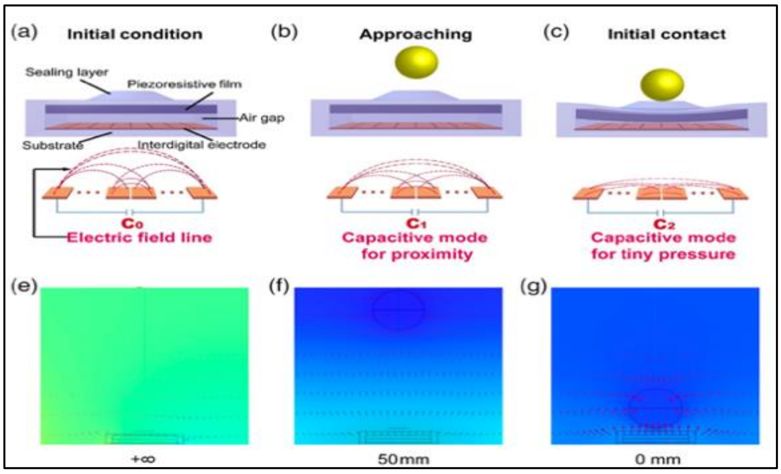

Fig. 1 Change of electrical field as object approaches [4].

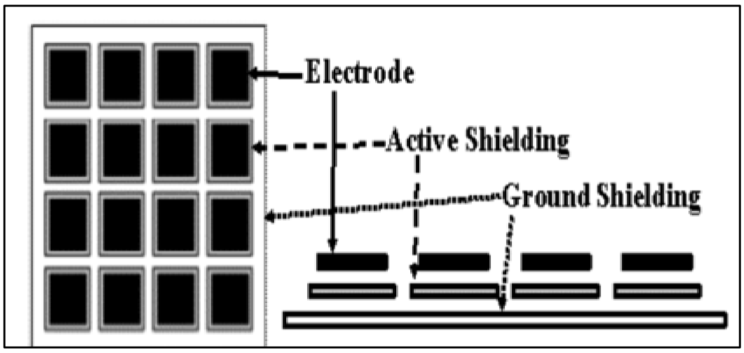

Fig. 2 Conceptual diagram and schematic diagram of the sensor [5].

In this paper, a proximity sensor based on the capacitors is designed to avoid collisions of robots and human [5]. The proximity sensors are composed of 16 capacitors in 4*4 square matrix, the picture of it is showed in Figure 2. As the objects approach the capacity, the electric is changed and is reflected on the capacitance value, which can be measured. Then the measured data is gotten and transferred to outside PC by the printed circuit board (PCB) and is processed by the outside computer. After processing, the vertical distance from the sensor to the object can be calculated and the motion of the objects can be tracked. In addition, this sensor can identify the surface approaching objects 'surface profile. This sensor can detect objects with distance up to 20cm and profile recognition accuracy is over 90%. The possible next-step is to turn data process procedure on-the-fly to enhance the practicability and flexibility of this sensor and enlarge the detecting distance [5].

2.3. Ultrasonic proximity sensors

The principles of capacitive proximity sensor are as follows: Ultrasonic sensors can be divided into two parts: ultrasonic generator and ultrasonic receiver (as shown in Figure 3). By analyzing the received ultrasonic signals bouncing back from external objects, the distance between the object and the sensor can be inferred.

In this article, a proximity sensor based on an ultrasonic proximity sensor has been designed [6]. It has a distance detection range of up to 35cm and can detect objects within a range of ±15 degrees.

However, in this sensor, the interference between the ultrasonic generator and the receiver is too large, thus the detection of objects at close range can have some problems. Meanwhile, the detection distance of the sensor can be further improved, the shape of the sensor size needs to be reduced (the shape size is 40 * 40cm), the detection angle also needs to be improved [6].

