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An Augmented Reality Environment for Connected and Automated Vehicle Testing and Evaluation*

Yiheng Feng[1], Chunhui Yu[2], Shaobing Xu[3], Henry X. Liu[4], and Huei Peng[5]

Abstract— **Testing and evaluation are critical steps in the development of connected and automated vehicle (CAV) technology. One limitation of closed CAV testing facilities is that they merely provide empty roadways, in which testing CAVs can only interact with a limited number of other CAVs and infrastructure. This paper presents an augmented reality environment for CAV testing and evaluation. A real-world testing facility and a simulation platform are combined together. Movements of testing CAVs in the real world are synchronized with simulation and information of background traffic is fed back to testing CAVs. Testing CAVs can interact with virtual background traffic as if in a realistic traffic environment. The proposed system mainly consists of three components: a simulation platform, testing CAVs, and a communication network. Testing scenarios that have safety concerns and/or require interactions with other vehicles can be performed. Two exemplary test scenarios are designed and implemented to demonstrate the capabilities of the system.**

I. INTRODUCTION

Connected and automated vehicles (CAVs) need to be tested extensively before they can be deployed and accepted by the general public. Currently, CAV testing and evaluation is mainly conducted by the following steps: simulation, closed testing facility, and public roads. Simulation is a cost effective way to test this new technology, but it is very difficult to model exact vehicle dynamics and driving behaviors in the simulation. Therefore, some studies developed hardware-in-the-loop (HIL) or vehicle-in-the-loop (VIL) simulation platforms which incorporated either part of a vehicle (e.g., a real engine with a virtual powertrain model) [1] or an entire vehicle [2] into simulation. To model real vehicle behaviors observed in the field, a parallel traffic system was proposed, which set up a mirror of the real world in virtual spaces [3][4]. The parallel system can be used to design different testing scenarios and evaluate how testing vehicles perform in these scenarios [5]. Companies such as Google has been demonstrating their self-driving cars[1] for a few years on public roads, although the debates of whether or not to allow testing CAVs running with general traffic never stop [6]. Safety has been an important issue since the technology is still at the development stage. A number of accidents have been reported regarding the self-driving functionality including a fatal accident happened in 2016 [7].

Closed testing facilities serve as the intermediate step between testing in simulation and on public roads. They not only improve efficiency but also provide a more controllable and safer environment. To encourage CAV testing in closed testing facilities, U.S. Department of Transportation (DOT) designated 10 pilot CAV testing facilities around the U.S[2] in 2016. The main disadvantage of a closed testing facility is that it merely provides empty roadways. Testing CAVs can only interact with a limited number of other testing vehicles and infrastructure (e.g., traffic signals). However, a complete testing environment should include background traffic as much as needed to interact with testing CAVs. Involving real background vehicles in a closed testing facility is not only costly but also difficult to coordinate and control. Without the interactions with real traffic, scenarios that can be designed are also limited.

To address the limitations, we propose an augmented reality testing environment. Background traffic is generated in microscopic simulation and provided to testing CAVs to augment the functionality of a test facility. The augmented reality environment combines a real-world testing facility and a simulation platform together. Movements of testing CAVs in the real world is synchronized with simulation and information of background traffic is fed back to testing CAVs. Testing CAVs can interact with virtual background traffic as if in a realistic traffic environment. As a result, test scenarios that require interactions with other vehicles or modes of travelers (e.g. pedestrians, cyclists, trains) can be performed. Compared to using real vehicles, simulated vehicles can be easily controlled and manipulated in generating different scenarios with much less cost and safety concerns. For instance, when the testing CAV fails in a safety related test and hit a simulated pedestrian, no one will get actual damage. Such tests can be repeated over and over again. The augmented reality environment can serve as a pre-step before involving real vehicles to ensure algorithms are thoroughly examined and parameters are fine tuned. The proposed system is extremely beneficial to testing and evaluating CAV technologies in a cost-effective fashion.

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[1]Yiheng Feng is with University of Michigan Transportation Research Institute, Ann Arbor, MI, 48109 USA (corresponding author; phone: 734-936-1052; e-mail: yhfeng@umich.edu).

[2]Chunhui Yu is with Key Laboratory of Road and Traffic Engineering of the Ministry of Education, Tongji University, Shanghai, P.R. China (e-mail: 13ych@tongji.edu.cn).

