Infrastructure-Based Cooperative Perception at a Traffic Intersection: Overview and Challenges

Preprint

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INTRODUCTION

Traffic intersections are crucial and challenging nodes in transportation networks where multiple lanes of vehicles and pedestrians converge. About one-quarter of traffic fatalities and about one-half of all traffic injuries in the United States happen at traffic intersections (1). Effective management of these intersections is important to ensure safety and efficiency of all users—vehicles, pedestrians, cyclists, and vulnerable road users (VRUs) (2, 3). With advancements in sensor perception technologies such as radar, light detection and ranging (lidar), and cameras, traffic intersections are developing into dynamic and data-rich environments. By using these data to create a real-time digital twin, we can enable real-time data-driven decision making and a range of applications such as sharing perception information to connected vehicles (CVs) and connected autonomous vehicles (CAVs), safety affirmative signaling, and curb optimizing to improve efficiency and enhance safety (4–7).

This paper presents an overview of the concept and examines the challenges involved in implementing an infrastructure-based cooperative perception engine at a traffic intersection. In addition to outlining the physical components, this study also addresses important challenges involved in a multi-sensor system. We present results from deploying the National Renewable Energy Laboratory's (NREL's) Infrastructure Perception and Control (IPC) mobile trailer at a traffic intersection in the city of Colorado Springs, Colorado, USA that employed multiple radars and lidars to capture the data. This study provides necessary practical learning for the Cooperative Driving Automation (CDA) and traffic engineering communities for next-generation infrastructure-based cooperative perception that promises improvements in signal control for optimized traffic flow, among other applications, and documents findings for ongoing research and development efforts in other areas.

METHODS

Infrastructure Perception and Control Framework

To create a safe and robust traffic intersection, it is important to integrate data from sensors of various modalities because each sensor has different optimal range, resolution, and accuracy. It is important to combine and fuse data from various sensors to create a unified picture of the intersection that is safe and reliable enough to work in any environmental conditions. The NREL IPC framework shown in Figure 1 integrates perception data from sensors and cooperative shared information from CAVs and CVs to perform late-stage track data fusion and create a high-accuracy digital twin of the intersection, which has potential for multiple control applications such as eco-approach and departure (8), signal optimization (9), safety affirmative signaling, curb optimization (10), and dilemma zone detection and prevention (11–13).

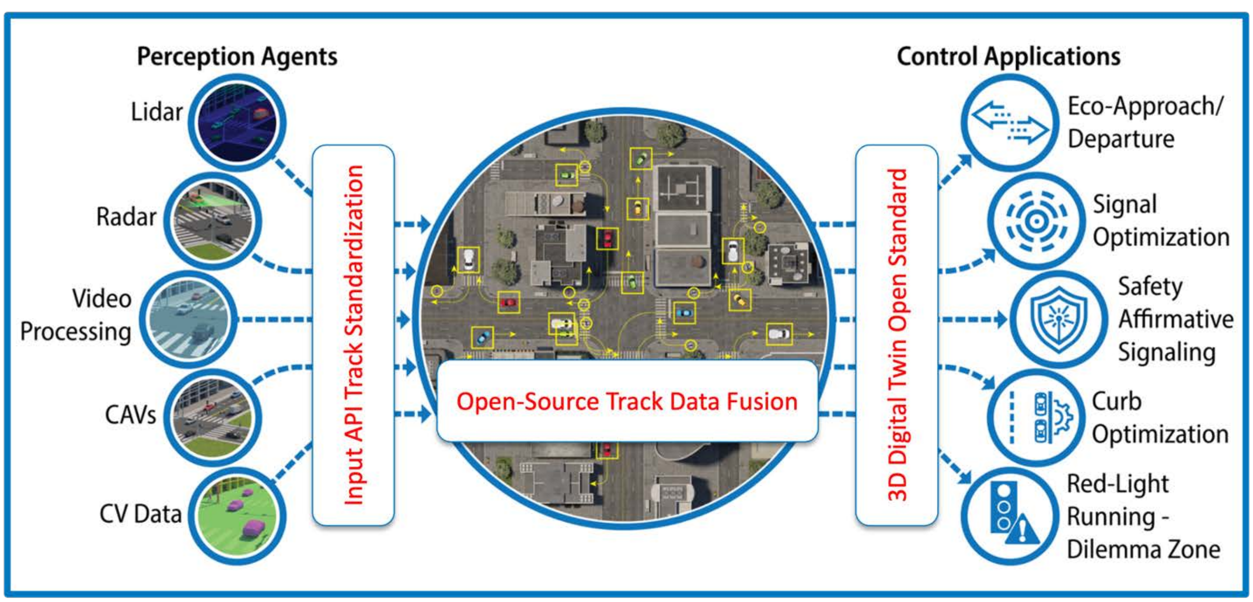

Figure 1. NREL IPC framework

Experimental Setup

The IPC mobile laboratory is a state-of-the-art mobile laboratory that can rapidly deploy multiple sensors and technologies at any traffic intersection and record data in real time. In this study, the IPC mobile laboratory was deployed at a four-way traffic intersection in the city of Colorado Springs, Colorado, USA. Two Econolite EVO radars and two Ouster lidars were deployed on extendable masts to capture the objects within and approaching the intersection and send object track data to edge compute devices located in the mobile laboratory.

