Application of Digital Twin Technology in the Field of Autonomous Driving Test

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***Abstract*— With the continuous development of digital twin (DT) technology at this stage, research and applications surrounding DTs have gradually become a hot spot. The application of DT technology in the field of autonomous driving tests is being studied. In this paper, we intend to build a highly open DT autonomous driving test platform, combining it with functional units such as simulation test tools, communication equipment, real test vehicles, etc., to form a rich test verification environment. This model supports various types of autonomous driving solutions and algorithm verification tests and has the ability to carry out real vehicle testing and verification in complex virtual scenes under the condition of limited resources. Finally, this article provides a brand-new test method for autonomous driving vehicles.**

Keywords—digital twin; autonomous vehicle; driving test method; vehicle to everything communication

I. INTRODUCTION

With the continuous development of the Internet of things (IoT), cloud computing, artificial intelligence (AI), big data and other new generation of information technologies, the research process of industrial informatization, intelligent manufacturing and smart city is advancing rapidly. At the same time, the "Made in China 2025" proposed by China and the German's "industry 4.0" have completed cooperation and docking, so as to realize the deployment and comprehensively promote the implementation of the manufacturing power strategy [1]. As one of the main concepts of industry 4.0, DT (digital twin) is more and more used in industrial fields and research projects [2]. Among them, the test and detection based on DT, as an application direction that can realize the virtual real combination and information fusion of physical system and virtual system [3], also plays an important role in the automatic driving test.

DT technology plays an important role in the industrial 4.0 system. Its main applications include "product DT", "production process DT" and "equipment DT". Driven by the DT technology, the traditional predictive maintenance method is transformed from passive response to active service, providing support for the transformation of China's manufacturing industry from "production-oriented manufacturing" to "service-oriented manufacturing" [4]. The concept of DT was first applied to the aerospace field. The US Department of Defense first proposed to use DT technology for the health maintenance and assurance of aerospace vehicles [5]. First, build a model of a real aircraft in the digital space, and fully synchronize it with the real state of the aircraft through sensors. After each flight, timely analyze and evaluate whether maintenance is required and whether it can withstand the next mission load according to the current situation and past load of the structure.

The DT builds a bridge between the physical world and the information world by mapping physical models and sensor data in the virtual space [6], as well as presents a complete life cycle in the virtual system. The process of integrating the content of the real environment into the virtual scene and realizing two-way interactive feedback is also called hybrid reality [7]. The feature of this technology is that it can realize the interaction between physical entities and virtual space through virtual reality technology. At the same time, it also has the ability to apply data fusion analysis and decision iteration optimization to the functional expansion of physical entities, so as to realize the system form of virtual reality combination and virtual reality interaction.

At present, the autonomous driving test system based on scene collection mainly includes software-in-the-loop (SIL), hardware-in-the-loop (HIL), vehicle-in-the-loop (VIL) and closed / open several methods of real vehicle field and road test in semi-open scenario [8]. Among them, SIL is tested by virtual simulation software, HIL is tested by deploying the real controller unit in a virtual test environment, and VIL is tested by taking the whole vehicle as the object in the automotive laboratory, and the real vehicle field test and road test are the tests conducted by the real vehicle on the test field and road, respectively. With the continuous development of autonomous vehicle technology and the increasing complexity of traffic scenarios, the above existing research has shown their shortcomings in the practice of autonomous driving test, which are specifically shown in the following facts:

1) The fragmentation of the test scenario does not conform to the actual use. Autonomous driving is a continuous behavior. The verification that fits the actual use must require a wide space to carry out continuous scene verification. If it is realized in the real physical space, the cost and time are unacceptable [9].

2) The construction of complex traffic scenarios is difficult, costly, and has high safety risks, such as tunnels, multi-vehicle conflicts, and expected functional safety scenarios [10].

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3) The software-hardware-in-the-loop test relies on the vehicle dynamics model, which is difficult to reproduce the real vehicle dynamics, and its accuracy has a great impact on the test [11].

