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Research on Intelligent Driving System Based on V2X Communication

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Abstract. A digital twin is a system that maps real objects to the virtual world using real-time simulation technology. The application of digital twin technology can enable the self-driving test of real intelligent cars in virtual road scenarios. A digital twin-based in-the-loop test system for intelligent driving vehicles was designed and applied to the development and validation of the Autonomous Emergency Braking system. A vehicle-in-the-loop test system is formed by combining simulation test tools, vehicle to everything (V2X) communication equipment, real test vehicles, and other functional units under the framework of digital twin technology. This system maps virtual and real environments to each other. A mirror simulation scene of the real driving environment is constructed using Unreal Engine 4. V2X communication technology is utilized to transmit real-time state data from the real vehicle to the virtual AirSim vehicle controller. Additionally, the environment perception data of the simulation scene is fed back to the test vehicle. Considering the impact of signal delay in the test system, the AEB control algorithm is optimized and improved through in-loop testing of the entire vehicle under various operating conditions. Real vehicle tests have verified the effectiveness and superiority of the digital twin-based intelligent vehicle test method. The results demonstrate that this test method maintains the authenticity of real vehicle tests and effectively avoids the risks associated with them.

Keywords. Digital twin, AEB system, V2X communication technology, optimization improvement, whole vehicle in-the-loop testing.

1. Introduction

Due to the continuous upgrading and improvement of advanced assisted driving system (ADAS) technology and its gradual development towards intelligence, automatic driving has become an inevitable trend in automobile driving. The major challenge for the industry is how to efficiently test and validate the rationality of autonomous driving algorithms and system stability. While safety is the top priority in the development of autonomous driving, the possibility of serious traffic accidents during road testing remains high for autonomous driving cars that use unproven software algorithms and hardware computing platforms. In 2016, a Tesla on the Beijing-Hong Kong-Macao Expressway was involved in a traffic accident with a road sweeper while in autopilot mode, resulting in the driver's death. Similarly, in 2018, an Uber self-driving vehicle collided with a pedestrian, leading to the revocation of its road testing license [1]. The accidents involving self-driving vehicles have prompted vehicle technology

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management departments in various countries to be more vigilant and accelerate the testing process. Currently, dozens of licensed test vehicles are conducting large-scale intensive testing on open roads across China [2]. However, the existing test sites and scenarios in China are insufficient to meet the testing needs of autonomous driving [3]. Therefore, this paper proposes applying the concept of digital twins to the field of autonomous driving testing to enhance the methods and means of testing.

The concept of digital twins was first proposed by Prof. Grieves at the University of Michigan and was later applied to aerospace by NASA in 2010 [4]. While the definition of digital twin may vary across different fields [5-7], the basic concept remains the same: it is an extension and development of simulation applications that not only mirrors the physical world but also receives real-time information from it, and in turn, drives the physical world in real-time. Digital twins have been applied in various fields, including equipment manufacturing [8], industrial engineering [9], and robotics [10]. In the field of automatic driving test, Qingtao Wang et al. [11] utilized digital twins. Gao et al. [12] conducted a real vehicle test using the digital twin framework to explore obstacle recognition by the test vehicle in virtual scenarios with different sampling frequencies. Additionally, Wang et al. [13] applied the digital twin framework to the ramp merging scenario and conducted a thorough analysis of its effectiveness. Although the research on the digital twin framework in the field of automated driving tests has made some theoretical progress, it lacks a comparison with traditional simulation tests and real-vehicle in-the-loop tests to prove its superiority. Additionally, it does not investigate how to ensure the normal and safe driving of vehicles under extreme working conditions when applied to the development of advanced assisted driving systems.

This paper applies the intelligent driving test scheme based on digital twin to the traditional automatic emergency braking (AEB) test. Specific car models are selected for verification in the designed simulation scenarios, and the traditional AEB control algorithm is analyzed and improved. Network communication technology is utilized to transmit environmental sensing information, real-world position coordinates, speed, and other real-vehicle state information in the twin world. Different working conditions are constructed in the twin world to verify the AEB control algorithm in a virtual simulation scenario. The control algorithm is then improved by combining it with the closed-course vehicle-in-the-loop test of the AEB control algorithm. This process verifies the validity of the digital twin framework and its advantages over traditional test methods. The effectiveness of the digital twin framework and its advantages over traditional testing methods have been verified. This test method can be generalized and applied to the intelligent driving test of different car models and scenarios.

