Sensor Comparison and study of intelligent sensing technology in intelligent assisted transportation

Weilin Wang*

School of Electronics and Information Engineering, Harbin Institute of Technology, Harbin, 150001, China

*Corresponding author: 2022111166@stu.hit.edu.cn

Abstract. In order to solve the technical defects of traditional sensors and the lack of systematic comparison in Intelligent Transportation Systems (ITS), four mainstream intelligent sensing technologies: radar, ultrasonic, image and infrared sensors are studied in this paper. The article first describes various technical principles, such as radar based on electromagnetic wave reflection, ultrasonic wave based on sound wave reflection, image sensor to achieve photoelectric conversion, infrared sensor using object infrared radiation. It also makes a comprehensive comparison from the working principle, environmental adaptability and other dimensions. Each technique was found to have its own strengths and weaknesses. In order to cope with the existing challenges, this paper looks forward to future development. Finally, the paper points out that multi-sensor fusion is the key to improve the reliability of intelligent transportation system and also puts forward the research limitations and future directions, which provides a reference for the selection, collaborative design and innovation of ITS sensing technology.

Keywords: Sensor, Radar, Ultrasonic wave, Infrared, Image.

1. Introduction

1.1. Research background

With the advancement of technologies like the Internet, artificial intelligence, and 5G, cutting-edge intelligent sensing systems such as LiDAR, millimeter-wave radar, visual sensors, and infrared sensors are rapidly emerging. Sensors are functional modules or subsystems that detect environmental changes and relay information to electronic devices. For instance, in vehicle-road coordination scenarios, multi-sensor fusion technology can extend obstacle recognition distance beyond 500 meters while reducing response time to milliseconds. Meanwhile, countries worldwide are implementing policies to boost smart transportation development. Chinas "14th Five-Year Plan for Modern Integrated Transportation System Development" explicitly proposes "building an intelligent sensing network," providing policy support for the application of smart sensing technologies.

In this context, Intelligent Transportation Systems (ITS) play a pivotal role. However, traditional sensing technologies suffer from limitations such as limited coverage, weak anti-interference capabilities, and single-dimensional data. For instance, loop detectors have an accuracy rate below 60% in identifying non-motorized vehicles, while video surveillance systems face failure rates exceeding 40% during heavy rain or smog. Different technologies each have distinct advantages and limitations in terms of perception accuracy, environmental adaptability, cost-effectiveness, and coverage scope. Smart sensing techniques provide high-resolution pavement information. The faster installation and flexible deployment of contactless sensors across various mobile data acquisition platforms facilitate convenient pavement inspection methods, overcoming spatial and environmental constraints[1]. However, most of the existing materials focus on the research of a single sensor or the application in specific scenarios, and there is insufficient systematic and comparative analysis of different technologies. As a result, in practical application, the selection

2. Research on sensor technology assisted transportation methods

2.1. radar sensor

2.1.1 Technical principles

The core working mechanism of radar sensors is based on the reflection laws of electromagnetic waves. By emitting high-frequency electromagnetic waves and analyzing the time delay, frequency, and phase variations in echo signals, they measure target distance, speed, and angle. Vision, radar, and laser sensors are widely used in autonomous driving perception technologies. In automotive electronic systems, radar sensors primarily perform target detection, distance measurement, speed measurement, and object classification. Technically speaking, these sensors utilize high-frequency electromagnetic waves that enable them to penetrate various materials while remaining unaffected by environmental lighting variations. This exceptional capability ensures consistent performance even under challenging operating conditions.

Furthermore, sensors can be categorized into passive and active types. Passive sensors generate output signals by receiving energy from environmental radiation, such as visual cameras. Active sensors, however, emit energy into the environment and detect the systems "response" to measure the energy, which is how LiDAR and radar sensors operate [2].

2.1.2 Classification and core parameters

Radar sensors can be categorized into millimeter-wave radar and LiDAR systems. Millimeter-wave radar is classified based on electromagnetic frequency bands, with the mainstream automotive applications operating at (24GHz) short-range and (77GHz) medium-to-long range frequencies. The core parameters of these systems directly determine their detection performance. The 77GHz band, with wavelengths approximately 4mm, enables smaller antenna dimensions and higher angular resolution. For example, a 77GHz millimeter-wave radar equipped with a 16-channel antenna array can achieve angular resolution below 1° .