4) The construction cost of the real closed site is high, and after completion, it cannot adapt to the testing needs of rapid changes in autonomous driving technology [12].

5) Traffic participants and traffic flows in open roads are not easy to copy, and it is inconvenient to carry out a large number of repeated tests [13].

Combined with the autonomous driving test, this article gives the narrow definition of DT [14]: the vehicle is in the real test site environment, and modeled and mapped to the virtual space through digital communication technology. Then, by constructing different complex traffic environments in the virtual space, the relevant signals are simulated and generated through the simulator, and then sent to the vehicles in the actual road. When the vehicle receives the signal, it analyzes and judges the signal, and then decides and plans to form a control signal and send it to the chassis to execute the control action. And the vehicle action is fed back to the virtual space, so as to achieve the assessment ability of the decision planning and control execution system of the vehicle. The autonomous driving test based on the DT relies on the real vehicle with the same structure and state in the physical space as the test object, and realize the synchronous correspondence in the virtual space.

Generally, this article proposes a mixed reality solution for the situation that vehicle power, road and driver cannot be brought into the test environment at the same time in several autonomous driving test systems at this stage, or the problems of value cost, safety and repeatability are ignored. The DT three-dimensional traffic environment construction method, through the DT technology, the real vehicle in the physical space is mapped to the virtual 3D scene in the form of a DT. At the same time, the road, weather and lighting environment in the virtual 3D scene are visualized. This paper proposes the construction method and application of DT for autonomous driving test system, and will strive to achieve the following state-of-the-art:

- Section II discusses the related-work of DT in the field of autonomous vehicles' development and manufacturing;
- Section III establishes the methodology of DT autonomous driving test including system framework;
- Section IV designs a mixed reality test environment through the virtual reality platform Unity3D to getting results;
- And section V draws conclusions with future instruction.

II. Related Work

At present, the DT technology is in the process of continuous development and enhancement in the research and construction of mixed reality scenarios. Bao et al. [15] analyzed and prospected the research and application of traffic scene DT from the perspective of the concept, development and key technologies of DT. The "DT application white paper 2020" [16] issued by the Ministry of industry and information technology of the people's Republic of China pointed out that the establishment of entity digital mapping is one of the cores of the DT system for building a virtual simulation platform included in the autonomous driving test system combining virtual simulation with real environment. Wang et al. [17-18] used vehicle to cloud V2C (vehicle to cloud) communication to transmit sensor data to the virtual space through the server. After corresponding model calculation, decision proposals were obtained and fed back to the driver in real time.

Pan et al. [19] built a more realistic DT in the virtual scene by fusing the images with texture features and continuous video clips obtained in the real world into the virtual scene through feature matching. Wu et al. [20] designed a hybrid reality framework for multi view real-time monitoring of large-scale scenes that integrates two-dimensional panoramas, satellite textures and three-dimensional models, and used it to generate DT three-dimensional road scenarios. In the research related to the construction of automatic driving test scenario, Bai et al. [21] proposed a 3D scene reconstruction method based on binocular vision, which can be used for scene reconstruction of large-scale intelligent driving scene and can meet the real-time requirements of intelligent driving system. Tang et al. [22] studied a method that integrated the simulated driver into the autonomous driving scene, and the driver controlled the vehicle through the driving simulator to pretend the driving behavior in the real world. This method can well promote the simulation test of autonomous driving vehicles.

Song et al. [23] proposed a virtual joint simulation technology platform covering sensor module, vehicle dynamics module, scene module and control algorithm module, which solved the difficult problems such as all-weather road, sensor type selection design, automatic control algorithm and driving performance test, and improved the autonomous driving performance of the system. However, the autonomous driving test scenarios constructed by combining virtual and real are compared with traditional tests. Test methods mainly include software / hardware-in-the-loop (S/HIL) test, closed site test and open road test. The three methods have their own advantages and disadvantages, and any part cannot guarantee the test effect very well, as shown in Table I.