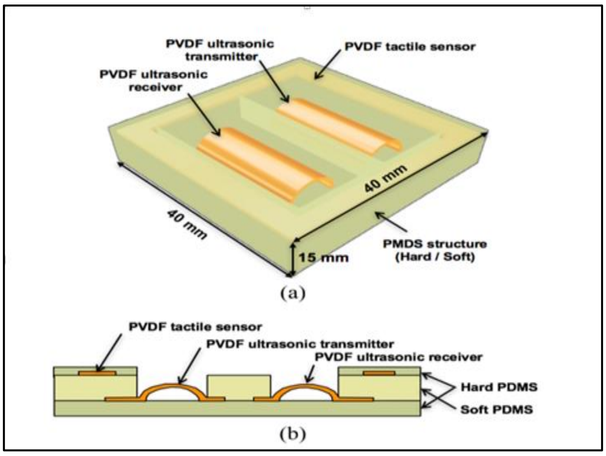

Fig. 3 (a) Three-dimensional sensor structure (b) cross-section structure [6].

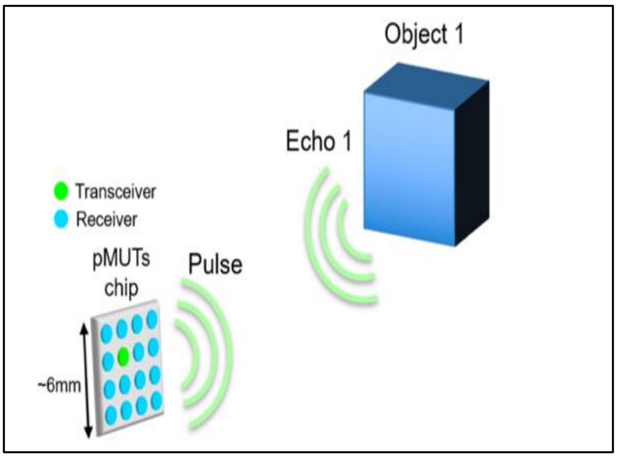

Fig. 4 Illustration of 3D-Object detecting [7].

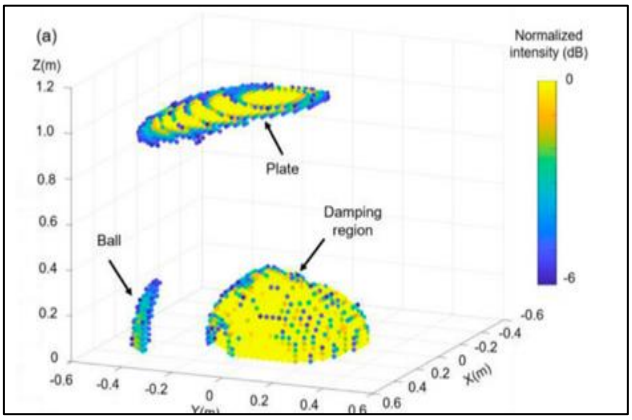

Fig. 5 The reconstruction imaging results [7].

In another article, Improved versions of ultrasonic sensors were proposed, and after using piezoelectric micromachined ultrasonic transducers (pMUTs) chips, the accuracy of ultrasonic sensing was greatly improved, making it possible to detect objects within a range of about one meter at 135 degrees, and at the same time, the size of the sensors was greatly reduced to 6*6mm, which greatly increases the portability of the object [7]. Meanwhile, the pMUTs chip features only one ultrasonic generator on it, but multiple ultrasonic receivers (as shown in Figure 4), different receivers receive different reflecting signals due to different relative position to the approaching object, by using these signals, the profile shape of the approaching object can be reconstructed using mathematical models, thus realizing 3D model detection of the ultrasonic sensor (as shown in Figure 5). At the same time, this sensor also has the characteristics of low energy consumption and high scanning efficiency [7].

2.4. Inductive proximity sensor

The principles of inductive proximity sensor are as follows: Inductive proximity sensing sensors detect the proximity of metal objects. In the detection circuit, an alternative circuit generates a magnetic field, and when a metallic object enters the magnetic field, the shape of the field changes, thus changing the impedance of the coil. By measuring the impedance of the coil and using the corresponding mathematical analysis, we can deduce the distance of the object. The schematic of the principle is shown in Figure 6 [8, 9].