2. Digital Twin Based In-Loop Test System for Intelligent Vehicles

The paper presents a two-tier architecture model of an automatic driving test system, as shown in Figure 1. The lower layer represents the real world, while the upper layer represents the virtual world or 'digital twin'. The communication module in this system framework facilitates real-time interaction and information exchange between the two layers.

2.1. Virtual Reality

2.1.1. Virtual scene construction

Digital twin testing begins by constructing a virtual external test environment. In this paper, the environment is built using the Unreal Engine with AirSim. The Unreal Engine was initially designed for developing 3D video games, providing it with powerful graphic rendering and visualization capabilities. AirSim, an open-source simulation software for simulating autonomous driving of drones and vehicles, is based on the Unreal Engine and was released by Microsoft Research. To ensure high reproducibility of digital twins, the interaction between the autonomous driving algorithm system and the simulation test scene can be achieved through AirSim. AirSim is based on the Unreal Engine plug-in, as can be seen in Figure 1.

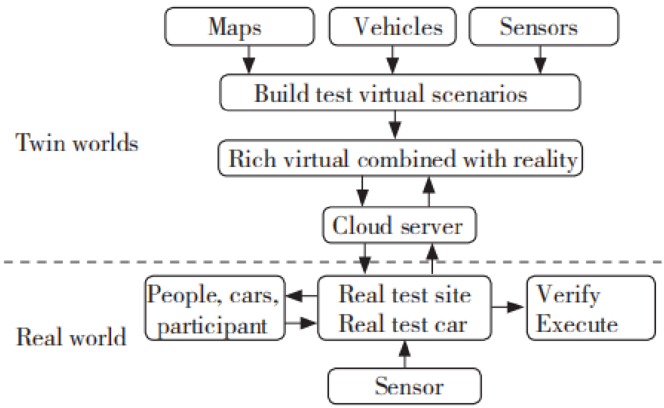

Figure 1. Framework of automated driving test system.

2.1.2. Virtual scene construction

The sensor's installation and configuration parameters can be defined in the simulation environment by modifying the. Json configuration file. The sensor reads distance information from forward obstacles and transmits it to the autopilot system of the real vehicle through remote communication. The effect and flow of the configured sensor in the simulation environment is shown in Figure 2.

Figure 2. Sensor effect.

2.1.3. Remote communications

The communication between the vehicle and the virtual test scene involves uplink communication (transmitting information from the vehicle to the virtual scene) and downlink communication (sending environment sensing information from the virtual scene to the vehicle). This process includes three steps: registering the vehicle terminal, uploading data, and sending information.

2.1.4. Position map

When localizing a moving vehicle, the choice of reference system affects the expression used. To describe vehicle position in the same coordinate system, the first step is to transform the coordinate system.

The GPS positioning device provides vehicle position information in the WGS-84 coordinate system. This information needs to be transformed into the local vehicle coordinate system. The position parameters under the WGS-84 coordinate system in the original GPS data are converted to be represented in the geocentric fixed coordinate system. In this vehicle coordinate system, only longitude L and latitude B are transformed into Gaussian plane coordinates (x, y) using the Gaussian transformation formula.

$$\begin{aligned} x = X + Ntl^2\cos^2B\Big[\frac{1}{2} + \frac{1}{24}l^2(5 - t^2 + 9u^2 + 4u^2)\cos^2B \\ + \frac{1}{720}l^4(61 - 58t^2 + t^4 + 270u^2 - 330u^2t^2)\cos^4B\Big] \end{aligned} \tag{1}$$

$$\begin{aligned} y = 50000 + Nl\cos B\Big[1 + \frac{1}{6}l^2(1 - t^2 + u^2)\cos^2B \\ + \frac{1}{120}l^4(5 - 18t^2 + t^4 + 14u^2 - 58u^2t^2)\cos^4B\Big] \end{aligned} \tag{2}$$

Where is the meridian arc length of the parallel circle from the equator to latitude, is the radius of curvature of the UY circle, is the difference between the longitude of the projection point and the longitude of the axis meridian, is the first eccentricity, is the second eccentricity, and is the subject-specific term for the second eccentricity.

Where X is the meridian arc length of the parallel circle from the equator to latitude B, N is the radius of curvature of the UY circle, l is the difference between the longitude L of the projection point and the longitude L_0 of the axis meridian, $t = \tan B, u = e^t\cos B$ is the first eccentricity, e is the second eccentricity, and e^t is the subject-specific term for the second eccentricity.

$$\begin{vmatrix} x \\ y \end{vmatrix} = \begin{bmatrix} cos\varphi & -sin\varphi \\ sin\varphi & cos\varphi \end{bmatrix} \begin{vmatrix} x_{GPS} \\ y_{GPS} \end{vmatrix} \tag{3}$$

Where: $(x, y)^T$ - coordinates in independent coordinate system; $(x_{GPS}, y_{GPS})^T$ - coordinates in Gaussian plane coordinate system; φ - rotation parameter i.e. heading angle of the vehicle.

