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Research Status and Prospect of Intelligent Robot Sensing Technology

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Abstract:

This paper focuses on advancements in visual sensing, laser radar, and tactile sensing technologies. It presents a comprehensive analysis of the current research status and anticipated future trends in intelligent robot sensing technology.” Firstly, we scrutinize the implementation of visual sensors in object recognition and positioning, elucidating its fundamental principles and emphasizing its crucial role in the domain of intelligent robotics. Secondly, we provide an overview of the current application status of laser radar sensing technology in distance and velocity measurement, highlighting the innovative advancements in laser velocity measurement techniques and their widespread adoption in navigation systems, thereby indicating its substantial potential in enhancing robot performance. Finally, with regard to tactile sensing technology, we examine the distinguishing features of force sensors and capacitive sensors, as well as their practical applications in diverse domains such as robotics, medical assistance, and scientific research. We underscore the significant value of these sensors in providing precise data support and operational assurance, which is crucial for the development and advancement of intelligent robot sensing technology.

Keywords: Visual Sensing; Laser Radar; Tactile Sensing; Intelligent Robotics.

1. Introduction

In today’s era of rapid innovation in computer and information technology, artificial intelligence is gradually integrating into our daily life with its unparalleled potential, showing inestimable application prospects in many fields such as industry, agriculture and biomedicine. Sensors are to robots what the five senses are to humans, playing an indispensable role in perceiving and understanding the world. Sensors act as the robot’s senses, helping them gain insight into their surroundings and capture key information to cope with various complex and changing environments. In recent years, with the continuous progress of technology, in addition to the traditional visual sensing technology, lidar, touch and other advanced sensing technologies have also begun to emerge in many industrial fields, providing robots with more accurate and comprehensive sensing capabilities. Visual sensing technology, based on image processing and camera systems, is widely used in intelligent robots. With the progress of The Times and the development of various intelligent technologies, the so-called visual sensor is gradually getting more and more widely used: face recognition payment, face recognition access control, ai recognition, the robot for the target and its own position and posture of the judgment and analysis. Tactile sensing technology can simulate human touch sensation, usually based on different physical principles, mainly divided into piezoresistive and capacitive forms, which can convert mechanical energy into electrical signals. Tactile sensing technology has a wide range of applications and is an important part of the robot sensing system. It is often used in areas such as industrial manufacturing, aerospace, medical, gaming and virtual reality. Lidar is a combination of modern laser technology and photoelectric detection (a high-precision sensor technology using laser pulse for distance measurement) principle is to emit laser beam (detection signal) to the target, to the response target echo (reflected back detection signal). The technology can be applied to the autonomous navigation, positioning and perception ability of the robot. The technology can play an important role in the application of robots.

2. Vision sensing technology

2.1 About the identification and location of objects

Object identification and localization involve enabling robots to recognize objects and determine their positions. That means machine vision is a subject that researching how to let machine learn how to look. In other worlds, it means let the camera to be used as robot’s eyes, then let the captured image data is passed to a computer that acts as the brain of the machine for processing to achieve target measurement, location and identification functions. The final purpose of computer vision is to let the computer act as human’s brain. Capture information with eyes and understand the information. In order to build some kind of AI system that could deal with image information or other multidimensional information data.

In 1980, professor Marr from MTI build the photographic geometry theory. From now on, the research about vision sensor started to appear in people’s view. Currently, vision sensors are widely used in various fields, including aeronautical engineering, aerospace engineering, military science, car backup systems, and autonomous driving [1].

In 2015, Lu et al. conducted research on vision sensor-based road detection for field robot navigation. Proposed a hierarchical vision sensor-based method for robust road detection. Introduce a multiple population genetic algorithm (MPGA)-based approach for efficient road vanishing point detection. Experiments were carried out on a real robot vision system to verify the effectiveness of the method [2].

Chin and Dyer conducted a comparative study on model-based robot visual object recognition algorithms. The three core problems common to each category, namely feature extraction, modeling, and matching, are studied in detail. The existing identification systems and algorithms for industrial parts were evaluated and compared [3].