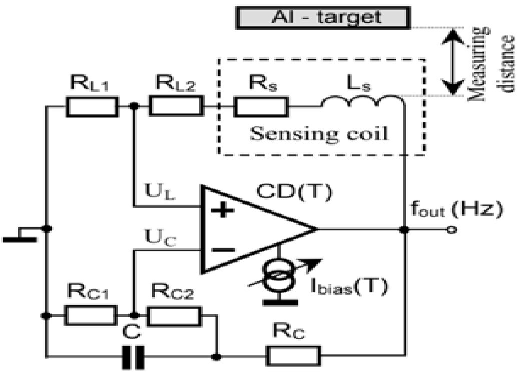

Fig. 6 Circuit of the oscillating circuit [8].

Generally, inductive-based proximity sensors have a small detection range, for example, in this article [9]. The maximum detection distance is 3mm. However, at the same time, inductive sensors are highly accurate and resistant to interference. Therefore, inductive sensors are often used to detect the distance of objects at close range.

In this article，An inductive sensor with an outer package of ceramics was designed (As shown in Figure 7) [10]. The characteristics of this sensor are not significantly affected by the outer package of ceramics. This sensor can detect objects at a distance of up to 7 mm, and although the accuracy is reduced in the detection range of 5 mm-7 mm, the accuracy within 5 mm is very high. Also, in this paper, the inductive proximity sensor is produced by hybrid manufacturing using 3D printing and other technologies, in which the inductive proximity sensor can resist extreme environments such as high temperature and high pressure by using different materials and designs. With this manufacturing technology, the geometry, dimension, etc., of the sensor can be adapted to different target environments. This allows the inductive sensors to work in different environments, enhancing their adaptability and flexibility [10].

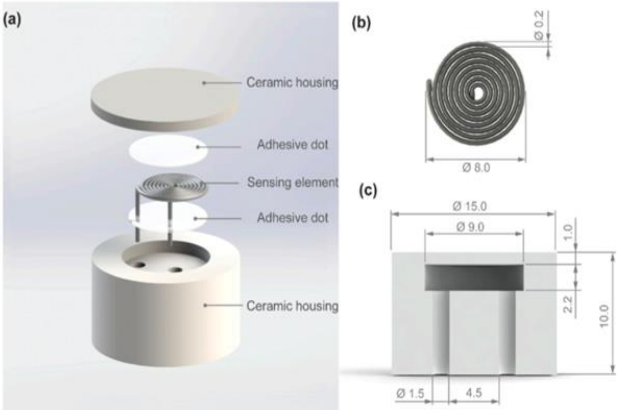

Fig. 7 Schematic of sensor structure: (a) Exploded view of the sensor; (b) Top view of the sensing element; (c) cross-section of the ceramic package.

2.5. Optical proximity sensor

2.5.1 LED-based Sensors

In this paper, an optical-based proximity sensor is proposed, which consists of LEDs and photon receivers. the light beam emitted by the LEDs reaches the sensor after reflection from the approaching object, and through mathematical analysis and calculation, the sensor can derive the distance between the object and the sensor and the angle between the surface of the object and the sensor. This proximity sensor is very accurate at close range, with a maximum measurement distance of 20 mm, a resolution of 44um per 3 mm, and a measurable angle of up to 45 degrees with an error of 1.47 degrees. Figure 8 shows a planar and three-dimensional model of the sensor [11].