Millimeter-wave radar systems are categorized into short-range and medium-long range configurations. Short-range radars operate within 0.1-50 meters, designed for detecting blind spots, while medium-long range models extend up to 250 meters to meet high-speed cruise requirements. Furthermore, 4D millimeter-wave radars enhance detection accuracy of stationary objects by incorporating vertical altitude measurement capabilities.

Lidar was initially used primarily in aerial surveying and aerospace topographic mapping. By the mid-1990s, manufacturers of laser scanners had begun producing commercial LiDAR devices specifically designed for terrain mapping applications. Over the past few decades, lidar technology has undergone rapid development and now stands as one of the core sensing technologies in advanced driver assistance systems and autonomous vehicles [2].

Lidar typically delivers measurement errors within 2 cm, demonstrating significantly higher accuracy than millimeter-wave radar. FMCW (Frequency Modulated Continuous Wave) lidars achieve micron-level precision in macro 3D scanning. Their high scanning frequency (e.g., 30 Hz) effectively reduces target blur during motion. A solid-state lidar system employing all-electronic scanning technology enables real-time point cloud output at 30 frames per second, making it ideal for high-speed driving scenarios.

Ultrasonic radar, also known as parking sensors, is primarily used in automated parking systems and reversing assistance. These devices typically operate within a detection range of 3cm to 3m. The working principle involves emitting ultrasonic waves that bounce off obstacles, allowing the system to determine their precise distances.

2.1.3 Typical application methods in intelligent assisted transportation

Taking Teslas Autopilot system as an example, radar is used to track distant obstacles and other vehicles, while cameras are responsible for identifying traffic signals, lane markings, and other details. Through data fusion, Teslas autonomous driving system can track vehicles ahead on highways and accurately calculate obstacle-avoidance paths to prevent collisions with front obstacles. In terms of innovative applications, radar sensors have also achieved significant breakthroughs in monitoring the vehicles sides and rear areas. Traditional radars are often used for detecting front obstacles, but modern intelligent driving systems now apply radar sensors throughout the entire vehicles surroundings, particularly in monitoring side and rear blind spots. Taking Mobileyes C2-270 radar system as an example, this system utilizes precise object recognition technology to effectively monitor surrounding blind spots. Even in densely trafficked urban environments, it can accurately detect surrounding obstacles, pedestrians, and other road users, enabling timely avoidance decisions[3].

2.2. Ultrasonic sensors

2.2.1 Technical principles

Ultrasonic sensors measure distances between vehicles and surrounding objects while locating nearby targets, operating based on the reflection principle of ultrasonic beams. These sensors consist of a transmitter and receiver. During operation, the transmitter emits ultrasonic pulses toward the target. When these pulses strike an object, they are reflected and captured by either the same sensor or a nearby receiver. By calculating the time difference between emission and reception (with sound waves traveling at approximately 344 m/s in air, a value that varies with environmental temperature and humidity), the round-trip distance is determined. Ultrasonic sensors primarily comprise two components: a transmitter and receiver. The transmitter generates sound waves using piezoelectric crystals that detect received signals after the pulse travels to and back from the target. The wavelength of ultrasonic waves can be calculated by dividing their frequency by the speed of sound[4].The core function of ultrasonic sensors is distance measurement, which provides precise distance readings for systems like PA and collision avoidance. Additionally, they can calculate relative speed by continuously measuring distance changes from the same obstacle, making them suitable for advanced driver assistance systems such as ACC. Although ultrasonic sensors have certain technical limitations and are susceptible to weather conditions (wind speed and temperature), their overall low cost makes them widely used in automotive applications[5].

2.2.2 Core parameters

The core specifications of ultrasonic sensors determine their adaptability in intelligent transportation systems. In terms of measurement range and accuracy, mainstream models like the SEN0592 achieve an effective detection range of 0.2-5 meters, suitable for urban close-range interactions. The URM06 extends this to 10 meters through signal amplification and filtering algorithms, meeting the safety requirements of 4.5-meter vehicle spacing monitoring at high speeds. The automatic parking scenario relies on temperature compensation technology, maintaining measurement errors within 1%, which aligns with the demands of low-speed, high-precision applications.

The latency of mainstream sensors typically ranges from 15 to 750 milliseconds, with significant variations in application scenarios. In urban traffic congestion where 100-millisecond delays are acceptable, while high-speed lane-keeping and emergency avoidance require ≤50 milliseconds, current ultrasonic sensors are often paired with hardware acceleration circuits like the onsemi NCV75215 chip. This integration reduces signal processing latency from millisecond-level to microsecond-level, enabling instantaneous trajectory capture for high-speed lane-changing monitoring.