2.2 About the location of objects

Vision sensor-based positioning and recognition technology has rapidly evolved into a cutting-edge field in recent years. And with the developing and popularize of the digitization, visualization, and automation of information in 21 century, more and more industrial production lines is needing the support and upgrade updates of the automatic visual recognition and positioning system.

Visual positioning systems have numerous applications in the intellectualization of welding robots, particularly in guiding them to locate welding seams. To welding more precise and efficient. Intellectualization of welding robots has important significance to modern industrial production.

The visual positioning system is a complete set of input, processing, and output structures [4]. In general, the input structure consists of a camera and a vision sensor, and its main function is to convert the image information into computer language, and then hand it over to the processing structure for processing. Normally, the processing structure is composed of a robot computer, and its main function is to “read” the computer language transferred from the previous input structure, and then carry out a series of recognition and positioning processing on the information, and then issue instructions such as “grasping”, “taking”, “forward” and “backward” to the output structure. The output structure is composed of the robot itself, and its main role is to execute the instructions of the processing structure to complete a series of tasks. In practice, the relative pose between the camera and the robot’s end-effector is often uncertain. Additionally, lens distortions (both radial and tangential) affect distance measurements. These factors necessitate camera calibration, which is typically performed using established calibration methods.

2.3 About the identification of objects

With the progress of the times and the development of digital automation of industrial information, the demand for visual sensors for object recognition, that is, visual recognition systems, is getting stronger and stronger, so it has a broad market and bright development prospects. Visual recognition systems are often used by intelligent robots to identify and sort parts inside factories and express delivery in warehouses. It is also commonly used for face recognition payment, face recognition access control, etc. The visual recognition system is similar to the visual positioning system, and it is also composed of several complete structures to form a complete system. Object recognition typically employs image processing techniques such as edge detection, feature extraction, and pattern matching to identify target objects in images. Image processing and analysis mainly includes image preprocessing, feature extraction, and recognition based on these features. In 2019, Zhang Haizhou proposed an object pose estimation method based on image semantic segmentation by constructing a 3D grasping environment for robots with depth sensors and pixel-level classification by building a fully convolutional neural network in deep learning [5]. In 2011, Ying Cheng discussed the research on visual recognition of motors as objects, using algorithms such as image processing technologies such as image edge detection and invariant moment for feature extraction, and finally using MATLAB to complete the development of recognition and positioning system after calibration.In 2023, Li Maoyong used the depth camera and the YOLOv5 algorithm and weld groove positioning algorithm to study the vision-based automatic weld breach identification and positioning technology [6][7].

3. LIDAR sensing technology

3.1 Application of distance measurement

Laser distance measurement is a technique that determines distance by emitting laser light to a target and analyzing the reflected signal the laser light is reflected from the target and detected by an electronic component. The distance is then calculated based on the time between emission and reception of the laser signal. Because of its high accuracy and wide range, it can be used in many fields.

Time-dependent photon counting is a specialized application in laser ranging. Due to the high sensitivity of photon detectors, this technique requires a low-noise environment to accurately count the echoed photons. At the end of the 20th century, research on time-correlated photon counting began to be carried out to make full use of the correlation properties of the target photons and to efficiently extract the target echo photons mixed in the noise. At the beginning, a time amplitude converter (TAC) was used to convert the collected time into voltage amplitude, and then the acquired value was processed to obtain the target distance value. The development of time-to-digital converters (TDCs) has significantly advanced single-photon ranging. TDCs convert time signals into digital format, enhancing data visibility and processing capabilities.

Time-to-digital converters (TDCs) are the heart of time-mode circuits, and TDCs convert time-coded analog signals to digital processing, which can drive hardware efficiency and purely digital architectures in deep-submicron semiconductor technology [8]. Modern TDC designs are driven by CMOS process and application requirements, focusing on optimization of digital implementation, resolution, input range, conversion time, power consumption and silicon area [9]. Calibration, fault tolerance, resistance to PVT variations, and resistance to sub-stability design techniques are becoming increasingly important in the face of nanoscale CMOS technology challenges.

The target echo photons have strong time correlation, and the detected target echo signal will produce an envelope shape similar to the laser outgoing waveform after multiple pulse accumulation, while the pulse accumulation process is shown in Fig. 1 [10].

