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Advances in Multimodal Sensor Fusion and Deep Learning for Autonomous Truck Reverse Parking

Xiang Li

Department of Mathematics, Tianjin University, Tianjin, China
1556876566@qq.com

Abstract: Reversing trucks into parking spaces is challenging, especially in complex and constrained environments due to limited visibility and real-time environmental changes. With the development of automated driving technology, sensory detection technology has been widely used, through multi-sensor fusion technology, such as cameras, LiDAR, radar, etc., to enhance the vehicle's ability to perceive the surrounding environment and reduce the safety risk. Meanwhile, the introduction of deep learning algorithms further optimizes the detection and decision-making ability of the system. This study explores the sensing technology of truck reverse parking, focusing on the application of sensor devices, data processing and fusion technology, and artificial intelligence in target detection and behavior prediction. In addition, this study analyzes the challenges faced by trucks in the process of reversing, such as blind field, obstacle detection, and misjudgment in complex environments, and proposes targeted solutions. Ultimately, this study offers insights for the continued development of safer, more efficient, and robust truck reverse parking systems.

Keywords: Truck reverse parking, autonomous driving, multi-sensor fusion, deep learning, target recognition

1. Introduction

Reversing a truck into a parking space is a complex operation, especially in restricted spaces or complex environments. Drivers often face difficulties such as limited vision, insufficient spatial perception, and rapidly changing surroundings. Recent advancements in automated driving technology have improved environmental perception through multi-sensor fusion technology that combines devices such as cameras, LiDAR, and radar [1]. In addition, the introduction of deep learning algorithms has enhanced the system's ability to optimize detection and decision-making, making automatic truck reversing more feasible.

Although automatic driving technology has made great progress in passenger car automatic parking, van reversing still faces many unsolved problems, such as traction angle uncertainty, dynamics complexity, and limited environmental adaptation ability. Existing research focuses on automatic parking for passenger cars, and the algorithms, path planning, and stability control related to van reversing still need to be explored in depth. Although some studies have proposed to optimize the reversing trajectory of trucks based on fuzzy theory, geometric path planning, deep reinforcement learning, and other methods, a mature system has not yet been formed.

Trucks are especially difficult to operate in real-world applications for existing perception systems cannot fully cover their surroundings due to their large size and many blind areas in the field of vision.

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Therefore, researching more accurate and intelligent reversing assistance systems to improve the safety and adaptability of trucks reversing into a garage has become an important topic to be solved. The complexity of a truck reversing into a parking space not only stems from the difficulty of operation but is also affected by environmental factors and the variability of truck dimensions. Traditional reversing methods rely on the driver's judgment and experience. By integrating sensors to collect real-time data from the surrounding 360 degrees, accidents caused by blind zones can be effectively reduced.

This study aims to improve the safety of reversing into position for trucks and to explore more advanced path planning and perceptual detection modules to help vehicles better understand their surroundings [2]. By optimizing the perception detection system and exploring more effective sensor combinations and data processing methods, the accuracy, reliability, and stability of the system can be improved, thus providing a feasible solution for the intelligence of reversing parking of trucks.

2. Overview of multimodal sensing technologies

In intelligent vehicles, sensing devices are the basis for realizing environmental awareness, and they provide the core support for sensing the environment, recognizing obstacles, and supporting autonomous driving. Vans, due to their larger size and load, require more powerful and diverse sensing devices to monitor their surroundings.

2.1. Vision-based systems (cameras)

Due to their large size and field-of-view blind zones, trucks need cameras with higher resolution and wider viewing angles to cover more field-of-view areas. Studies have shown that the intelligent detection and alert system for obstacles in the blind spot of the field of view of large trucks can detect obstacles in different blind spot ranges through the camera and alert the driver. This contrasts with a small car, which has a less restricted rearward field of view due to its smaller size, and the type and distribution of obstacles are usually simpler requiring a relatively low field of view for the camera. Therefore, multiple cameras are usually required to improve perception accuracy. This multi-view camera arrangement provides a panoramic image to help the driver understand the surroundings in real-time. In addition, when a truck is backing up, it may encounter a low wall, the front of other vehicles, and pedestrians. This requires the camera to have a strong dynamic adjustment capability and be able to adapt to environmental changes in real-time.

