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Common Sensors in Industrial Robots: A Review

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Abstract. The application of industrial robots has greatly promoted the development of industry in the past decades. Now with the proposal and prevalence of Industry 4.0, industrial robots are required to be more independent and intelligent to accomplish more complex and flexible tasks. The advancement of industrial robots relies on the development and progress of multiple technologies, among which sensors are the indispensable part. They can acquire abundant information to help industrial robots implement their functions. This paper reviews the recent literatures and gives a summary and introduction of the commonly used sensors in industrial robots. Additionally, the applications of these sensors in diverse functions of industrial robots are also presented. Finally, the developing direction and challenges of industrial robots in the future are discussed in the last part of this article.

1. Introduction

Nowadays many countries focus on the development of Industry 4.0 to promote the transition and upgrade of the manufacturing sector. Industry 4.0, which is considered to be the fourth industrial revolution, is proposed by Germany at the industrial fair in Hannover in 2013. Its objective is to realize the intelligent, flexible and personalized process of manufacture with the help of Internet of Things (IOT), digital information technology, and computer technology [1]. In Industry 4.0, industrial robots are the indispensable component.

Industrial robots have a history of more than 60 years [2]. The development and utilization of them have vastly improved the productivity and promoted the progress of industry, as well as relieved workers of onerous and iterative tasks. What's more, with the advancement of sensors technology, automation and computer information technology in recent years, industrial robots are developed to be more intelligent. Now they can implement multiple functions and are extensively employed in many fields of manufacture, i.e., welding, assembly, materials transportation, mechanical processing, etc [2].

Sensors are the essential parts for industrial robots to accomplish their tasks. The information acquired by sensors can be used to judge the state of industrial robots and the circumstances of external environment, thus helping control and regulate robots to execute appointed functions. This paper reviews the recent literatures and summarizes the frequently-used sensors and their applications in industrial robots.

The structure of this article is organized as follows: The introduction of background in Section 1 is followed by the presentation and analysis of the common sensors employed in industrial robots in Section 2. Section 3 introduces the concrete applications of these sensors in industrial robots. And the last section concludes this article and makes a discussion about the future works.



2. Common Sensors in Industrial Robots

Sensors are of great importance to industrial robots. They are equivalent to the sensorium of industrial robots to help recognize the motion status of the robot and the circumstance of environment. With the help of these information, the controller can issue corresponding instructions to make the robot complete the required operations. After a survey on literatures in recent years, the common sensors deployed in industrial robots are presented as follows.

2.1. Tactile Sensors

Just as the significance of tactile perception for people to perceive multiple properties of external objects and interact with the environment, industrial robots also need the sense of touch to cognize the outer world. Therefore, tactile sensors, which endue industrial robots with the ability of tactile sensation, are vital components to make them more intelligent.

Tactile sensors have been developed for several decades, and they are gradually used in various robots now. The types of tactile sensors mainly include capacitive, piezoelectric, piezo-resistive and optical [3]. The capacitive tactile sensor utilizes the change of capacitance to measure the contact force. It has great spatial resolution and low power consumption, but its robustness to interference is poor [4]. The piezoelectric tactile sensor depends on the theory of piezoelectric effect which means that the electrical charge will be emerged on the surface of piezoelectric materials when exterior load is exerted. The frequency response of it is good and its measuring range is large, but its resolution is not very satisfying [3]. The piezo-resistive tactile sensor bases on the principle of piezo-resistive effect which refers to the variance of resistance when outer force is implemented. It has large measuring range and good robustness, however, it is impressionable to hysteresis [4]. The optical tactile sensor can transduce the external contact information into the variance of parameters of light. It is resistant to the external interference and possesses great spatial resolution [5]. Furthermore, some researchers have developed artificial skins to imitate human's skin, which may be the development trend of the future. Multiple sensors are deployed on each cell of the skin to provide abundant data.

Although tactile sensors are attracting more and more attention and interest, their performance, like versatility and adaptability, is not very satisfying at present. The development of them depends on the advancement of various domains of technology, such as materials, electronics, relevant algorithms, and so on [5]. To achieve the level of human's tactile perception, there is still a long way to go.