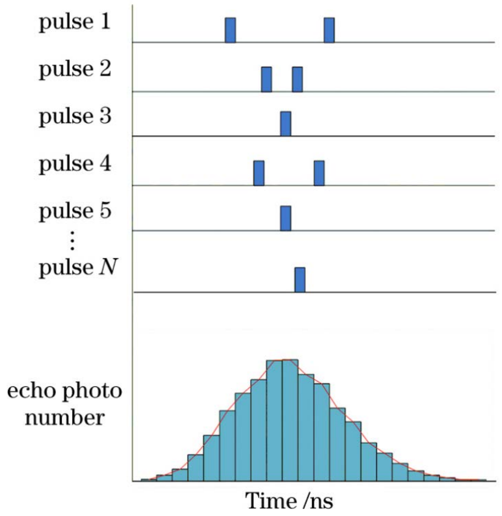

Fig. 1 Histogram of time-correlated single photon counting distribution [10].

Three methods are commonly used to process echo photon accumulation histograms and extract target location information: the peak method, the center of mass method, and deep learning approaches [11]. The peak method refers to an algorithm that extracts the position of the histogram peak; the center-of-mass method refers to calculating the center-of-mass position of the cumulative histogram to obtain the target position; and the deep learning method refers to the use of one-dimensional convolutional neural networks to train a large number of datasets in order to settle the echo moments with a high degree of accuracy,

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but needs to include datasets for all possible cases (with the drawback that the datasets need to cover all cases, or else the measurement results cannot be evaluated for the untrained cases). In the deep learning method, it is necessary to perform the solution of the relevant signals and repeat the results many times to obtain a sufficient number of sample data sets and label sets. The neural network model is trained with the sample data and label sets, and then computations are performed to obtain accurate results. The effectiveness of the deep learning method heavily relies on high-quality training and comprehensive testing of datasets, which ensures more accurate data processing and robust performance across various scenarios. It can be solved by different echo moments and transformed into a waveform classification problem, thus improving the adaptability of application scenarios.

As LIDAR technology advances, the demands for improved transmission and reception performance are increasing. In order to meet these higher requirements, a telescope-type structure is used to expand the beam for parallel light, which not only reduces the far-field divergence angle during laser propagation, but also expands the application range of the system. In addition, the use of three sets of spherical lenses can also realize the collimation of the laser beam, although increasing the focal length can also play a collimating effect, but within a certain range of adjustment. These methods enable the integration of transceiver functions in the optical system, allowing for beam adjustability and continuous doubling simultaneously. Through the application of these methods, the performance and application range of this optical system have been greatly improved. In addition, this system has a great advantage in terms of cost, because it saves a lot of unnecessary expenses, which makes the whole scheme optimized. Overall, the development of this LiDAR technology has both improved the performance of the system and reduced the cost, and it has made an important contribution to the development of LiDAR technology in China, as well as providing a useful reference for the development of this technology [12].

3.2 On the application of measuring speed

Laser speed measurement technology utilizes the principles of laser ranging. It performs two distance measurements at specific time intervals to determine the object's displacement, from which its speed can be calculated. Based on these ranging data, the moving speed of the object is calculated, and accurate measurement of its speed can be realized. Lei Shi et al. developed laser-based measurement techniques to study heat transfer and fluid flow phenomena in thermoacoustic systems. The main challenge of the research is to deeply understand the energy transfer regime between key components such as stacks (or heat accumulators) and cold heat exchangers under oscillatory flow conditions in the acoustic field. To achieve this goal, they combined planar laser-induced fluorescence (PLIF) and particle image velocimetry (PIV) techniques, enabling simultaneous two-dimensional temperature and velocity field measurements [13]. Under the operating conditions of a simulated thermoacoustic system, Lei shi et al. successfully captured the velocity and temperature field distributions of 20 different phases in the acoustic cycle by adding a pair of fins simulating a heat exchanger to a quarter-wavelength standing-wave acoustic resonator and keeping them at a constant temperature by resistive heating and water cooling. The analysis exhibits the influence of inertial, viscous and thermal effects on the local temperature and velocity variations with time, as well as the interactions between temperature and velocity fields, which are important for understanding the heat transfer mechanisms in thermoacoustic systems. Lei Shi et al.'s study establishes a foundation for understanding heat transfer correlations under oscillatory conditions [14]. It paves the way for future research aimed at deepening our understanding of complex thermoacoustic phenomena and advancing technology in this field.