2.2. Radar sensors

Radar sensors are mainly used in vehicle sensing systems to detect the distance and speed of obstacles. Unlike vision systems, radar sensors are unaffected by light conditions and can operate in a variety of weather and light environments. For vans, radar sensors play an important role in rearward parking, and their long-range detection capability makes them especially critical in rearward collision warning systems for vans as well, especially when sensing obstacles farther behind. Radar sensors in vans are usually equipped with multiple radars of different frequency bands to accommodate the detection of different types of obstacles [3]. Low-frequency radar can be used to detect obstacles at longer distances, while high-frequency radar is used to accurately detect objects at closer distances. Van relies highly on radar and requires significantly higher radar performance compared to smaller cars.

2.3. LiDAR technologies

LIDAR is a technology widely used in autonomous driving in recent years, and it can generate high-resolution three-dimensional point cloud maps that accurately capture spatial information about the

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surrounding environment. Compared to trucks, the LiDAR layout in minivans is usually more expensive. As a result, the use of LiDAR is more limited in traditional minivans, which are mainly used for autonomous driving or high-end driver assistance systems (ADAS). For vans, LiDAR is very useful when reversing, especially in complex environments such as low visibility conditions, rain, and snow, where it can provide more reliable obstacle detection results. A truck usually needs to be equipped with multiple LiDARs, making it possible to accurately recognize static and dynamic obstacles, especially for rear and side obstacles with higher recognition ability. Some laser obstacle detection techniques such as Voxelnet and Pointnet deep learning algorithms are widely used for processing point cloud data, which are especially important for trucks because they need to deal with larger data volumes and more complex environments[4].

2.4. Infrared sensor

Infrared sensors can provide clear obstacle imaging in low-light conditions and are particularly effective at night or in bad weather. For trucks, rear obstacle perception is often limited by visibility, especially when backing up, and low-light conditions may make it difficult to rely on the vision system to provide accurate information. Infrared sensors can recognize heat sources in the rear such as pedestrians, animals, and other vehicles through thermal imaging. Infrared sensors in trucks are usually mounted at the rear or side of the vehicle and can accurately sense obstacles behind and around the vehicle in low visibility conditions by combining thermal imaging images with data from radar and LIDAR.

3. Data processing and multisensory fusion

In intelligent vehicles, especially trucks, multi-sensor data fusion is a key technology that involves the comprehensive processing of data collected from multiple sensors to achieve more accurate and comprehensive environmental sensing. The data collected by sensing devices must be efficiently processed and fused to realize functions such as obstacle detection, localization, and warning.

3.1. Multi-sensor data fusion

A single sensor often cannot reflect the environmental information comprehensively and accurately, so it is necessary to improve the sensing accuracy by Multi-sensor Fusion (MSF), the core of which is to integrate the data from different sensors to obtain richer and more reliable information than that of a single sensor. This process is similar to how the human brain processes information, which produces a consistent interpretation of the observed environment through the complementary and optimal combination of multi-level and multi-space information processing. Van sensing systems fuse data from cameras, radar, lidar, and infrared sensors. Through data fusion, the system can provide more comprehensive and accurate environmental sensing with the complementary strengths of different sensors.

3.2. Real-time data processing challenges

Real-time data processing is a key challenge in intelligent vehicle systems, especially when dealing with large amounts of data from multiple sensors. Issues such as data latency and inconsistent data arrival, resulting from network delays or system failures, can compromise accuracy and reliability. Utilizing parallel and distributed processing methods, such as edge and cloud computing, can effectively enhance processing speed and system capacity[5]. In vehicle-road cooperative platforms, safety-critical data requiring rapid analysis (within 5-10 milliseconds) are processed by edge computing nodes, whereas cloud computing manages less latency-sensitive tasks.

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Ensuring data consistency and accuracy across distributed systems is essential, especially in maintaining temporal and spatial alignment of multi-sensor data for accurate environmental modeling [6]. Systems must efficiently store historical data for timely retrieval, supporting tasks like trend analysis and anomaly detection. Additionally, scalable and cost-effective allocation of computational resources is necessary to manage increasing data volumes and evolving operational demands.

4. Deep learning in truck reverse parking systems

Artificial Intelligence (AI) and Machine Learning (ML) technologies are playing an increasingly important role in perception and detection systems for trucks.

4.1. Object detection and recognition

The application of target detection algorithms in van perception systems is particularly important, especially in the reversing process, where it is crucial to accurately recognize rearward obstacles. In rearward obstacle detection in vans, target detection algorithms not only need to recognize common static obstacles (e.g., walls, barricades, vehicles, etc.), but also be able to detect dynamic obstacles (e.g., pedestrians, other moving vehicles, etc.). For example, algorithms such as YOLO (You Only Look Once) and Faster R-CNN can efficiently and accurately identify and localize obstacles by segmenting the image into multiple regions and performing target detection in each region[7].