2.2. Visual Sensors

Visual sensing technology has developed rapidly over the past few years, and nowadays it is extensively utilized in many fields, such as face recognition, three-dimensional reconstruction and multiple robots, etc. Images captured by visual sensors are processed by the processor to extract useful information for specific tasks.

Visual sensors mainly include various kinds of cameras, like RGB cameras, multispectral cameras, and depth cameras [6]. The photosensitive elements equipped in multiple cameras are usually CCD or CMOS, which can transduce the light information into electrical signals based on the principle of photoelectric effect. The flexibility and pictures' quality of CCD cameras are better than that of CMOS cameras, but CMOS has its superiority in the aspects of cost and power consumption [7].

Different types of cameras can provide diverse information. RGB cameras, the mostly used one in people's daily life, capture chromatic images on the basis of the theory that each kind of visible color can be obtained by three colors: red, green, blue and their combination. Multispectral cameras are able to acquire images in diverse bands of spectrum, involving visible and invisible wavelength, consequently, they can get the information that cannot be provided by RGB cameras [8]. Depth cameras add the distance information to two-dimensional images, thus realizing stereo imaging. They can be classified as RGB binocular, structured light and TOF according to their operational principles.

Visual sensors enjoy great popularity for their advantages of low cost, luxuriant information supplied and ease of use [6]. Nonetheless, the processing of data from visual sensors are complex and time-consuming. Although many researchers have put forward several algorithms, the applicability and

flexibility are still not very satisfying.

2.3. Laser Sensors

Laser is invented in twentieth century and has outstanding monochromaticity, directivity and brightness [9], thus being widely employed for diverse applications. Laser sensors are the kind of sensor that utilizes laser technology to accomplish measuring tasks. They are usually composed of laser emitter, detector and measuring circuit. The working substance of the emitter mainly contains four categories: solid, liquid, gas and semiconductor [10].

Laser sensors are mostly utilized to measure physical parameters, like distance, velocity and vibration. The common types are laser range finder, laser displacement sensor, laser scanner, laser tracker, etc. The fundamentals of laser range measurement mainly include three kinds: time of flight (TOF), triangulation method and optical interference [11]. TOF refers to the time from projecting laser to receiving the catoptric light. It is often used in laser range finder for long distance measuring, and the accuracy depends on the measuring precision of the flying time because of the high speed of light. The triangulation method utilizes the homothetic triangle theory and trigonometric function to calculate the distance of objects. Laser displacement sensor is based on this method to implement short range measuring. Optical interference is a phenomenon that the superposition of two light beams with different phase will generate bright and dark fringes. It is employed in the laser tracker to gauge the moved distance of the target fitted with a reflector.

Laser sensors can realize contactless telemetering, and the measuring speed and accuracy are satisfying [6]. However, the wavelength of laser can be influenced by temperature, atmospheric pressure and air humidity, so the compensation will be required when the above parameters change.

2.4. Encoder

The encoder is a kind of sensor that can transduce the angular displacement or velocity into electrical impulse or digital quantity. It can be divided into four categories: photoelectric, magnetic, inductive and capacitive according to the detection principles [12].

The frequently-used type is the photoelectric encoder, which utilizes the theory of photoelectric effect to complete signal conversion. It is usually composed of an optical coded disc and the photoelectric detecting appliance. In terms of the calibration mode of the coded disc, photoelectric encoders can be classified into incremental encoders and absolute encoders. The output of incremental photoelectric encoders is a series of square wave pluses. The rotation angle can be calculated on the basis of the amount of the pluses, and a zero reference position is required to determine the absolute position of the rotating shaft. Absolute photoelectric encoders output the binary digital quantity that corresponds to each location of the axis, therefore, they can get the absolute position directly.

Encoders have been widely used for many years on account of their advantages of compactness, long service life, ease of use, and mature technology [13]. The resolution of encoders relies on the amount of scribed lines on the coded disc in one circle. Smaller angle can be discriminated with more lines, thereby generating higher resolution, in the meanwhile, the cost will be higher too.