Asakura et al. investigated dynamic scattering phenomena from uniformly moving diffuse objects illuminated by Gaussian beams. Their analysis revealed the statistical properties of these scatterings, focusing on the spatio-temporal correlation of scattering intensities. In the article, T. Asakura et al. provide an in-depth discussion of scattering motions in diffracted and image fields, identifying and explaining two significant scattering modes, advection and boiling. In addition, they show innovative applications of dynamic scattering in metrology, especially its use in velocity measurements of diffuse objects. These methods not only enrich the technical means of velocity measurement, but also provide new perspectives and possibilities for accurate measurements. Through their research, T. Asakura et al. have not only improved the understanding of the dynamic scattering phenomenon, but also provided the theoretical basis and practical guidance for the technical development in the related fields.T. Asakura et al. expect that these discoveries will inspire more explorations on dynamic scattering and its applications, and further promote the technical progress in metrology and related fields.

3.3 Touch-sensing sensing technology

3.3.1 Force perception sensor

"Force or torque sensors are typically installed at robot joints [15]. The sensor itself mirrors the outside world. When the robot grabs, pushes, or performs other tasks that require force force, the force sensor can monitor and record the changes in these forces in real time, ensuring the accuracy and safety of the robot's movements. With advancing technology, force sensors find wider applications. For instance, in underwater robots, these sensors can detect real-time force changes when the robot arm contacts objects [16]. This ensures accurate operation and prevents damage to the surrounding environment. On the micro-nano operation platform, the force perception sensor, with its high-precision measurement capability, provides valuable data support for researchers to help them carry out more detailed operations in the micro world. In the 100-ton loadometer, the force perception sensor can ensure the accuracy and stability of the loadometer, providing strong support for the logistics industry. In the flexible assembly system, the strength of the sensor sensor can be monitored in real time to ensure the smooth progress of the assembly process. In robot-assisted surgery, the force perception sensor can help doctors to more accurately grasp the surgical intensity, reduce the surgical risk, and improve the success rate of surgery, as shown in Fig. 2 [16].