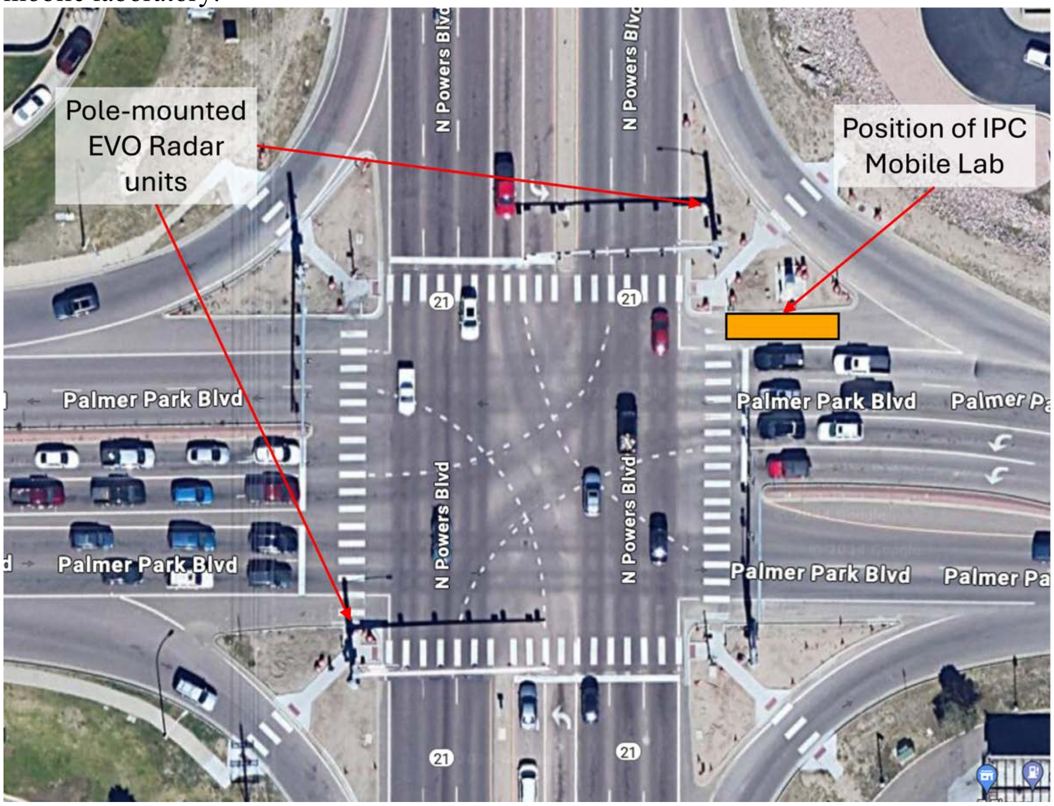

Figure 2. Traffic intersection where IPC mobile lab was deployed for data collection

RESULTS AND DISCUSSION

In this section, we present the results and the challenges that must be addressed for the deployment of cooperative perception framework such as the proposed IPC fusion engine to output the fused object trajectory from the sensor data. The following sections explain the importance of these issues and how they were resolved within the framework of the data collection exercise.

Sensor Calibration

To create a robust digital twin of the traffic intersection, accurate spatial registration is required from the sensors for data fusion. To handle the growing number of sensors—especially in multisensor systems—automatic calibration is crucial to enable robust performance. Classical calibration methods have been developed that require a calibration object such as a checkered board to be detected within the sensor field of view. However, implementing such manual calibration procedures is disruptive at a traffic intersection because frequent road closures negatively impact the flow of traffic. Calibration would need to be performed each time the sensor moves; movement can be caused by excessive structure vibration, contact with an object, or inclement weather.

For a sensor capturing data at an intersection, a ground plane is determined to reduce the dimensionality from a 3D problem into a 2D transformation by omitting the height of vehicles. The detection points in world coordinates (w_i) and sensor coordinates (s_i) are given as shown in **Equation (1):**

$$s_i = [x_i^s, y_i^s]^T, \quad s_i \in R^2 \tag{1}$$
$$w_i = [x_i^w, y_i^w]^T, \quad w_i \in R^2$$

For every point, we define the coordinate transformation as given by **Equation (2):**

$$w_i = \underbrace{\begin{bmatrix} cos\theta & -sin\theta \\ sin\theta & cos\theta \end{bmatrix}}_{R} \times \begin{bmatrix} x_i^s \\ y_i^s \end{bmatrix} + \underbrace{\begin{bmatrix} t_x \\ t_y \end{bmatrix}}_{T} \tag{2}$$

where R and T represent rotation and translation matrices, respectively.