2.2. Real Word

2.2.1. Combined navigation module

The module is equipped with a test vehicle, the BAIC EU260 (Figure 3), to acquire GPS positioning data and parse it according to standard protocol. The parsed position information, including longitude, latitude, altitude, and vehicle speed, is then sent to the server through network communication.

Figure 3. Combined navigation system.

2.2.2. 5G terminal module

To fulfill the functional requirements of the vehicle terminal for data transmission and reception, the 5G terminal incorporates a serial communication module, CAN module, 5G communication module, and ARM processor for data preprocessing and remote communication with the server. The adoption of 5G terminals is due to their high-bandwidth and low-latency communication capabilities, which can meet the real-time data transmission requirements of the digital twin architecture.

3. AEB System Design

To assess the effectiveness of digital twin technology in automatic driving tests, we conducted a case study using the automobile collision avoidance AEB system. The forward collision avoidance test scenario is depicted in Figure4.

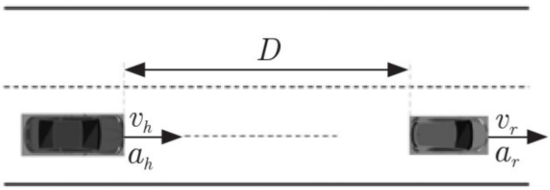

Figure 4. Forward collision avoidance scenario.

3.1. Vehicle AEB System

During the car's travel, on-board sensors acquire real-time position and motion state information of both the main car and the target vehicle in front. The Time To Collision (TTC) evaluation index is then calculated based on the safety time model [14]. The kinematic equation is obtained by analyzing the motion process of both vehicles.

$$\mathrm{v} \cdot \mathrm{TTC} + \frac{1}{2}\mathrm{a} \cdot \mathrm{TTC}^2 + \mathrm{D} = 0 \tag{4}$$

$$\mathrm{v} = \mathrm{v_r} - \mathrm{v_h} \tag{5}$$

$$\mathrm{a} = \mathrm{a_r} - \mathrm{a_h} \tag{6}$$

The following variables are used to calculate the collision: v- relative speed between the main vehicle and the target vehicle in front; $\mathrm{v_r}$ - speed of the vehicle in front; v_h - speed of the main vehicle; a - relative acceleration of the main vehicle and the target vehicle in front; a_r - acceleration of the vehicle in front; a_h - acceleration of the main vehicle; D - longitudinal relative distance between the main vehicle and the target vehicle in front; TTC - remaining time until the collision.

The formula for calculating the remaining time to collision changes when the relative motion state and position of the main vehicle and the target vehicle in front of it change. This results in a different specific TTC expression.

$$TTC = \begin{cases} -\frac{D}{v} & v < 0, \quad a = 0 \\ \sqrt{-\frac{2D}{a}} & v = 0, a < 0 \\ -\frac{v}{a} - \sqrt{\frac{v^2 - 2Da}{a}} & v < 0, a \neq 0 \\ -\frac{v}{a} + \sqrt{\frac{v^2 - 2Da}{a}} & v > 0, a < 0 \end{cases} \tag{7}$$

During the road test with an actual vehicle, the driver perceived two warning moments subjectively, which occurred at 1.9 seconds and 1.0 seconds, respectively [15]. The Time-to-Collision (TTC) was calculated in real-time and compared to a preset fixed threshold. When the Time-to-Collision (TTC) is less than the safe time for light braking of 1.9 seconds, the Automatic Emergency Braking (AEB) system applies 40% braking force [16], resulting in a braking deceleration of 0.3 g. If the TTC is less than the safe time for full force braking of 1.0 second, the AEB system applies full force braking, resulting in a braking deceleration of up to 0.7 g. Additionally, the AEB system can apply 40% braking force [15], resulting in a braking deceleration of up to 0.7 g.

3.2. System Implementation

The digital twin-based vehicle-in-the-loop test system is constructed by combining the virtualized scenario and the real vehicle platform, as shown in Figure 5, starting from the two-layer architecture (real world and virtual world).