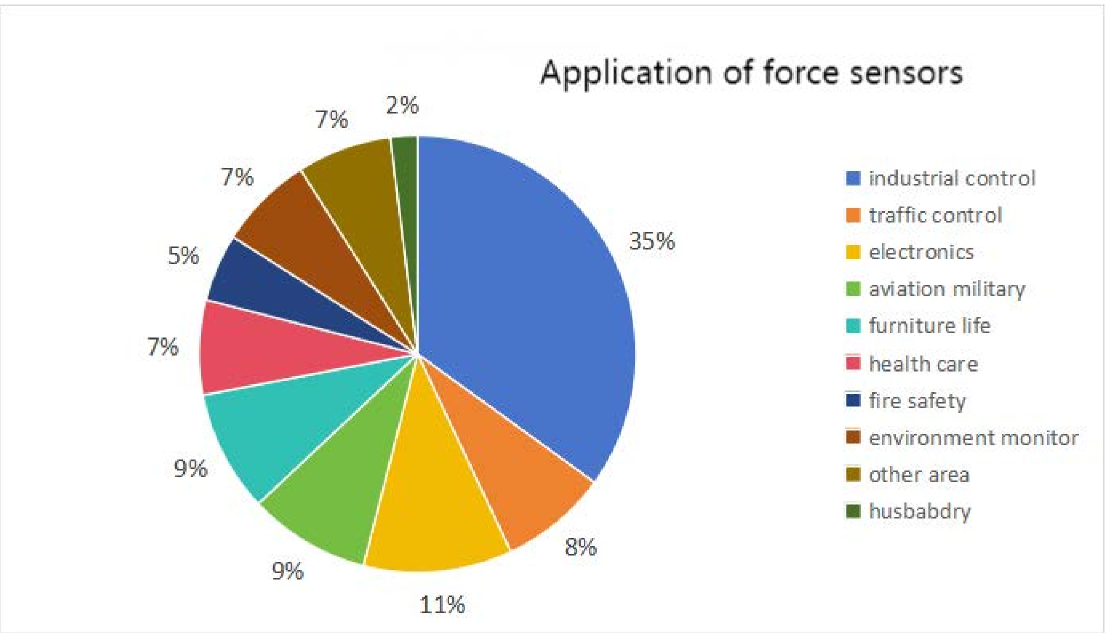

Fig. 2 Application of force sensors [16].

Sensor also plays a crucial role in the medical-assisted rehabilitation training system [17]. Force tactile sensors are installed in upper limb rehabilitation robots to provide tactile feedback, preventing injuries that could occur from prolonged immobility. The results of Tang et al. show that, their manufactured piezo-electric force tactile sensing fibers have significant advantages in stability. Such fibers can efficiently convert mechanical stress into electrical signals, thus enabling sensitive detection of forces. Using this feature, one can create a variety of functional wearable sensors.

3.3.2 Capacacitive sensor

Capacitive sensors, as high-precision measurement tools, can convert various physical quantities into capacitance changes. Its core component is a capacitor, and its capacitance value can be adjusted accordingly with the change of external physical conditions. In the process of work, the sensor senses the changes of the external environment through the accurate detection of the changes of the capacitor value, and further analyzes and handles these changes, and transforms them into the electrical signals of the subsequent circuit. After intensive research, Li Wenwen et al. successfully developed a new flexible capacitive pressure sensor. The sensor uses polydimethylsiloxane (PDMS) quadruprism microstructure film as the dielectric layer, and silver nanowire-polyethylene terephthalate (AgNW-PET) transparent conductive film as the upper and lower electrode layer, forming a unique "sandwich" structure. To ensure the stability and reliability of the sensor performance, the research team strictly tested the pressure device and the capacitor acquisition device. The test results show that the sensor has extremely low hysteresis, fast response time and recovery time, and shows excellent repeatability and stability in multiple cycle tests. It can accurately detect small pressure as low as 0.73Pa, showing extremely high sensitivity and accuracy. The research results have shown a broad application prospect in the field of contact detection and proximity induction, and provided strong support for the development of intelligent sensing technology.

4. Conclusion

Intelligent robot sensing technology currently finds wide applications and shows promising prospects in fields such as intelligent transportation, medical imaging, military industry, and aerospace. Researchers are primarily focused on enhancing the accuracy and efficiency of intelligent robot sensor positioning and recognition, while reducing costs, through advanced computer algorithms and hardware technologies. This paper reviews the current research status and development trends of intelligent robot sensing technology, covering its applications across various fields. This paper specifically examines three key intelligent robot sensing technologies: visual sensing, LiDAR sensing, and tactile sensing, discussing their applications, underlying technologies, and related research. This paper mainly expounds the recognition and positioning algorithm of visual sensor, the ranging method and principle of lidar sensing technology, the ranging method and principle, and the technology and classification of tactile sensing technology. The functionality of intelligent robot vision sensors primarily encompasses two aspects: localization and object recognition. Among them, visual recognition and positioning algorithms such as YOLOV5 algorithm have been widely used, and advanced computer technologies such as deep learning have also been introduced to further improve the accuracy and speed of visual sensor positioning and recognition. The data measurement methods of intelligent robot lidar sensors are mainly time-correlated photon counting method, peak method, centroid method and deep learning method. The velocity measurement methods and technologies of LiDAR sensors are mainly array velocity, LiDAR and laser Doppler velocimetry. There are two main types of tactile sensors for intelligent robots: capacitive sensors and piezoelectric force haptic sensing fibers. Intelligent robots are increasingly integrated into daily life, showing rapid development. Intelligent robot sensing technologies serve as crucial components, acting as the perceptual systems of these robots. In the future, intelligent robot sensing technology has a broad space for development.

Authors Contribution

All the authors contributed equally and their names were listed in alphabetical order.

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