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Study of the Principles and Applications of Common Distance Measuring Sensors

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Abstract. With the development of intelligent devices and automation systems, the need for high-precision, stable, and reliable distance measurement technology is growing fast as well. Distance measurement sensors play an important role in unmanned driving, robotics, industrial control, and other fields. This article discusses the classification and fusion of distance measurement sensors and introduces the working principles and characteristics of various mainstream sensors, such as laser, infrared, ultrasonic, millimetre wave radar, and camera, respectively. This article introduces the differences in distance measurement accuracy, response speed, environmental adaptability, and cost of various sensors through literature research and comparative analysis, and focuses on the combination solutions to achieve fusion and the advantages of sensor fusion technology. The research results show that a single sensor works well under specific conditions, but is easily affected in complex environments, while multi-sensor fusion can effectively improve the overall ability of the system. The article also lists typical applications of various fusion solutions in autonomous driving, robot navigation, and security systems, which shows their potential and development prospects. In summary, sensor fusion is an effective method to improve the performance of distance measurement systems and has good application prospects in future intelligent systems. At the end of the article, it is pointed out that the current fusion technology still faces challenges such as algorithm complexity and system integration, which should be centrally developed in the future.

Keywords: distance sensor, sensor principles, sensor comparison, sensor fusion

1. Introduction

With the rapid development of science and technology, ranging technology has been an Indispensable part in industrial automation, unmanned driving, smart devices, and such fields. Therefore, accuracy is very important for distance measurement, as different devices now have a higher requirement for security and reliability. Among various technologies, ultrasonic, laser, infrared, and millimeter wave sensors are the most common sensors to be used. Each of them has its situations where they are suitable for use, which show their different advantages and disadvantages in practical applications.

In recent years, research on various types of sensors around the world has made significant progress. Ultrasonic sensors are widely used in short-distance detection because of their low cost

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and simple structure, such as the ultrasonic sensor type HC-SR04 and type AJ-SR04M which can achieve 99.95% and 99.99% accuracy at 15 to 25 cm, respectively [1]. Laser sensors have become the first choice for autonomous driving, industrial mapping, and robot navigation as they are highly precise and have a high-speed response. For example, ToF LiDAR can achieve 5 cm accuracy at 200 meters [2]. Infrared sensors are outstanding in close-range ranging and obstacle avoidance due to their small size and low power consumption. For instance, VL53L1X can detect up to 3.6 meters with ±3% accuracy with a size of 4.9 × 2.5 × 1.56 mm and power consumption which is about 20 mW [3]. Millimeter wave radars have shown excellent anti-interference ability in harsh environments. The milliMap system can achieve a <0.2m error and ∼90% accuracy in object classification, even in smoke. However, as sensors tend to be used in more and more complicated environments now, a single sensor is often difficult to meet the needs of high-precision ranging; therefore, multi-sensor fusion technology has been highly valued and has gradually become a research hotspot.

Although the multi-sensor fusion technology has great potential, it is still challenging to achieve highly accurate distance measurement in an extreme environment. For example, in high-humidity and strong-interference environments, the signal attenuation and error accumulation problems of different sensors have not been well solved. Therefore, it is of great research significance to optimize the sensor fusion solution, which the study aims to do.

The study will evaluate the performance and limitations of the four sensors in different complex environments, and introduce the optimization methods of multi-sensor fusion work by comparing and analyzing the working principles, unique characteristics and practical applications, which aims to provide a basic and comprehensive reference for preliminary understanding various sensors, sensor selection and application.

2. Principle and application of each single sensor

This article will introduce four different types of distance sensors, including laser, infrared, ultrasonic, and millimetre wave, and cameras will also be mentioned as it has been an essential part in sensor fusion. First of all, the Time of Flight (ToF) is first explained, as it underpins the operation of most ultrasonic sensors and a significant number of laser-based sensors. Cameras will also be introduced first, as it is widely used in sensor fusion technology.

