An Indoor-Outdoor Layered HD Map Construction for Unmanned Ground Vehicles

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Abstract

High-Definition Maps (HD Maps) are lane-level 3-dimensional road network models that ensure the safe operation of autonomous vehicles and drive the continuous advancement of autonomous driving technology to higher levels. However, HD Maps currently face challenges regarding limited coverage and description of indoor environments (e.g. underground parking), as well as the lack of uniformity between indoor and outdoor map formats. Therefore, this paper proposes a Layered HD Map model for both indoor and outdoor environments. The map model consists of 6 layers, allowing effective representation of indoor and outdoor environments, as well as transitional areas. The paper also establishes an Unmanned Ground Vehicle (UGV) to collect and update map data using LiDAR (Light Detection and Ranging) SLAM (Simultaneous Localization and Mapping) and autonomous exploration technology, aiming to enhance the efficiency and automation of HD Map acquisition. In order to verify the validity of the proposed map model, this paper conducted a navigation experiment in a double decker parking lot containing entrances and exits. The results of the experiments demonstrate that the Layered HD Map generated through autonomous LiDAR SLAM can effectively describe the indoor and outdoor environments, and enable successful navigation of UGVs.

1. Introduction

Autonomous Driving Systems (ADS) represented by unmanned ground vehicles (UGVs) have made considerable progress since the 21st century (Yurtsever, E., et al., 2020). As one of the core technologies to achieve high-level AD technology, High-Definition Map (HD Map) is a powerful 3D spatial model containing lane-level road network information. HD Map can fill in sensor blind spots and effectively improve the safety and stability of UGVs (Elghazaly, G., et al., 2023). By utilizing the HD Map, autonomous vehicles can accurately determine their position and make intelligent decisions, enabling them to navigate autonomously especially in harsh environments (Levinson, J., et al., 2011).

At present, the internationally mature HD Map formats and model standards include NDS, OpenDRIVE, Apollo, Lanelet2 (Poggenhans, F., et al., 2018), etc. In the meanwhile, many scholars have proposed more specific map models to adapt to different application scenarios. For example, Jiang, K., et al. (2019) proposed a 7-layer autonomous driving map model with accuracy adaptive ability. The WHU HD Map model proposed by Zhang, P., et al. (2021), which can serve as a universal exchange mode.

However, HD Maps currently face challenges regarding limited coverage and description of indoor environments, as well as the lack of uniformity between indoor and outdoor map formats. Some scholars have considered the issue of seamless indoor and outdoor positioning and proposed corresponding solutions, such as Yao, Y., et al. (2016), Costa, C., et al. (2019), and Gamarra, M. V., et al. (2023).

Based on the above, this paper proposes a layered HD Map that integrates indoor and outdoor coordinates, unifying indoor coordinates to the outdoor geodetic coordinate system, thereby achieving integrated indoor and outdoor positioning. Indoor-Outdoor Layered HD Map we designed provides a comprehensive representation of both indoor and outdoor environments, can be used for UGVs such as ground inspection robots, cleaning vehicles, and express delivery vehicles, and in indoor and outdoor low-speed driving scenes such as underground parking lots, storage centers, campuses, and industrial parks. In addition, this paper attempts to use autonomous exploration for point cloud data collection to improve automation and reduce labor costs.

2. Methodology

2.1 Autonomous point cloud data collection

Currently, utilizing SLAM (Simultaneous Localization and Mapping) for HD Map data acquisition is one of the commonly methods. LiDAR (Light Detection and Ranging) SLAM technology utilizes LiDAR to perceive and analyze environmental data, enabling simultaneous localization and the generation of high-resolution point cloud maps that accurately capture road positions and shapes. However, this approach still suffers from drawbacks such as high human involvement and low efficiency. Therefore, this paper constructs an autonomous exploration robot to collect raw map data efficiently and automatically.

