# Autonomous Driving Test Method Based on Digital Twin: A Survey


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2021 International Conference on Computing, Electronic and Electrical Engineering (ICE Cube) | 978-1-6654-0154-8/21/$31.00 ©2021 IEEE | DOI: 10.1109/ICECube53880.2021.9628341

***Abstract*—The digital twin (DT) can virtualize the entire life cycle of the system and is very suitable for use in autonomous driving tests. A framework based on DT to test connected autonomous driving in a limited environment is proposed, in which, the maneuver of DT is used to realize the real connected autonomous driving test in virtual complex road scenes. LTE/G5 used for data communication procedure between self-driving vehicle sensors and roadside environment. However, DT is not indistinguishable from many perceptions, including its basis, development, industrial practices, cyber–physical plotting, and basic elements. In order to highlight the applications and challenges, this paper surveys and analyzes the digital twins from multiple views.**

***Keywords—autonomous driving, cyber-physical system, digital twin, V2X,***

## I. Introduction

Digital twin (DT) is a digital representation of a physical entity, which can simulate the entire life cycle of the operating system and synchronize the mapping with the physical twin [1]. The idea of DT began in 2002 and was first used in the aerospace field. However, it was NASA who first contained the DT perception and, in a 2010 Roadmap Report, the concept was used to create digital models of space shells and craft for testing [2-4].

Recently, other industrial sectors such as manufacturing, industrial production, and robotics have gradually begun to understand and experiment with this technology [5]. Two important prerequisites namely DTs and cyber-physical systems are proposed in [6], for a smart manufacturing industry 4.0 to grant manufacturing schemes with great productivity, resilience, and intelligence.

With the progress of self-driving, testing and authentication of DT models has become one of the major challenges in research and improvement of autonomous vehicles [7]. Some researchers believe that the use of simulation testing can solve this problem [8], such as software-in-loop (SIL) testing [9], hardware-in-loop (HIL) testing [10], and hybrid testing in virtual simulations test [11]. It can quickly simulate any scenario but cannot verify the real situation. Compared to simulation testing, the traditional automotive industry relies more on field testing. However, the real road test is expensive and time-consuming in extreme cases, and some scenarios cannot even be tested [12], [13]. This is a DT-oriented method, but this method is developed from the perspective of active safety and does not introduce vehicle wireless communication (V2X) technology.

V2X technology can not only provide non-line-of-sight perception information for road vehicles, but also establish communication links between vehicles and cloud data centers; therefore, we believe that V2X technology can be used as a link between physical space and digital space [14-16]. It plays an important role in the automated driving test. V2X technology can send scene information to the tested vehicle on the road and provide road virtual test functions. In DT, the data flow between existing physical spaces and digital spaces will be fully integrated in two directions [17-19]. In this combination, digital objects can also serve as physical object management instances. Changes in the state of physical spaces directly lead to a change in the state of digital spaces, and vice versa, as shown in Fig. 1.

A DT-based networked autonomous driving test prototype system uses V2X technology to realize the entire process of sensor data upload and virtual scene information release and conduct road vehicle testing. Corresponding test models show that the system can support low latency connected automated driving tests.

This paper is organized as follows: the next section briefly presents the basic autonomous driving test framework based on DT. Then, applications of DT to manufacturing, i.e. Industry 4.0, Automatic vehicles, and Healthcare procedure, are reviewed. In addition, some existing challenges and future trends are highlighted. Finally, the paper is summarized in the last section.

