OpenCDA-ROS: Enabling Seamless Integration of Simulation and Real-World Cooperative Driving Automation

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***Abstract*—Autonomous driving (AD) and Cooperative Driving Automation (CDA) hold great promise for transforming mobility. However, current off-the-shelf AD or CDA platforms such as Autoware, Apollo, and CARMA, are subject to gaps between simulation and the real world and do not offer integrated pipelines for CDA research, development, and deployment. In this letter, we conceptualize OpenCDA-ROS, building on the strengths of an open-source framework OpenCDA and the Robot Operating System (ROS), to seamlessly synthesize ROS's real-world deployment capabilities with OpenCDA's mature CDA research framework and simulation-based evaluation to fill the gaps aforementioned. OpenCDA-ROS will leverage the advantages of both ROS and OpenCDA to boost the prototyping and deployment of critical CDA features in both simulation and the real world, particularly for cooperative perception, mapping and digital twinning, cooperative decision-making and motion planning, and smart infrastructure services. By offering seamless integration of simulation and real-world CDA, OpenCDA-ROS contributes significantly to advancing fundamental research, development, testing, validation, prototyping, and deployment of autonomous driving and CDA.**

***Index Terms*—OpenCDA, ROS, simulation, real-world cooperative driving automation, digital twin.**

I. Introduction

Autonomous driving represents a significant frontier for advancing technology and reshaping mobility. As a discipline, it aims to develop vehicles capable of sensing their environment and navigating without human input, thus improving safety, efficiency, and accessibility in transportation systems [1].

According to SAEJ3216 [2], cooperative driving automation (CDA) is a subset of autonomous driving that enables vehicles to interact and cooperate with other vehicles and the infrastructure through communication. This interaction facilitates efficient traffic flow, energy conservation, and improved safety [3], [4]. Despite considerable attention and rapid developments on CDA in recent years, there remain numerous open challenges that hinder the full realization of CDA in real-world [5], [6], [7], [8]. Among the challenges, the integration of CDA into simulation platforms and real-world applications has been less than seamless. This is due to the critical gap between existing ADS platforms that mainly focus on single-vehicle intelligence like Autoware [9] and Apollo platforms [10] and the broader demands of CDA development. Notwithstanding CARMA [11], the only platform in the literature dedicated to cooperative driving automation, exists aiming to contribute to the acceleration of development and deployment of connected and automated vehicles and it has shown good potential for CDA application. However, it focuses more on a subset of CDA guidance features such as platooning and cooperative lane change (CDA applications for traffic improvement), less on supporting cooperative perception, prediction and localization, and advanced decision-making (critical autonomous driving features for CDA). Additionally, its simulation tool (CARMA XiL) is developed for testing CDA vehicle functions, meaning that it is limited to simulating one agent with full CARMA software and does not offer flexibility for early-stage research in algorithmic development, which requires running and testing algorithms with a large number of scenarios. There is a need for a comprehensive tool and framework, to be able to serve CDA development in both simulation and real-world environments in an integrated manner for connected autonomous driving and smart infrastructure, benefiting both academic and industry communities. To fulfill this goal, in this letter, the UCLA Mobility Lab conceptualizes a holistic framework OpenCDA-ROS on top of our previous work in OpenCDA, allowing users to easily transfer their CDA algorithm prototypes from simulation to real-world vehicles/infrastructure and vice versa without much effort. OpenCDA-ROS will be open-sourced via the UCLA Mobility Lab Github repository later in 2023.