TABLE I. Analysis of Advantages and Disadvantages of Test Evaluation Methods

Method	S/HIL test	Closed site test	Open road test
Object	Software, components, virtual environments	Real vehicles, real roads and fake participants	Real vehicles, real roads and real participants
Advantage	Individual verification of components; Rich and repeatable scenes; High test efficiency;	Real road and vehicle movements; Scenario repeatable test; Safe and controllable;	Wireless annoying real scenes; Real traffic participants; Fit for actual use;
Disadvantage	Dependent dynamic model; Unable to verify vehicle execution capability;	The number of test scenarios is limited; poor site sharing and upgrading;	Uncontrollable road conditions and high safety risks; A lot of time and cost investment; Poor repeatability;

The SIL in the method has the advantages of the real vehicle and the control unit. For the HIL, the whole vehicle can be tested as an object. Compared with the VIL, it can achieve lower costs and can be tested in different road environments. Compared with field and road tests, it has the characteristics of better safety, repeatability, and low cost. DT technology has its special application value in the field of autonomous vehicle testing, which can solve the shortcomings of existing testing methods. Now, a feasible solution has been proposed on how to apply DT technology in the field of autonomous driving test evaluation.

III. Methodology

The core of the autonomous driving test and evaluation method based on DT modeling lies in the DT technology. Its key feature is the "combination of virtual and real", which closely links the real vehicle dynamics with the virtual complex traffic scene, and interacts in real time during the test process to generate the evaluation results in real time. This method has the resulting advantages: 1) The scene setting is continuous and customizable, which fits the actual continuous driving scene; 2) It can realize the rapid construction of complex scenes and autonomous driving test, and save the site cost; 3) The dynamic model is not required. The evaluation is based on the actual road surface and vehicle dynamics, and the test results are more practical; 4) All tests are based on the digital test field, which can quickly adapt to the new test requirements brought about by the upgrading of autonomous driving technology; and 5) High test efficiency, reproducible scenarios, good scalability, and massive simulation tests can be realized on the cloud platform. This paper introduces the model from four aspects: framework, hardware model, key difficulties and application expectation.

A. *System Framework*

The concept starts from the key characteristics of the "combination of virtual and real" DT technology, and mainly includes three dimensions: DT, test development, and evaluation, which constitute the main line of the DT autonomous driving test evaluation system as shown in Fig. 1.

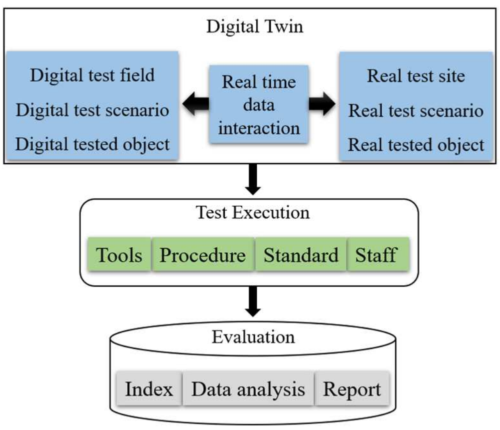

Fig. 1. Conceptual diagram of digital twin test evaluation system

The primary task of DT application is to create a DT model of the application object [24], that is, to form a DT. Its construction and real-time information interaction are the key to this scheme. It is necessary to digitize the test site, test object, test scene, etc. in the real world to form a twin digital test site, digital test object, digital test scene, so as to make the two become an interconnected DT. Working mechanism of test: the digital tested object is twinned with the real tested object and driven by the real tested object → it is sent to the real tested object under the digital test scenario → the decision-making and execution actions of the real tested object are returned to the digital tested object → the digital tested object completes its actions in the digital test field → data is collected in the digital test field and test evaluation is completed.

In order to realize the above DT autonomous test concept, the system composition is designed as follows, as shown in Fig. 2. It mainly includes 4 parts: DT test equipment (simulation platform, data distribution and acquisition equipment), real tested object, evaluation analysis, and display platform.

