DRISI

CALTRANS DIVISION OF RESEARCH, INNOVATION AND SYSTEM INFORMATION

TRANSFORMING IDEAS INTO SOLUTIONS

Research Notes

Traffic Operations

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Project Title: LiDAR Data Fusion for Multi-Modality at Traffic Signals

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Caltrans

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LiDAR Data Fusion for Multi-Modality at Traffic Signals

This project seeks to explore the application of LiDAR sensors in intersection traffic signal control systems, in conjunction with additional multi-modal sensors in other connected automated vehicles or infrastructure to perform sensor fusion tasks. This initiative aligns with the broader goal of improving safety for vulnerable road users (VRUs).

WHAT IS THE NEED?

The pressing need to improve traffic safety, especially for vulnerable road users (VRUs) such as pedestrians, cyclists, and scooters, is a significant factor in urban planning and transportation management. According to the National Highway Traffic Safety Administration (NHTSA), US intersections witnessed 10,626 traffic fatalities in 2020, including 1,674 pedestrians and 355 cyclists, which constituted 27% of all traffic-related deaths. The escalating trends in pedestrian and cyclist fatalities underscore the urgent need for enhanced and effective traffic safety measures at intersections.

A key challenge in enhancing intersection safety is the need for accurate, detailed, and real-time data that captures the complexities of the dynamic and uncertain environment of intersections. This environment includes a diverse array of vehicles, pedestrians, cyclists, and scooters, each with unique movement patterns and safety needs. Particularly challenging is the task of object detection and tracking, and trajectory prediction of vulnerable road users due to their unpredictable and diverse nature. Additionally, the importance of collecting intricate data like vehicle type, speed, direction, occupancy, pedestrian, and cyclist volumes cannot be overstated for informed and efficient traffic control decisions.

Traditional traffic signal control systems are fundamentally limited in their ability to meet these intricate data requirements for multi-modality. They primarily rely on preset timing schedules based on historical traffic patterns and broad generalizations, often resulting in a mismatch with dynamically changing, real-time traffic conditions. Some systems utilize inductive loop detectors for real-time data, but these devices are limited in their ability to detect non-motorized traffic and provide complex data such as specific vehicle types or intricate pedestrian movement patterns. Traditional detection for vulnerable road users only provides single discrete events to serve bike and pedestrian movements. The installation and maintenance complexities and costs associated with these detectors further complicate matters.

WHAT ARE WE DOING?

The primary objective of this project is to leverage the capabilities of LiDAR technology in improving traffic signal operations and intersection safety, particularly for vulnerable road users such as pedestrians, cyclists and scooters. This will involve the development and implementation of advanced algorithms for LiDAR-based object detection, tracking, and trajectory prediction for vulnerable road users, considering the unique challenges posed by the dynamic nature of vulnerable road users, occlusion, point cloud sparsity, and sensor limitations. Overcoming these challenges will necessitate pioneering research to build sophisticated models that can process LiDAR data, handle point cloud irregularities, achieve data fusion from multiple agents, and effectively predict the behaviors of vulnerable road users in the complex intersection environment. Another key objective is to devise and refine traffic analytics derived from the LiDAR-based detection and tracking results as well as vulnerable road users trajectory predictions. These analytics, including traffic volumes, pedestrian volume, and pedestrian crossing times, and special events or incidents, can significantly enhance traffic signal operations by enabling functionalities like dynamic green extension, touchless pedestrian service, detection of vulnerable locations, and traffic flow analytics. The project also aims to demonstrate via state-of-the-art simulation a mechanism to relay these analytics to the traffic signal controller and the approaching vehicles through Road-Side Equipment (RSE) in a connected vehicle environment.

WHAT IS OUR GOAL?

The project is expected to provide a clear roadmap for infusing LiDAR data into local traffic signal operations, which will guide future developments in connected vehicle applications, Performance Measurement System (PeMS), and other central management systems. Ultimately, the insights gained from this project should significantly inform and shape the ongoing efforts of the California Department of Transportation (Caltrans) and other transportation agencies towards improving intersection safety and efficiency through innovative technology integration.

WHAT IS THE BENEFIT?

Upon successful completion of this project, we expect to have a demonstrated solution that effectively integrates LiDAR technology into traffic signal systems, providing significant enhancements in intersection safety and efficiency. This solution is expected to be capable of robustly detecting and tracking VRUs and accurately predicting their trajectories, overcoming the previously identified challenges, while also providing comprehensive traffic analytics for real-time operations and post-processing analysis. Moreover, we anticipate that the refined traffic analytics, derived from the advanced LiDAR-based detection and prediction system, will enrich the data set available for traffic management, thereby facilitating more effective and responsive control of traffic signals. This system will also enhance service for vulnerable road users and other road users, supporting extended green lights, touchless pedestrian services, and other safety and efficiency improvements.

WHAT IS THE PROGRESS TO DATE?

Data collection was conducted at the UCLA smart intersection testbed, where a multi-sensor system captured real-world urban traffic interactions. The dataset includes 75 hours of driving logs, 33,000 LiDAR frames, and 171,000 camera images, covering a range of traffic conditions and interactions. Structured annotation, precise sensor synchronization, and multi-modal data fusion techniques were implemented to ensure high data accuracy and usability. The project integrates cutting-edge machine learning approaches to enhance perception and predictive modeling, helping to improve traffic monitoring and signal control.

Several challenges were encountered during data collection and processing, including occlusion, point cloud sparsity, and object identity inconsistencies across multiple sensor perspectives. These were addressed through adaptive machine learning models, multi-agent fusion strategies, and refined annotation techniques, improving the dataset's reliability for future applications. Lessons learned from these challenges will inform better practices for large-scale multi-modal traffic perception systems.

During the most recent quarter, the focus was on testing LiDAR-based object detection and tracking. Object tracking in intersections can be challenging due to structural complexity and the presence of diverse road users, including vehicles, cyclists, pedestrians, and micromobility devices. To help alleviate these challenges, a real-time cooperative perception framework was tested at the UCLA Smart Intersection.

The cooperative perception framework system was designed to operate in real time by integrating object detection results from multiple connected agents such as vehicle-to-everything (V2X) and infrastructure-to-infrastructure (I2I) communication systems. Testing results during this phase revealed real-time cooperative perception presents fundamental challenges, including limited communication bandwidth and model heterogeneity among participating agents. These constraints complicate the integration of perceptual information in multi-agent systems, especially in complex urban environments. To address these issues, this work introduces a feature-based late fusion framework designed to operate efficiently under real-world conditions. The proposed method reduces communication overhead by utilizing compact detection outputs and enhances fusion accuracy by incorporating additional consistency measures beyond conventional confidence scores.

The insights from this research align with Caltrans' mission to enhance traffic management through innovative technology solutions. The dataset and findings will serve as a valuable resource for developing adaptive, multi-modal traffic signal control systems, improving roadway safety, and facilitating the integration of connected and automated vehicle technologies at traffic intersections.