Standard sensors with narrow 30°-60° beam angles are ideal for monitoring side-rear blind spots. Autonomous parking systems require directional sensors like Toposens TS3 to achieve 180°×180°3D perception through beamforming, which can identify obstacle heights to avoid curb stones and low bollards. When using multi-sensor fusion (e.g., ultrasonic + fisheye camera), content-aware dilation convolution algorithms compensate for viewing angle differences, ensuring complete obstacle detection in low-light conditions and rainy/foggy environments while preventing missed detections.

2.2.3 Typical application methods in intelligent assisted transportation

Traditional ultrasonic sensors mostly focus on distance measurement, and it is difficult to directly obtain the azimuth information of obstacles. To solve this problem, a Doppler effect based ultrasonic sensor azimuth estimation method for vehicles is proposed in this paper, which provides a new technical path for near-range azimuth sensing of vehicles.

The core logic of this method revolves around "the correlation mapping between Doppler effect and azimuth angles". Its technical implementation process can be divided into three major stages: signal acquisition, data processing, and azimuth calculation. First, an ultrasonic sensor installed on the moving vehicle continuously emits continuous ultrasonic pulse signals. When these signals reach the surface of surrounding objects, they are reflected due to object occlusion. Subsequently, the sensors receiver collects these reflected signals in real-time and precisely records key information through the Data Acquisition System (DAQ)—— specifically capturing the Doppler frequency shift generated by the relative motion between the sensor and obstacles.

To extract azimuth information from frequency shift signals, this study employs the Fast Fourier Transform (FFT) to convert time-domain signals recorded by Digital Anemometers (DAs) into the frequency domain. By analyzing characteristic parameters of Doppler frequency shifts in the frequency domain, the method calculates obstacle azimuths. A critical discovery reveals that the number of recorded Doppler frequency peaks in the frequency domain is proportional to the number of obstacles within the ultrasonic sensors beam coverage area. This finding provides technical support for distinguishing and detecting scenarios with multiple coexisting obstacles.

To ensure detection accuracy in automotive scenarios, the study conducted quantitative comparisons between "measured Doppler frequency shifts" and "expected shifts caused by known standard angular obstacles." By first deducing the actual azimuth of detected objects and then analyzing deviations from theoretical values, multiple experiments ultimately validated the reliability of azimuth estimation results. This approach effectively mitigated detection biases caused by environmental noise and multi-object interference[6].

The study introduces a n ovel methodology formiti-gating vehicular accidents by implementing a combined system that inte- grates collision detect ion and alert mechanisms.

2.3. Image sensor

2.3.1 Technical principles

The core function of image sensors is to convert external light signals (visible light, infrared, etc.) into processable electrical signals, which are then processed by subsequent circuits to form digital images. These components serve as essential elements in applications such as cameras, autonomous driving environment perception, and intelligent traffic monitoring. Currently, mainstream image sensors fall into two categories: analog CCD sensors that convert photons to electrons, and digital CMOS image sensors that transform photon intensity into voltage. While both fundamentally rely on "photoelectric conversion," significant differences exist in their signal storage and readout method[7].

The fundamental functional units of both types of sensors are pixel units, with each pixel unit centered around a "photodiode." Simply put, when light (photons) strike the photodiode, it excites semiconductor materials to generate "photogenerated charges," with stronger light intensity producing more charges. This step completes the initial conversion from "light signals to charge signals," which is the principle underlying all image sensors. For installation and application of image sensors, distributed data processing and edge computing methods should be adopted. This approach delegates various perception tasks to cameras and vision sensors, allowing them to process their own collected data independently. By distributing computational load, this method effectively enhances the overall data processing efficiency of environmental perception systems[8].

Image sensor plays a vital role in automotive electronics technology, which can convert the captured light signal into electrical signal, so that the car has the ability to perceive the surrounding environment.

2.3.2 Classification and core parameters

CCD image sensors boast five key features: mature technology, outstanding resolution performance, VLSI manufacturing process (though with relatively complex production), and high sensitivity. CMOS image sensors share these five characteristics as well, offering excellent imaging clarity, capability to capture images in high dynamic range scenarios, low power consumption, compact size, lightweight design, high integration, and overall cost-effectiveness with significant price-performance advantages.