OpenCDA-ROS is built on OpenCDA and Robot Operating System (ROS) to develop an open-source framework integrated with co-simulation for CDA research. OpenCDA offers a full-stack CDA software in co-simulation that includes sensing, computation, actuation capabilities, and cooperative features [12], [13]. OpenCDA is highly modularized, allowing users to conveniently replace any default modules with their designs and test them in various scenarios. Despite these strengths, OpenCDA faces limitations in its integration with real-world control and algorithm development, thereby creating a need to develop OpenCDA's interface with the real

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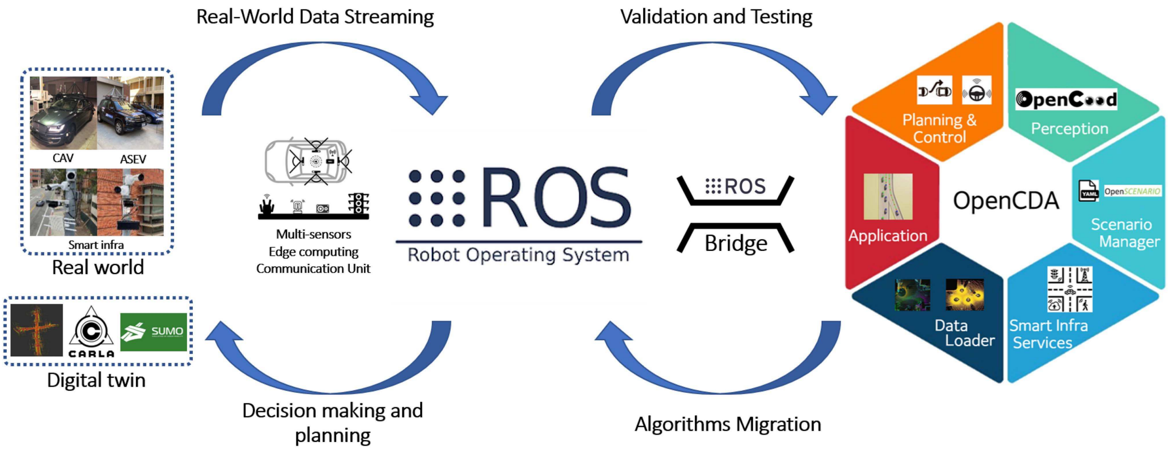


Fig. 1. This figure demonstrates the fundamental concepts of OpenCDA-ROS and its interaction with real-world hardware and the digital world we built. Real-world hardware encompasses not only connected and automated vehicles (CAV), and advanced sensor-equipped vehicles (ASEV), but also smart infrastructure (Infra).

world. ROS is a powerful platform for orchestrating the various software processes needed for robotics and automation research [14], [15], [16], [17]. Its strengths lie in its flexible, modular architecture that promotes code reuse and its rich ecosystem of tools and libraries [13]. However, despite its capabilities, ROS requires an ecosystem similar to OpenCDA to provide algorithms for handling cooperative perception, planning, and application aspects of CDA. OpenCDA ecosystem [13], [18] aids in the efficient and effective deployment of ROS in the real world, leveraging the co-simulation capabilities it offers for algorithm validation and testing. OpenCDA-ROS synthesizes OpenCDA and ROS and is a platform to bridge the gap between simulated and real-world CDA, in order to ensure that the performance of algorithms and vehicles in simulation closely mirrors their performance in the real world. It is worth mentioning that, as shown in Fig. 1 OpenCDA-ROS will leverage the advantages of OpenCDA, such as its diverse community resources, to accelerate critical CDA features development and deployment, in particular for cooperative perception [19], [20], [21], advanced cooperative decision-making and motion planning [22], [23] and smart infrastructure services with miscellaneous features. Overall, OpenCDA-ROS represents a significant step toward enabling the seamless integration of simulated and real-world CDA. By addressing the current limitations of OpenCDA and other platforms, and by leveraging the advantages of the OpenCDA ecosystem, we offer a platform that can enhance the development, testing, and validation of CDA systems, thereby advancing the field of autonomous driving.

