

ENGAGING HUMAN-IN-THE-LOOP FOR AUTONOMOUS VEHICLE SIMULATION

John di Battista

Christian Johnston

Valerie Randall

Jackson Shanahan

Department of Computational Modeling and Simulation Engineering

Old Dominion University

4700 Elkhorn Ave, Norfolk, VA 23529, USA

jdiba001@odu.edu, cjohn083@odu.edu,

vrand002@odu.edu, jshan001@odu.edu

ABSTRACT

Many autonomous vehicles are still in the development phase due to limited research and testing and will take a considerable amount of time to further develop before they are ready for public release. The main objective of this study is to introduce a human-in-the-loop simulation framework for supporting autonomous vehicle research. Our proposed simulation framework aims to facilitate AV assessment by providing a safer and more efficient way. Functionally, it is focused on the understanding of AVs' operations in the presence of pedestrian users. The developed simulation framework allows a human pedestrian avatar to be integrated into the high-fidelity 3D virtual environment and interact with simulated autonomous vehicles via standard keyboard input methods or virtual reality (VR) methods. This enables safer pedestrian-AV integration research and testing, and the ability to implement a series of risky edge-case scenarios in less time and cost than would be feasible in a real-world setting.

Keywords: Human-in-the-loop; 3D Map Modeling; Simulation; Autonomous Vehicle; Pedestrians; Virtual Reality

1 INTRODUCTION

1.1 Project Overview

The majority of research on autonomous vehicles to date has been primarily focused on the development of collision avoidance algorithms based on pedestrian behavior [1] and vehicle recognition or detection systems [2, 3]. These existing studies are invaluable and offer important references for planning and controlling AVs. However, there is an urgent need for safer, higher fidelity models and increased quality of testing procedures used in AV research. The present project fills that gap by developing a human-interactive AV simulation modeled after the Old Dominion University (ODU) campus. This simulation is also considered a high-fidelity model as it includes intersections, traffic lights, street signs, crosswalks, sidewalks, and major landmarks of the campus, all textured and modeled to scale. While the user can interact with the simulation via conventional keyboard input methods, the simulation also has the capability to incorporate a VR headset if desired, which further increases the fidelity and overall experience for the user. This simulation will be used specifically for future experimentation and research on autonomous vehicles and their interactions with pedestrians.

1.2 Related Works

Pedestrian-based AV simulation research is limited. However, some recent literature researched AV reliability in agent-based simulations [4]. With respect to pedestrian and AV interactions within a simulated environment, Praticò *et al.* (2021) discussed their work in comparing various augmented reality interfaces and assessing the AV-to-pedestrian communication within them by developing a VR simulation and conducting a user study [5]. Nacu *et al.* (2018) has also conducted work with autonomous vehicles, specifically with electric vehicles and their AI systems, using MATLAB's Simulink to run the environment [6]. Their aim during these tests was to evaluate the vehicles' energy management rather than the interaction between the vehicles and pedestrians. Much like our team's work, students at Tallinn University of Technology (TalTech), Estonia [7], discuss the simulation of an AV shuttle they created that incorporates a virtual environment with certain fidelity constraints. The main factor that sets our team apart is that our project focuses on developing a pedestrian test module within a realistic virtual environment that will allow for safer and more efficient analysis and testing.

2 METHODOLOGY

2.1 Research Objectives

The following are objectives that our simulation fulfills to provide an efficient and effective testing environment for autonomous vehicle research: develop a high-fidelity virtual environment, allow a human user to sense and interact with an autonomous vehicle and vice versa within a driving simulator, and enable the user to interact with the simulation via virtual reality methods. Emphasis is placed on the interaction of the human-pedestrian and the autonomous vehicles within the simulation.

2.1.1 The Development of High-Fidelity Virtual Environment

The developed 3D map environment visualizes the roads along the perimeter of the Old Dominion University campus. This road network is comprised of Hampton Blvd, 43rd St, Powhatan Ave, 49th St, Elkhorn Ave, and surrounding side streets in Norfolk, Virginia, USA. The major landmarks of the campus are modeled to scale and textured to match their real-life counterparts. These landmarks include the Chartway Arena, the Darden Education Building, the Barry Art Museum, the Chemistry Building, the Engineering and Computational Sciences Building, the Oceanography Building, the Norfolk Fire Department Station 7, the townhouses along 43rd St, and the campus's parking garages. Detailing to increase fidelity was also added, including but not limited to trees, signs, fences, and road markings. Figure 1 shows a snapshot of Hampton Blvd within the virtual environment taken during the map's development.