2.5. Other Sensors

Apart from the above four kinds of sensors, some other sensors are also deployed in industrial robots to realize several functions, such as proximity sensors, inertial sensors, torque sensors, acoustic sensors, magnetic sensors, ultrasonic sensors, etc.

The proximity sensor is a kind of non-contact device that can detect the approach of objects and output homologous switching signals. It can be categorized into capacitive, inductive and photoelectric on the basis of the operational fundamentals [14]. Capacitive proximity sensors utilize the alteration of the circuit status caused by the capacity variance of the detecting electrode to perceive the approaching objects. Inductive proximity sensors are based on the electromagnetic induction to work. The sensing elements of them are the detecting coils, whose inductance will change when a metallic conductor comes near. Photoelectric proximity sensors are usually composed of the light emitting diode and the

photoelectric device. The light emitted from the diode will be reflected to the photoelectric device when objects approach, then the detecting circuit will generate corresponding output signals.

Inertial sensors usually refer to the accelerometer, gyroscope and magnetometer. They are widely employed to **measure the kinematical parameters of moving objects, including the acceleration, angular speed and azimuthal angle.** Specially, the triaxial combination of them is known as the inertial measuring unit (IMU). **The measurement principle of inertial sensors is dead reckoning (DR) that utilizes the method of integration to calculate the amount of objects' movement.** **The precision of inertial sensors is satisfying in a short time, but the error will be larger and larger as time goes by [15].**

Table 1. A brief summary of the presented sensors.

Sensor type	Principle	Information obtained	Applications in industrial robots
Tactile sensors	capacitive, piezoelectric, piezo-resistive, optical	contact force, area, position	human-robot collaboration (HRC), objects grasping, quality monitoring
Visual sensors	CCD or CMOS imaging	images	human-robot collaboration (HRC), navigation, manipulator control, assembly, robot programming
Laser sensors	time of flight (TOF), triangulation, optical interference	distance, displacement	human-robot collaboration (HRC), navigation, manipulator control
Encoders	photoelectric, magnetic, inductive, capacitive	angular displacement	navigation, manipulator control
Proximity sensors	capacitive, inductive, photoelectric	approaching of objects	human-robot collaboration (HRC), objects grasping
Inertial Sensors	dead reckoning (DR)	acceleration, angular speed, azimuthal angle	navigation, manipulator control
Torque sensors	inductive, resistance strain	torque	human-robot collaboration (HRC), objects grasping, robot programming
Acoustic sensors	capacitive	sound signals	human-robot collaboration (HRC), welding
Magnetic sensors	Hall Effect	magnetic field intensity	navigation
Ultrasonic Sensors	time of flight (TOF)	distance	obstacles avoidance

Torque sensors are mostly used to measure the torque exerted to mechanical axis. The common types are the inductive torque sensor and the resistance strain torque sensor. The structure of them usually consists of a torsion bar and detecting elements like coils or resistance strain gage. The input shaft and the output shaft are connected by the torsion bar, and the torsional deformation of the torsion bar caused by a torque can be transduced into electric signals via the variance of parameters of detecting elements, thus realizing the torque measurement.

Acoustic sensors are able to transduce the sound waves into electric signals. A capacitive electret microphone is installed in them, and sound waves can cause the vibration of the electret membrane in the microphone, thus resulting in the variance of capacity and generating weak voltage. Then the voltage is transformed for subsequent processing.

Magnetic sensors are mainly deployed to detect the magnetic field intensity. The principle of them is **Hall Effect** which refers to the phenomenon that when the electricity flows through a conductor, an

electric field which is perpendicular to the direction of the magnetic field and the electricity will be generated, thus causing a potential difference on the surface of the conductor.

Ultrasonic sensors are often used to detect obstacles. They estimate the range of objects according to the time from projecting the ultrasonic waves to detecting the echo. The size and weight of them are small, and their cost and power consumption are low [16].

Table 1 provides a brief summary of the above presented sensors.