In this letter, we are thrilled to announce the initiation of a specialized research initiative: Scenarios Engineering for Smart Mobility (SE4SM). This significant venture will focus on pioneering effort aimed at bridging the gap between simulated and real-world applications in the realm of smart mobility. SE4SM is set to investigate various scenarios of smart mobility, encompassing automated driving, connected vehicles, and digital infrastructure, under diverse environmental conditions. To this end, we will be making use of a comprehensive array of tools, including simulation technologies, digital twins, and parallel simulation. Our ultimate goal is to provide a robust, versatile platform for detailed examination and validation of a broad spectrum of smart mobility solutions.

As part of this initiative, we are also excited to introduce our work on OpenCDA-ROS, an instrumental component of SE4SM. OpenCDA-ROS uses the power of the Robot Operating System to support our exploration and evaluation of smart mobility scenarios, effectively acting as a building block in our broader SE4SM framework.

We warmly invite scholars from both academia and industry to contribute to SE4SM and play a part in shaping the potential future trends in smart mobility. Our collective endeavors under this initiative can significantly advance the development and application of smart mobility systems, ultimately driving safer, more efficient, and sustainable transportation ecosystems.

II. OpenCDA-ROS Platform

In this section, we focus on how OpenCDA-ROS enable the full-stack CDA framework in both simulation and real-world. This discussion will revolve around the key components: Cooperative HD mapping and digital twin, Cooperative localization, Cooperative object detection and tracking, Cooperative decision-making and motion planning, and smart infrastructure services. Each of these elements plays a significant role in enhancing the efficiency and effectiveness of OpenCDA, enabling seamless integration between simulation and real-world CDA.

In OpenCDA, a wealth of sharable algorithms are available that can be effectively applied to both CARLA simulation and ROS. The set of modularized sharable assets includes components for cooperative vehicle detection and tracking, cooperative localization, and cooperative decision-making and motion planning. These assets have been carried over to OpenCDA-ROS, where they now sit alongside a suite of development toolkits and software utilities among not only fully drive-by-wire-equipped (connected) AVs but also advanced sensing-equipped vehicles (ASEV) and smart infrastructure. Together, these components empower users to efficiently test, develop, and deploy their CDA systems and algorithms at vehicles and infrastructure ends. Their modularity allows them to be detached, adapted, and integrated

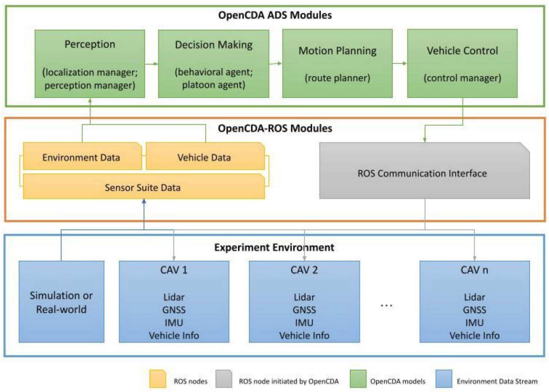


Fig. 2. OpenCDA-ROS system structure.

as per specific needs, thereby streamlining development and fostering a more dynamic and innovative environment for advancements in autonomous driving. The OpenCDA-ROS system structure is composed of three distinct yet interconnected modules: the openCDA autonomous driving system (ADS) module, the openCDA Robot Operating System (ROS) module, and the experimental environment module. The detailed system structure is presented in Fig. 2.

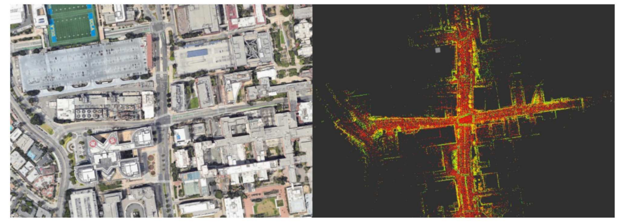
A. Cooperative HD Mapping and Digital Twin

Ubiquitous multi-modal sensing information from intelligent vehicles and smart infrastructure empowers the HD mapping iteration in a cooperative manner [5]. Further, with HD maps, digital twins of the real world can be generated to replicate the traffic, buildings, road users, and lane markings for the simulation tests of diverse CDA features such as cooperative object detection and tracking and cooperative motion planning. On the other hand, high-fidelity simulation tests contribute to reducing the gaps for algorithms to be deployed in the real world.