The UGV is equipped with a 16-line LiDAR sensor (HESAI PandarXT-16), a high-precision IMU (Inertial Measurement Unit), a GNSS (Global Navigation Satellite System) antenna, and a high-performance industrial computer. The vehicle's chassis utilizes a tracked design, enabling it to navigate various terrains and move seamlessly between indoor and outdoor environments. The UGV's structure is shown in Figure 1, and the software framework is illustrated in Figure 2.

We attempt to use autonomous exploration to collect and update HD Map data, in order to improve production efficiency. The autonomous exploration component utilizes the Far Planner path planning method (Yang, F., et al., 2022), while SLAM component employs Fast-LIO2 (Xu, W. et al., 2022). In additional, we have incorporated a loop closure module into Fast-LIO2. This module utilizes GNSS information during outdoor exploration and mapping. As a result, it outputs point cloud data with absolute coordinates.

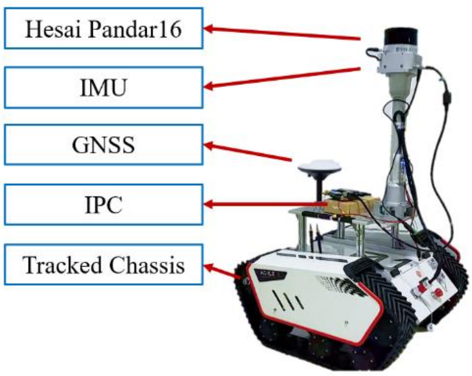


Figure 1. The UGV's Structure.

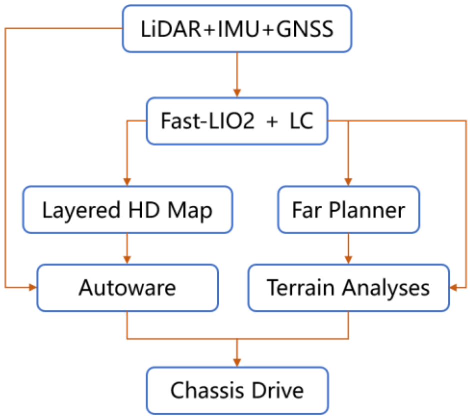


Figure 2. The UGV's Software Framework.

2.2 Indoor-Outdoor Layered HD Map

We first analyzed the different characteristics between indoor spaces and outdoor environments. The indoor spaces are usually divided into several areas by walls, doors, and windows, and each area is connected by corridors, doors, etc., ensuring the accessibility between them. This paper divides indoor spaces into the following elements: (1) spatial segmentation elements: including windows, walls, etc.; (2) spatial connectivity elements: including entrances and exits, doors, corridors, forks, etc.; (3) Space elements: including rooms, lobbies, etc.; (4) functional elements: including parking spaces, no parking area, etc. The outdoor environment that this paper focuses on is enclosed or semi enclosed areas, such as parking lots, industrial parks, campuses, etc. This type of area is usually a low-speed driving environment, and the road network topology is relatively simple.

Based on the different characteristics of indoor and outdoor environments, we designed the indoor-outdoor layered HD Map. It consists of six layers, as illustrated in Figure 3. From bottom to top, they are respectively Indoor Topology Layer, Indoor Feature Layer, Outdoor Road Network Layer, Outdoor Lane Layer, Outdoor Feature Layer and Dynamic Object Layer. Here is a detailed introduction to them, and Table 1 to 6 correspond to the factors and description of each layer, respectively:

2.2.1 Indoor Topology Layer: This layer describes the spatial connectivity elements, spatial elements and functional elements, as well as the topological relationships between them, as shown in the Table 1. Due to the diverse situations of indoor spaces, it is possible to accurately describe the environment by extending the factors.

Factor	Description
Corridor	Drivable indoor areas, represent with straight lines, arcs, and curves with continuous curvature, with attributes including width, length, connectivity, direction, etc.
Door	Interconnection areas between indoor areas and between indoor and outdoor areas.
Parking Space	Rectangular areas can be parked.
Others	Other elements, users can expand.

Table 1. Synopsis of Indoor Topology Layer.