2.1. The ToF principle and cameras

The algorithm that the ToF uses is $d = (c \times \Delta t)/2$. d is the depth to be measured; c is the speed of light. To get Δt , a pulsed or modulated source, such as a laser, will emit light (or waves), and then the light beams will be captured by a sensor or camera after being reflected off one or more objects. The time between when the light beam is emitted and when it is received is called Δt [4].

In recent years, cameras have also become important tools for distance measurement in many applications. There are three most common camera-based distance sensing technologies: stereo vision, structured light, and ToF [5]. Stereo vision uses two cameras to simulate human eyes. By comparing the images from both cameras, the system can calculate the depth of objects. It works well in environments with enough texture and is used in robotics, self-driving cars, and industrial systems [5].

Structured light works by projecting a known light pattern, like dots or lines, onto an object. The camera captures how the pattern changes, and then measures the 3D shape according to this, which uses triangulation to calculate. It is very accurate at short distances and is used in face recognition

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and 3D scanning [5]. The principle of ToF has been introduced. ToF cameras can achieve fast and wide-area depth sensing. ToF is used in smartphones, indoor navigation, and warehouse systems [5].

Each type of camera has its strengths and weaknesses of cost, speed, accuracy, and lighting conditions. Which one to choose depends on the situation and needs.

2.2. Ultrasonic sensors

As mentioned above, almost all ultrasonic sensors are based on the Time-of-Flight (ToF) principle. They are widely used in microcontroller technology, which is developing rapidly. These micro-controllers can be easily used with Arduino platforms [1].

Ultrasonic sensors have the advantages of small size, low price, and high accuracy in close-range distance measurement. They have a simple structure and are widely used in many applications that require distance measurement. For example, the ultrasonic sensor types HC-SR04 and AJ-SR04M can achieve 99.95% and 99.99% accuracy at 15 to 25 cm, respectively [1]. However, in actual applications, the error can be much larger. The JSN-SR04T and HC-SR04 sensors have shown error rates of 1.28% and 2.48%, respectively [6]. Although ultrasonic water-resistant sensors have better resistance to environmental factors like rain water and dust, they are still easily disturbed by noise, and their effective distance is usually limited to between 2 cm and 5 m [1].

Applications for ultrasonic sensors include assisting vehicles, detecting air flow velocity in pipes, pool water level control, alarm systems, and other areas where distance measurement is required [1, 7, 8].

2.3. Laser sensors (LiDAR)

Laser sensors, or LiDAR (Light Detection and Ranging), can be based on three principles: ToF, which has been explained, Phase Shift, and Triangulation. The principle of the phase difference method is: continuous waves are emitted and received, the phase difference between them is compared then to calculate the distance, which has high precision. Triangulation uses geometry to measure distance by detecting the angle change of the reflected laser beams [9].

The advantages of laser sensors are that they can offer high accuracy, fast response, and are not easily affected by ambient light. For example, ToF LiDAR can achieve 5 cm accuracy at 200 meters, making it suitable for robot navigation and SLAM mapping [2]. However, there are still some limitations. High-end devices like the Velodyne VLP-16 cost over $8000, and they have worse performance in fog, rain, or with low-reflective surfaces [2, 9].

Laser sensors are widely used in industrial automation, construction, forestry, and smart transportation for distance measurement, object detection, and environmental monitoring [2, 9].

2.4. Infrared sensors

Infrared sensors are often used to refer to sensors that detect thermal radiation emitted by objects, while the type introduced in this paragraph is used for measurement, which are usually called infrared distance sensors or IR(Infrared) rangefinders. According to different distance measurement principles, there are mainly two types of infrared sensors, which are IR LEDs with triangulation and VCSEL lasers with ToF technology.

IR systems based on triangulation usually use IR LEDs and photodiodes to estimate the position of the object according to the light angle. One such system can achieve a 50 Hz update rate, which is better than many commercial laser sensors with a typical 10-40 Hz [10]. It showed an average

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position error of 6.55 cm, with an angular error of around 0.51°, which is acceptable for an indoor localisation. The advantage of the system is that it is static and low-cost, but it is sensitive to signal reflections from walls and performs best near the centre of the beacon layout [10].