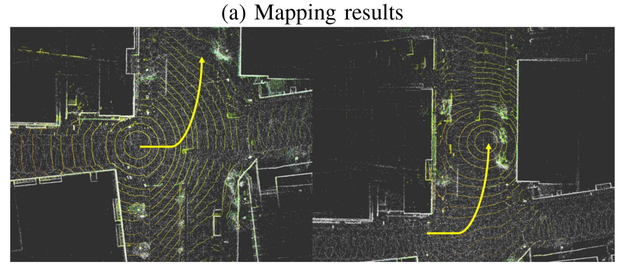
Taking the multi-modal sensing data stream through this OpenCDA-ROS platform, advanced techniques such as crowdsourcing and machine-learning methods in the core engine of OpenCDA can be implemented to generate the elements in the HD maps and make instant dynamic updates given the corresponding map changes caused by work zone, temporal construction, et.al. In OpenCDA-ROS, information is sharable through the ROS network between the digital twin simulation and real-world environment and also between the different agents involved in the traffic. This feature enables the online cooperative HD-mapping and digital twin creation in both simulation and real-world environments, supporting the rest CDA functionality such as cooperative localization, cooperation object detection and tracking in this section.

B. Cooperative Localization

Localization plays a crucial role in OpenCDA-ROS due to its ability to provide real-world comparable location information [24], [25], [26]. In most simulations, including OpenCDA, algorithms are tested using the ground truth data



(a) Mapping results



(b) Localization examples

Fig. 3. (a) Left side of the figure shows a satellite top-down view of the intersection of Charles E Young Dr and Westwood Blvd near the UCLA campus. On the right side, we have a LiDAR scan map generated using our mapping interface. (b) The yellow arrows shown in the figure indicate the operational direction of our test vehicle at the intersection. The left image displays the initial pose obtained through the localization interface, while the right image depicts the final pose of the test vehicle.

directly acquired from the CARLA server, and these data underpin numerous operations, including vehicle perception result evaluation, planning, and waypoint generation. However, such ground truth location information is non-existent in the real world.

In real-world settings, researchers often resort to RTK-GNSS data as a ground truth surrogate, given that its error can be minimized to centimeters or less under optimal conditions. Besides, some researchers also adopt map matching to acquire vehicle pose. To obtain continuous, reliable, and accurate localization information, a localization system based on multi-sensor fusion will have better performance. In our OpenCDA-ROS framework, we employ HD maps to represent the global world in our digital twin as shown in Fig. 3(a). In tandem with this, we use a GNSS/IMU/LiDAR Fusion localization framework to output the ego vehicle's real-time pose.

Although the multi-sensor fusion-based ego vehicle's localization system performs well most time, the sensor signal quality and algorithm performance are still influenced by driving environments. By fusing more information from the cooperative vehicles and infrastructure, cooperative localization enables more reliable localization estimation. The cooperative localization in OpenCDA-ROS operates on a multi-stage basis. Besides the ego vehicle's GNSS/IMU/LiDAR Fusion localization framework, the cooperative localization system could also output the relative pose of the vehicle leveraging the detection module. In combination with the pose information from other agents in the cooperative driving network, the reliability, robustness, and accuracy of the localization estimation could be further improved through an optimization process considering information from all the agents in the network. This technique has proven to be highly accurate in GNSS-denied scenarios, and it could help the agents re-localize, who lose accurate localization estimation from ego's localization system. This localization framework within OpenCDA-ROS, akin to directly acquiring the pose from the CARLA server, can output the coordinate and heading of the vehicle as shown in the Fig. 3(b). Therefore, OpenCDA-ROS provides and handles cooperative localization in a reliable, realistic manner for testing and validating algorithms, bridging the gap between simulated environments and the real world.