[3]Shaobing Xu and [5]Huei Peng are with Department of Mechanical Engineering, University of Michigan, Ann Arbor, MI, 48109 USA (e-mail: xushao@umich.edu and hpeng@umich.edu).

[4]Henry X. Liu is with Department of Civil and Environmental Engineering, University of Michigan and University of Michigan Transportation Research Institute, Ann Arbor, MI, 48109 USA (e-mail: henryliu@umich.edu).

[1]`https://www.google.com/selfdrivingcar/`

[2]`https://www.transportation.gov/briefing-room/dot1717`

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The rest of the paper is organized as follows. Section 2 first gives an overview of the system and then introduces each system component in detail. Section 3 first analyses the communication delay and then demonstrates two testing scenarios designed based on the system. Section 4 concludes the paper and discusses the potential implementations.

II. SYSTEM DESCRIPTION

The overall architecture of the augmented reality testing environment is shown in Fig. 1. The real world consists of testing CAVs, infrastructure equipment, and roadside processors (RSP). The infrastructure equipment includes roadside units (RSUs), traffic signal controllers and vehicle detectors. Testing CAVs broadcast vehicle information and communicate with RSUs through Dedicated Short Range Communication (DSRC). The RSP is responsible for receiving and processing data from the infrastructure equipment and sending processed information to the Simulation Platform and the Data Management Component. It also receives data from simulation platform and forwards to the Infrastructure Equipment. The same traffic network in terms of road geometries and traffic signals is built in the simulation platform as in the real world testing facility. Virtual CAVs are generated and updated in simulation based on the vehicle information received from the testing CAVs. Their behaviors are synchronized with real vehicles. Similarly, virtual traffic signals in the simulation are also synchronized with real world traffic signals. Background traffic in the simulation is broadcast by the Infrastructure Equipment (e.g., RSU) to the testing CAVs. The Data Management Component is responsible for collecting and managing testing data generated in both real world and simulation platform, so that performance measures can be evaluated. In the following subsections, three major components of the system, namely, the simulation platform, the testing CAV and the communication network, will be presented.

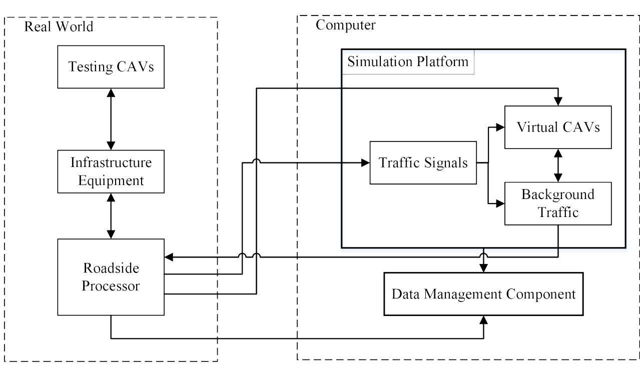


Fig. 1: Overall design of the augmented reality environment.

A. Simulation Platform

The framework of the simulation platform is shown in Fig. 2. It consists of two parts, namely, VISSIM simulator [8] and a simulation managing application. VISSIM provides various APIs as add-on modules to integrate VISSIM with user's own applications. SignalControl.DLL, DriverModel.DLL, and COM interfaces in VISSIM are used for interaction with the real-world environment and the simulation managing application. Traffic signals in VISSIM are synchronized with those in the real world by the SignalControl.DLL. Information from simulated traffic is encoded and sent out by the DriverModel.DLL. The simulation managing application receives information from testing CAVs and transforms GPS coordinates to local coordinates [9], which are used to update the locations of virtual CAVs in VISSIM via COM interface. Furthermore, the simulation managing application also builds testing scenarios via COM.

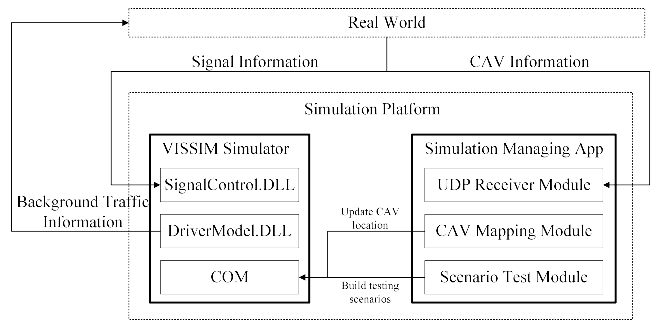


Fig. 2: Framework of the Simulation platform.