2.2.2 Indoor Feature Layer: Due to the difficulty in receiving GNSS information in indoor environments, while using static feature matching for indoor positioning can produce good positioning results without relying on too many devices, this layer describes the impassable obstacles and records feature information within the indoor environment, such as static obstacles like corners, signs, and pillars, as shown in the Table 2.

Factor	Description
Wall	The walls and corners of indoor buildings.
Sign	Windows, patterns, signs, etc. can be used for indoor positioning.
Pillar	The pillars of indoor buildings.
Facility	Fixed facilities and items.

Table 2. Synopsis of Indoor Feature Layer.

2.2.3 Outdoor Road Network Layer: This layer contains the position and topological structure of roads and intersections, including the coordinates, connectivity and length of roads, as shown in the Table 3. This layer of map has an accuracy of meters, equivalent to existing electronic navigation maps.

Factor	Description
Road	Road elements, including a set of lanes in the same direction, represent with straight lines, arcs, and curves with continuous curvature, with attributes such as starting coordinates, ending coordinates, direction, and connecting roads before and after.
Junction	The intersection area of roads in multiple directions, connected to the front and back of road factor.

Table 3. Synopsis of Outdoor Road Network Layer.

2.2.4 Outdoor Lane Layer: This layer describes the geometric shape, attributes, and topological relationships of lanes, as shown in the Table 4. This layer of map has an accuracy of decimeters or even centimeters, which can provide necessary information for vehicle navigation and path planning.

Factor	Description
Lane	The lane elements in a road, represent with straight lines, arcs, and curves with continuous curvature, with geometric attributes such as length, width, slope, and slope, while topological attributes include direction, speed, and connecting lanes.
Lane Line	The lane markings on the road surface are yellow/white in the form of double lines, single lines, and dotted lines.
Road marking	Road markings, such as direction arrows.
Crosswalk	The crossing marks on the road surface, generally rectangular in shape.

Table 4. Synopsis of Outdoor Lane Layer.

2.2.5 Outdoor Feature Layer: As shown in the Table 5, this layer records other geographical features in the road network environment, such as roadside signs, streetlights, gantries, and other roadside objects, which geographical location can be used for aided positioning.

Factor	Description
Roadside sign	Signboards on the roadside, with attribute recording coordinates and meanings.
Gantry	The signboard on the gantry above the road, with coordinates and meanings.
Traffic lights	Traffic lights with real-time color.

Table 5. Synopsis of Outdoor Feature Layer.

2.2.6 Dynamic Object Layer: This layer displays the real-time detection results of onboard sensors (especially the cameras), and record dynamic objects in the environments, such as moving vehicles, pedestrians, and other mobile objects, as shown in the Table 6.

Factor	Description
Pedestrian	Pedestrians, cars and cyclists on the road, real-time detection by vehicle mounted cameras and LiDAR for avoiding.
Car	
Cyclist	

Table 6. Synopsis of Dynamic Object Layer.