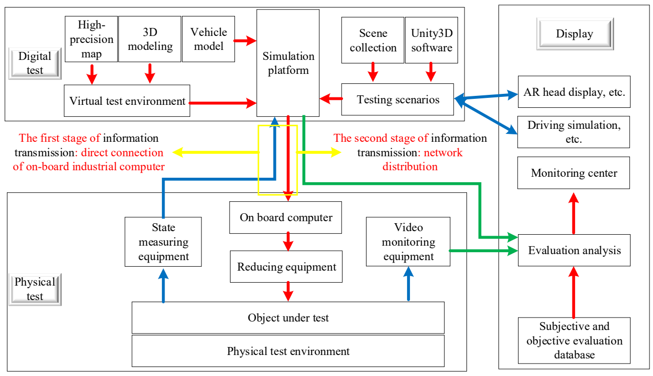

Fig. 2. Composition of digital twin test evaluation system

Taking an autonomous vehicle as the tested object, state the working process of the system: the simulation platform runs the virtual test field, vehicle sensor model, and test scenarios to form one or more autonomous driving test scenarios (such as intersection traffic scenarios), and sends the scene information to the controller of the autonomous vehicle through the input equipment. The autonomous vehicle processes the intersection information according to its own algorithm, send decision-making signals (such as decelerating and passing), and the vehicle executes decisions (such as braking and decelerating, and slowly passing through the intersection); The motion data of the vehicle is collected in real time by the dynamic measuring equipment installed at the vehicle end and uploaded to the simulation platform to drive the virtual autonomous vehicle model, and the dynamic data of the vehicle is marked in the scene of the simulation platform; The evaluation and analysis module processes the vehicle dynamic data, and evaluates the vehicle behavior based on the evaluation dimension and database; The information of vehicle end and road end video monitoring equipment and the pictures of simulation platform are transmitted to the display platform. Interact with users through various interfaces to present the test process and results.

IV. Results and Discussion

A. *Results*

Combined with subjective and objective evaluation databases, multi-dimensional analysis of the functional performance of autonomous vehicles is carried out. In order to simulate the driving test for connected autonomous vehicles conducting cooperative lane change/merge actions, a DT based same approach has been constructed and presented in [25]. Similar methods were used by the author in [26] to create a free test site for autonomous vehicles and define driving test scenarios for various types of tractor and trailer combinations using DT technology. Ultimately, our objective is to reduce the amount of chance in the simulations by controlling for nondeterminism.

The evaluation indicators are based on international and domestic standards and norms, and integrate a large number of actual test data accumulated, and are comprehensively set from the four key dimensions of safety, intelligence, comfort and reliability. United with the current technology maturity, the development of the DT autonomous driving test and evaluation system scheme is carried out in three stages, as shown in Table II.

TABLE II. PLANNING FOR DEVELOPMENT STAGE OF THE TECHNICAL SCHEME

Stage	Vehicle end delivery stage	Network transfer stage	Extended application stage
Main content	Build a twin device mounted on the test vehicle, and the simulation scene is directly connected to the vehicle.	Build a control center, and send simulation scenarios to test vehicles through 5G/network	Carry out extended application of DT test system, research sensor model, dynamic model calibration, cloud simulation and other applications
Scope of application	Poor network, single vehicle test	Network optimization, batch real vehicle test	Calibration test, cloud simulation

In this article, LTE-V and wireless network communication environments are respectively built according to 3GPP standards and VANET physical layer security development technology of vehicle application equipment. OBU intelligent vehicle terminals based on multi-mode interaction modes are adopted, which support multiple communication methods including LTE-V, GPS, WI-FI, and 5G, and integrate multi-functional V2X applications including driving safety and information services. Under the condition of low 5G network coverage and unstable network delay, carry out the construction of vehicle end distribution scheme, and ensure the single vehicle test capability through the direct connection and injection of on-board DT test equipment and vehicle controller; Under the condition that 5G network is mature and stable, the construction of network distribution scheme can reduce the number of vehicle end equipment, reduce the cost of single vehicle equipment, and improve the test scale and efficiency; Once the research in the first two stages is mature, expand the application, such as cloud and sensor dynamic model calibration on the DT simulation platform.