The work flow of the simulation platform is shown in Fig. 3. Each testing scenario is constructed as a VISSIM project. Different testing scenarios may include different CAV routes, background vehicle inputs, and signal timings. Before running the simulation, the simulation platform needs to load one scenario through the COM interface. After initialization, it begins to receive testing CAV and traffic signal information from the real world. Upon receiving the first message from the testing CAV, the simulation platform creates a virtual CAV in the VISSIM network at the same location as it is in the testing facility and updates its position each time a new message is received. A trigger based interaction mechanism is implemented. The update of the virtual CAV location may trigger a testing event in VISSIM. For example, generate a virtual vehicle at a certain speed or force off the current signal phase. The advantage of using a trigger based mechanism is that it guarantees the testing can be repeated under exactly the same condition. Similar to virtual CAVs, virtual signals are updated when new signal status messages are received. VISSIM then executes a simulation step to update and broadcast the information of background traffic.

B. Testing CAV

A Lincoln MKZ Hybrid is used as the testing vehicle in the proposed augmented reality environment. The Lincoln MKZ is fully connected and automated and equipped with various sensors. The sensors include a 16 channel Velodyne LiDAR on the roof, a Ibeo fusion system (two four-layer LUX LiDAR modules in the front, and one in the rear), a long range RADAR in the front, four short range RADARs at the corners, Mobileye, Pointgrey camera, and a high-precision (about 2 cm) GPS module, called Real Time Kinematic (RTK) 3003 from Oxford Technical Solutions. An

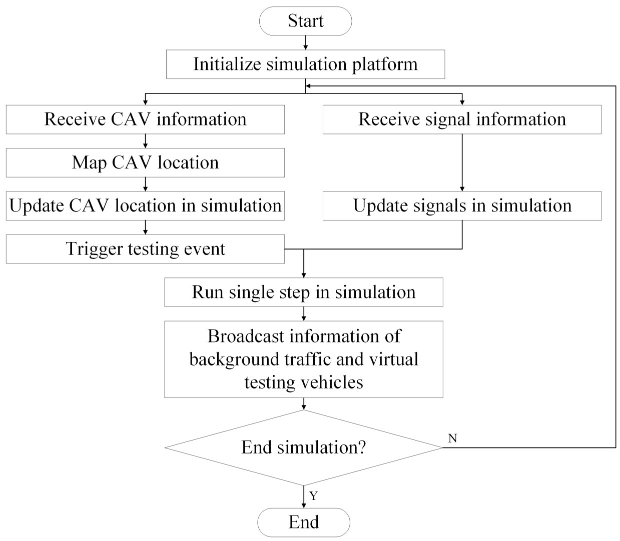


Fig. 3: Workflow of the simulation platform.

Inertial Measurement Unit (IMU) is also embedded. These sensors enable accurate positioning and 360-degree obstacle perception. By-wire control allows us to command the steering wheel, throttle, brake, and transmission by software. An onboard Unit (OBU) from Cohda Wireless is installed as the DSRC communication device to transmit messages from/to the simulation environment. The OBU mainly has three tasks. First, it receives Signal Phase and Timing (SPaT) messages, which are broadcast by the RSU located at the intersections in the testing facility. Second, it receives Basic Safety Messages (BSMs) from both real vehicles (e.g., other testing vehicles) and simulated vehicles. Finally, it broadcasts BSMs of the testing vehicle to the RSUs.

With the received SPaT and BSM data, the CAV can interact with real traffic signals and simulated vehicles automatically. The underlying path planning, vehicle speed control, and steering control are developed by the Open-CAV project from the University of Michigan[3]. Different algorithms are developed to perform basic capabilities such as speed planning/control, path planning/following, and obstacle avoidance. For example, when following a simulated vehicle, the behavior of the CAV follows the Gipps car-following model [10].

C. Communication Network

The communication network transmits data between the simulation platform and testing CAVs. The information flow is shown in Fig. 4. The Signal Controller at each intersection broadcasts signal data including current status and remaining time of each phase to the RSP located in the signal cabinet, where SAE J2735 SPaT messages are generated. The SPaT messages are forwarded to both RSU at the same intersection and the Master RSP. The RSU broadcasts SPaT messages to testing CAVs and receives BSMs from testing CAVs through DSRC. The received BSMs are forwarded to the Master RSP. Both SPaT and BSM are sent to the Simulation Platform to update virtual signals and virtual CAVs in the simulation. Both BSM and SPaT are broadcast at a frequency of 10Hz.