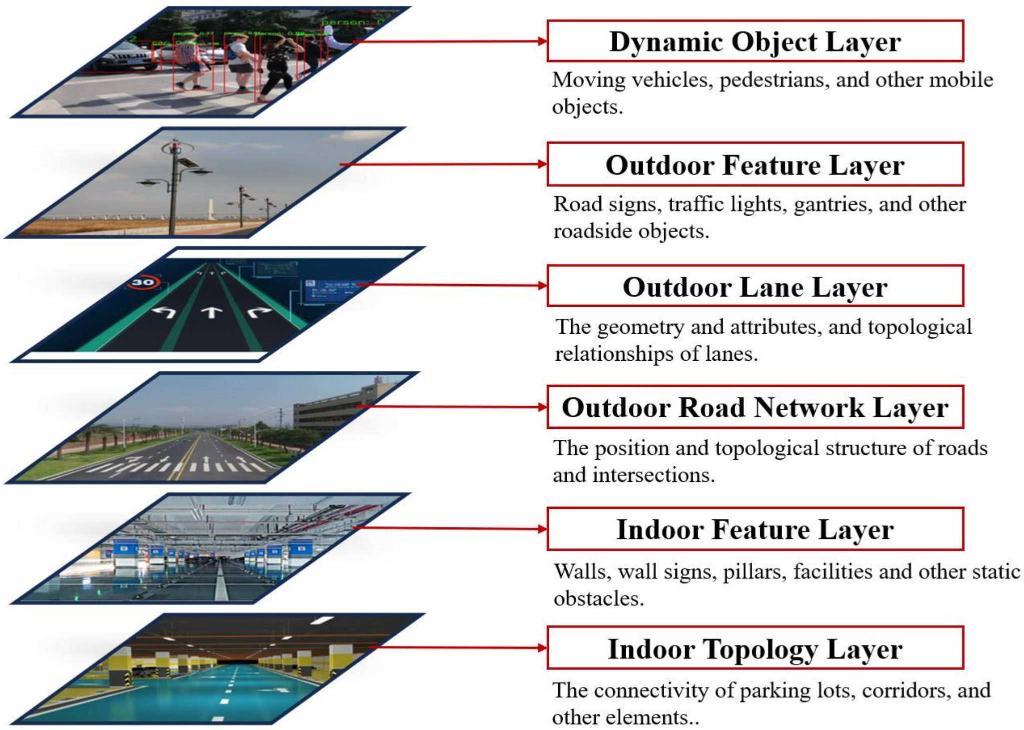


Figure 3. The Model of Indoor-Outdoor HD Layered Map.

The layered structure allows for seamless localization and navigation between the indoor and outdoor environments. The Indoor Topology Layer stores the indoor drivable routes, while the Indoor Feature Layer captures specific features such as wall signs and pillars. Therefore, in indoor environments, UGVs can utilize the Indoor Feature Layer for localization with LiDAR/IMU/Camera and obtain path information from the Indoor Topology Layer. While in outdoor environments, UGVs can rely on GNSS for positioning. The Outdoor Feature Layer can assist in localization by road features like roadside signs and gantries. The Road Network Layer and Lane Layer are used for path planning and navigation. Additionally, the Dynamic Object Layer is responsible for real-time detection and tracking of dynamic objects by camera and LiDAR. Therefore, based on the map model, UGVs can achieve positioning, obstacle avoiding, path planning and navigate in both indoor and outdoor environments.

2.3 Layered HD Map Construction

This paper develops an HD Map platform for map production and updates. The platform includes functions such as point cloud upload and processing, road network topology and attribute generation, and HD Map output in standard format.

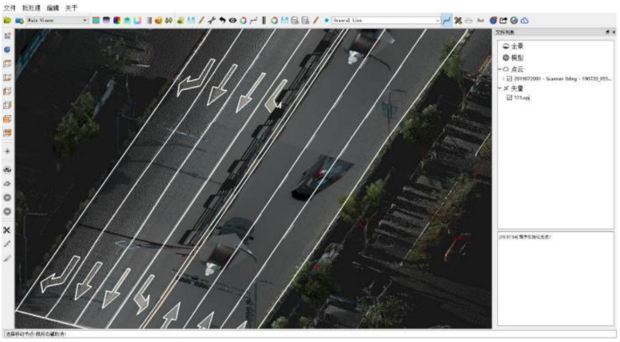


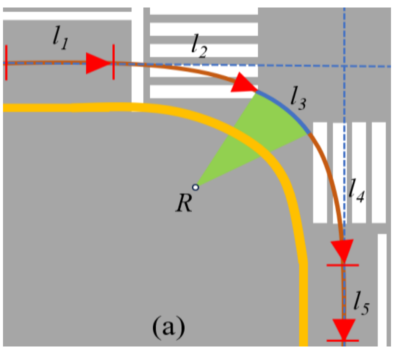
Figure 4. The HD Map Platform.

The process of constructing indoor-outdoor layered HD Maps using the map platform is as follows:

2.3.1 Lane Network Generation: In order to accurately describe the geometric shape of roads and lanes, the lane geometry consists of straight lines, spiral lines and arc lines in the map platform, based on the properties of vehicle dynamics and linear changes in road curvature. Figure 5. (a) shows the centerline of a right turn lane at an intersection, from l_1 to l_5 represent straight lines, spirals, arcs, spirals, and straight lines, respectively. And their curvatures are shown in Figure 5. (b).