Figure 1. Hampton Blvd-43rd St Intersection within the Developed Virtual Environment.

2.1.2 Enabling Human Users and AV Recognition

Programming for autonomous vehicles and a human test module were implemented to allow a pedestrian to be integrated into the virtual environment so that they can interact with the autonomous vehicles and vice versa. The sensors of the simulated vehicle recognize traffic lights, stop signs, and human pedestrians and respond appropriately to each stimulus. The human user can also sense and interact with its surroundings and simulated vehicles.

2.1.3 Virtual Reality Interaction

To increase fidelity even further, a virtual reality component was added so that the user can visualize and interact with the simulated environment through a VR headset. This headset allows the user to view the environment and walk around using motion tracking capabilities. The headset can track the user's head and body movement as they walk around or look around in the real world and relay it to the simulation in real-time.

3 SIMULATION FRAMEWORK DESIGN AND DEVELOPMENT

Our simulation framework can be broken down into three major components: the 3D map, the AV simulation, and the virtual reality component. Each component was developed using different open-source software that required successful integration before moving on to the next step. Figure 2 shows an overview of the simulation framework design. First, the 3D map environment was created using MATLAB RoadRunner [8] and Geographical Information System (GIS) data [9] to lay the road networks. To further increase the fidelity of the map, 3D models of major campus landmarks were developed and textured using Blender [10] and imported into RoadRunner. From there, the 3D map was imported into CARLA [11] and further refined. Next, the simulated autonomous vehicle and human avatar were added to the simulation. Finally, virtual reality capabilities were added using the Unreal Engine (UE4) [12] and Oculus Quest 2 [13].

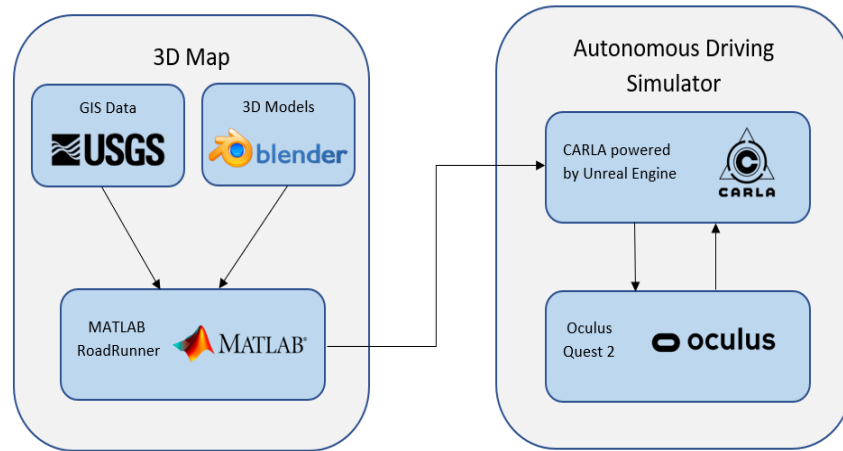


Figure 2. Autonomous Vehicle-Pedestrian Interaction Simulation Design Framework.

3.1 3D Map Development

The 3D map and traffic environment were created using MATLAB RoadRunner. This software allows the developer to design three-dimensional traffic scenes by including built-in assets such as road networks, road signs, road markings, trees, sidewalks, and more. It also has capabilities to simulate automated driving systems by outlining traffic patterns and road network logic for autonomous driving simulators to use in the future.

3.1.1 GIS Data

To ensure that our map's road networks, elevation mapping, and landmark locations were as true to life as possible, our team imported GIS data from the U.S. Geological Survey (USGS) into RoadRunner to serve as a baseline for where the roads and developed 3D models should be placed. USGS offers point cloud data, aerial imaging, and elevation maps of different areas of the US. The point cloud data and elevation mapping of Norfolk, VA were overlaid on the map and acted as a template for us to match the roads and models accordingly. Figure 3 shows a snapshot of the point cloud data overlaid on top of the map developed in RoadRunner.

This allowed us to confidently model the roads and buildings of Old Dominion University with a higher degree of accuracy. Traffic rules and desired lane behavior were also defined within RoadRunner to be used later for AV simulation purposes.



Figure 3. Point Cloud Data from USGS overlaid on RoadRunner Map.