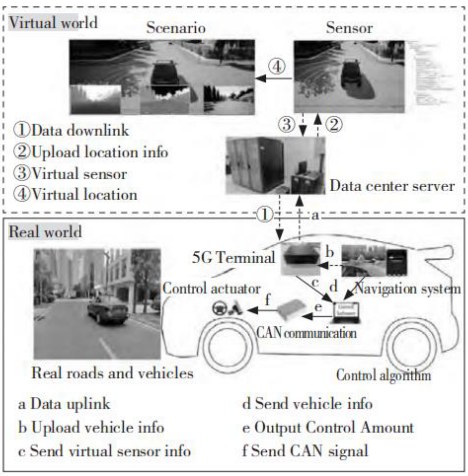

Figure 5. Real world and virtual world of simulation architecture.

Figure 6 demonstrates the test effect after completing the construction of the test platform. The image depicts a comparison between the test car in a real park scene on the left and the same test car in a simulated scene on the right. The simulated car is able to follow the movements of the real car.

Figure 6. Synchronization of real and virtual vehicles.

3.3. Information Preprocessing and Delay Time Analysis

When testing the AEB function using the digital twin-based intelligent vehicle in-loop test system, the delay of the entire system can be categorized into information transmission delay and braking process delay. In comparison to the real-vehicle test system, the digital twin system exhibits a more pronounced information transmission delay. Therefore, this paper primarily focuses on analyzing this type of delay in the real-vehicle experiment.

4. Experimental Validation and Analysis of Results

The current evaluation criteria for AEB tests are primarily based on the system's ability to avoid collisions during testing, which is a simplistic approach. Early intervention by the AEB system can disrupt the driver's normal operation and impact road capacity, while late intervention can result in significant braking deceleration, posing a greater danger. It is important to consider additional factors when evaluating AEB systems. This paper examines the relationship between Time-to-Collision (TTC) and the distance between a vehicle and the target in front after braking. For driving scenarios below 60 km/h, we optimized the design of TTC thresholds in a pure simulation environment. We then validated and optimized the TTC thresholds again using the real-vehicle-in-the-loop test method based on the digital twin framework.

4.1. Simulation Verification and Optimization

Using the joint simulation platform of CarSim and MATLAB/Simulink, we conducted tests in which a test vehicle approached a stationary vehicle at speeds of 10, 20, 30, 40, 50, and 60 km/h. To ensure ride comfort, we modified the TTC thresholds for applying partial braking force, enlarging them so that full braking was not necessary. Simultaneously, to maintain the distance between the vehicle and the target in front, the fixed TTC thresholds have been adjusted and appropriate ones have been selected for different speeds, as illustrated in Figure 7.

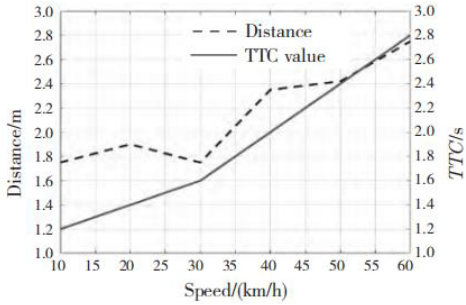

Figure 7. TTC Threshold and Distance to Front Vehicle after Braking Stop at Different Vehicle Speeds.

4.2. Test Method Validation and Optimization

The automatic driving test was conducted in a park that is not completely closed, which poses a certain risk. Only the improved TTC thresholds were tested under the forward collision avoidance scenario at 20 and 40 km/h working conditions. The test results are as follows:

(1) The experiment began with the test vehicle approaching the target vehicle at a constant speed of 20 km/h in a forward intersection collision avoidance scenario. Data recording commenced when the distance between the test vehicle in the virtual scenario and the vehicle in front of the virtual scenario was less than 25 m. When the distance between the self vehicle and the vehicle in front is 7.7 meters, a braking signal is sent to the real vehicle to start braking. The braking deceleration quickly reaches 0.26 g and the preset maximum braking deceleration of 0.3 g is reached in 0.2 seconds (as shown in Figure 8). The vehicle then maintains this braking deceleration. The actual vehicle stops 1.02 meters away from the obstacle vehicle, while the virtual vehicle in the scene is 1.23 meters away. As shown in Figure 9, there is a delay of approximately 0.2 seconds in synchronizing the positions of the real and virtual vehicles. The virtual vehicle experiences a delay of about 0.2 seconds.

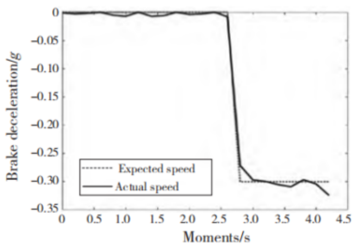

Figure 8. Braking deceleration curve at 20 km/h.

