Autonomous Vehicle Mapping and Localization in Carla

Pranav Raj H[1], Jonathan Sivakumar[1] and B Uma Maheswari[1]

[1]St. Joseph's College of Engineering, OMR Chennai - 600119, India

Abstract. This paper introduces an advanced autonomous navigation system utilizing RTAB-Map for simultaneous mapping and localization in the CARLA simulation environment, integrated with ROS2 for efficient data processing. Designed to enable the ego vehicle to autonomously explore and map its surroundings, the system employs Visual SLAM techniques based on stereo RGB and depth data to create detailed 3D maps while continuously tracking the vehicle's location. This dual capability is critical for effective path planning and environmental awareness, allowing the vehicle to adapt its navigation path based on real-time changes in its mapped surroundings. Key to the system's robustness is RTAB-Map's loop closure detection, which significantly enhances mapping accuracy by minimizing localization drift over time, ensuring reliable navigation in larger, complex environments. Additionally, the ROS2 framework facilitates smooth data transfer and synchronization between sensors and RTAB-Map, optimizing real-time performance in dynamic, simulated scenarios. With a modular architecture and scalable components, this project lays the groundwork for future developments in autonomous navigation and SLAM research. By demonstrating the effectiveness of high-fidelity mapping combined with real-time localization, this provides valuable insights into the development of autonomous driving solutions, with applications that can be extended into the real-world.

Keywords: CARLA, RTAB-Map, ROS2, Simulation, Simultaneous Localization and Mapping.

1 Introduction

1.1 Background

The automotive industry is on the verge of a transformative revolution, driven by the rapid advancements in self-driving vehicles. These vehicles hold the promise of making mobility solutions safer, more efficient, and smarter. At the core of this innovation lies the ability of driverless cars to perceive, understand, and navigate their surroundings with minimal human intervention. A key technology enabling this capability is Simultaneous Localization and Mapping (SLAM).

SLAM empowers a vehicle to determine its position within an unfamiliar environment while simultaneously building a map of its surroundings—an essential component for ensuring safe and successful navigation. Among the diverse range of SLAM algorithms, RTAB-Map (Real-Time Appearance-Based Mapping) has emerged as a front-runner due to its ability to perform visual SLAM in real-time using RGB and depth

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camera data. This algorithm excels in high-precision scenarios, offering features like loop closure detection, which minimizes drift and enhances map accuracy.

This project leverages RTAB-Map within the CARLA simulator, a high-fidelity, open-source platform widely utilized in autonomous driving research. CARLA extends the capabilities of ROS2 (Robot Operating System 2), facilitating experiments in real-world-like autonomous systems. By integrating RTAB-Map with CARLA, this project establishes a foundation for advanced mapping and localization, serving as a stepping stone toward comprehensive autonomous vehicle frameworks.

1.2 Motivation

Reliable and accurate navigation is a critical requirement for the successful deployment of self-driving vehicles. Localization and mapping techniques form the backbone of this capability, enabling vehicles to operate in dynamic, real-world environments where obstacles, terrain, and lighting conditions can change unexpectedly. Autonomous vehicles must adapt to these challenges with robustness and precision.

However, developing and testing such advanced systems in real-world settings is resource-intensive and time-consuming. The CARLA simulator offers a cost-effective and practical alternative, allowing developers to experiment with autonomous algorithms in realistic virtual environments. By integrating ROS2 with CARLA, the system supports seamless data exchange, modular design, and scalability—key attributes for building sophisticated autonomous systems.

The motivation for this project is to create a flexible and reliable autonomous framework. This framework can be extended to include advanced functionalities like path planning and collision avoidance. At its core, it emphasizes mapping and localization, showcasing the potential and versatility of autonomous navigation systems.

1.3 Objectives

This project aims at having an autonomous mapping and localization system in a simulated environment as realistic as possible. Specifically, it would do the following:

High-accuracy Mapping: The system will create a 3D map of the CARLA environment using visual SLAM with RTAB-Map while concentrating on the detailed and consistent maintaining of spatial data.

High Precision Localization: While mapping, the system will also track the position of the ego vehicle inside the created map for reliable localization when the vehicle returns to previously mapped areas.

Modularity and Scalability: The integration with ROS2 makes the setting modular so that, in the future, systems such as autonomous path planning and collision avoidance could easily be incorporated.

Simulation Testing and Validation: The proposed system will be validated within CARLA under various scenarios, and the accuracy of both map and localization will be assessed in terms of robustness.

Contribution to Autonomous Navigation Research: A working mapping and localization setup could open avenues for further studies in this technology involving the autonomous driving project.