3.1.2 3D Modeling

The 3D models of campus landmarks were developed in Blender and later imported into RoadRunner once fully developed and textured. The modeling began with an initial physical assessment of each building which included taking photographs and approximating real-world measurements using a laser range finder. Then, a reference structure was created in Blender using photogrammetry and google earth images. An example of one of the developed reference structures can be seen in Figure 4. From there, finer detail geometry was modeled around the reference structure and textured to match the photographs taken previously. The completed model was then exported as an .fbx file to be imported into RoadRunner.

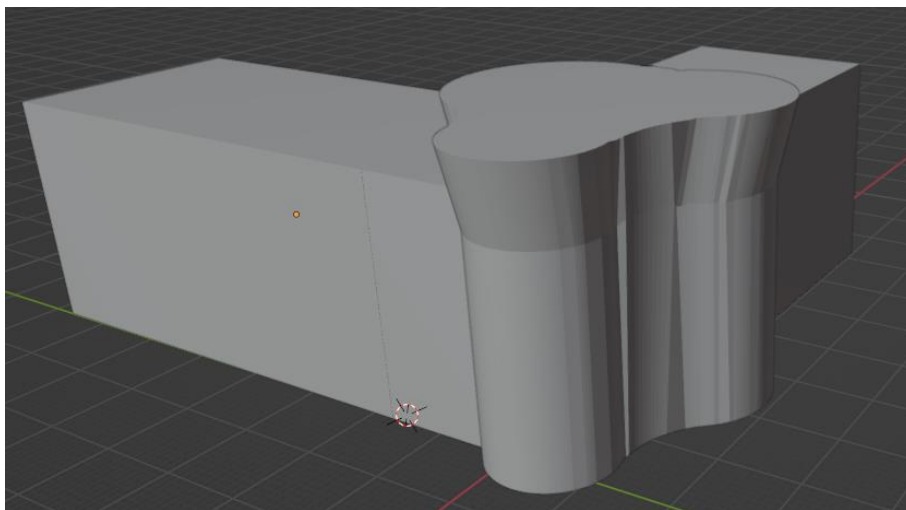


Figure 4. Reference Structure of Darden Education Building Developed in Blender.

3.1.3 Modeling Traffic and Roadway Components

Once the road networks were laid out using the GIS data and the surrounding buildings were modeled, imported, and placed in their respective locations, traffic and roadway components were then programmed to be used later for the driving simulator. These traffic and roadway components were implemented using OpenDRIVE, a functionality of RoadRunner that describes a road network's logic. This road network logic is exported as an .xodr file with the finalized map and defines traffic rules for the autonomous vehicles within the simulation to follow.

3.2 AV Simulation Development

The AV simulation was developed using CARLA powered by the Unreal Engine. After developing the 3D map and traffic environment using MATLAB RoadRunner, the .fbx file containing the map and the .xodr file containing the road logic were both imported into CARLA. Once the map was imported and normalized, functionality for the autonomous vehicle and human interaction components were added.

3.2.1 Autonomous Vehicles

CARLA has built-in functionalities to program autonomous vehicles. We utilized this built-in functionality and implemented multiple spawn points for AVs to be generated throughout the road network to simulate high traffic flow areas. These autonomous vehicles followed the traffic patterns that were programmed previously in MATLAB RoadRunner. We were also able to access CARLA's manual driving control script using a python terminal. This script allowed the user to take over the vehicle's movement using the W-A-S-D keys or arrow keys rather than having the vehicle follow the programmed traffic patterns. The user can toggle between autonomous and manual control as they see fit.

3.2.2 Human Avatar

Once the autonomous vehicles were implemented and responding appropriately, our team edited CARLA's base script for the AV's manual control to implement the pedestrian. At this point of development, the user can move the human avatar to interact with the AVs and surrounding environment by using either the arrow keys or W-A-S-D keys as conventional input methods of movement. The avatar also has the ability to run by pressing and holding the shift key or jump by pressing down the spacebar.

3.3 Virtual Reality Development

Virtual reality capabilities were programmed to increase the simulation immersion and allow the human avatar to interact with the virtual environment and simulated vehicles using the Oculus Quest 2. A custom VR pawn, which is comprised of the avatar, viewport, controls, and input functions, is imported into the editor with the motion capture and controller inputs configured. Once the VR pawn is imported, the program can be compiled, launched, and streamed to the headset. The user can move their avatar within the simulation by utilizing the motion tracking capability of the headset to pan the camera when they look in a specific direction and move when they walk around in the real world.