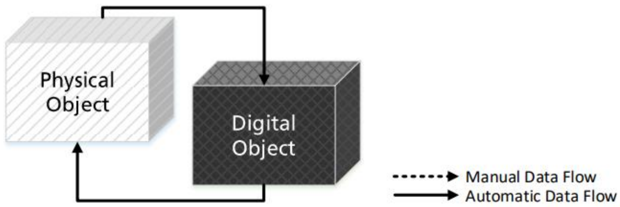


Fig. 1. Data flow in Digital Twin

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## II. Literature Review

Before 2017, the growth of the digital twin in academics was quite gradual. However, the number of academic articles on DTs increased dramatically after 2017. The quantity of literatures on the concept, paradigm, and framework of DTs expanded steadily until 2018, but then began to decline in 2021. This shows that DT is progressing from its infancy to a stage of rapid development, where researchers are beginning to investigate real-world methods and technology in 4.0 industry. Although, all researchers claimed a DT in their articles, the distribution of level of integration in DT literatures shows that there are three types of DTs: 'digital model, 'digital shadow, and 'digital twin, as shown in Fig. 2.

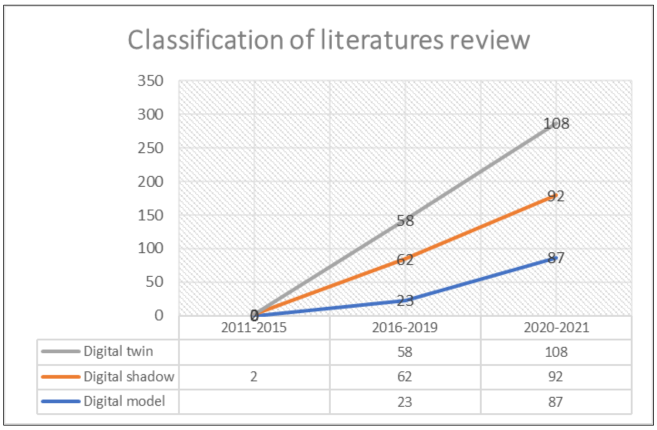


Fig. 2. Distribution level of integration in Digital Twin literatures

The foundation of a DT is data. To capture total-element data for DTs, sensors, gauges, readers, cameras, scanners, and other devices should be chosen and integrated. The data should then be delivered in real-time or near real-time. Literature [20] reviewed industrial IoT and signal processing techniques in digital twins for real-time and multisource data collecting. Authors in [21] examined the concept of digital twins and their properties in both a narrow and broad meaning. Digital twin prototypes (DTP) and digital twin instances (DTI) were defined in [22], and it was in a digital twin environment (DTE). There are 10 papers explicitly mentioning the digital twin object among the examined academic publications in this work. The distributions of integration level and lifetime phases of digital twin objects are summarized in Table. 1.

Table 1. Novel summary of the implementation of digital twin

| References | Year | Digital Twin |
|---|---|---|
| [23] | 2017 | Simulation for real-time product and production system control and optimization |
| [24] | 2018.2 | A digital twin is a virtual clone of a "technical asset" that is one-to-one. |
| [25] | 2018.12 | Digital twins dynamically represent physical entities, including their operations, behaviors, and laws. |
| [26] | 2019.1 | New technology, and their actions in real-world interactions with their surroundings |
| [27 | 2021 | Concepts, technology, and industrial applications of the digital twin are discussed. |
| [28] | 2021 | In industry 4.0, digital twin as a service: an architecture reference model |
| [29] | 2021 | For the green transition, a digital doppelganger of Earth has been created. |

## III. Autonomous Driving Test Framework Based on Digital Twin

In practice, different industries may have different definitions and understandings of DT. Autonomous driving developers see it as a set of augmented reality solutions. In a sense, the DT-oriented test system is a kind of Cyber-Physical System (CPS) which refers to collecting information in the real world (physical entity) through the communication network, using the large-scale data processing technology of cyberspace (virtual world) to analyze the data, and feedback the results to the physical entity to solve the real world issues.

A method for interconnected systems such as CPS is proposed in [30], to monitor the information between physical space and cyberspace, and a unified framework for CPS in manufacturing is presented. CPC based DT which meats the logistic behavior of automated guided vehicle (AGV) is described in [31], to show that the combined CPS-DT architecture allows a calculated optimization of the plant resources in Industry 4.0 structure. Each CPS includes intelligent technologies, storage systems and manufacture facilities, which can interchange data autonomously and intelligently, create decisions, and can control each other [32].