ToF sensors use a different light source, which is a VCSEL (Vertical-Cavity Surface-Emitting Laser). For instance, VL53L0X and VL53L1X use a VCSEL to emit 940 nm IR light for measurement. VL53L1X can detect up to 3.6 meters with ±3% accuracy, and it is not easily affected by the color or reflectivity of the target. It has a compact size, which is only 4.9 × 2.5 × 1.56 mm, and a low power consumption of about 20 mW as well [3]. However, ToF sensors can be affected by ambient light easily and perform worse when measuring some objects with certain materials like glass or acrylic. Besides, when multiple targets are present, it returns a weighted average distance, which reduces accuracy [3].

In conclusion, triangulation systems are suitable for indoor positioning in wide spaces, while ToF sensors are more effective for short-range, touchless applications like smart buttons or interactive displays.

2.5. Millimetre waves sensors

Different from other types of sensors, millimeter wave (mmWave) radar works mainly based on the FMCW (Frequency Modulated Continuous Wave) principle to measure distance and speed by analyzing the frequency difference between signals sent and reflected. It also estimates direction by using the Angle of Arrival (AoA) to calculate from antenna phase differences.

The most significant advantage of mmWave radar is that it works well in low-visibility environments such as smoke or darkness, where optical sensors often have poor performance. The milliMap system, which uses a low-cost radar, can achieve <0.2m error and ∼90% accuracy in object classification, even in smoke. It is also cheap ($299), light (<30g), and low-power (2W) compared to lidar systems, which are larger and more expensive, such as VLP-16 [11].

However, it has its weaknesses as well. The point cloud is sparse, with only ∼100 points per scan. It also suffers from multi-path noise, with up to 75% ghost points, especially indoors. The angular resolution is limited to 15° horizontally, which makes it hard to detect small or close objects. Therefore, complex algorithms like GANs are needed to improve mapping [11].

mmWave radar is ideal for robot navigation and emergency rescue, where it can build reliable maps and recognize walls, doors, glass, and elevators in challenging environments [11].

3. Sensor fusion

As mentioned, one single type of sensor can not meet all the needs due to the various environments. Each sensor has its own strengths and weaknesses. To overcome their limitations, sensor fusion combines information from different kinds of sensors to improve accuracy, robustness, and adaptability. This method is now widely used in areas like autonomous driving, robotics, and smart surveillance systems. The following text will introduce sensor fusion, which focuses on the several types mentioned above.

3.1. Common types of sensor fusion

This section focuses on sensor fusion involving the sensors that have been introduced. These sensors are often used together in modern perception systems.

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3.1.1. Millimeter-wave radar and camera fusion

Millimeter-wave radar has an excellent ability to measure under poor weather conditions such as fog, rain, or dust. Cameras can provide rich color and texture details, but are sensitive to lighting and weather. When used together, the system becomes much more reliable. Wei et al. found that combining these two types of sensors can increase obstacle detection accuracy in bad weather conditions [12].

3.1.2. Millimeter-wave radar and LiDAR fusion

LiDAR gives a clear 3D view of the surroundings, but its performance degrades in harsh environments. Millimeter-wave radar helps by adding speed and motion data, which can achieve complementary advantages. According to Yan, this combination reduced detection errors, making it useful for tracking moving objects like cars or pedestrians [13]. However, fusion is not always beneficial. It can have problems with tall objects like a truck [14].

3.1.3. Camera and LiDAR fusion

This is a popular method in autonomous driving. LiDAR measures exact distances to objects, while cameras can recognize traffic signs, road markings, and colors. With these two, a full understanding of the scene can be provided. Zhang et al. reported that this kind of fusion can reach very high accuracy in 3D object detection tasks, which is critical for safe and reliable self-driving [15].

3.1.4. Ultrasonic sensor and camera fusion

Ultrasonic sensors are low-cost and good at detecting nearby objects, but they can't recognize what the object is. When combined with a camera, the system is able to gain visual details. Lee et al. showed that this fusion achieved high accuracy in real-time object detection with a lightweight embedded system, which makes it suitable for parking assistance and close-range obstacle detection [16].