Simulated vehicles in VISSIM generate simulated BSMs (sBSM) through the DriverModel.DLL API and send to the Master RSP. Based on the vehicle ID, the Master RSP distributes the sBSMs to different RSUs to balance the communication load. sBSMs are broadcast from all RSUs to testing CAVs.

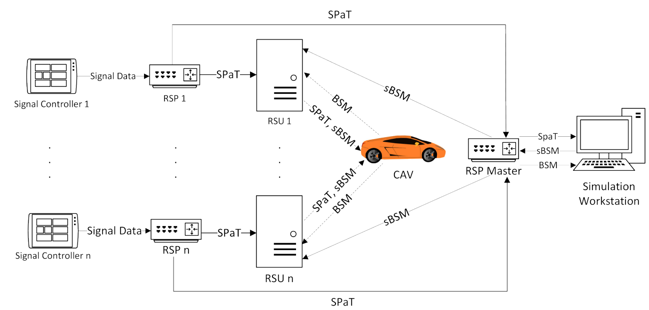


Fig. 4: Communication network and data flow.

III. SYSTEM IMPLEMENTATION

The augmented reality testing environment is implemented at Mcity, a newly established closed CAV testing facility at the University of Michigan. To setup the simulation platform, Mcity traffic network is built and calibrated in VISSIM through a high resolution map. One critical question for implementing the system is the communication quality between simulated environment and the real world. This section will first give a brief introduction to Mcity. Then a communication test is conducted and the results are presented. Finally, two exemplary testing scenarios are designed and demonstrated.

A. Mcity Introduction

Mcity is a small scale high-fidelity simulated urban environment for CAV testing[4]. Occupying 32 acres at the University of Michigans North Campus Research Complex, Mcity includes approximately five lane miles of roadways with different attributes such as a highway segment, multi-lane arterial roads, intersections, and traffic signals. Mcity is the world's first full-scale simulated city designed solely for testing the performance of CAVs.

Mcity has eight signalized intersections including six low-speed intersections in the downtown area, one high-speed intersection at the highway segment, and one intersection near the entrance. Four RSUs are installed at four downtown intersections. The RSUs radio ranges cover the entire testing facility.

[3] https://mcity.umich.edu/news-events/media-resources/

[4] https://mcity.umich.edu

B. Communication Test

A communication test is conducted to ensure that the system can meet real-time performance requirement. Since the communication delay is at millisecond level, it is very difficult to synchronize the clocks between the simulation environment (e.g., a computer) and testing CAVs. To address the problem, we apply an alternative way to test the delay. When a simulated BSM is generated in VISSIM, the first timestamp is created. The sBSM is sent to the master RSP (Fig. 4) and broadcast through RSU1. RSU2 receives the sBSM and then sends back to the master RSP. Finally, the master RSP forwards the BSM back to the computer that runs VISSIM and the second time stamp is created. In this test configuration, RSU2 is considered as the OBU in a testing CAV, which receives BSMs and forwards to the vehicle control system. The delay is calculated as the time difference between the two timestamps. This implementation guarantees that the system time to create timestamps comes from the same source, so that the delay calculation can be accurate.

The test is conducted under 5 different cases with numbers of simulated vehicles from 1 to 100. Each case is performed for a period of 300s in real time. Fig. 5 shows the delay histograms under different numbers of vehicles and corresponding package loss rates. The average delay is about 31 ms with 1 vehicle and 102 ms with 100 vehicles. Both the average delay and package loss rate increase with the number of vehicles. The percentage of delay that below 100ms under each case is calculated. The percentages are 99.71%, 99.16%, 95.81%, 91.52%, and 73.66% for vehicle number 1, 10, 20, 50, and 100 respectively. Note that 100 ms is the shortest transmission interval between DSRC messages according to the SAE standard. If a message can be received and processed before the sending time of next message, the delay can be considered as sufficiently short. The test results show that, except for the 100 vehicles case, more than 90% of packages can be transmitted and processed within this interval. Although about 30% of packages in 100 vehicles case have delays more than 100 ms, testing scenarios that require 100 vehicles are also very rare.