2.3.2 Feature Element Generation: When generating static map feature elements, we have specifically added indoor feature elements generation functionality in the map platform. In the map feature elements bar, we have added indoor map features such as parking spaces, no parking areas, pillars, corridors, entrances and exits, and walls. Therefore, it can effectively express the indoor environments.

2.3.3 Map Output in Lanelet2 Map Format: The HD Map platform supports outputting in shapefiles, Lanelet2, and OpenDRIVE map format. Due to Lanelet2's widely used read-write interface, it can be represented in XML format for convenient map updates; and the content can be freely expanded through <key_value>, we highly recommend output the indoor-outdoor layered HD map in the XML format of Lanelet2.



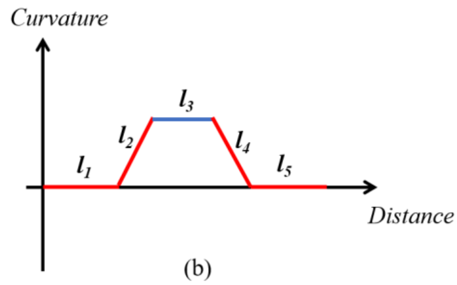


Figure 5. The Centerline of a Right Turn Lane, and Its Curvature Changes.

3. Experiments and Analysis

3.1 Experimental Process

3.1.1 Experimental Area: This paper selected a double decker parking lot in a certain area as the experimental area. The experimental area includes an above ground parking lot and an underground parking lot, as well as an entrance and an exit connecting indoor and outdoor areas (Figure 6. (f)). The above ground area is outdoor, where there are parking spaces, lanes and pedestrian crossings (Figure 6. (e)). While in the underground part there are multiple parking spaces (Figure 6. (b)), landmarks (Figure 6. (a)), pillars (Figure 6. (d)), and no parking signs (Figure 6. (c)). Figure 7 is a plan view of the experimental area.

Figure 6. Images of Experimental Area. (a) ground arrow; (b) parking space; (c) no parking area; (d) pillar; (e) pedestrian crossing sign; (f) exit ramps of parking lot.

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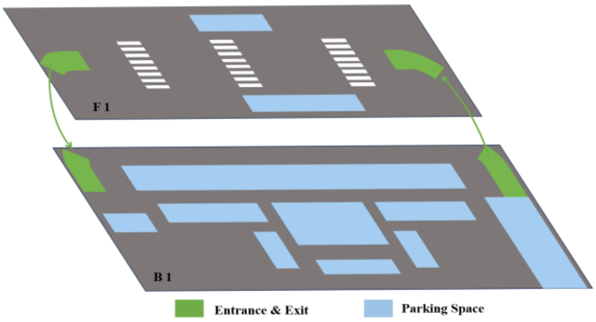


Figure 7. The Plan View of the Experimental Area.

3.1.2 HD Layered Map Construction: We use the UGV described in 2.1 for automatic exploration of SLAM and point cloud acquisition. Based on the point cloud data, we built the indoor-outdoor layered HD map in the XML format of Lanelet2 by the HD Map platform described in 2.3, as shown in Figure 8.