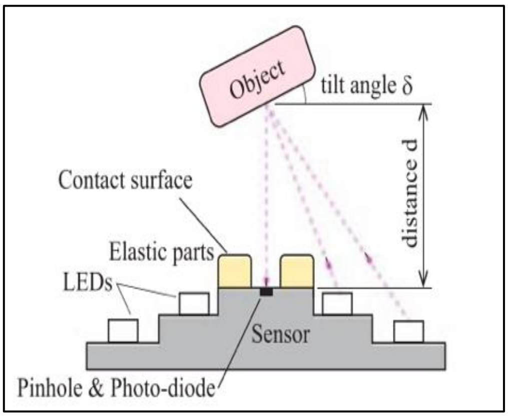

Fig. 8 The schematic of the LED-based proximity sensor [11]

2.5.2 Flight-of-time(laser) proximity sensor

This sensor mainly has two parts: a laser transmitter and a laser receiver. The laser transmitter emits a laser and bounces back after contacting the object, the receiver receives the returned laser after a certain time and calculates the distance between the sensor and the object based on the time difference between emitting and receiving. This proximity sensors can measure absolute distance up to 2m, this sensor is now commercially available as showed in Figure 9 [12].

Fig. 9 Flight-of-time proximity sensor [12].

2.6. Other sensors

2.6.1 Electroreception-based proximity sensor

Nowadays, a number of novel proximity sensors have been proposed, and many of them are based on the bionic structure of animals. Here, I will focus on introducing one of these sensors.

In this paper, a new type of proximity sensor is proposed. Inspired by elasmobranch fishes, a sensor composed by artificial electroreceptors is designed to detect approaching objects [13]. The electroreceptor can turn environment precontact information into voltage pulse series by detecting the charges approaching objects carried naturally. By this way, varies of targets like glasses, metal and polymer etc. are detected successfully. This sensor is advantageous in terms of intrinsic softness, negligible power consumption, applicability to plenty of materials and high short-distance accuracy. However, this sensing accuracy reduces when the distance is long. The schematic diagram of the principle of this sensor is shown in Figure 10 [13].

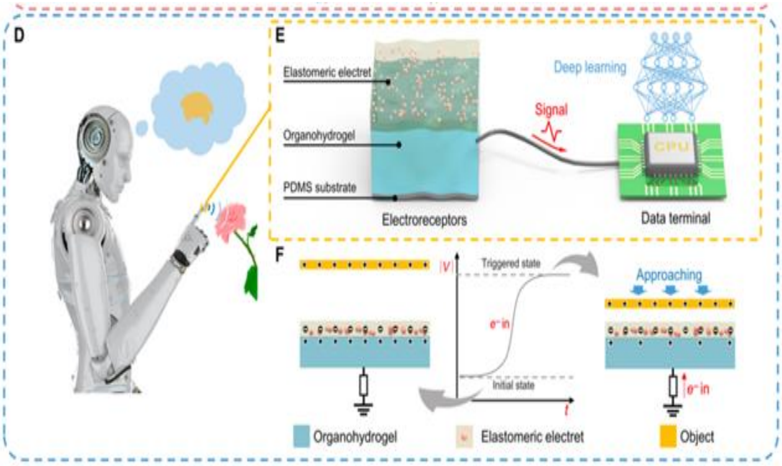

Fig. 10 The schematic of proximity sensor [13].

In addition, there are some other proximity sensors, such as infrared proximity sensors, microwave proximity sensors and so on, but relatively speaking, they are of small use range. So, they will not be further explained in this article.

2.7. Summary

In this part, a table of different kinds of proximity sensors is made to summarize their main features, which is shown in Figure 11**.**

Types of proximity sensors	Detecting Range	Theory	Constraint	Other Function
Capacitive sensor	up to 200mm	Change of electrical field	Different Relationship curve for different targets	Profile Recognition
Ultrasonic sensor	more than 1m	Sending and receiving ultrasonic wave		Profile Recognition
Inductive sensor	up to 7mm	Change of magnetic field	Only can apply to metal target	
LED-based sensor	between 2.85–20 mm	Sending and receiving LED light	Only can apply to objects with reflectance of 18% and 90%	
Laser sensor	up to 2m	Sending and receiving Laser light	Cannot be applied to transparent objects	
Electroreception-based sensor	up to 90mm	Detecting the charges carried by approaching objects		3D-object recognition

Fig. 11 Summary on different proximity sensors.