C. Testing Scenarios

In this section, two testing scenarios are presented, namely, railway crossing and red light running.

1) Railway Crossing: In the railway crossing scenario, a simulated train is generated in VISSIM when the testing CAV is approaching the rail crossing located in Mcity. The testing CAV should stop before the rail-crossing and wait for the train. Fig. 6 shows the views from both simulation and the testing CAV. The simulation network of Mcity is presented in the left part of the figure. A blue train is generated and traveling on the track. Several vehicles are waiting behind the rail-crossing including the testing CAV (the red vehicle in the circle). The upper right part of the figure shows the view from the testing CAVs windshield as well as from inside of the vehicle. It can be seen that the testing CAV stopped at the corner, although there is no real vehicle in front of it. Three virtual vehicles in the simulation block the way of the testing CAV. The lower right part of the figure shows the view from the testing CAVs control system. The big (red) rectangle is the testing CAV and all smaller rectangles represent simulated vehicles. The small (red) rectangle in front of the testing CAV indicates that this is a potentially conflicting vehicle.

2) Red Light Running: Red-light running is a dangerous driving behavior and accounts for about 26.5% of total signalized intersection fatalities in 2014[5]. The purpose of this scenario is to evaluate how a testing CAV reacts to a red-light running vehicle and avoids collision under different situations.

The scenario design is shown in Fig. 7. The intersection at Wolverine Ave. and Main St. in the downtown area of Mcity is chosen to be the testing intersection. The testing CAV travels westbound on Main St. and tries to make a left turn. A simulated vehicle is generated in simulation at Wolverine Ave. and travels northbound, when the testing CAV is close to the intersection. The signal status indicates that the testing CAV has the right of way. The signal timing of the intersection is adjusted so that the testing CAV meets green light every time when it approaches the intersection.

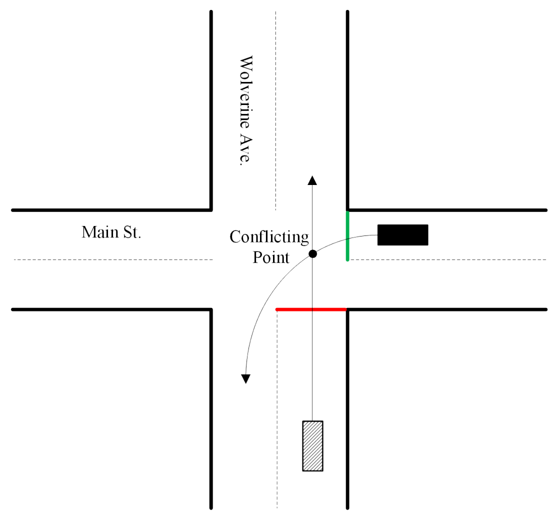
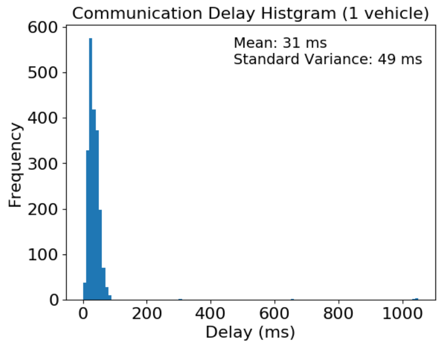


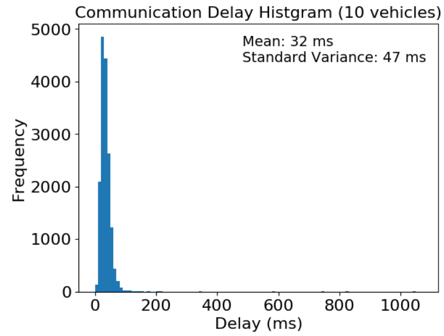
Fig. 7: Red light running test scenario design.