Given these characteristics, CCD image sensors are primarily used in industrial cameras and similar applications requiring high imaging accuracy and reliability due to their superior resolution and stable performance. In contrast, CMOS image sensors excel in meeting consumer electronics demands through their low power consumption, compact size, and cost-effectiveness, finding widespread adoption across various daily-use devices. The alignment between CMOS sensors features and automotive scenarios requirements for low power consumption, compact design, and cost control explains why most current vehicle-mounted cameras utilize CMOS image sensors[9].

2.3.3 Typical application methods in intelligent assisted transportation

With advancements in CMOS image sensor technology and device integration, particularly the adoption of back-illuminated sensor (BSI) technology and high-density interconnects, achieving multiple HDR techniques within a single pixel size has become feasible. This paper explores HDR technologies for CMOS image sensors and their automotive applications. While dynamic range (DR) is defined in various ways, this article categorizes automotive HDR implementations based on technical characteristics, outlines development trends, and summarizes enhancement strategies. HDR systems are primarily categorized into three types: nonlinear response methods, linear response methods, and hybrid approaches combining both. The paper comprehensively discusses hybrid HDR applications in automotive systems, including pixel-based and stacked hybrid HDR techniques, while analyzing future development directions. Considering the diverse imaging requirements in automotive systems, it emphasizes prioritizing sensor performance and selecting appropriate HDR solutions. Another promising innovation combines word exposure dynamic range with nonlinear compression technology. Through pixel conversion algorithms (ABC) and digital compression techniques for highlight signal processing, global shutter pixel technology can significantly mitigate temperature variations and data storage noise.To achieve these capabilities, integrating pixel and stacking technologies within compatible pixel sizes has become an indispensable key technology. The automotive industrys strong demand for safer and more automated driving technologies is propelling the development of HDRCIS (High Dynamic Range Color Imaging System) technology. This paper systematically reviews various HDR imaging solutions and their application scenarios. The single-exposure/single photodiode (PD) solution maintains complete image integrity under different optical conditions, making it an ideal choice. Thanks to continuous R&D investments and mass production efforts in the CIS industry, high-density electrical connection stacking processes have now become a trendsetter in semiconductor technology, providing reliable solutions for automotive applications. By adopting pixel-level stacking technology, HDR performance and functionality are expected to be further enhanced. Additionally, this approach enables hybridization of HDR solutions to boost capabilities, including real-time perception in pixel data compression, signal processing, and knowledge management, while ensuring efficient control.

Pixel and stacking technologies will undergo a huge evolution in CIS HDR technology for automotive applications, which is driving the development of HDR CIS technology.

2.4. Infrared sensors

2.4.1 Technical principles

Infrared radiation is a type of electromagnetic wave. When an objects temperature exceeds the thermodynamic absolute zero, it generates infrared radiation. Thermal infrared imaging typically refers to mid-infrared and far-infrared imaging technologies[10].

Infrared sensors are detection devices that utilize the physical properties of infrared radiation. They can emit infrared light only when objects possess sufficient temperature. These sensors are categorized into two types based on their working principles: thermal sensors and quantum sensors. Thermal sensors convert absorbed infrared energy into thermal resistance changes and electromotive force signals, though they have limitations such as low sensitivity and slow response. Their cost-effectiveness is notable. Quantum sensors employ semiconductor migration phenomena to generate photoelectric effects through energy absorption differences, offering high sensitivity, rapid response, and precision, though at a higher price point[10].

2.4.2 Classification and core parameters

The core of infrared sensors lies in the seamless collaboration between infrared detectors and optical imaging objectives. As target objects continuously emit infrared radiation due to their thermal properties, these imaging objectives precisely focus and guide this energy, ensuring stable and efficient transmission to the detectors. Serving as the primary sensing component, infrared detectors continuously capture this radiation and accurately convert its spatial distribution patterns into signals that specialized photosensitive elements can detect. This process effectively transforms the invisible infrared radiation into tangible initial signals for analysis.

The sensor electronics connected to the photosensitive element initiates the processing workflow. The initial signal is first amplified to enhance its strength, then filtered to eliminate interference noise, and finally digitized. After this series of precise treatments, the electronics convert the processed information into clear and intuitive infrared thermal images, ultimately achieving visual representation of the target objects temperature distribution. Infrared sensors can be categorized into various common types based on their functional positioning and application scenarios. Among these, infrared thermal imagers and infrared rangefinders are the two most widely used types in industrial, medical, and security fields.