To resolve this bottleneck of sensor calibration for the IPC framework, we employ Global Navigation Satellite System (GNSS) trajectory of vehicles traveling through the intersection to calibrate the sensors both initially and ongoing. As CAVs and CVs travel through the traffic intersection, they would share their spatial information to the intersection-based roadside unit (RSU) via Vehicle-to-Infrastructure messaging. Mir et al. (14) demonstrated this concept by deploying a test vehicle equipped with a post-processed kinematic (PPK) GNSS unit at the subject intersection. The vehicle was driven through the intersection multiple times and from multiple approaches. The position data from the vehicle were associated with the corresponding traces from the infrastructure sensors to obtain the absolute position and orientation of each sensor to a degree of accuracy that enabled high-fidelity sensor fusion.

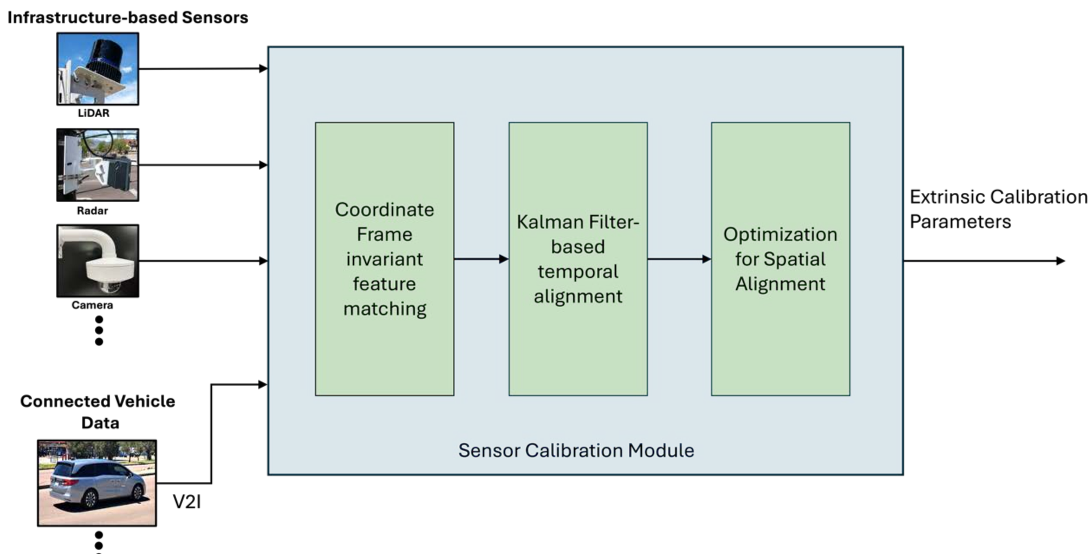

Figure 3. Multisensor calibration framework using Global Navigation Satellite System

Clock Synchronization

Sensor fusion—which integrates data from multiple sensors to achieve better accuracy and reliability than could be obtained from any single sensor—relies heavily on precise temporal alignment of data from each sensor. Time misalignments cause corresponding spatial misalignments, ultimately degrading the accuracy of the system. Accurate spatial sensing from multiple sensors requires 4D calibration—three spatial dimensions and time. Time drift occurs when the local sensor clocks deviate from a common reference because of the lack of periodic synchronization. Variations in the oscillator frequency of clocks lead to inaccuracies in each sensor time reference and can be caused by factors such as clock inaccuracies, temperature variations, power supply fluctuations, and hardware inconsistencies. Network Time Protocol (NTP), which uses a data network to access an accurate time server over the internet to adjust the local sensor clock, can achieve an accuracy within a few milliseconds. Many perception sensors (radar, lidar, camera) are designed to use NTP to address the issue of an accurate time reference and to adjust for any local clock drift. However, infrastructure-based applications may not have access to a reliable data network and therefore are more subject to both time initialization and clock drift issues. GPS time provides highly accurate time signal because of the presence of atomic clocks on satellites, which are highly accurate and stable and can be used to synchronize ground system clocks using National Marine Electronics Association (NMEA) 0183 standard protocol sent to a GPS receiver. GPS time is typically accurate to within nanoseconds of Universal Time Coordinated (UTC). Because of the distributed nature of sensors within infrastructure applications—sometimes bridging multiple miles—and the uncertain availability of a reliable data network, the authors advocated for GPS referenced sensor data as the most robust time reference for the IPC framework.

