Hierarchical Composite Highway Vehicle Precise Identification Based on Multi-Source Data Fusion

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Abstract. In the hierarchical composite highway environment, anomalies such as misidentification and reverse identification may occur between ETC gantry antennas and onboard media, leading to confusion in stored path and billing information within onboard media, causing abnormalities in toll collection at exits. To achieve precise identification of vehicles in both upper and lower layers, a multi-level data fusion-based hierarchical vehicle identification method is proposed. The basic idea is to utilize front-end perception devices such as ETC positioning antennas, LiDARs, video cameras, and license plate recognition camera. The target positioning information formed by the fusion of LiDARs and video cameras is fused with the target positioning information identified by ETC positioning antennas and gantry cameras, the identification information of successfully matched vehicles is extracted from the transaction records of ETC positioning antennas to obtain accurate vehicle perception data. The identification information is written into onboard media through ETC positioning antennas, achieving precise matching of driving vehicles and onboard media at the front end, forming complete structured vehicle information and unstructured vehicle images to support hierarchical and precise vehicle identification. The accuracy of the algorithm was validated through the development and testing of a prototype system.

Keywords: Hierarchical composite highway; Vehicle precise identification; ETC gantry; Multi-sensor fusion

1 Introduction

Hierarchical composite highways can be classified into same-directional and opposite-directional layers based on the direction of traffic flow. According to spatial positioning, they can be further divided into upper-lower layers, intersection layers, and staggered high-low side-by-side layers. However, due to the high sensitivity of onboard

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media, especially composite passes, they can be identified even from positions more than 500 meters away from the gantry antenna, leading to confusion in the stored passage information. This results in the inability to accurately identify the hierarchical information of vehicles. Vehicle trajectory tracking and identification has garnered significant attention in recent years, particularly with the advent of sensor fusion techniques integrating cameras and laser rangefinders. Gangqiang et al. [1] propose a data fusion technique for a 3D-LIDAR scanner and a video camera. This fusion mechanism enhances the capability of environmental perception systems, offering richer and more comprehensive data for trajectory tracking applications. Su Pang et al. [2] introduce a novel Camera-LiDAR Object Candidates (CLOCs) fusion network aimed at improving the performance of single-modality detectors. Feihu et al. [3] present a sensor fusion-based vehicle detection approach by integrating information from both LiDAR and cameras. Their method utilizes stereo cameras for hypothesis generation and LiDAR for verification. Junxuan et al. [4] conduct investigations based on LiDAR data collected in the field, investigations were conducted in the order of background filtering, object clustering, pedestrian and vehicle classification, and tracking. To accurately detect and track pedestrians and vehicles at intersections. LiDAR technology has been successfully applied in toll gates as camera trigger devices, as demonstrated by Deren [5], enhancing vehicle identification accuracy. Weiming et al. [6] integrated LiDAR technology into the ETC system, achieving precise vehicle positioning and classification. This approach was validated through field tests, demonstrating its effectiveness and reliability in real-world scenarios. Additionally, Goyat et al. [7] combined camera and laser rangefinder data, introduced a novel likelihood function based on simplified 3D vehicle models, and developed an efficient computation method. They also improved the particle filter to naturally merge multiple data sources, with their methods validated through real-world experiments. Cumulatively, these studies underscore the importance of sensor fusion techniques, particularly the integration of cameras and LiDAR, which has significantly advanced the field of vehicle trajectory tracking and identification. Despite the wealth of research in sensor fusion techniques, there remains a noticeable gap in studies specifically addressing the precise identification of vehicles on hierarchical composite highways. This gap serves as the focal point of this paper's research objective, aiming to bridge this void by proposing a novel approach to vehicle identification in such complex highway environments.

2 Gantry Layout Scheme

In addition to the existing traditional gantry setup, one additional LiDARs and one video camera will be added to achieve precise identification of vehicles in hierarchical composite highways.

Utilizing fusion perception algorithms based on deep learning, real-time point cloud data received from the LiDARs and video stream data from the video camera will be merged for analysis and feature extraction. This approach maximizes the utilization of multi-sensor data resources in different times and spaces, such as antennas, LiDARs, snapshot cameras (License Plate Recognition Cameras), and video cameras, to collect all relevant attributes of vehicles passing through the section. These attributes include at least the vehicle's position, license plate, and onboard media, enabling precise identification of passing vehicles.