C. Cooperative Object Detection and Tracking

Cooperative object detection [20], [27], [28], [29] and tracking [30], [31] play a crucial role in the OpenCDA-ROS platform. These capabilities bolster the reliability and performance of autonomous driving systems, thereby advancing the field of CDA. To this end, we have adapted and modified our learning-based cooperative multi-agent detection and segmentation framework, OpenCOOD [32]. With these adjustments, OpenCOOD has been seamlessly integrated as a plugin to OpenCDA-ROS, a newly minted component we've named OpenCOODX [33].

Through the inclusion of OpenCOODX, OpenCDA-ROS is furnished with powerful, shareable, and customizable cooperative detection algorithms. These are designed to further bolster its capability and versatility, ensuring that OpenCDA-ROS can meet a wide array of needs in the CDA field, thus helping to push the boundaries of autonomous driving.

By leveraging the cooperative detection results yielded by these processes, we can also facilitate better cooperative tracking from multiple agents. This approach significantly reduces the domain gap between simulation training models and real-world training models, thereby enhancing the reliability and performance of autonomous driving systems.

D. Cooperative Decision Making and Motion Planning

As an all-in-one simulation framework, OpenCDA is already structured with modularized strategic decision-making and low-level motion-planning components [34], which are vital aspects of autonomous driving, [35]. The integration of ROS into the OpenCDA platform makes OpenCDA-ROS a uniformly adaptable simulation platform for all ADS cooperative decision-making and motion-planning methods. Additionally, the inclusion of ROS effectively amplifies the efficacy of these modules by affording a dedicated channel for communication management. Unlike traditional simulation systems that are constrained by their own data format, the OpenCDA-ROS ensures a seamless and unhindered transfer of critical data among modules, thereby fostering an environment of dynamic adaptability and interoperability.

Locally, the application of ROS in the OpenCDA fundamental algorithms and functions significantly augments its adaptability and flexibility. ROS engenders an ecosystem conducive to effortless integration. This facilitates the rapid incorporation of both existing and nascent modules into the system, enabling swift adaptation to the continuously evolving demands inherent in the realm of autonomous driving. This capability extends beyond the mere addition of new modules, facilitating the refinement of established functionalities to enhance overall system efficiency and reactivity. Consequently, this fortifies the robustness of the OpenCDA platform, thereby rendering it more resilient in the face of the uncertainties characteristic of mutable traffic environments.

In terms of cooperative behaviors, ROS provides a uniform platform for information exchange. This platform stipulates the protocol for data transmission, enabling each participant to comprehend the exact content to be transmitted and the precise timing of these transmissions. This synchronization is paramount in the context of cooperative autonomous driving, where time-bound decision-making and planning can mean the difference between efficient cooperation and potential collisions among multiple ADS vehicles.

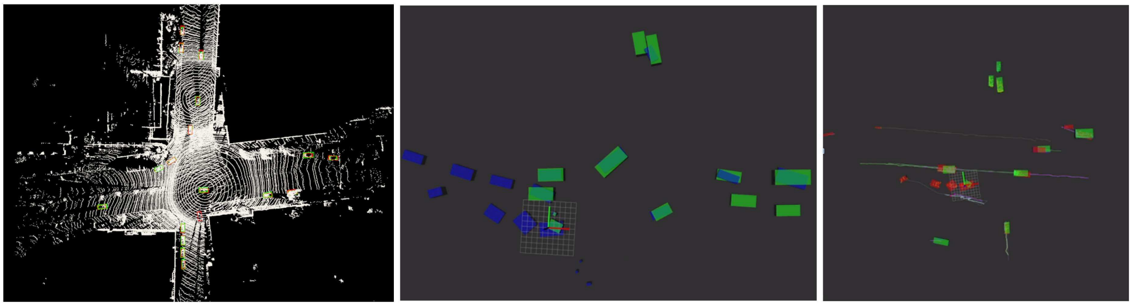
Lastly, a profound advantage of OpenCDA-ROS is the facilitation of multi-modal cooperation and communication. The OpenCDA-ROS system provides a communication bridge, enabling vehicle-to-vehicle, sensor-to-sensor, and vehicle-to-infrastructure interactions. This is particularly significant in today's evolving traffic environment, where multiple types of entities - from other vehicles to road infrastructure, to various sensors deployed in the environment - need to communicate seamlessly for effective and safe operations. By offering a common communication and cooperation platform, OpenCDA-ROS simplifies these interactions, promoting cooperation among diverse entities within the traffic ecosystem.