The core parameters of infrared thermal imagers include resolution and temperature measurement range. Resolution determines the thermal imaging systems ability to accurately reproduce details, with higher resolutions enabling better detection of subtle temperature variations in target objects. The measurement range defines the devices effective detection zone, requiring selection based on practical needs to prevent data invalidation caused by exceeding the specified parameters.

The core parameters of infrared rangefinder focus on ranging accuracy and response speed. Ranging accuracy measures the deviation between the measured result and the real distance, which is the key to ensure the reliability of positioning, mapping and other scenarios.

2.4.3 Typical application methods in intelligent assisted transportation

In the experimental study "Robust Thermal Infrared Vehicle-Pedestrian Detection in Complex Environments", the paper highlights that accurately identifying motion-blurred objects and small-area targets in thermal infrared images poses significant challenges. Traditional infrared object detection algorithms typically employ sliding window strategies to generate candidate region frames, followed by manual feature extraction using techniques like scale-invariant feature transform (SIFT) and histogram of oriented gradients (HOG) to extract shape or texture features. However, these methods suffer from redundancy in candidate frames, computational complexity, and insufficient capture of high-level semantic information, ultimately limiting detection accuracy.

To address this issue, the paper proposes a robust thermal infrared vehicle-pedestrian detection method. First, parameter β is introduced to reconstruct the loss function of the feature selection module (FSAF) during online feature selection. The optimized FSAF module not only significantly improves the average precision (mAP) of infrared object detection but also effectively resolves the low detection accuracy issue for moving blurred objects. Subsequently, the optimized anchor-free branch is integrated into the YOLOv3 single-sample detector, enabling collaborative operation with YOLOv3s anchor-based branch during both training and inference phases. This combined approach substantially enhances detection accuracy for small and dense objects. Experimental results demonstrate that the method exhibits significant performance advantages, with mAP scores surpassing those of some typical single-stage detectors (e.g., SSD, YOLOv3) and two-stage detectors (e.g., Faster R-CNN).

2.5. parison

2.5.1 Radar sensors

Radar sensor works based on the law of electromagnetic wave reflection, and belongs to active sensor. It transmits high frequency electromagnetic wave and analyzes the delay, frequency change and phase change of echo.

Millimeter-wave radar systems are categorized by frequency bands and serve as the mainstream technology in automotive applications. The 24GHz band operates in short-range mode with a detection range of 0.1-50m, ideal for blind spot monitoring. The 77GHz medium-range variant achieves up to 250m detection capability using approximately 4mm wavelength waves, enabling smaller antenna designs. When paired with 16-channel antenna arrays, it delivers angular resolution below 1°, meeting high-speed cruise requirements. Furthermore, 4D millimeter-wave radar introduces vertical height measurement capabilities, significantly enhancing detection accuracy for stationary objects.

Lidar systems operate through laser beam time-of-flight (ToF) or phase difference measurement, with core performance metrics focusing on "point cloud quality" and "real-time capability". In terms of point density, the RuiChi ZhiGuang HaloBeam 120 series demonstrates equivalent 120-line scanning at 1,000 points/㎡, enabling clear differentiation between pedestrian limbs and vehicle outlines. The ranging accuracy error remains below 2 cm, while FMCW lidar achieves micron-level precision in macro 3D scanning. Regarding scanning frequency, solid-state lidars can operate at 30 frames per second, making them suitable for dynamic target detection in high-speed scenarios.

Ultrasonic radar has a ranging range of 3cm-3m. It relies on ultrasonic reflection to achieve distance measurement and is only suitable for low speed and close range scenarios.

In intelligent transportation systems, Teslas Autopilot employs radar technology to track distant obstacles and vehicles while coordinating with cameras to identify traffic signals and lane markings. Through data fusion, it calculates obstacle-avoidance routes. The Mobileye C2-270 radar monitors vehicle side-rear blind spots, detecting obstacles and pedestrians in dense urban traffic. Furthermore, the radar integrates with LiDAR and cameras to form a collision avoidance system that continuously monitors road hazards in real time.

2.5.2 Ultrasonic sensor

Ultrasonic sensors operate on the principle of ultrasonic reflection and function as active sensors. The system consists of a transmitter emitting ultrasonic pulses, while a receiver captures the reflected waves. By multiplying the time difference with the speed of sound (a reference value of 344 m/s that fluctuates with temperature and humidity), the round-trip distance is calculated. Furthermore, relative velocity can be derived through continuous distance measurement.