3 Model Architecture for Real-Time Perception-Based Hierarchical Vehicle Identification Using Multi-Source Data

In hierarchical composite highway system, the ETC antennas and video devices on the upper level road may cover vehicles on the lower level road, leading to misidentification of lower-level road vehicles as those passing through the upper-level gantry. This constitutes a major cause of vehicle information misidentification. In contrast, radar data does not suffer from misidentification between upper and lower levels but generates point cloud data only for vehicles passing through the same level road. Leveraging this characteristic, this study primarily employs the ETC transaction system, supplemented by the effective identification information from the integrated radar and vision system, to exclude misidentified vehicles, significantly reducing the probability of vehicle misidentification.

The algorithm model is based on a unified spatiotemporal reference frame and utilizes four types of field-deployed perception devices: LiDARs, video camera, license plate recognition camera, and ETC positioning antenna. The overall algorithm comprises two sequential internal fusion processes, as illustrated in figure 1.

(1) Fusion of perception data from the fusion video camera and LiDARs.

(2) Fusion of three types of target perception information.

Finally, by matching vehicle targets with vehicle identities, a unique set of vehicle data is formed, comprising vehicle identity, vehicle perception targets, and vehicle positioning, each corresponding uniquely to one another.

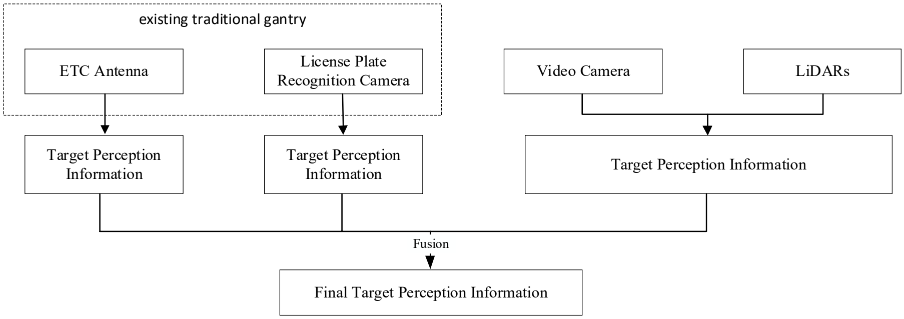

Fig. 1. Vehicle Hierarchical Identification Method Model Based on Real-time Perception of Multi-source Data.

4 Spatiotemporal Synchronization Techniques for Multi-Sensor Fusion

4.1 Time Synchronization

On highways, the fusion of laser radar and video information data requires ensuring that the timestamps of the data are consistent. This is because the data is collected at different time points and needs to be aligned for data fusion and analysis to ensure the accuracy and reliability of vehicle identification.

(1) Obtain the timestamps of the laser radar and the camera and calibrate them against the system timestamp.

(2) Cache the laser radar data, storing it in chronological order.

(3) Due to the delay of the camera, use the camera data as the reference. Upon receiving a frame of camera data, search for the closest frame of radar data in the cache, fuse them together, and output them for display.

(4) After processing a frame of camera data, clear the radar data cache and continue with the above steps.

4.2 Spatial Synchronization

Before fusion, it is necessary to perform spatial registration of the laser radar and the camera. Spatial registration is primarily aimed at obtaining the pose transformation relationship between the laser and the camera, as well as the intrinsic parameters of the camera. It aligns the differently acquired data to achieve more accurate and comprehensive 3D reconstruction and environmental perception.

4.3 Fusion of Laser and Video data Fusion Algorithm

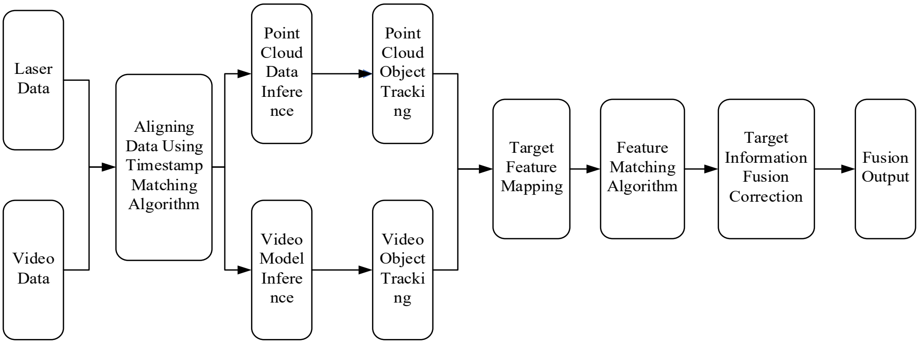

Fig. 2. Fusion Strategy Flowchart.