2 Literature Review

The technologies, approaches, and resources essential to autonomous car navigation are examined in this literature review, with a particular emphasis on Simultaneous Localization and Mapping (SLAM) in both simulated and real-world settings. SLAM has become a key method in autonomous navigation, especially when used in dynamic, large-scale environments. Five important research are included in this review, each of which offers distinct perspectives on how SLAM should be applied for different use situations. This section offers a thorough grasp of how various SLAM techniques might facilitate autonomous navigation, especially through the use of simulation, open-source libraries, and frameworks, by examining the development of SLAM and its real-world applications. The usefulness of SLAM for autonomous systems has advanced thanks to each of the provided papers, which have improved the scalability, performance, and resilience of autonomous navigation configurations.

Real-Time Appearance-Based Mapping, or RTAB-Map [1], is a powerful and adaptable SLAM library made for extensive, continuous online use. RTAB-Map is an open-source program created by Mathieu Labbé and François Michaud that can handle both visual and LiDAR data, making it versatile for a range of robotics and autonomous vehicle applications. This study emphasizes RTAB-Map's ability to carry out appearance-based loop closure in real-time, a method that lessens drift and preserves mapping accuracy over time. Accurate 3D reconstruction of environments is made possible by RTAB-Map's real-time sensor data fusion capability, which is especially important for autonomous vehicles working in a variety of dynamic scenarios.

The authors highlight RTAB-Map's adaptability and scalability in both indoor and outdoor settings, highlighting how well-suited it is for settings where visual signals are continuously changing. An essential component of RTAB-Map is its loop closure mechanism, which enables the SLAM system to identify previously visited locations and adjust map accuracy appropriately. Since RTAB-Map's methods have set the standard for other SLAM systems, this study is essential to comprehending the foundation of visual SLAM. RTAB-Map is positioned as a potent tool for autonomous navigation tasks by combining visual and LiDAR data with real-time analysis. Steve Macenski and Ivona Jambrecic created the SLAM Toolbox, a contemporary SLAM framework designed for dynamic situations [2]. SLAM Toolbox provides specific techniques and setups for mapping in quickly changing environments, in contrast to conventional SLAM implementations that mostly concentrate on static or semi-static environments. Key features of SLAM Toolbox, including lifetime map management and multi-robot SLAM, which enable a variety of navigation needs in autonomous systems, are introduced in this work.

The integration of SLAM Toolbox into the ROS2 ecosystem is covered in the article, along with an example of how its modular design enables smooth communication between various systems. For autonomous cars navigating metropolitan environments or other dynamic settings, SLAM Toolbox's resilience in handling environmental changes is a noteworthy characteristic.

The study offers information on sophisticated parameter adjustment that improves mapping precision and makes SLAM Toolbox a flexible option for challenging SLAM jobs. Understanding how to optimize SLAM for real-world applications where environmental changes occur frequently is made easier by this study.

Alexey Dosovitskiy et al. [3] introduced CARLA, a simulation framework designed to make testing and developing autonomous driving systems easier. Before being used in the real world, autonomous navigation algorithms can be thoroughly tested in CARLA, a realistic, high-fidelity environment created specially to mimic urban driving circumstances. The simulator is perfect for simulating real-world driving circumstances in a controlled environment since it incorporates a variety of environmental variables, including changing weather, vehicle and pedestrian traffic, and intricate road networks. The study offers information on sophisticated parameter adjustment that improves mapping precision and makes SLAM Toolbox a flexible option for challenging SLAM jobs. Understanding how to optimize SLAM for real-world applications where environmental changes occur frequently is made easier by this study. Alexey Dosovitskiy et al. [3] introduced CARLA, a simulation framework designed to make testing and developing autonomous driving systems easier. Before being used in the real world, autonomous navigation algorithms can be thoroughly evaluated in CARLA, a realistic, high-fidelity environment created especially to mimic urban driving circumstances. The simulator is perfect for simulating real-world driving circumstances in a controlled environment since it incorporates a variety of environmental variables, including changing weather, vehicle and pedestrian traffic, and complex road networks.

The architecture of ROS2 and its applicability for autonomous systems are thoroughly examined in this work by Steven Macenski and colleagues, emphasizing the technology's contribution to enhancing inter-device communication and enabling sophisticated autonomous operations. High-performance applications like autonomous car navigation can benefit from ROS2's enhanced security, dependability, and multiplatform deployment support.The writers talk about ROS2's communication model, which uses Data Distribution Service (DDS) to facilitate smooth real-time data sharing across different sensors and CPUs. ROS2 is a strong tool for this project because of its versatility and interoperability with SLAM tools like RTAB-Map and SLAM Toolbox, which allow for the integration of mapping, localization, and navigation features into a single framework. Understanding the fundamental architecture that enables efficient autonomous navigation and data processing requires reading this paper. With an emphasis on applications for autonomous cars, the review by Gao, Lang, and Ren [5] offers a thorough summary of stereo visual SLAM approaches. The vehicle's comprehension of spatial relationships and object distances is improved by stereo visual SLAM, which uses both left and right camera viewpoints to produce a depth-aware model of the surroundings. The authors examine a number of stereo SLAM techniques, such as feature-based and direct methods, and point out the benefits and drawbacks of each.