3. Concrete Applications

Sensors are frequently deployed to assist the controller to control industrial robots to implement appointed functions, which involve various aspects, such as human-robot collaboration (HRC), autonomous navigation, manipulator control, etc. In the following part, this article gives a presentation and analysis of the above sensors' concrete applications in industrial robots.

3.1. Human-Robot Collaboration

Recently the concept of human-robot collaboration (HRC) has been brought out to realize the collaborative operation of workers and robots. This mode of production can combine the cognitive ability and strain capacity of human beings with the accuracy and tirelessness of robots to improve the flexibility and adaptability of manufacture systems [17].

The primary problem needed to be considered in HRC is safety [18]. Robots should be able to detect and recognize objects to avoid collisions or stop moving immediately when collisions occur. The common sensors applied to implement this function are vision sensors, laser sensors, proximity sensors, torque sensors and tactile sensors. For example, in [19, 20], tactile sensors are deployed to perceive the physical contact and locate the position of collisions to protect workers cooperating with the robot. And the internal joint torque sensors are utilized to detect and classify collisions by estimating the external forces in [21]. However, tactile sensors and torque sensors have a shortcoming that they can only detect but cannot avoid collisions. The other three kinds of sensors can fill the gap. In [22, 23], the capacitive or photoelectric proximity sensors are deployed to detect the approaching humans or objects so as to help the industrial robots react timely before collisions happen. Depth cameras are used to recognize humans in the operating scope of industrial robots to ensure safety in [24]. And in [25], laser scanners are equipped to monitor the working circumstances of robots for collisions avoidance. Furthermore, multiple sensors fusion is applied to guarantee the collaborative safety in HRC. For instance, in [26], a RGBD camera, proximity sensors and a laser range finder are utilized to monitor the working area of industrial robots and detect the approaching human beings. In [27], RGBD cameras and laser scanners are employed to recognize and track the workers in the working range of robots.

The interaction of humans and robots is also an important part in HRC. Workers can effectively control computer programming. For example, speech recognition assisted by acoustical sensors is exploited to help humans interact with robots in [28]. But the performance of this method may not be satisfying when the environment is noisy. Targeting this problem, hand gestures recognition with the help of vision sensors is proposed to control the robots in [29].

3.2. AGV Navigation

Nowadays AGV (Automated Guided Vehicle) is widely deployed in industrial environment for materials transportation, flexible production lines and some other applications [30]. Autonomous navigation is the primary function of it, and the current technology can be classified into two main types: physical paths and virtual paths [31].

Physical paths mainly refer to magnetic tapes or optical lines. In this method, magnetic sensors [32] or vision sensors [33] are commonly used to detect the path to estimate the position deviation of AGV, then the controller can make homologous adjustments to ensure AGV travels along the predetermined trajectory. The physical path has advantages of low cost, high reliability and maturity, but its flexibility is poor [31]. In contrast, the mode of virtual paths is more convenient to alter the route of AGV, and the sensors frequently utilized in it are vision sensors, laser sensors, encoders and inertial sensors. For

instance, in [34], a TOF camera is deployed to perceive the environment and locate and guide a forklift AGV. And in [35], laser sensors are employed to calculate the position of AGV robots based on the triangular measurement method. Encoders and inertial sensors are also used to estimate the shift amount of AGV to execute navigation [36]. Additionally, the mode of multiple sensors fusion is utilized to improve the performance of navigation. In [37], magnetic sensors are appended to calibrate the location of AGV and modify the cumulative deviation of encoders and inertial sensors. And TOF cameras and laser range finders are used together to complete autonomous navigation in [38].

In addition to the above navigation technology, obstacles detection and avoidance is also an essential component in automated traveling of AGV. Ultrasonic sensors [39] or laser sensors [40] are usually deployed to detect obstacles to help the controller re-plan the route of AGV for collision avoidance.

3.3. Manipulator Control

Manipulator control is of great importance to the accuracy of various tasks implemented by industrial robots, such as mechanical processing, assembly, welding, etc. It involves the position and motion trajectory control of the end-effector. In order to get high precision of industrial robots, errors caused by several factors like compliance of joints, transmission of gears and temperature variation are needed to be gauged and modified [41].