The fusion perception algorithm based on deep learning mainly involves the integration and feature extraction of real-time collected perception data. figure 2 illustrates the overall fusion strategy flowchart. During the fusion of result-level data obtained from laser radar point cloud data and camera video stream data, traffic participant perception information is extracted separately from the video stream data and the laser point cloud data. Subsequently, time synchronization and spatial coordinate synchronization are achieved, followed by target feature mapping, information matching and correlation, data fusion correction, and finally, the output of fusion perception information.

Based on the imaging principle of cameras as depicted by equation (1), the three-dimensional coordinates of objects in the real world, after undergoing rigid body transformation and camera intrinsic parameter conversion, can be projected onto the pixel plane of videos or images.

$$Z_c \begin{bmatrix} u \\ v \\ 1 \end{bmatrix} = \begin{bmatrix} f/dx & s & u_0 \\ 0 & f/dy & v_0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} R & T \end{bmatrix} \begin{bmatrix} X_w \\ Y_w \\ Z_w \\ 1 \end{bmatrix} \tag{1}$$

Therefore, drawing on this theory, laser radar data can be transformed into pixel data. Here, $[X_w, Y_w, Z_w, 1]$ represents the world coordinates of the laser radar target, $[R \quad T]$ denotes the rotation and translation matrices, and $[u, v]$ represents the pixel coordinates, with f/dx and f/dy being the focal lengths in the horizontal and vertical axes, respectively, and u_0, v_0 being the principal point pixel coordinates in the horizontal and vertical axes. This method requires two calibration processes. Firstly, it involves computing the camera's intrinsic parameter matrix through calibration methods such as chessboard calibration. After obtaining the camera's intrinsic parameters, further calibration is performed by selecting feature points from laser radar data and camera data that are temporally aligned, to calculate the rotation and translation matrices between the laser radar and the camera.

4.4 Fault-Tolerant Position Matching Algorithm

In this model, vehicle positioning results include vehicle positioning data based on toll-gate cameras and ETC antennas, as well as data based on the fusion of perception data from LiDARs and video). Antenna positioning devices commonly used on highways may lead to a sharp decrease in the location matching rate and accuracy, thereby affecting the normal operation of the gantry system. Incorporating the perception data with both upper and lower layer information with ETC positioning antenna perception data through a fault-tolerant position matching algorithm enables the fusion of vehicle target information and ETC positioning information for unique matching. The fault-tolerant position matching algorithm addresses the issue of low accuracy in location matching fusion existing in related technologies. Through the fault-tolerant position matching algorithm fusion, the uniqueness of vehicle target information can be achieved.

4.5 Matching of Vehicle Targets and Vehicle Identities

Based on the fusion of multi-sensor target perception information, it is possible to achieve fusion matching based on target perception information (such as position, trajectory, speed, and vehicle type), forming unique target perception results based on vehicle information. The data sources involved in this process include the fusion perception results of LiDARs and video, the perception results of ETC positioning antennas, and the perception results of tollgate cameras. By integrating license plate recognition information with ETC data plate matching, matching fusion based on the license plate field is achieved, establishing a one-to-one correspondence between tollgate information and ETC transaction data.

5 Prototype System Test

The prototype system was constructed using the previously proposed fusion algorithm for testing purposes. Among all the devices, only the ETC antenna experienced issues with identifying multiple vehicles that were not under the gantry, due to misidentification. In contrast, other devices accurately identified vehicles passing through the gantry, as demonstrated in Table 1. The result confirm the accuracy and consistency of the vehicle identification process.

Table 1. Prototype system test results.

Devices	Fusion output vehicle identity	License plate color	Vehicle color	Accurate vehicle passing the gantry
ETC Antenna	HFL533 N1XM28 PV8226	/	/	
License Plate Recognition Camera	HFL533	blue	white	HFL533
Video Camera& LiDARs	HFL533	blue	white	

6 Conclusion

Through the strategic integration of traditional video cameras, LiDARs scanning, high-definition tollgate cameras, ETC antennas, and other technologies, alongside the implementation of advanced data fusion techniques including time synchronization, spatial synchronization, and fault-tolerant position matching algorithms. Despite the heightened cost per ETC gantry, the achievement of precise vehicle identification is feasible. This breakthrough effectively mitigates the challenges associated with accurate vehicle identification on hierarchical composite highways, markedly diminishing instances of misidentification. Consequently, it furnishes robust assurance for the stable operation of the dual-layer high-speed gantry system, thereby delivering tangible benefits for transportation management and highway systems. By elevating the accuracy of vehicle identification, the functionality of layered composite highway traffic is vastly improved, amplifying toll collection efficiency and accuracy. Moreover, this innovative approach lays the groundwork for the development of more sophisticated traffic management systems adept at accommodating the evolving needs of modern complex transport networks.

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