3. Applications on Robots

3.1. Overview

Proximity sensors are widely used in two applications: in the process of grasping and transferring objects, and in collision avoidance. At the same time, proximity sensors are also useful in some other specific situations, such as the bouncing and landing process of the legged robot. In the next part, the typical applications of proximity sensors in these areas will be introduced separately.

3.2. Grasping and Handover

3.2.1. Handover things from robots to human.

In this paper, a process of using a capacitive proximity sensor to deliver items from a robot to a human is presented. The main part of the device consists of two mechanical grippers and a capacitive sensor on top of the gripper (see Figure 12**).** The capacitance of the sensor is affected by the objects it holds and the approaching hand. The capacitance value of the sensor is minimal when the human hand is far away. When the human hand approaches the object to be gripped, the capacitance gradually becomes larger due to the change of the electric field, which enables the machine to detect the approach of the hand and be ready to release the object. When the hand touches the object, the capacitance spikes and reaches the threshold value, and the gripper receives the signal and releases the object, as shown in Figure 13. Using this method, the monitoring of the whole process from approaching to grasping by hand can be completed to ensure the smooth process of object delivery [14].

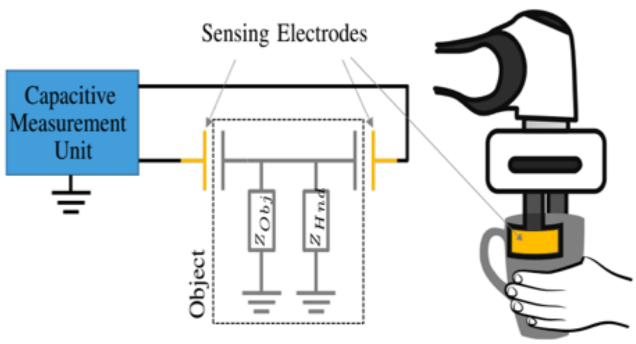

Fig. 12 Schematic of grasping capacitive sensor [14].

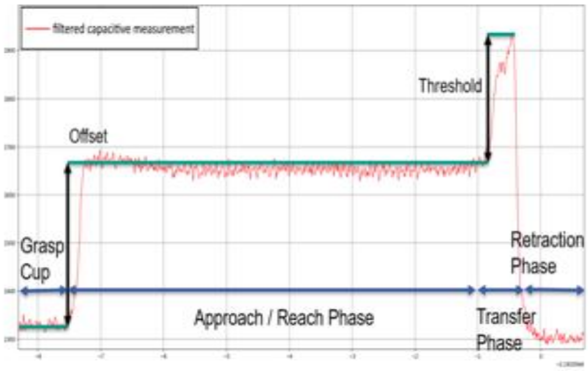

Fig. 13 Relationship between capacity and object distance [14].

3.2.2. Grasping soft objects

In this paper, a device based on vision sensors and proximity sensors is proposed for grasping soft objects with high speed and small deformation. The difficulty in grasping soft objects without deformation is that the vision sensor has poor detection accuracy when the object is close and the tactile sensor cannot detect the contact before deformation, and the device in this paper solves both problems using proximity sensors. This device consists of 2 high-speed active vision sensors and high-precision optical proximity sensors shown in Figure 14**.** In the process of object approaching the device, the Vision sensor will initially adjust the position of fingertips according to the position of the object, when the object is closer, optical proximity sensor will be used to further adjust the position of the fingertips and make it within 20mm to the hand (high precision). Subsequently, the proximity sensor will further detect the distance between the object and fingertips and complete the detection of contacting process when the object deformation is 0, the last process is elaborated in this article [11]. When the contact process is finished, the fingers will stop moving and thus the gripping of soft objects without deformation is accomplished. The gripping process is showed in Figure 15 [15].

