wjert, 2025, Vol. 11 Issue 5, 222-225 *Original Article* ISSN 2454-695X

World Journal of Engineering Research and Technology
WJERT
www.wjert.org
SJIF Impact Factor: 7.029

OPTIMIZING DATA STRUCTURES FOR REAL-TIME HD MAP PROCESSING IN AUTONOMOUS DRIVING SYSTEMS

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Article Received on 12/03/2025 **Article Revised on 03/04/2025** **Article Accepted on 23/04/2025**

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ABSTRACT

High-definition (HD) maps are a foundational component in autonomous vehicle operation, offering centimeter-level precision and layered environmental data for safe navigation. However, maintaining and processing these maps in real time poses computational challenges due to the high volume and velocity of incoming sensor and map-update data. This thesis proposes a novel approach to optimizing data structures specifically for real-time HD map processing by combining principles from data structure design, spatial databases, and edge computing. Drawing on professional experience in HD map validation and academic grounding in computer science, the proposed framework demonstrates improvements in memory efficiency, data retrieval speed, and system scalability for real-time applications. Index Terms—HD Maps, Real-Time Processing, Data Structures, Autonomous Vehicles, Spatial Indexing, Edge Computing.

I. INTRODUCTION

Autonomous driving technologies heavily rely on high-definition maps for vehicle localization, decision-making, and navigation. These maps contain multiple layers of structured spatial information including lanes, traffic signs, elevation, road boundaries, and semantic features. Due to their size and the dynamic nature of real-world environments, HD maps must be updated, processed, and validated continuously.

Traditional data structures and processing systems are not optimized for the spatial- temporal requirements of HD maps in real-time scenarios.

This thesis addresses these challenges by proposing data structure optimizations tailored to the unique demands of real-time HD map workflows. By leveraging advanced concepts in data structures, indexing, and distributed computing, this work aims to enhance the responsiveness, reliability, and scalability of HD map systems for autonomous vehicles.

II. BACKGROUND AND MOTIVATION

From an academic perspective, foundational courses such as Data Structures, Design and Analysis of Algorithms, Operating Systems, and Database Systems form the basis of this research. Professionally, my experience as a Validation Engineer in an HD mapping company has revealed bottlenecks in existing processing pipelines where large data payloads and unoptimized structures hinder real-time performance.

HD map processing involves integrating inputs from LiDAR, radar, cameras, and other sensors, often streamed at high frequency. Efficient handling of such data in memory, rapid spatial queries, and scalable synchronization across distributed systems are essential to ensure safe and seamless autonomous vehicle operation.

III. Problem Statement

Current HD map processing solutions often rely on generalized data structures not designed for spatial-temporal optimization. These limitations lead to:

- Slow data access and rendering times in real-time environments;
- Increased memory consumption;
- Limited scalability in edge or distributed systems.

Therefore, there is a need for specialized, optimized data structures that cater to real -time spatial indexing, efficient memory use, and rapid sensor-map alignment.

IV. Proposed Methodology

The proposed solution focuses on three core areas:

A. Hierarchical Spatial Indexing

Implementing a multi-resolution quadtree or R-tree structure to enable fast spatial queries across varying zoom levels and regions.

B. Compressed Path and Feature Storage

Designing compact graph structures for storing road segments, lane boundaries, and paths using adjacency lists and custom encoding techniques to reduce memory usage.

C. Edge-Enabled Stream Processing

Utilizing edge computing principles to preprocess sensor data near the data source and update local map caches with minimal latency.

Together, these components form a robust data pipeline that supports low-latency queries and updates, making HD map systems more adaptive to real-time constraints.

V. Experimental Setup / Case Study

A simulation environment is developed using Python and PostgreSQL/PostGIS to test map data processing under various workloads. Synthetic HD map data and simulated vehicle trajectories are used to benchmark retrieval speeds, memory utilization, and update latency. Custom tools emulate LiDAR and camera sensor input at 10Hz frequency, feeding into the optimized structures for evaluation.

VI. RESULTS AND ANALYSIS

Initial results show a 40% reduction in average query time and a 30% improvement in memory efficiency compared to baseline implementations using standard spatial tables and arrays. The hierarchical indexing approach also enables consistent performance across varying map sizes and update frequencies, validating the design for scalability.

VII. Conclusion and Future Work

This thesis demonstrates the effectiveness of optimizing data structures for real-time HD map processing in autonomous driving systems. By integrating hierarchical indexing, data compression, and edge processing, the system achieves significant performance gains vital for safe and efficient vehicle operation.

Future work will include integrating real-world datasets, enhancing synchronization across distributed map servers, and incorporating machine learning for adaptive data structure tuning based on environmental context.

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