The commonly used sensors in this respect are laser sensors, vision sensors, inertial sensors and encoders. For example, in [42], laser trackers are deployed to measure the current location of the end-effector to get the absolute position deviation, then the controller can make a real time calibration to improve the accuracy of industrial robots. And in [43, 44], the method of visual servoing is utilized to compensate errors of the robot actuator timely and realize the accurate path tracking. IMU is also used to measure the joint angles to estimate the position of the end-effector [45], but its precision is not very satisfying because of the accumulated errors. In addition, the accuracy of encoders equipped on servo motors of the robot joints is also not good because they cannot detect the deviation generated by the mechanical deformation or transmission of gears. Targeting this problem, the secondary encoders are deployed on each output axis to obtain high position accuracy of the actuator and improve the performance of mechanical processing [46], however, their price is a little expensive. Furthermore, the combination of inertial sensors and encoders is also employed to get better location estimation of the robot end-effector in [47].

3.4. Objects Grasping and Assembly

Objects grasping is a common operation in industrial manufacture. To complete this task, robots need to recognize the target object and determine its position coordinates, then the actuator should pick it in a proper force in case of damage or slippage. The frequently applied sensors in this process are usually vision sensors, proximity sensors, torque sensors and tactile sensors. In [48], depth cameras are deployed to identify the location and posture of the objects to help the controller plan the motion path of the robot end-effector. And in [49], proximity sensors are also configured to help modify the approaching deviation and improve the accuracy of grasping. On the other hand, grasping force of the end-effector are ordinarily estimated and controlled by torque sensors [50]. Additionally, in order to detect and avoid the slippage of the grasped object, tactile sensors are often employed to help adjust the picking force [51, 52].

Assembly is an important component of the industrial production lines. Apart from the above presented operation of parts grasping, the recognition of assembly position is also essential to autonomous assembling. In [53, 54], vision sensors are utilized to detect and localize the installation site to guide the end-effector to implement assembly. Moreover, torque sensors [55] or laser sensors [56] are also configured to help compensate the location error of visual sensors to improve the accuracy and efficiency of assembling.

3.5. Other Applications

In addition to the above introduced applications, sensors presented in section 2 are also applied in some

other aspects of industrial robots, such as welding, quality monitoring, robot programming, etc.

For instance, in [57, 58], visual sensors are deployed to capture the real time welding images which will be processed to obtain the position of welding seam, then the controller can control the end-effector to execute welding accurately. Furthermore, acoustic sensors are also used to realize welding seam tracking by analyzing the characteristics of arc sound signals in [59]. And in [60], vision sensors and acoustic sensors are integrated to monitor the welding penetration status to control the quality of welding.

In the aspect of quality monitoring on production line, in [61], stereo vision sensors are utilized to inspect the quality of products via the processing and features extraction of the acquired images. And tactile sensors are also deployed on the robot end-effector to implement quality control by perceiving the surface information of products in [62].

Currently some intuitive methods are employed with the help of several sensors to simplify the process and improve the efficiency of robot programming. For example, in [63, 64], torque sensors are utilized to measure forces and torques to estimate the motion parameters of the robot manipulator during the procedure of manual guidance programming. And in [65], cameras and a luminous marker are used to track the movement of the human wrist to realize the demonstration programming of industrial robots. Additionally, in [66], tactile sensors are also deployed to recognize the tactile gestures to implement robot programming.

4. Conclusion

This article reviews the common sensors and their concrete applications in industrial robots in recent years. From the literatures, it can be seen that industrial robots are developing towards the direction of more independent and intelligent at present, which will help realize more flexible, accurate and personalized industrial manufacture. However, one challenge in the development of industrial robots is to develop sensors with better properties to improve the robots' perception of the external environment and their own status, and this relies on the development of multidisciplinary technologies. Additionally, the algorithms for handling the information acquired from sensors are also needed to be optimized to improve the processing speed and accuracy to meet the higher performance requirements of industrial robots.

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