The core parameters are as follows: In terms of range, standard products like the SEN0592 measure distances from 0.2 to 5 meters. With optimizations such as the URM06 signal amplification algorithm, this extends to 10 meters, meeting requirements for short-range interaction and high-speed safe vehicle spacing. For measurement accuracy, temperature compensation technology keeps errors below 1%, fulfilling precision demands for autonomous parking. Response speed typically ranges from 15-750ms, but hardware acceleration is required in high-speed scenarios to achieve microsecond-level response for emergency avoidance. The beam angle typically ranges from 30° to 60° (suitable for side-rear blind zone monitoring), while directional products like the Toposens TS3 achieve a 3D sensing range of 180°×180°, effectively preventing vehicle collisions with road curbs.

In intelligent transportation applications, this technology enables automated parking and reversing assistance by measuring distances to nearby obstacles. It also utilizes the Doppler effect and Fast Fourier Transform (FFT) frequency domain conversion for azimuth estimation, which helps determine obstacle angles and distinguish multiple objects like parked vehicles in parking lots.

Additionally, it integrates with microcontrollers to create a collision warning system that triggers audible alerts and assisted braking, with detection ranges spanning 0.03-4 meters.

2.5.3 Image Sensor

The core mechanism of image sensors is photoelectric conversion. When light (visible or infrared) hits the photodiodes in pixel units, it excites semiconductors to generate photogenerated charges (the stronger the light, the more charges produced). These charge signals are then converted into electrical signals, which are processed to form digital images. They are primarily categorized into two types: CCD (analog, with independent signal storage and readout) and CMOS (digital, featuring high integration).

In terms of classification and core parameters, CCD sensor technology is mature, offering advantages such as high resolution, image clarity without artifacts, and high pixel integration. However, it features complex production processes, higher costs, and greater power consumption, making it suitable for industrial high-precision imaging scenarios. On the other hand, CMOS sensors excel in sensitivity (low noise) and fast response (ideal for high-dynamic environments), consuming only one-tenth of the power of CCDs while being compact and cost-effective. Through back-illuminated (BSI) and pixel stacking technologies, they further enhance HDR performance, establishing them as the mainstream choice in automotive applications.

In intelligent transportation systems, vehicle-mounted cameras utilize CMOS sensors for semantic recognition of lane markings, traffic signals, and pedestrians. For environmental perception, distributed processing combined with edge computing effectively offloads data loads. HDR technology adapts to complex lighting conditions like backlighting and nighttime scenarios through techniques such as "single exposure + nonlinear compression" and "hybrid HDR". Furthermore, stacking technology enhances real-time signal processing capabilities and interference resistance for sensors.

2.5.4 Infrared Sensor

Infrared sensors operate through infrared radiation and are primarily categorized into two types. The first category is thermal infrared sensors, which convert absorbed infrared radiation into thermal energy to trigger changes in resistance or electromotive force. While cost-effective, they exhibit lower sensitivity and slower response speeds. The second category involves quantum-based infrared sensors that utilize the semiconductor photoelectric effect for operation. These sensors deliver high sensitivity, rapid response, and superior precision, though at a relatively higher cost.

The classification and core parameters are as follows: the core parameters of infrared thermal imager include resolution and temperature measurement range, while the core parameters of infrared rangefinder are ranging accuracy and response speed.

In intelligent transportation systems, thermal infrared vehicle and pedestrian detection serves as a critical application scenario. To address challenges in motion blur mitigation and small object detection, the FSAF module can be optimized by integrating YOLOv3s "Anchor-Free + Anchor-Branch" architecture. This enhanced approach demonstrates superior mean average precision (mAP) performance compared to SSD, YOLOv3, and Faster R-CNN, while maintaining adaptability for complex scenarios including nighttime illumination and low-light conditions (Table 1).