System Health Monitoring

In modern intelligent transportation systems (ITS), which incorporate multiple perception sensors at the traffic intersection, it is imperative to employ a robust system for health monitoring to ensure these systems are always functioning correctly. Efficient traffic management depends on the system's capacity to operate continuously, and fail-safe procedures make sure backup systems can take over during a malfunction. Fault detection with traditional sensors has been well established; however, for a multisensor setup continuously monitoring all sensors, their calibration, and accuracy is more complex. Figure 4 shows a schematic for the deployment of an IPC fusion engine with trajectory-based signal timing control sent to the controller. The system employs loop detection as a failure mode if the fusion engine seems to be working incorrectly because of faulty sensor data. Note the loop detection can also be loop detection emulation from one or more of the modern sensors deployed.

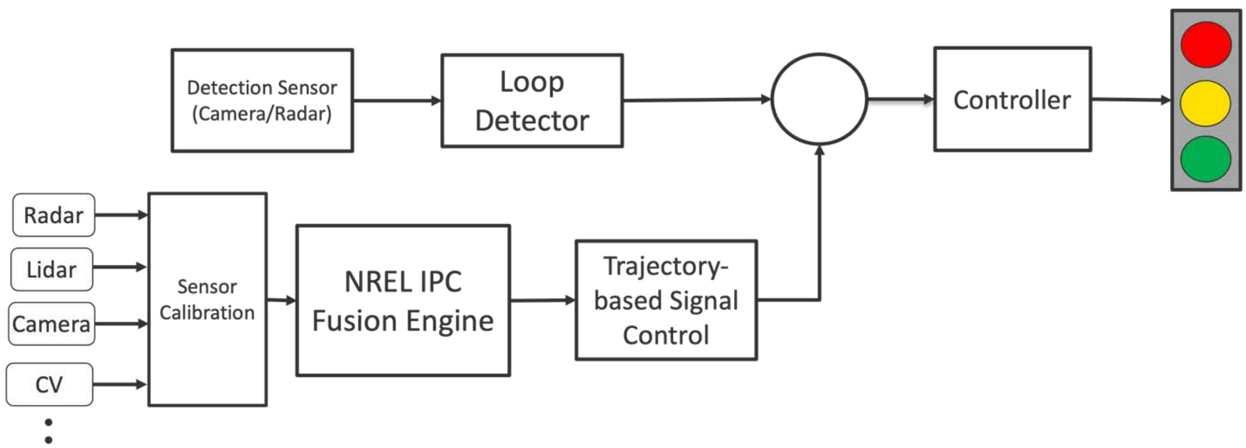

Figure 4. Real-time deployment of IPC fusion engine framework for optimal signal control with a loop detection as a fail-safe mode

Real-time sensor fidelity monitoring is crucial for the sensors to continue to collect reliable and accurate data. Furthermore, real-time sensor fidelity monitoring would allow the system to adapt to changing environmental conditions such as lighting and precipitation and prompt the necessary compensatory algorithms in the IPC fusion engine to account for increased uncertainty in the data captured by that sensor. This ensures the cooperative track data fusion from the IPC fusion engine is robust under various conditions—a crucial attribute of traffic management systems.

CONCLUSIONS

This paper provides an overview of IPC cooperative perception framework, the implementation of such systems, and the challenges associated with their deployment. Experimental results indicate a need for an auto calibration algorithm to bring the sensor output data to a common coordinate frame and the necessity for robust clock synchronization to register correct spatial and temporal data from the sensors, which is necessary for data fusion. GPS synchronization is highly recommended for infrastructure-based applications where connectivity to NTP servers can be problematic. The research also expands on the requirement for a system health monitoring system to validate the overall system accuracy and monitor sensor fidelity in real time. Whenever the system detects a fault, the sensor suite will need to fall back on loop emulation mode to allow seamless system degradation.

Future work is planned to evaluate the performance of the IPC fusion engine by deploying various sensor configurations, evaluating the performance of the algorithm in various road settings such as rural, urban, and highway and in varying environmental conditions. To evaluate the capabilities of information sharing from infrastructure sensors via I2V communication, we plan to deploy roadside units and an onboard unit in the test vehicle in future studies to facilitate real-time implementation. Finally, the digital twin output will be configured to feed various downstream applications such as trajectory-based optimal signal control at a traffic intersection.

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AUTHOR CONTRIBUTIONS

The authors confirm contribution to the paper as follows: study conception and design: F. Mir, S. Young, Q. Wang, R. Sandhu, C. Tripp; data collection: F. Mir, S. Young, Q. Wang, R. Sandhu, T. Osborn; analysis and interpretation of results: F. Mir, R. Sandhu; draft manuscript preparation: F. Mir, S. Young. All authors reviewed the results and approved the final version of the manuscript.

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