Fig. 8 illustrates how the testing CAV responds to the red light running vehicle in two situations. The horizontal axis represents time steps (0.1 s per time step), and the vertical axis represents the distance to the conflicting point of each vehicle. The trajectory of the virtual red light running vehicle is presented in the red dotted curve. It travels at a constant speed. The trajectory of the testing CAV is presented in three different formats. The dark blue curve uses the testing CAVs coordinates in VISSIM simulator. The light blue curve uses the testing CAVs coordinates from the OBU GPS. The black curve uses the testing CAVs coordinates from the RTK GPS installed in the vehicle. Currently, the OBU GPS is used to generate and send BSMs to simulation. Due to the high

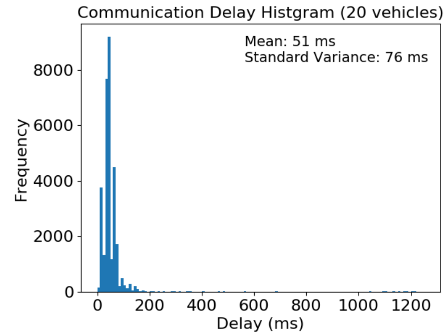
[5]https://safety.fhwa.dot.gov/intersection/conventional/signalized/rlr/#technical



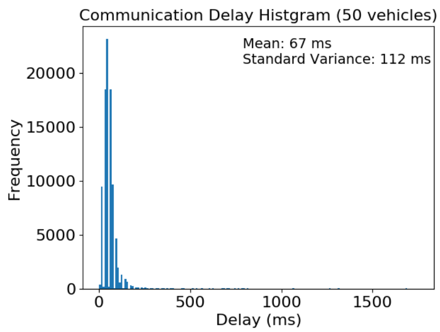
(a) 1 vehicle



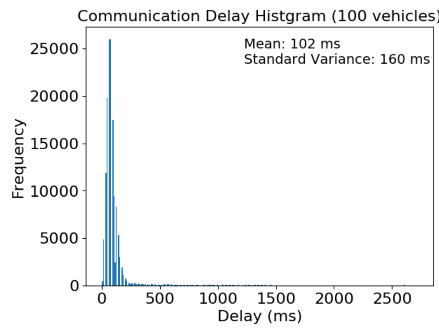
(b) 10 vehicle



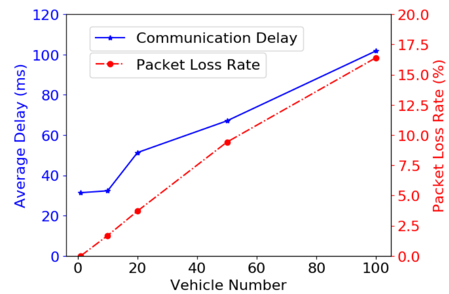
(c) 20 vehicle



(d) 50 vehicle



(e) 100 vehicle



(f) average delay and package loss rate

Fig. 5: Communication delay and package loss rate with different numbers of virtual vehicles.

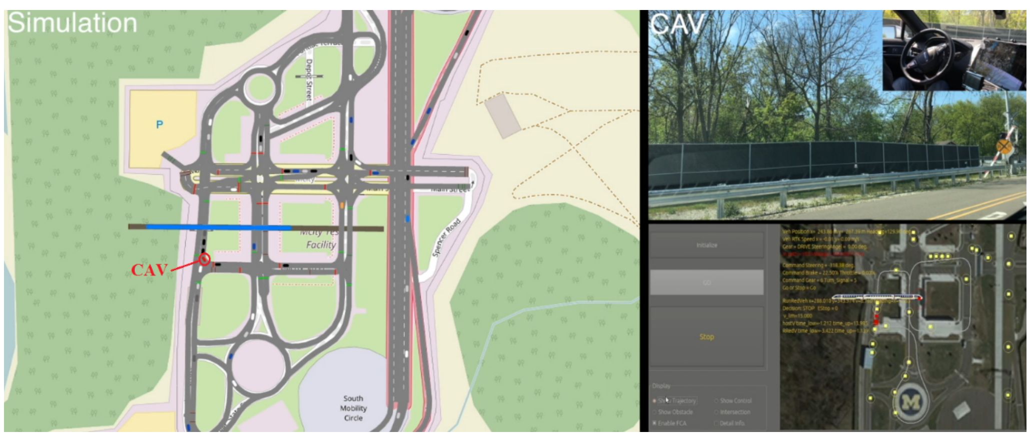
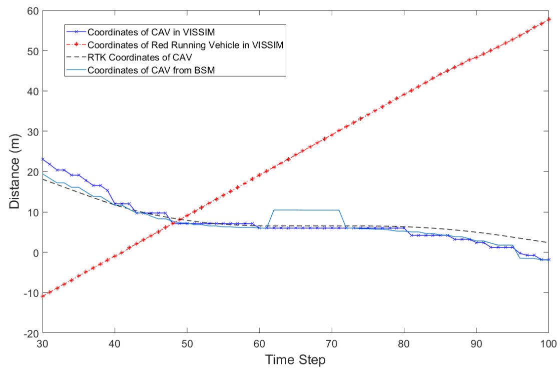


Fig. 6: Railway crossing testing scenario.