The importance of stereo SLAM in providing real-time depth perception—which is necessary for applications like autonomous vehicle path planning and obstacle detection—is emphasized in the paper. The authors go over a number of algorithmic developments in stereo SLAM, including depth estimation and optimal feature matching strategies that increase mapping accuracy in difficult-to-reach settings. Because it sheds light on the efficacy of stereo SLAM for autonomous navigation and establishes the foundation for incorporating comparable techniques into the current system, this review is especially pertinent to the project.

3 Methodology

3.1 System Architecture

Three primary parts make up the system architecture: the CARLA simulator, RViz, and ROS2 with RTAB-Map. The ego vehicle works in a simulation environment called CARLA, which provides RTAB with sensor data. Maps are used for SLAM. The smooth transmission and processing of data from CARLA sensors is ensured by ROS2, which controls communication between CARLA and RTAB-Map. By viewing the mapping process, RViz makes it possible to view the ego vehicle's surroundings and localization information in real time.

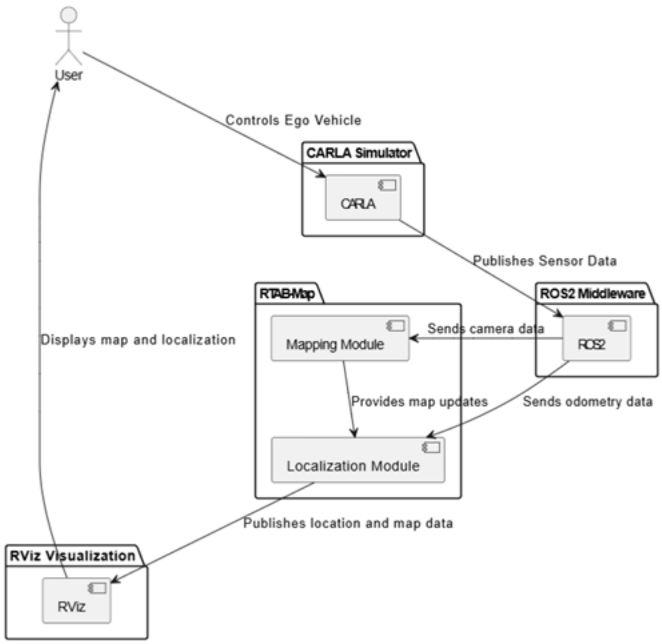

Fig. 1. System Architecture Diagram, showing the connectivity between the modules.

3.2 Sensor Integration and Data Flow

The ego vehicle in CARLA is outfitted with a variety of sensors, including odometry, RGB, depth, and LiDAR cameras. For real-time processing, RTAB-Map subscribes to ROS2 topics, which receive data from these sensors.

Odometry data helps follow the movements of the vehicle, while RGB and depth camera data offer the visual and spatial information necessary for mapping.

These subjects are processed by RTAB-Map to create a continuous map and track the location of the vehicle. In order to update the map and localization in real-time, RTAB-Map subscribes to the sensor topics once CARLA publishes sensor data to ROS2.

The key topics include the topic for RGB data (/carla/ego_vehicle/rgb_front/image) and the topic for depth data (/carla/ego_vehicle/depth_front/image).