3.1.5. Fusion of Infrared distance sensor and ultrasonic sensor

Infrared distance sensors are fast and accurate at short ranges but sensitive to surface reflectivity. In contrast, ultrasonic sensors are not easily affected by different material properties but are less precise. When fused, these sensors can complement each other. Experiments show a reduction in measurement error, which makes it a prior when the distance is less than 0.5m [17]. This combination is widely used in mobile robotics for reliable obstacle avoidance [17].

3.1.6. Fusion of infrared distance sensor and LiDAR

Infrared rangefinders are lightweight and ideal for near-field detection, while LiDAR provides high-accuracy long-range mapping. Combining them can enhance multi-scale perception. PX4 documentation highlights that infrared ToF sensors are faster and more compact than ultrasonic or laser-based systems, making them suitable for helping LiDAR in tight environments [18].

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3.2. Advantages of sensor fusion

Sensor fusion has several clear benefits compared with a single type of sensor: The first advantage is better accuracy and reliability. By using sensors with different strengths, the system can detect more things with fewer errors. For example, if a camera has trouble seeing in the fog, a radar can still detect objects. This kind of cooperation makes the system more dependable and can cope with different occasions.

It can offer more information for proper decisions as well. Fusion sensors can give the system a fuller picture. It can know how far away something is from information given by LiDAR, how fast it's moving from information given by radar, and what it looks like from information given by a camera, which helps the system make safer and more reliable decisions.

Another benefit is that it can achieve a good balance between speed and cost. Some fusion systems can run in real time on affordable hardware. For instance, the system designed by Lee et al. used simple sensors and still can achieve high accuracy [16]. This means fusion can be used even in low-cost applications without losing performance.

3.3. Applications of sensor fusion

Finally, some applications of fusion sensors will be introduced, namely, autonomous driving, robotics, surveillance, and security. Self-driving cars need to recognize lanes, pedestrians, traffic signs, and obstacles at all times. Sensor fusion allows these vehicles to "see" better and react more safely in complex traffic environments.

Mobile robots use fusion to build maps, avoid obstacles, and move around by themselves. Combining vision, distance, and motion data helps robots make better choices in real time. Fusion sensors can be used in intelligent security systems. Through the lidar ranging and camera face recognition, they can accurately track targets even at night or in backlight conditions. In close-range situations like parking, ultrasonic sensors and cameras work together to detect nearby objects and guide the driver or vehicle safely.

4. Conclusion

This paper analyses the working principles, performance characteristics, and performance in application of several mainstream ranging sensors in different application scenarios, including laser, infrared, ultrasonic, and millimetre wave types, respectively. Camera is also mentioned as it has played an indispensable role in assisting sensors. Various types of sensors have their own advantages in ranging accuracy, ability to resist interference, environmental adaptability, and cost. For example, some are suitable for high-precision measurement in short ranges, while others can work stably even in bad weather. However, they also have certain limitations, such as being easily affected by noise, light, or surface materials, resulting in measurement errors or failures. Therefore, it is almost impossible to complete so many kinds of tasks in complex environments with a single type of sensor.

To solve this problem, sensor fusion technology came into being. By complementing and integrating data from different types of sensors, it not only makes the sensor more adaptable to various environments but also increases the accuracy of target recognition and helps make more proper decisions. Nowadays, this technology has been widely used in fields such as autonomous driving, robot navigation, and security monitoring, which shows good potential and development prospects.

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In the future, with the continuous development of artificial intelligence and edge computing, sensor fusion will be further improved. It will be more instantaneous, more intelligent, and have a lower cost, which will be highly adaptable for unmanned driving, or be used in robotics and such automation. But at the same time, it is also necessary to solve some challenges, such as optimising algorithms and systems to achieve better data fusion. Therefore, sensor fusion is not only a trend in the future's technological development, but also an important direction for continuous exploration in future research and application in engineering.

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