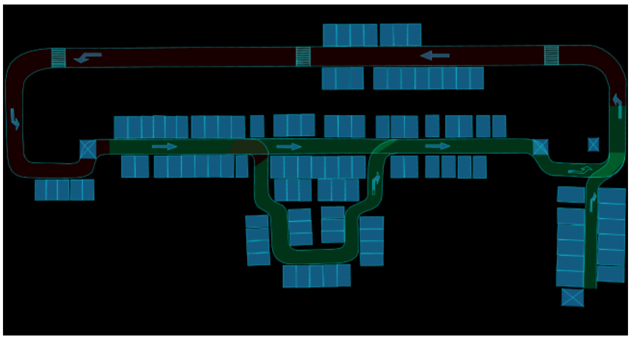
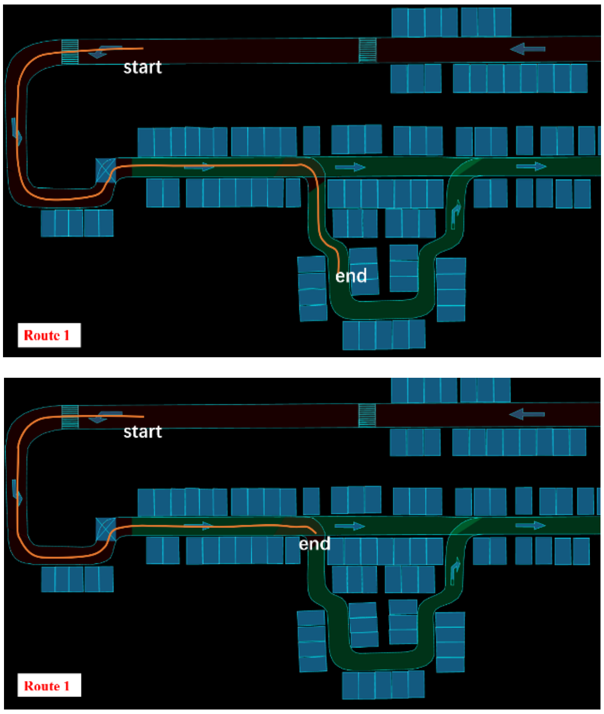


Figure 8. Experimental Area Layered HD Map in Lanelet2 Format. It shows several HD Map elements such as lanes, parking spaces, no parking areas, pedestrian crossings, ground arrows, etc.

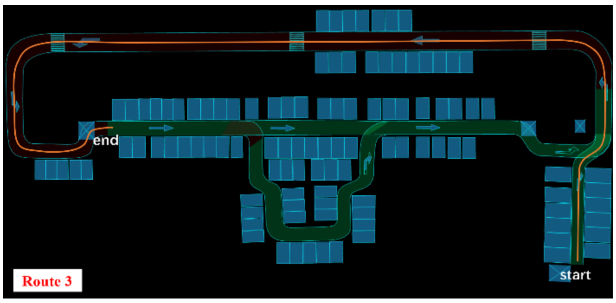
3.1.3 UGV Navigation Test: For indoor and outdoor scenarios, UGVs usually have the following driving situations: (1) driving from outdoors to indoors (such as parking); (2) driving from indoors to outdoors (such as leaving parking lot); (3) always driving indoors (such as indoor inspections); (4) always driving outdoors (such as outdoor roads cleaning). Therefore, here were 4 test routes we had designed. The first was starting from the ground area, so the UGV could get absolute positioning by GNSS at the beginning. After entering the underground parking lot from the entrance, it would switch to target recognition and matching for positioning based on indoor feature layer. The second approach was departing from the parking lot and drive out from the exit, then switch to GNSS absolute positioning, assisted by the outdoor feature layer, while path planning is carried out jointly by the indoor topology layer and the outdoor lane layer. The third and fourth routes were loop lines, so the UGV would travel from indoors to outdoors and then back indoors, as well as from outdoors to indoors and back outdoors.

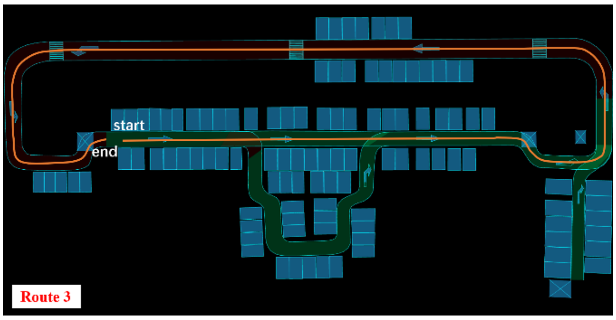
By the UGV deployed with Autoware autonomous driving system, we conducted the autonomous navigation driving test based on Layered HD Map. We conducted on-site testing based on the four designed routes, and each route was tested twice separately. We used the positioning trajectory of our UGV to match with the corresponding lane segments of the map, in order to visually detect the effectiveness of the map for positioning and navigation. The driving trajectories of the UGV are overlaid on the map as shown in Figure 9 (a) to (d).