### A. *Applications required for self-driving*

Before self-driving vehicles can actually land on the ground, they must pass a number of safety tests. Virtual simulation tests and actual road tests are an essential part of them. Currently, HIL devices are commonly used for performance testing of controllers related to active safety [10]. In the system tested by the HIL device, only the controller is real, while the vehicle dynamics, road, power, gearbox and other systems of the vehicle related to the test controller are virtual and need to pass simulation model to simulate, because HIL test is a real-time test, in order to ensure the real-time performance of simulation model calculation. The entire vehicle dynamics, road, driver and power, and gearbox are all simulated as a more simplified system, which leads to less accurate performance of the controller under test.

Therefore, many vehicle companies and automatic driving system suppliers are more inclined to choose the digital twin automatic driving test evaluation method that combines automatic driving simulation test and actual road test [33], which helps to solve this series of problems. Save at least 80% of the time cost through the digital twin autopilot test, repeat the same test conditions for multiple tests, with high repeatability. However, in the future, a driver model can be introduced and a virtual driver can perform vehicle control.

### B. *Self-driving test framework*

The DT-based networked self-driving test method includes two key steps: one is to collect real driving data, and the other is to generate complex scenes. Road vehicles collect and release driving information through sensors and V2X, and complete data fusion processing, and then upload the corresponding information to the simulation platform. The simulation platform selects test scenes based on real-time driving information and feeds the corresponding information back to the road vehicles. The road vehicle control system responds to the scene information, and outputs and uploads the response to the simulation platform. The simulation platform judges the test results and generates a test report. As shown in Figure 1, the test plan contains three layers, namely the field test layer, the network transmission layer, and the experimental test layer, as shown in Fig. 3.

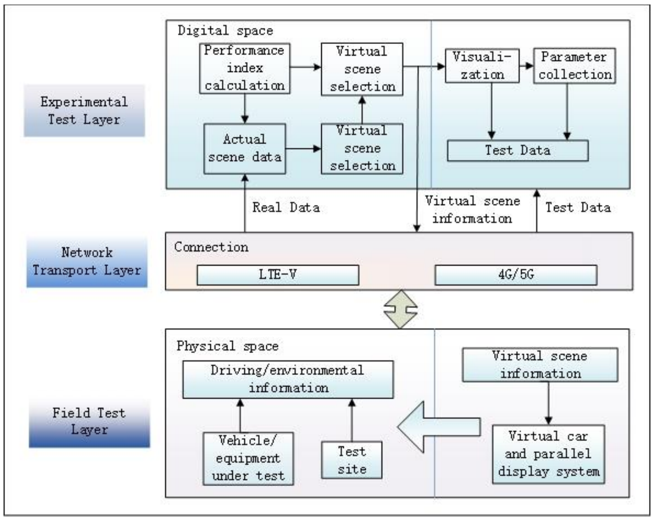


Fig. 3. Test framework of linked self-driving vehicle based on DT

*1) Field test layer:* The field test layer consists of three parts: the tested vehicle [34], virtual vehicle [35] and head up display (HUD) [36], real test site and so on. Vehicle driving information is collected by in-vehicle sensors. Real driving environment information is collected by surrounding vehicles and roadside equipment such as radars and cameras. Virtual scene information is provided by cloud database and displayed on HUD. It is assumed that all vehicles are equipped with LTE-V2X and 4G/5G modules

*2) Network transport layer:* The network transmission layer includes two communication methods: one is the direct communication link of LTE-V2X, and the other is the 4G/5G cellular communication link [37]. LTE-V2X is used to collect environmental information, such as road information, driving status of surrounding vehicles, pedestrian status, etc., and 4G/5G is used to establish a connection between physical space and virtual space. Obviously, the performance of the network transmission layer will have a fatal impact on the real-time performance of the self-driving test, which can be reflected by the response delay of the vehicle controller. The basic performance parameters as follows [38].