Table 1. Comparison of each sensor

	millimeter-wave radar	ladar	ultrasonic sensor	Image sensor (CMOS)	infrared sensor
operational principle	Electromagnetic wave reflection + Doppler effect	LaserToF/phase difference	Ultrasonic reflection + time difference	photoelectric conversion	Infrared radiation + semiconductor photoelectric effect
environmental suitability	Extremely strong (resistant to rain/fog/night/light)	Strong (no light-dependent)	Weak (interference from temperature, humidity and wind speed)	Medium (high light resistance, need to avoid rain and fog)	Strong (no light-dependent)
Range measurement capability	Range 0.1-250m, medium accuracy	Wide range, high precision (≤2cm)	The range is 0.03-10m, with high accuracy	No direct ranging	The rangefinder has high accuracy (centimeter level)
Resolution/ Identification	Low (only target outline)	High (point cloud details, limb recognition)	Low (distance/position only)	High (pixel level, semantic recognition)	Central (temperature distribution)
response speed	Fast (high-speed scenario adaptation)	Fast (30 frames/ second)	Medium (can be accelerated to microsecond level)	Fast (high frame rate, stacking technology)	Fast (millisecond level)
prime cost	Upper middle	tall	low	low	tall
Core scenario	High speed cruise and long distance obstacle avoidance	self-driving	Autoparking, near collision prevention	Traffic sign/road lane line recognition	Low light vehicle pedestrian detection
Key limitations	Low resolution, no detail recognition	Costly and difficult to deploy on a large scale	The measurement range is limited, and I am afraid of temperature and humidity	Light dependent, weak in rain and fog scenarios	Affected by ambient temperature interference

3. Research Challenges and Future Prospects

3.1. Analysis of advantages and disadvantages of various sensors

To address technical bottlenecks in intelligent transportation systems and optimize application strategies, it is essential to fully understand the performance characteristics of various sensors. As core components enabling autonomous vehicles to perceive their surroundings, the integration and functionality of multiple sensors directly determine their safety and operational viability[13].The following analysis examines the practical applications of four sensor types—radar, ultrasonic, image, and infrared—in traffic scenarios, highlighting their core advantages and current limitations to provide targeted guidance for future technological improvements.

3.1.1 Radar sensors

Radar sensors demonstrate exceptional adaptability to harsh environments and superior dynamic parameter measurement capabilities. The high-frequency electromagnetic waves they emit remain largely unaffected by factors such as rainfall, haze, or low light conditions, maintaining over 90% effective detection rates even during torrential downpours. Millimeter-wave radars can control ranging errors within 1% in measurement precision, while LiDAR systems achieve measurement accuracy of ≤2 cm. By leveraging Doppler effect and time-of-flight (ToF) principles, these technologies enable precise determination of target velocity and position. Additionally, the penetrating capability of electromagnetic waves allows partial penetration through non-metallic obstacles like thin fog and foliage, supporting target detection in complex terrains.

However, radar sensors also have inherent limitations. For instance, millimeter-wave radars suffer from low angular resolution. Products operating at the 24 GHz band typically achieve a resolution of 5°-10°, while even 77 GHz models with 16-channel antenna arrays can only attain ≤1° resolution. This makes it difficult to distinguish targets in dense traffic scenarios, resulting in multi-target misjudgment rates exceeding 25%. Although LiDAR provides high-quality point clouds, its high cost and complex data processing pose significant challenges. Processing millions of data points per second is required, yet LiDAR point cloud attenuation reaches 40% during rain or snow conditions, severely compromising detection accuracy.

3.1.2 Ultrasonic sensors

Ultrasonic sensors, renowned for their cost-effectiveness and high-precision performance at close range, are extensively utilized in low-speed, short-distance applications. Standard models cost just a few dollars each and support multi-point deployment across vehicles. With temperature compensation technology, these sensors maintain measurement errors under 1%, achieving precision within 2 cm at 2-meter distances – fully meeting the accuracy requirements for automated parking systems and parking assistance technologies. Furthermore, their exceptional electromagnetic interference resistance ensures stable performance over 85% of the time in complex automotive electronic environments.

The systems limitations primarily manifest in two aspects: narrow application scenarios and strong environmental sensitivity. Conventional ultrasonic sensors have a maximum detection range of less than 5 meters. Even with technical optimizations, the range can only be extended to 10 meters, failing to meet the 50-meter warning distance required for high-speed driving. The response time struggles to adapt to high-speed environments, resulting in over 50% probability of delayed warnings. Additionally, air temperature, humidity, and wind speed significantly affect ultrasonic propagation. A 1℃ change in temperature causes a 0.6 m/s fluctuation in sound velocity, potentially increasing measurement errors by 30% under extreme weather conditions.

3.1.3 Image sensor

Image sensors, particularly CMOS sensors, demonstrate unique advantages in semantic recognition and information richness, serving as core components for traffic sign interpretation and lane detection. They can capture detailed features such as target colors, textures, and shapes, achieving over 98% accuracy in traffic light recognition and detecting lane markings from distances exceeding 100 meters. Additionally, CMOS sensors offer cost-effectiveness and low power consumption, making them ideal for mass production applications.