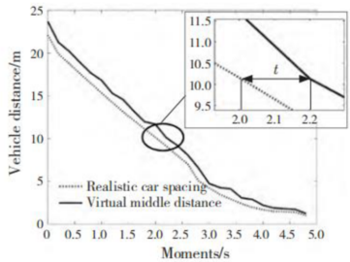

Figure 9. Vehicle distance between real and virtual scenes at 20 km/h.

(2) In the scenario of avoiding a collision at a forward intersection with a vehicle speed of 40 km/h, Figure 10 shows the braking deceleration curve. The test vehicle records data from a distance of 27 m from the vehicle in front. In the real scenario, the vehicle failed to stop in time after receiving the braking signal, causing a collision with the obstacle car in front. The distance between the real vehicle and the preset obstacle car was less than 0 after stopping. In the virtual scenario, the distance between the vehicles was 1. The vehicle was 4 meters away from the obstacle car. Upon analyzing

Figure 11, it can be seen that there is a delay of 0.18 seconds between the virtual scenario of the braking signal sending and the real scenario in which the vehicle actually brakes.

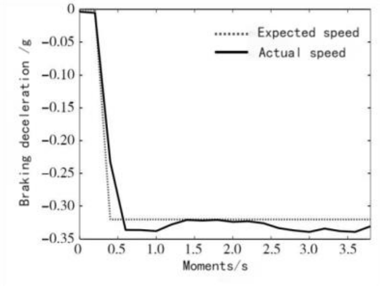

Figure 10. Braking deceleration curve at 40 km/h.

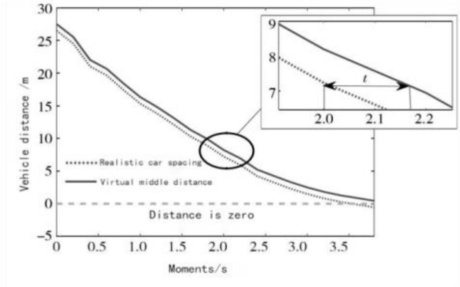

Figure 11. Vehicle distance between real and virtual scenes at 40 km/h

4.3. Algorithmic Improvements

After analyzing the experimental results, it was determined that the system's information transmission delay is 0.2 seconds. The algorithm for collision residual time has been improved, resulting in an improved TTC expression.

$$\mathrm{TTC} = \begin{cases} -\frac{D - vt_{delay}}{v} & v < 0, \quad a = 0 \\ \sqrt{-\frac{2(D - vt_{delay})}{a}} & v = 0, a < 0 \\ -\frac{v}{a} - \sqrt{\frac{v^2 - 2(D - vt_{delay})a}{a}} & v < 0, a \neq 0 \\ -\frac{v}{a} + \sqrt{\frac{v^2 - 2(D - vt_{delay})a}{a}} & v > 0, a < 0 \end{cases} \tag{8}$$

From the above, it can be seen that under the working condition of 40 km/h, the test car in the real scene will collide with the preset obstacle car, for this working condition the TTC algorithm after considering the delay is tested on the real car, at the same time in the recording of the distance dunreal in the virtual scene when the introduction of tdelay to make its position synchronization, at this time the distance dunreal in the virtual scene is.

$$D_{unreal} = vt_{delay} + d_{unreal} \tag{9}$$

The Time to Collision (TTC) was tested in a real vehicle under operating conditions of 40 km/h, after taking into account any delays. At the start of the experiment, the test vehicle approached the target vehicle at a constant speed of 40 km/h. In the virtual scenario, the test vehicle began recording data when it was 30 meters away from the vehicle in front of it. When the test vehicle was 25 meters away from the vehicle in front in the virtual scenario, a braking signal was sent to the real vehicle to initiate braking. The braking deceleration quickly reached 0.22 g, and the preset maximum braking deceleration of 0.33 g was achieved in 0.2 seconds. The vehicle then maintained the braking deceleration, and the real vehicle came to a stop 2 meters away from the obstacle vehicle.

5. Conclusion

In this study, a digital twin framework was constructed to test and validate autonomous driving technologies. The framework uses advanced Unreal Engine and AirSim tools to build highly realistic virtual test scenarios, comprehensively validating autonomous driving algorithms. This approach ensures the authenticity of real-vehicle testing and effectively avoids potential risks, improving the safety and efficiency of testing. At the same time, we have optimized the forward collision algorithm by considering the delay characteristics of the digital twin system. This optimization further improves the realism of the vehicle-in-the-loop test. In the future, we will continue to expand more complex automatic driving test scenarios and fully utilize the technical advantages of digital twin testing. Our goal is to promote the rapid development of automatic driving technology and provide people with a safer and smarter travel experience.

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