4 TESTING AND VALIDATION

The success of this simulation was assessed in the following categories: autonomous vehicle capabilities, human avatar capabilities, virtual reality capabilities, and the validity/fidelity of the overall simulation. Since fidelity is subjective, we determined that comparing the models of major landmarks around the campus to their real-world counterparts would be the best course of action to validate their fidelity.

4.1 AV Incorporation

When testing the capabilities of the autonomous vehicle, we were mainly interested in the ability of the AV to respond to the programmed driving paths as well as to the traffic lights and signs at each intersection. To assess this, the following test cases were implemented.

4.1.1 Driving Path Response

Testing the ability of the AVs to respond to the driving paths was reasonably straightforward. In this case, we ran the simulation and assessed whether the cars drove within the simulation according to the road network logic. The vehicles responded appropriately to the programmed logic, so this test was considered a success.

4.1.2 Traffic Light Intersections

Traffic lights were modeled and programmed at the intersections along Hampton Blvd. These intersections consist of 43rd St, W 45th St, W 47th St, and W 49th St. To test the AVs' response to the traffic lights, we toggled the timing of the lights to see if the vehicle reacted appropriately despite the length of the interval between light changes. The vehicle should drive at the green light, slow down at the yellow light, and stop at the red light. The vehicles responded appropriately to the various light signals, so this test was considered a success.

4.1.3 Stop Sign Intersections

Stop signs were also modeled at various intersections along the road network. These intersections include Elkhorn Ave and 43rd St as well as Powhatan Ave and 43rd St. At the time of writing this paper, the stop signs are still being programmed, so testing has not yet been conducted. However, our plan to test the AVs' response to the stop signs is to run the simulation and assess if the AV stops at each stop sign.

4.1.4 AV Response to Stimulus

To test the AVs' response to stimulus, four different tests were conducted at the intersection of Hampton Blvd and 43rd St to see if the vehicle responded appropriately in each case. In every case where an autonomous vehicle senses a pedestrian or another AV, it should stop to avoid a collision. Figure 5 depicts the four different test case scenarios. In Figure 5(a), a pedestrian is in the middle of the crosswalk when the AVs are given the green light. This causes the AV in the lane they're blocking to stop, but the other lanes continue because the pedestrian is not blocking their paths.

Figure 5(b) shows a pedestrian standing in the middle of the intersection when the AVs are given the green light. The first AV senses the pedestrian and stops, while the other AVs sense that an AV in front of it has stopped and also stop to avoid a collision. In Figure 5(c), a pedestrian is standing in the path of a vehicle that stops to avoid hitting them. Shortly after, two other vehicles are given the green light, and they also stop in front of the pedestrian, surrounding it with three vehicles. In Figure 5(d), you can see a pedestrian blocking a single lane while the other lane next to it can still continue through the light because the pedestrian is not blocking their path. The AVs responded appropriately in all four test cases, so they were all considered a success.



(a) Test Case 1



(b) Test Case 2



(c) Test Case 3



(d) Test Case 4

Figure 5. Response to Human Stimulus Test Cases.

4.2 Human Avatar Incorporation

When testing the capabilities of the human avatar, we were mainly interested in the ability of the avatar to respond to the AV and the inputs of the keyboard. To assess this, the following test cases were implemented.

4.2.1 Avatar Response to Movement Input

In this test case, we assessed if the avatar moved in the appropriate direction when pressing each key. The avatar should move forward when pressing the up key or W key. When pressing the left key or A key, the avatar should rotate to the left.

The avatar should rotate to the right when pressing the right key or D key. The avatar should run when pressing the shift key, and the avatar should jump when pressing the spacebar. The avatar responded appropriately to all keyed inputs, so this test was considered a success.

4.2.2 Avatar Response to AV Stimulus

In this test case, we assessed whether the human avatar recognized and responded appropriately when interacting with an autonomous vehicle. A new avatar must be spawned into the simulation when the pedestrian touches the AV or vice versa. The avatar responded appropriately, so this test was considered a success. It should be noted that this functionality could potentially be considered a bug rather than a feature in some cases. For example, when the human avatar touches a vehicle, no matter the vehicle's speed, the avatar "dies" and must be re-spawned to continue in the simulation.

4.3 Virtual Reality Capabilities

When testing the capabilities of the virtual reality headset, we were mainly interested in the hardware components displaying the simulation appropriately, as well as the avatar controls responding correctly to the inputs of either the headset or the joystick controller. To assess this, the following test cases were implemented.