4.2. Image processing and adaptability

Traditional target detection methods rely on manual feature extraction, limiting adaptability in complex conditions affected by lighting or weather. In recent years, the introduction of deep learning techniques has greatly improved the accuracy of target detection. In particular, deep learning algorithms such as convolutional neural networks (CNNs) and regional convolutional neural networks (R-CNNs) can automatically learn effective features for classification and localization from a large amount of image data without relying on artificial features, and these algorithms can process a large amount of data collected from sensors, such as cameras and LIDAR, and accurately identify obstacles and road signs. The biggest advantage of deep learning in image recognition over traditional algorithms is its powerful feature learning capability[8]. In the complex environment of reversing trucks, obstacles may exhibit different morphologies due to different angles, occlusion, light changes, and other factors, and it is often difficult for traditional image processing algorithms to accurately extract these features. The deep learning model, however, can effectively learn the deep semantic information in the image through a large-scale training dataset, and automatically extract relevant features from the image, such as the edges of the body, the road texture, the contours of the pedestrians, etc., which in turn improves the accuracy of the recognition. In addition, deep learning has good adaptive ability. As the environment of the perception system changes (e.g., new obstacle types, different lighting conditions, etc.), the deep learning model can continuously optimize its performance through incremental learning or migration learning. This enables the truck perception system to maintain efficient obstacle recognition in different roads, cities, and environments.

5. Challenges in truck reverse parking

5.1. Blind spot

Due to their large body size and restricted driving field of vision, trucks often face significant blind spots in the driver’s field of vision when backing into a parking space. These blind spots make it difficult for drivers to accurately judge the situation behind and to the sides of the vehicle, thus increasing the risk of a collision.

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Blind spots also exist for reversing radar and cameras, which cannot achieve complete detection of the vehicle area coverage. This issue is more prominent in large trucks with longer bodies. The current laser radar (LiDAR) and millimeter wave radar, etc., also need to consider how to ensure safety under the premise of balancing the cost and performance, which is currently an important topic in the development of truck perception systems.

Many methods have been proposed for reversing control of trucks, and to overcome the blind spot in the field of view, and perceiving the external road participant information more stably. the fusion of multiple sensors such as cameras, radar, LiDAR, and other sensors are mostly used to form a sensor system to build a more complete environment model, which partially requires that the rotational direction of the LiDAR is consistent at the same moment with a high degree of synchronicity. The system is highly synchronized. When there are dynamic objects around, the point cloud will not be misaligned or overlapped, and at the same time, it ensures that all the LiDAR point cloud data can be collected together and centralized processing, maximizing the use of all the information. Through the data fusion algorithm, the information collected by these sensors can be integrated to form an omnidirectional, dead-angle-free perception network.

5.2. Obstacle detection complexity

There are various static and dynamic obstacles in the truck reverse parking scenario, such as other vehicles, pedestrians, shelves, buildings, and so on. The static obstacles are of various types, with different shapes and sizes, and are difficult to recognize. For example, different types of shelves, different shapes of buildings, different materials of traffic signs, etc., all of which require the perception system to have strong recognition capabilities. Dynamic obstacles make it difficult to predict the trajectory of movement, which requires the perception system to have the ability to track and predict within a short period and issue timely warning information [9].

In the process of a truck reversing into position, the sensing system needs to be able to recognize the obstacles in the far distance and near distances and conduct risk assessment according to the type and distance of obstacles, to provide timely and effective information for the driver. Due to the limitation of resolution and weather factors, radar sensors are more suitable for long-distance detection than visual sensors, while the close distance detection of trucks needs to overcome more problems of the field of vision obstruction and blind zones, for example, potholes on the ground are obstructed by the chassis of the vehicle and so on.

5.3. Misjudgment in complex environments

Truck reversing environments are complex, affecting sensor accuracy significantly. Camera modules may fail under poor or overly intense lighting conditions, leading to misrecognition. Sensor performance also suffers from environmental interference, including rain and snow, where radar accuracy decreases as precipitation reflects radar waves, introducing false signals and degrading reliability; multipath effects, with radar waves reflecting off buildings create overlapping signals, causing ambiguous target localization; Electromagnetic Interference (EMI), with interference from power lines and electronic devices can disrupt sensor data, reducing performance; and reflection Issues, which specular reflection from metallic surfaces and diffuse reflection from rough surfaces may distort obstacle detection, affecting positional accuracy.