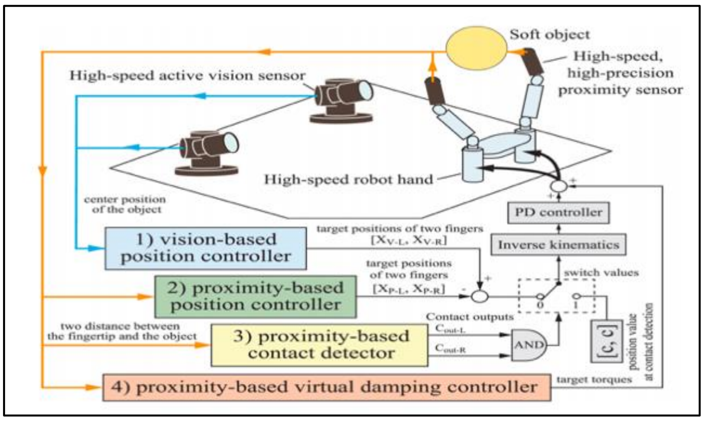

Fig. 14 Control module of catching process [15].

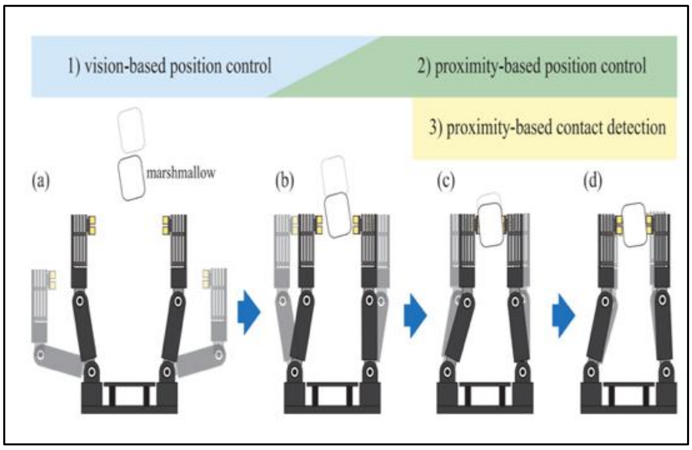

Fig. 15 Catching process of paper-balloon [15].

3.3. Collision Prevention and Human-robot Interaction.

This paper gives a specific application about ultrasonic distance sensor. Based on the use of piezoelectric micromachined ultrasonic transducers chips (PUMTs), this paper proposes the design of a robot sensor skin that can detect nearby obstacles, the schematic is shown in **Figure 16**. This skin can detect obstacles within 60 degrees in front and 300mm distance. When an obstacle is encountered, the robot will perform 3 stages to avoid collision - detection stage, deceleration stage (acceleration about 0.1m/s^2), and stop stage (stop at a distance of about 100mm from the object). In this way, the avoidance of collision of robots and approaching objects can be accomplished [16].

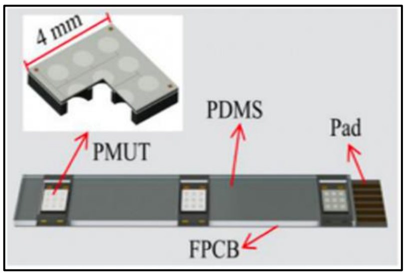

Fig. 16 Schematic of ultrasonic proximity sensing skin.

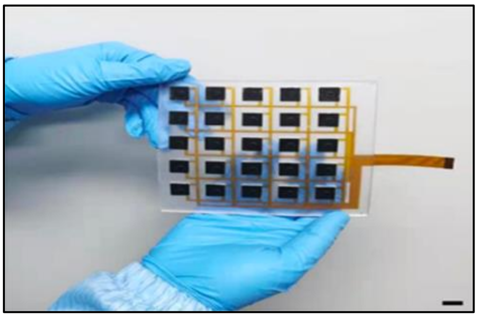

Fig. 17 the picture of the e-skin.