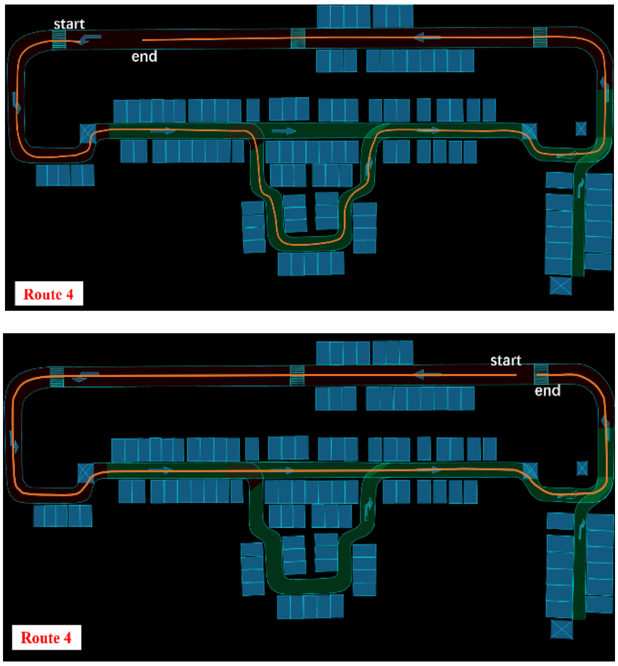
(a) The UGV's trajectory of Route 1.

(b) The UGV's trajectory of Route 2.





(c) The UGV’s trajectory of Route 3.



(d) The UGV’s trajectory of Route 4.
Figure 9. The Experimental Testing Results.

3.2 Results and Discussion

The results indicate that according to the indoor-outdoor layered HD Map, UGV can achieve good results in indoor and outdoor positioning and navigation. Not only can UGV achieve autonomous navigation in a single indoor or outdoor environment, but it can also switch positioning modes to cope with indoor and outdoor environment transitions during the process of entering and exiting indoors. However, we also found that the effect of map navigation at the entrance and exit ramps (e.g. Figure 6. (f)) is not very ideal. This is due to the large elevation fluctuations and unclear features at the ramps, which makes it difficult to match the real-time scanning results of the radar with the map.

Additionally, this experiment only focused on the positioning and navigation effects of indoor-outdoor Layered HD Map, so it involved the indoor topology layer, indoor feature layer, outdoor lane layer, and outdoor feature layer testing and verification. Due to the relatively simple road environment in the experimental area and the UGV without any cameras, outdoor road network layer and dynamic object layer was not conducted.

4. Conclusion

This paper proposes an indoor-outdoor layered HD Map and constructs an autonomous exploration robot to collect raw map data efficiently and automatically. The indoor-outdoor layered HD Map refers to a map model that captures detailed accurate information about both indoor and outdoor environments. Therefore, based on this map model, autonomous vehicles can achieve accurate positioning, make intelligent decisions, and navigate safely in both indoor and outdoor scenarios.

The map model proposed in this paper is suitable for both modular and end-to-end applications. In modular applications, the high-precision road network layer can assist in planning and control for autonomous vehicles, while the feature layer aids in perception and localization, resulting in more accurate autonomous driving capabilities. In end-to-end applications, the road base map serves as a driving assistance map that dynamically fuses with real-time perception of local maps. This integration allows for a comprehensive understanding of the driving environment and aids in making real-time decisions.

However, we should also note the limitations of this study. The map model proposed in this paper is only applicable to small UGVs and relatively simple indoor and outdoor environments, such as underground parking lots, warehouses, industrial parks, campuses, etc. It may not be practical for motor vehicles. In addition, the method proposed in this article for autonomous exploration to collect and update point cloud maps, although reducing manual operations, does not necessarily improve efficiency. In the future, we will further explore various possibilities of indoor and outdoor autonomous navigation.

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