E. Smart Infrastructure Services

The OpenCDA-ROS system, harnessing the power of ROS and a modularized framework, is primed to offer a host of comprehensive infrastructure services. Example services include dynamically controlling signal timings based on live traffic patterns, conducting real-time edge computing for vehicles and other road users, offering assistance to vulnerable road users, and providing guidance on traffic rules and regulations as per the existing traffic conditions.

The true potency of the smart infrastructure services shines in its capacity to foster dynamic information sharing between different system modules and traffic ecosystem participants. This cooperative interplay allows for an integrated and harmonized orchestration between the diverse components of the system. Unlike conventional CAV systems that focus on the individual vehicle, OpenCDA-ROS creates a comprehensive cooperative driving scenario. Smart infrastructure services, as a holistic approach, considering not just the optimization of a single vehicle's trajectory or behavior, but rather, it is evaluating the entire traffic scenario, allowing for more strategic and globally optimal decisions.

The standout feature of OpenCDA-ROS is its capability to assimilate real-world information seamlessly into its operational paradigm. This is made possible through ROS, which creates a unified communication platform for all traffic ecosystem entities including sensors, roadside units, edge computing devices, and ADS vehicles. Hence, the system can foster an interconnected web of information exchange, ensuring an accurate reflection of the real-world driving scenario, which is a significant upgrade over conventional simulation platforms.



(a) Offline OpenCOOD detection (b) Online multi-agent clustering results (c) multi-agent tracking

Fig. 4. (a) This is the detection results generated from OpenCOOD framework. Green and red 3D bounding boxes represent the detection from ground truth and prediction, respectively. (b) Green and blue 3D bounding boxes represent the detection from agent1 and agent2, respectively. (c) Green and red 3D bounding boxes represent the detection from agent1 and agent2, respectively.

III. Use Case Study

A. V2X 3D LiDAR Detection and Tracking

Scope: In this case study, we aim to illustrate the application of OpenCDA-ROS in cooperative LiDAR detection research for both simulated and real-world cooperative driving. Our offline training framework, OpenCOOD [32], is deployed for the training, testing and evaluation of cooperative 3D LiDAR detection tasks across four datasets. These include two from the OpenCDA ecosystem - OPV2V [36] and V2XSet [37] - and two from our real-world data collection pipeline - V2V4real and V2X4SmartIntersection. The coalescence of these datasets bolsters the authenticity and complexity of the research process.

Implementation: For the implementation, we harness the benefits of both simulation data and real-world data to conduct mixed training within the OpenCOOD and OpenCOODX [33] framework. The advantage of simulation data lies in its capacity to generate an abundance of corner cases [29], thereby enhancing the diversity and unpredictability of our training scenarios. On the other hand, real-world data provide invaluable real point cloud data along with the unpredictability of urban terrain and unknown vulnerable road users.

Through mixed training, the cooperative LiDAR detection becomes more robust and generic, enabling it to handle complex urban scenarios effectively as shown in Fig. 4(a). Additionally, we deploy other detection modules like the 3D point cloud clustering algorithm for simpler freeway case scenarios. These modules have proven particularly effective for detecting larger vehicles like trucks, which aren't as common in urban scenarios but appear frequently on freeways. By leveraging the cooperative results, our cooperative tracking can have better tracking results from urban scenarios as well. All the cooperative detection and tracking results can be seen in Fig. 4.