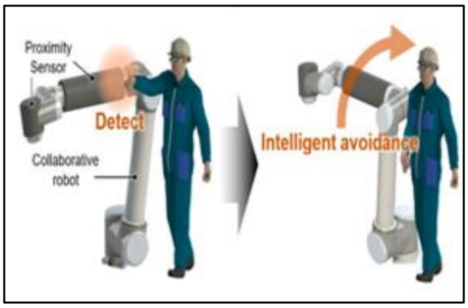

Fig. 18 Schematic of collision avoidance and the inner structure of the proximity sensor

Another paper proposes a long-range proximity sensor based on capacitive and piezoelectric tactile sensors, which is used in array to make the electronic skin (e-skin) of robots as shown in Figure 17. This skin can detect objects up to a 100mm distance and prevent the robot from hitting the object. Meanwhile, based on piezoelectric tactile sensor, this sensor can also function as a pressure sensor, which can detect the contacting force up to 450N if the collision unfortunately happens. In all, this e-skin is of high Stability and practicality. This sensor now has been used on 2 types of commercial robots until now [4].

In this paper [17], a dual-type proximity sensor based on capacitive and inductive transducers is proposed. The schematic is shown in Figure 18. This sensor can detect objects up to 300mm away, when the human body or other objects are too close to the machine, the machine will automatically plan the corresponding route to avoid collisions [17]

There are many other applications that use proximity sensors to prevent collisions, such as in paper [18], an array of laser proximity sensors is used to prevent high-speed collisions between medical robots and patients. And in paper [19], Time-of-Flight sensors are used to detect the distance between robots and people to prevent collisions between them.

3.4. Other Applications

Proximity sensors can also be used to control the landing process of the legged robot to reduce the impact of the mechanical leg when it hits the ground. If the distance between the tiptoe and the ground before the leg hits the ground is known, the leg's landing posture can be adjusted in advance to reduce the force on the leg and reduce the wearing. However, at the tiptoe of the mechanical leg, the visual sensor cannot be used because of high measurement error and occlusion. However, with optical reflective proximity sensors, these problems can be solved, the distance between the ground and the tiptoe can be measured accurately, and the mechanical leg can adjust its gesture accordingly in time to reduce the landing impact force. The schematic is showed in Figure 19 [20].

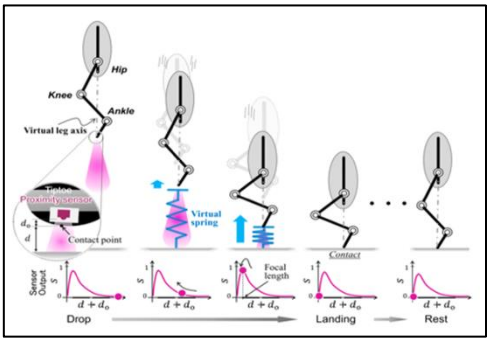

Fig. 19 the basic concept of landing force mitigation process [20].

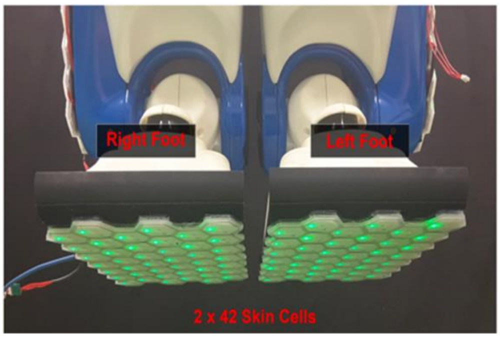

Fig. 20 Picture of feet proximity sensors [21].

In another article, proximity sensors are used on the soles of the robot's feet for real-time detection of ground conditions to help the robot walk in different ground conditions (terrain situation). The schematic is shown in Figure 20 [21]. Also, proximity sensors have applications in other specific situations, which will not be further explained here.

4. Discussion

4.1. Overview

In this section, some future directions for the development of proximity sensors are proposed based on the current development of proximity sensors to help future researchers in their exploration. The possible development direction can be divided into: Higher accuracy and reliability, The Mixed usage of different sensors, more application scenarios, development of bionic sensors and processing of data. These directions will be elaborated in this part.