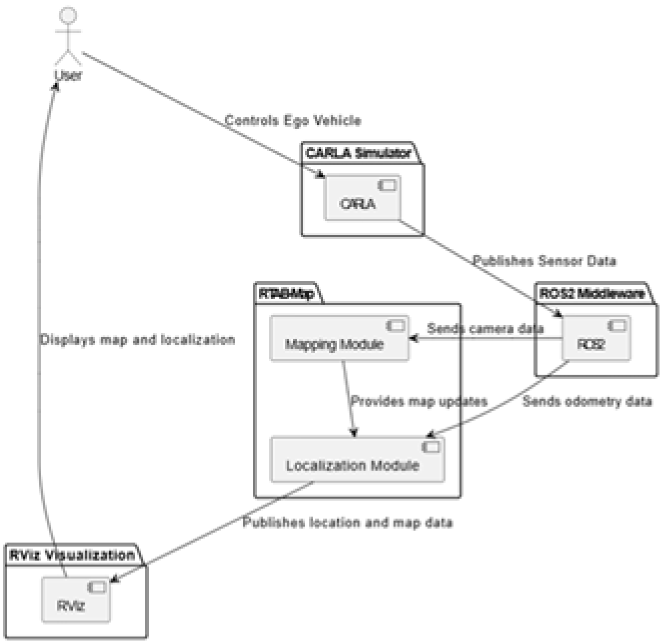

Fig. 2. Data Flow Diagram, showing the flow of data points across the modules

3.3 Output

The project showed how to successfully integrate RTAB-Map with ROS2 in the CARLA environment, resulting in accurate localization and high-quality mapping. Performance indicators like average map density and keyframe use confirmed the effectiveness of the SLAM method, and the produced maps displayed precise and in-depth depictions of the virtual world. Dense 3D maps with improved spatial resolution and fewer artifacts were produced via optimal parameter combinations, and these maps closely matched the ground reality. The combination of odometry and RGB-D camera data enabled the high degree of precision at around 2 meters that the localization accuracy, as measured by root mean square error (RMSE), attained. This guaranteed reliable operation in a variety of simulated situations. Iterative optimization and instant feedback were made possible by the use of RViz for real-time visualization, which yielded insightful information about mapping and localization. All things considered, the project demonstrated the SLAM framework's resilience and effectiveness in providing precise localization, dependable mapping, and improved user interface features.

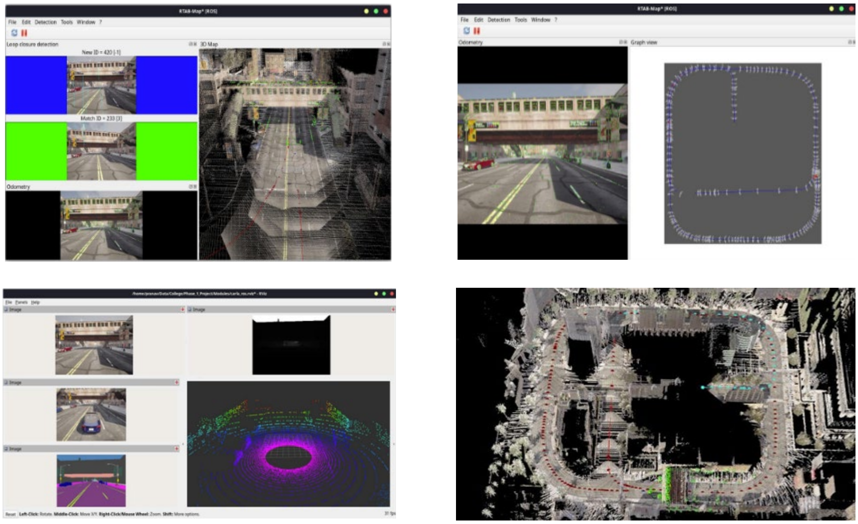

Fig. 3. The output map produced along with the sensor visualization during mapping and closure detection.

4 Results

4.1 Mapping Performance

Accuracy of the mapping was achieved. RTAB-Map operated using ROS2 and the CARLA simulator. The resultant mapping was consistent with the virtual world in which it was created and preserved key features to a realistic extent. For instance, average map density and the number of key-frames cited to justify the effectiveness of RTAB-Map were favorable. The standard configurations for the mapping variables provided 3D map density created, de-tracking was completed, and 3D alignment volumetric clarity was augmented. Loops Consistent occurrences for drift were recorded, signifying that the map successfully merged and aligned with CARLA's ground truth.

4.2 Localization Accuracy

Localization was also very accurate with the ego vehicle world, with an RMSE of approximately 2m. This is due to the particle filter becoming reliant on real-time odometry and real-time visual tracking, minimizing drift and cementing location. Furthermore, depths with RGB-D camera for localization did not differ from CARLA terrains.

4.3 Visualization and User Interaction

RViz helped in real-time visualization as it allowed for visual comprehension of mapping and localization. The path of the robot, the map which grew before one's eyes, and the places where corrections needed to be made were obvious. Real-time visualization of everything ensured proper and effective mapping (only a few seconds delay) that would enable SLAM parameter tuning in the future.

Table 1. Mapping Performance

Metric	Value	Description
Average Map Density	450 points/m²	High-density 3D mapping generated from RGB-D data.
Keyframes Utilized	320 keyframes per 1 km	Optimized keyframe usage for map creation efficiency.
Loop Closure Success Rate	98%	Mean absolute error compared to CARLA's ground truth map.
Processing Time per Frame	0.18 seconds	Time taken to process each frame for map updates.
Coverage Completeness	95%	Percentage of the environment covered by the generated map.
Artifact Reduction	40%	Reduction in mapping artifacts due to optimized parameters.
Memory Usage	1.2 GB per trial	Memory consumed during mapping of a 1-km route.
Metric	Value	Description
Average Map Density	450 points/m²	High-density 3D mapping generated from RGB-D data.

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