Building the network and communication system involves creating a data transmission channel to send vehicle data collected by the intelligent vehicle terminal to the cyberspace data center for processing. The system's LTE-V communication capacity and TCP/IP network stability should also be tested to meet the test environment's basic criteria under diverse road situations, weather circumstances, and communication conditions. Site environment, climate conditions, interference sources, equipment power, etc. affect the communication system's transmission distance and efficiency. Network bandwidth demand, equipment hardware failure, number of nodes, etc. affect network transmission rate and quality. The following parts make up the process of sending data in the network and communication systems built in this paper:

1) During vehicle driving, the intelligent on-board equipment communicates with the external environment through LTE-V and collects data to return to the equipment itself.

2) The upper computer and the intelligent on-board equipment establish a network connection through Ethernet/WLAN and the equipment transmits the acquired data to its upper computer.

3) The upper computer and the infrastructure roadside facilities establish a connection through serial port and realize the state synchronization process with the virtual space.

4) The upper computer and the system transfer the data to the system by establishing a TCP/IP network connection, so that the data obtained by the upper computer is calculated and processed, and the processed results are returned to the upper computer and the three-dimensional space scene.

The hardware configuration scheme is divided into two types: vehicle-side distribution and connected distribution, corresponding to the first two stages shown in above Table II. Based on the above conceptual scheme, the realizable HIL layout scheme is designed, as shown in Figs. 3 and 4.

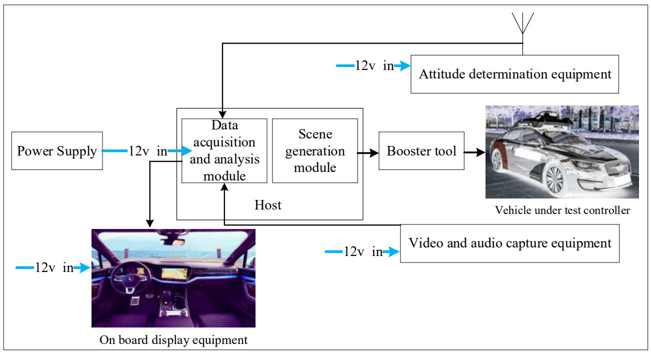

Fig. 3. Vehicle-end distribution scheme: host and related equipment of on-board distribution scheme are installed on the tested vehicle, and connected with the controller of the tested vehicle through injection equipment and hardwires to realize information contact.

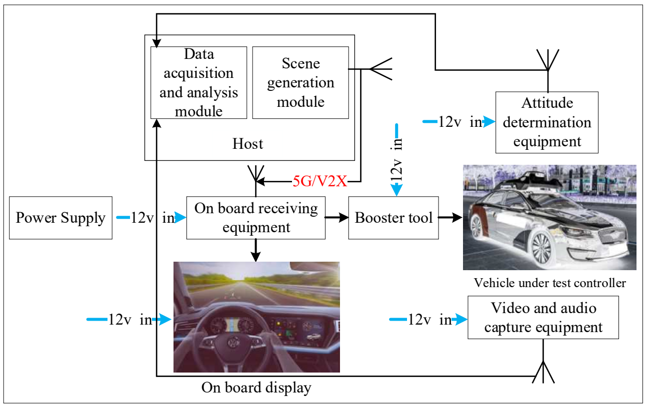

Fig. 4. Network transfer scheme: host of the network distribution scheme is dispersed to the on-board equipment in the laboratory or in the cloud through the network (5G/V2X). After receiving and converting, the injection and information interaction are completed.

A mixed reality test environment is built through the virtual reality platform Unity3D. The actual test subject is an electric vehicle, the test road is an autonomous driving closed field test base, and the data collection and transmission process are completed through the intelligent on-board terminal and roadside facilities deployed in the test base. Corresponding to the DT prototype vehicle, the dynamic parameters of the DT vehicle as the test subject in the virtual scene need to be adjusted after matching calculation in combination with the real vehicle configuration and the collision characteristics of the virtual-physical entities. Table III shown the parameter configuration of the DT vehicle in the virtual scene.