4.2. Accuracy and Reliability

Sensors serve as the eyes and ears for robots and is essentially important for the development of robot industry. Nowadays， robot-human collaboration become more and more popular. Medical robots' industry and home robots' industry are thriving. The most important factor in the process of human-robot interaction is the safety factor. Therefore, the accuracy and reliability of sensors need to be further improved to ensure safety.

4.3. Mixture usage of different sensors

Single sensors often have some drawbacks, for example, inductive proximity sensors are highly accurate at close distances but cannot detect objects at long distances, and capacitive proximity sensors are relatively inaccurate but can detect objects at long distances. A presumed direction of development is that in the future, there will be more and more hybrid applications of proximity sensors, such as the mixing of capacitive and pressure sensors, ultrasonic and pressure sensors, inductive proximity sensors and capacitive sensors, etc. [4, 16, 17]. For example, by mixing mentioned electronic detection-based proximity sensors and ultrasonic sensors, it is possible to make the detection of both long-range and close-range objects convenient and reliable. At the same time, it can be a challenge to avoid the interference caused by the mixing of the two sensors in this process.

4.4. More application scenario

Currently, the application scenario of proximity sensors is relatively homogeneous. As mentioned above, they are mainly used in grasping objects and preventing collisions. In the future, one of the development directions that can be met is to increase the use scenarios of proximity sensors. For example, in some low-light or no-light scenarios, ultrasonic proximity sensors can be used to replace visual sensors since the surface 3D shape of the approaching object can be restored by using the front ultrasonic proximity sensor arrays [7].

4.5. Development of bionic sensors

The theoretical basis for many current proximity sensors comes from observations of the way animals' sense in nature. For example, ultrasonic proximity sensors were originally inspired by bats' usage of ultrasound waves for localization [22]. In this paper, we also present a proximity sensor inspired by elasmobranch fishes, this sensor is based on the detection of electrons on approaching objects to sense approaching objects [13]. It is believed that in the future, more bionic sensors will be proposed to enrich the variety of proximity sensors.

4.6. Processing and analyzing of data

Take the capacitive proximity sensor as an example, when different objects approach the sensor, the change curve of the sensor capacitance is different, for example, in the article [23]. When aluminum, copper, and plastic approach the same capacitance sensor, the relationship between capacitance value and distance is not the same. Which is shown in Figure 21. Therefore, the processing and analysis of capacitance data becomes important. For example, by using artificial intelligence, machine learning and other technologies, the capacitance data obtained can be processed in reverse to more accurately determine the approaching objects' types, speed and other parameters. In my opinion, this is a very important development direction.

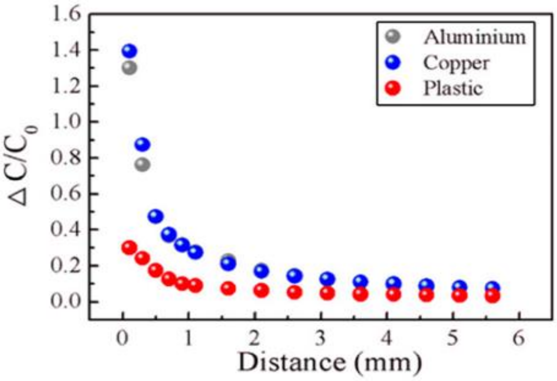

Fig. 21 Different relationship between distance and capacity

5. Conclusion

In this article, main robot proximity sensors are introduced, such as inductive proximity sensors, ultrasonic proximity sensors and capacitive proximity sensors etc. The basic principles of these sensors are described and some specific sensors are introduced. Also, the applications of proximity sensors are presented, such as anti-collision applications, object grasping applications and so on. In addition, some possible future development directions of proximity sensors are presented, such as higher accuracy and reliability, hybridization of sensors, more application scenarios, etc. This article fills the gap of review articles in the field of robotic proximity sensors and helps later researchers to understand the development of proximity sensors and related applications faster, and provides some research directions as well as perspectives for future researchers.

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