The OpenCDA-ROS framework, therefore, offers diverse detection modules, allowing users to efficiently handle a wide range of tasks. This is made possible by combining the strengths of simulated and real-world data to create a robust, flexible, and highly accurate system for cooperative LiDAR detection.

B. Multi-Lane Cooperative Platooning

Scope: OpenCDA-ROS provides a fresh perspective on multi-lane cooperative platooning, confronting the complex task of coordinating multiple autonomous vehicles to enhance traffic flow and safety. The openCDA Autonomous Driving System (OpenCDA ADS) module is at the heart of this system, handling all computational and decision-making procedures. This module is marked by its dynamic nature, allowing potential replacement or modification of algorithms for a high degree of customization and flexibility. This ensures the openCDA system's capacity to evolve alongside advancements in autonomous driving technology, thus boosting its longevity and efficacy. Meanwhile, the experimental environment module encapsulates all environmental information derived from simulated or real-world sources. Its flexibility allows openCDA-ROS to meet a variety of experimental needs, contributing to a comprehensive and adaptable testing framework.

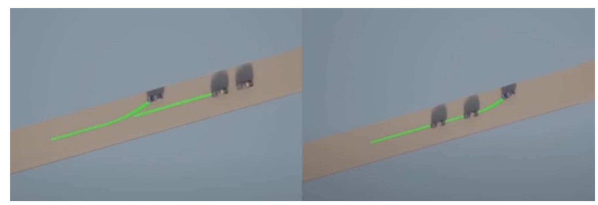


Fig. 5. (Left) Platoon joinint from back. A single CAV merging into the mainline to join the target two-vehicle platoon from the back. (Right) Platoon joining from front. A single CAV merging into the mainline to join the target two-vehicle platoon from the front.

'*Implementation:* The implementation of this system hinges on the seamless coordination between the OpenCDA ADS module, the OpenCDA ROS module, and the experimental environment module, Fig. 5 presents two multi-lane platoon joining examples. The OpenCDA ADS module provides a modular ADS suite to support the behavioral reasoning of the ADS vehicles. The OpenCDA ROS module plays a crucial role by directing data flow from the experimental environment and communication between various topics and nodes, ensuring the system functions flawlessly when these elements are properly aligned. ROS's ability to facilitate real-time data communication and processing significantly enhances the system's performance and reactivity. Furthermore, the integration facilitated by ROS accelerates the validation or prototyping process. The system's inherent modularity allows for the replacement of individual modules while keeping others intact, thus facilitating a variety of experimental requirements and fair comparisons. This structure, mimicking a software-in-the-loop testing approach, sets openCDA-ROS apart from other ADS platforms. Therefore, the implementation of ROS into OpenCDA results in a versatile, innovative tool for developing and testing autonomous driving systems, thereby narrowing the gap between simulations and real-world ADS workflows.

IV. Conclusion

In this letter, we conceptualize OpenCDA-ROS, a novel framework that builds on the strengths of the OpenCDA ecosystem and adapts its algorithms and perception frameworks for the Robot Operating System (ROS). This re-organization of modular cooperative functions into a more shareable structure benefits both simulation and real-world application prototyping and deployment, effectively reducing development time and streamlining the validation process.

Moving forward, our focus will be on expanding the capabilities of OpenCDA-ROS through the development of additional features in terms of cooperative mapping and digital twin, cooperative object detection and tracking, cooperative localization, cooperative decision-making and motion planning, and smart infrastructure services. We plan to transfer more use cases from the OpenCDA ecosystem, which are contributed by the community stakeholders, to OpenCDA-ROS, including but not limited to camera-based detection and tracking, prediction, and control.

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