Multi-sensor data fusion integrates camera, radar, and LiDAR data is challenging due to differing sensor strengths and update frequencies. Ensuring spatial and temporal alignment requires precise calibration [10]. Computational resources and real-time processing enables modern trucks equipped with multiple sensors generate vast, diverse data requiring immediate processing. Real-time obstacle detection, 3D environmental modeling, and dynamic path planning place substantial demands on

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onboard computational resources. Decision-making processes must occur rapidly, typically within milliseconds, to avoid delayed responses that could compromise safety, especially in constrained environments.

6. Future trends

Currently, the perception of the environment in the process of reversing the truck into position relies on the fusion of multi-sensor systems. In the future, multisensory fusion technology will develop in the direction of greater intelligence and efficiency. By combining the advantages of multiple devices such as cameras, radar, LiDAR (laser radar) and infrared sensors, the system will be able to provide more comprehensive and accurate environmental sensing information.

6.1. Advanced sensor fusion optimization

With the continuous improvement of hardware performance and the advancement of different types of sensor technology, the future truck reverse parking system will further optimize the multi-sensor data fusion algorithm to improve the real-time response speed and accuracy of the system. Combining the advantages of multiple devices such as cameras, laser radar (LiDAR), radar, and infrared sensors, the system will be able to provide more comprehensive and accurate environment-sensing information [11]. Especially in complex environments, the fusion of sensor data will be a key factor in improving system robustness and safety. The future challenge will be to better process and fuse data from different sensors for more efficient obstacle detection, distance estimation, and risk prediction[12].

6.2. Enhanced AI and deep learning applications

Deep learning techniques, especially algorithms such as Convolutional Neural Networks (CNN) and Regional Convolutional Neural Networks (R-CNN), will play an increasingly important role in perception and decision-making in truck reverse parking systems. By combining with sensor technology, deep learning will be able to process complex visual information and predict and track obstacles in dynamic environments. With the accumulation of big data and the optimization of algorithms, deep learning will make the truck reversing system perform better in complex environments, and reduce the misjudgment and risk brought by the visual field blindness and complex scenes. In addition, in the future, we should focus on the further application of deep learning technology in image recognition, dynamic obstacle prediction, and path planning to promote the development of the perception system to higher precision and intelligence.

6.3. High precision localization and path planning technology

Accurate positioning and path planning technology is an integral part of the truck reversing process. In the future, SLAM (Simultaneous Localization and Mapping) technology will be closely integrated with multi-sensor fusion technology to provide more accurate vehicle positioning and environment mapping. With the data fusion of LIDAR and vision systems, the path planning algorithm will be able to adjust the reversing trajectory according to the real-time environment, avoiding the risk of collision and ensuring a smooth reversing operation. With the improvement of computing power and optimization of algorithms, the real-time and flexibility of the path planning system will be continuously enhanced, which can provide more accurate reversing paths for trucks in dynamic environments.

6.4. Environmental adaptation and robustness enhancement

With the continuous progress of technology, future sensing systems will pay more attention to adaptability in various harsh environments, especially in extreme environmental conditions such as rain and snow, low light or strong light, the robustness of sensors and algorithms will be significantly improved. Multimodal data fusion and deep learning algorithms will further enhance the stability of the system in complex environments and avoid misjudgments and failures caused by environmental factors [13]. Therefore, future research on sensing systems in harsh environments should be strengthened, especially to optimize the performance of infrared sensors, LiDAR and other devices in low visibility conditions to enhance the environmental adaptability of the system.

6.5. Application of vehicle-road collaboration technology

Vehicle-to-Guideway Collaboration (V2X) technology will become an important development trend for future truck reverse parking systems. By enhancing the real-time interaction between trucks and their surroundings, V2X technology will provide more information support for reversing operations. The future truck reversing system can be interconnected with surrounding facilities and road traffic management systems to further improve safety and automation. Through the VMT technology, the system can not only sense the surrounding obstacles in real time but also adjust the reversing path in real time according to the traffic condition and road surface information to improve the overall efficiency and safety.

7. Conclusion

With the development of automatic truck driving and reverse parking technology, the continuous progress of perception and detection technology provides strong support for improving safety and operational efficiency. By combining multiple sensors, such as camera, radar, LIDAR, and infrared sensors, the existing system has been able to solve to a certain extent the problems of blind spots, obstacle detection, and misjudgment of complex environments in truck reversing. However, the current technology still has some limitations, especially in the face of extreme weather, complex lighting conditions, and dynamic obstacles, the system's perception accuracy and stability still need to be improved.

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