4.3.1 Hardware Integration

When testing the hardware, we assessed the ability of the headset to display the simulation appropriately. In other words, does the display of the user wearing the headset match what is seen on the monitor when the simulation is running? To test this, we connected the headset and ran the simulation. The display was identical on both the headset and the monitor, so this test was considered a success.

4.3.2 VR Avatar Controls

To test the visual capabilities of the VR headset, we assessed the ability of a user to look around and move around using the headset. The main question we are answering here is, does the VR headset appropriately track the user's head and body movement and translate it to the simulation? To test this, we ran the simulation with a human user operating the headset while vehicles were navigating through the road network. The user can freely look around and roam the map under the assumption that they are in an open area indoors, so this test was considered a success.

4.4 Fidelity

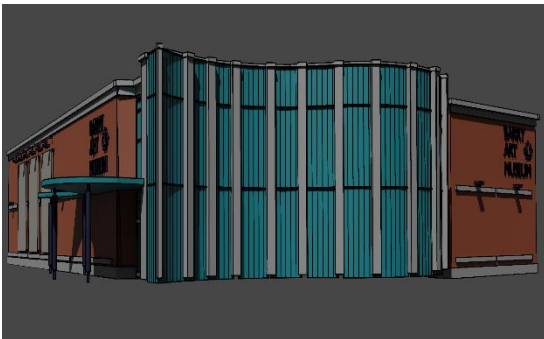
Once each simulation component was tested, the simulation's fidelity was then assessed by comparing the virtual models of major campus landmarks to their real-world counterparts. Figure 6 shows side-by-side comparisons of the Darden Education Building, the Barry Arts Museum, the New Chemistry Building, and a bird's eye view of 43rd St. In each of the figures, you can see the strong resemblance between the virtual and real-world buildings or streets. The main pieces to point out are the unique architecture and lettering on each building and the placement of houses, trees, fencing, and more along 43rd St.



(a) Virtual Darden Education Building



(b) Real World Darden Education Building



(c) Virtual Barry Arts Museum



(d) Real World Barry Arts Museum



(e) Virtual Chemistry Building



(f) Real World Chemistry Building



(g) Virtual 43rd St View



(h) Real World 43rd St View

Figure 6. Virtual Models and Real-World Comparisons.

5 CONCLUSION

Our team identified a need in the AV research field for a method to more safely and efficiently test the interactions between human pedestrians and autonomous vehicles. To provide support for these studies, we developed a high-fidelity simulation framework modeled after Old Dominion University's campus. Our simulation framework allows users to insert a pedestrian avatar into the simulation environment to interact with the autonomous vehicle and vice versa via a virtual reality headset for experiencing the simulation. As the simulation framework is under the final assessment stage, we expect more updates will be available shortly. This project was focused on a single pedestrian user and therefore can be further extended for multi-user engagement in future work. This will enable more pedestrian-AV research that involves multiple pedestrians.

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7 AUTHOR BIOGRAPHIES

JOHN DI BATTISTA is a senior at Old Dominion University. He is a Modeling and Simulation Engineering major with a minor in Computer Science. He has built expertise in several 3D modeling and physics simulation software alongside the Modeling and Simulation curriculum programs. Upon graduating, John will be working full-time as a test analyst for Aermor. jdiba001@odu.edu.

CHRISTIAN JOHNSTON is a senior in Old Dominion University's Computational Modeling and Simulation Engineering program. While studying at ODU, Christian is working part-time as an intern at Gryphon Technologies assisting the Model-Based Systems Engineering department. Upon graduation, Christian will be working full-time with ManTech, who absorbed Gryphon Technologies in 2021. cjohn083@odu.edu.

VALERIE RANDALL is a senior in Old Dominion University's Computational Modeling and Simulation Engineering program. While studying at ODU, she works part-time as a modeling and simulation engineering intern with SAIC supporting the Department of Homeland Security. Upon graduation, she will continue her work with SAIC full-time. vrand002@odu.edu.

JACKSON SHANAHAN is a senior in Old Dominion University's Computational Modeling and Simulation Engineering program. Jackson is currently enlisted in the United States Marine Corps Reserves as a Heavy Equipment Operator and works part-time in the service industry. Upon graduation, he seeks full-time employment with the Marine Corps Warfighting Center in Quantico, Virginia, USA. jshan001@odu.edu.

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