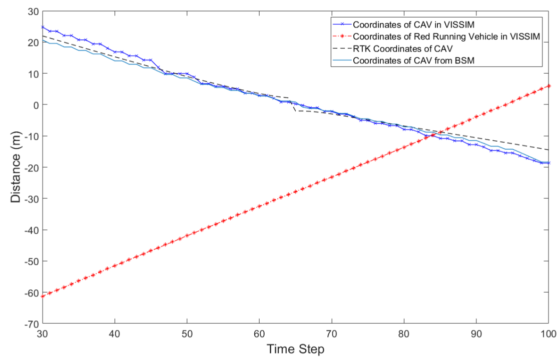
accuracy of the RTK GPS (2 cm accuracy), coordinates from the RTK GPS are considered as the ground truth. Therefore, the difference between the black curve and the light blue curve represents the GPS error. The difference between the light blue curve and the dark blue curve represents two types of errors from simulation. The first type comes from the vehicle mapping algorithm. The second type represents the deviations of the VISSIM road network from the real world road network.

The testing CAV calculates the time gap of the arrival times at the conflicting point between itself and the red light running vehicle. A three seconds threshold is used to determine whether a potential collision may happen. Fig. 8a shows the situation that the testing CAV detects a potential collision and made a full stop. Fig. 8b shows the situation that the two vehicles are far away so that the CAV does not stop.

In Fig. 8a during the deceleration period (time step 30-50), the deviation between RTK GPS and OBU GPS remains small, but the deviation between OBU GPS and VISSIM coordinates are large. It is mainly due to the inconsistency between the actually Mcity roadway and the Google Earth map. When the testing CAV is stopped (time step 50-80), the three trajectories match well except that the OBU GPS is drifted for about 1 s. The same phenomenon is observed in all of our tests. However, the vehicle mapping algorithm is designed to be insensitive to the fluctuations so that the virtual CAV does not move in the simulation because of



(a) with potential collision.



(b) without potential collision.

Fig. 8: Vehicle trajectories under different situations.

GPS coordinate fluctuations. When the testing CAV begins to accelerate, the VISSIM coordinates and the OBU GPS match well but have a larger deviation from the RTK GPS. The non-stopping situation Fig. 8b shows the similar pattern except that the OBU GPS does not have obvious fluctuations.

IV. CONCLUSION AND DISCUSSION

This paper presents an augmented reality environment for CAV testing, which greatly enhances the capabilities of closed testing facilities. In the proposed system, movements of testing CAVs and status of traffic signals in the real world are synchronized with a simulation platform in real time. Information of background traffic in the simulation platform is fed back to testing CAVs through wireless communications. The augmented reality environment provides a realistic traffic environment to testing CAVs for the purpose that testing scenarios that require interactions with other vehicles or modes of travelers (e.g. pedestrians) can be performed. Two testing scenarios, railway crossing and red light running, are designed to demonstrate the capabilities of the system.

The proposed testing environment merely serves as a platform for CAV testing and evaluation. Based on the platform, numerous testing scenarios can be implemented. However, it is impossible to enumerate all scenarios that a vehicle may encounter on the roadway. How to design testing scenarios efficiently and comprehensively to cover various traffic conditions becomes a critical question. It is important that CAVs should be evaluated thoroughly before they can be sold to the general public. A recent study proposed an accelerated evaluation approach for CAVs testing with some simple scenarios such as car following and lane changing [11][12]. Compared to widely used Naturalistic-Field Operational Test (N-FOT), the new approach can accelerate the evaluation process by 2,000 to 20,000 times. However, this study is done in a pure simulation environment and the testing scenarios considered are limited. It is interesting to integrate the augmented reality testing environment with the accelerated evaluation approach. The augmented reality environment can be used to generate different scenarios with the involvement of real CAVs, while the accelerated evaluation approach can speed up the testing process.

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