In typical applications, the back-illuminated (BSI) and pixel stacking technology further increases its dynamic range (HDR) to 140 dB, enabling stable imaging in medium light conditions.

However, image sensor performance is highly dependent on ambient lighting and weather conditions. In scenarios with strong backlighting, backlight exposure, or dense fog, issues like overexposure, underexposure, or blurry images may occur. The accuracy of object detection drops from over 90% in normal conditions to below 50%. High-speed moving targets can generate 5-10 pixel motion blur, causing texture and edge feature loss that leads to over 30% false detection rate in subsequent semantic recognition algorithms. Additionally, complex algorithms require processing tens of MB of computational power per frame, exceeding the capacity of automotive edge microcontrollers and potentially causing processing delays.

3.1.4 IR sensors

Infrared sensors are indispensable in low-light and nighttime environments, operating without active light sources by detecting infrared radiation emitted by objects. Quantum-based infrared sensors achieve pedestrian detection distances exceeding 30 meters at night while distinguishing between living and non-living entities through thermal signature analysis, reducing false detection rates by 40% compared to image sensors. Additionally, they remain unaffected by visible light interference and maintain stable performance even in high-intensity light or backlighting conditions.

The core limitations of this sensor category lie in high costs and low resolution. High-resolution infrared sensors (e.g., 1280×1024 pixels) require specialized materials like cadmium telluride and mercury, along with complex manufacturing processes, costing 20-30 times more than CMOS sensors (each unit exceeds $5,000). Low-resolution models (320×240 pixels) fail to detect small targets like children or low stone markers. Additionally, atmospheric attenuation causes performance degradation at distances beyond 100 meters, where infrared signal strength diminishes by over 50%, reducing accuracy from centimeter-level to decimeter-level. The limited dynamic range (60-80 dB, detecting temperatures from-20℃ to 150℃) leads to overexposure of high-temperature objects (e.g., engine surfaces) and loss of low-temperature object details, with false negatives exceeding 25%.

3.2. Key research challenges

Current intelligent traffic sensing technologies face multidimensional challenges that limit their reliability in complex scenarios. Radar sensors struggle with insufficient multi-target resolution, while LiDAR systems face cost-performance imbalances and spatiotemporal synchronization errors in sensor fusion. Ultrasonic sensors underperform in high-speed adaptability, vehicle-to-vehicle coordination under signal interference, and precision drift in extreme environments. Image sensors encounter robustness issues in harsh conditions, blurred tracking of fast-moving targets, and computational power limitations at edge devices. Infrared sensors confront trade-offs between resolution and cost, dynamic range constraints, atmospheric attenuation, and noise interference.

3.3. Future Outlook

Based on the above analysis, intelligent traffic sensing technology should focus on two key areas for future development: breakthroughs in single-sensor technologies and cross-sensor optimization. At the single-sensor level, millimeter-wave radar should evolve to higher frequency bands, LiDAR should advance solid-state integration and chip-based solutions, ultrasonic sensors need to develop new materials and multi-band technologies, image sensors should create integrated products while promoting quantum technology commercialization, and infrared sensors should optimize cost-efficiency through MEMS processes. At the cross-sensor level, efforts should include developing high-precision spatiotemporal synchronization modules, building hierarchical perception systems to enhance multi-sensor fusion, establishing unified interfaces and testing standards for standardization, and integrating quantum sensing with traditional sensors as well as sensor data with vehicle-road coordination technologies to improve overall system reliability and safety.

4. Conclusions

This paper studies the technical characteristics and applications of four core sensors in intelligent transportation system: radar, ultrasonic, imaging and infrared. It identifies the best application scenarios for each sensor, such as radar for harsh and high-speed environments, and ultrasound for low-speed, close-range operations. The performance limitation is discussed and the necessity of multi-sensor fusion is verified. The study demonstrated significant complementarities of these sensors in specific scenarios. Given the inherent limitations of a single sensor system, A hierarchical sensing framework combining " short-range ultrasonic + long-range radar + semantic imaging / infrared " is very important to improve the reliability of the system. The framework provides a valuable reference for sensor technology selection and collaborative design. The study also compares four mainstream sensing technologies, but there are three limitations: incomplete technical coverage, insufficient depth of scene contrast dimension, And the lack of adequate support from actual application data. Future research should focus on deepening multi-sensor dynamic fusion algorithm, Promote the establishment of cross-technology standard systems and enhance the integration of emerging technologies with traditional sensing methods to improve intelligent perception systems.

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