TABLE III. PARAMETERS OF DIGITAL TWIN VEHICLE

Parameter	Value
Maximum direction angle	30 deg
Rigid body mass	1500 kg
Maximum speed	150 km/h
Impactor structure	Bounding box
Front & rear track width	1525/1535 mm
Collision volume	13.07 m^3

According to the safety performance evaluation test method, virtual vehicle and pedestrian are set in the scene, respectively, and the safety tests of different items are carried out. Fig. 5 shows the tests of pedestrian collision detection item. The DT vehicle in the virtual space has a collision detection system based on a bounding box and rigid-body [27] component properties, so it will produce a physical collision effect when it collides with the virtual vehicle and pedestrian.

Fig. 5. The scene of pedestrian collision detection of the virtual vehicle

Fig. 5 shows the result and schematic diagram of the collision between the DT vehicle and the pedestrian. The collision detection boundary refers to the edge attribute of the object with bounding box structure, and the center distance refers to the distance between the center points of the bounding box of two objects. The results of the real test process show that the mixed DT autonomous driving test environment constructed in this paper has the interactive characteristics between real vehicles and virtual traffic participants, and can carry out basic crash tests. In terms of system performance, a statistical analysis of packet loss was carried out on the collected data sequences at the sampling frequency of 50 ms, 200 ms and 1000 ms. The statistical standard was that the interval between two samplings in the sequence time exceeded the sampling frequency.

B. Discussion

In this solution, information interaction technology is the key difficulty in determining whether the DT can truly realize the combination of virtual and real. The versatility of scene injection on various models is a problem that must be considered. This solution attempts to solve it in two ways:

- The first step is to open the outside world, i.e., to standardize the scene injection format with reference to mainstream communication protocols and clarify the key injection parameters so that the tested object can actively adapt and receive.
- The second step is to make multiple injection templates. This means doing research and making multiple scene injection format templates that work for major protocols, manufacturers, etc., so that scene injection can be used more quickly.

In this article, the vehicle DT test environment and vehicle pedestrian test process under the test environment are respectively demonstrated. At the same time, the one-step and multi-step vehicle trajectory predictions are verified and analyzed. The frame rate change and system delay are looked at under three different sampling intervals, and the system's stability is judged based on how well it works in real life. The higher the autonomous driving speed, the greater the impact of the information transmission delay. For example, when the tested vehicle passes through point A at a speed of 60 km/h, the virtual test scenario is triggered. The information transmission delay is 100 ms. When the virtual test scenario arrives at the tested vehicle, the vehicle has exceeded point A by about 1.7 m, which creates a large position difference between the digital scene and the real scene at the same time. This error is unacceptable for the automatic driving safety function test. At the same time, in the implementation of the DT technology scheme, it is necessary to solve this problem from two aspects at the same time: one is to reduce the transmission delay as much as possible, such as using hard-wire direct connection and 5G communication; Second, the synchronization technology is used in the simulation platform to compensate for the error caused by time delay. Therefore, when choosing a DT simulation platform, we must consider the future expansion of applications, have the ability to deploy the cloud, and implement a system that supports simultaneous testing of multiple vehicles and simulation of massive scenarios in the cloud.

V. CONCLUSION

This paper combines the DT technology and the autonomous driving test evaluation technology, studies the application scheme of the DT technology in the self-driving test field, and forms an implementable system architecture. We put forward a new, efficient and safe real vehicle in the loop test method and discussed the key technical difficulties and solution points in the application of the DT technology, which can provide a reference for similar applications of DT technology. It is concluded that the vehicle has good DT characteristics and the system is stable under certain conditions. The next step will consider the delay problem generated by the vehicle in the network transmission and communication process. By solving and improving the system delay characteristics, the accuracy and reliability of the vehicle DT result can be used for vehicle collision detection, including vehicle collision results and schematic diagram for further improvement.

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