*a)* The speed of the tested vehicle: 0~130 km/h;

*b)* Communication coverage radius: >300 m;

*c)* Vehicle status information update frequency: 10~20 Hz;

*d)* Data rate (downlink)>100 Mbit/s, data rate (uplink)>20 Mbit/s;

*e)* Transmission delay.

In addition, Table 2 lists the content of reference messages that need to be sent through V2X for the development of networked autonomous driving tests and reference message content of linked automatic driving test based on DT.

*3) Experimental test layer:* The experimental test layer includes channel modeling, performance index calculation, virtualization, and performance acquisition. In the scene generation process, the road environment (lane, lane line, road surface, weather and lighting, scene elements), traffic conditions (vehicle flow, pedestrian congestion, adaptive cruise control), traffic participants (vehicles, pedestrians, obstacles), environmental sensors (radar, camera, global positioning system/map, wireless communication), and other influencing factors build a 1:1 digital scene model. During the test, the tester will select the test scenario and send the corresponding scenario information to the tested vehicle through 4G/5G network.

Table 2. Reference message content of linked automatic test based on DT

| **Message transmission direction** | **Information** | **Description** |
|---|---|---|
| Virtual to physical space | List of traffic participants | Generated by virtual simulation |
| Virtual to physical space | Traffic participant ID | Unique ID, assigned by virtual emulator |
| Virtual to physical space | Time | Timestamp |
| Virtual to | Location | Horizontal |

| | | |
|---|---|---|
| physical space | (longitude and latitude) | location information of traffic participants |
| Virtual to physical space | Location (altitude) | Vertical location information of traffic participants |
| Virtual to physical space | Traffic participant information | Customized information for traffic participants |
| Virtual to physical space | Vehicle ID | Unique ID, assigned by virtual emulator |
| Virtual to physical space | Time | Timestamp |
| Virtual to physical space | Target location (longitude and latitude) | Target horizontal position information |
| Physical to virtual space | Vehicle ID | The unique ID of the tested vehicle, assigned by the virtual simulator |
| Physical to virtual space | Time | Timestamp |
| Physical to virtual space | Location (longitude and latitude) | Horizontal position information of the tested vehicle |
| Physical to virtual space | Location (altitude) | Vertical position information of the tested vehicle |
| Physical to virtual space | Vehicle status information | Customized information of the tested vehicle |

## IV. Smart Network Based on Digital Twin Modeling

On-board sensors and roadside units collect data about the surrounding atmosphere of the tested vehicle. Each device captures surrounding information according to its configuration, and then synchronizes the collected information under the same time-stamp tag with other devices on the network. The data of the physical system is uploaded to the server running at DT application. Virtual objects are shown in the central control simulator, and the real vehicle behavior will be fed-back to the central console by the camera. The test plan includes three stages [38]: pure virtual testing, sensor data testing and real vehicle test, as shown in Fig. 4.

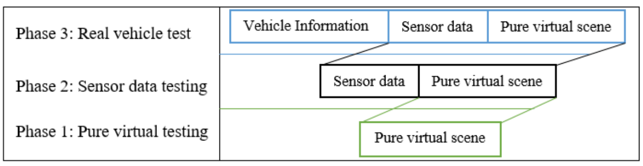


Fig. 4. Test framework of linked self-driving vehicle based on DT

### A. *Pure virtual testing*

The initial phase of the DT test plan is pure virtual testing. This test is similar to traditional virtual model, and the main steps are as follows:

*a)* The first step is to construct road scenes based on test requirements and data;

*b)* To set vehicle factors (driving parameters and sensor parameters);

*c)* Step 3, is to increase mixed traffic interference;

*d)* The four step is to add control algorithm;

*e)* Last step is to start the experiment simulation.

### B. *Sensor data testing*

Another stage of the test is based on real sensor information. In this procedure, physical-world sensor information is collected and sent to the records center through the wireless network. The remote driving system makes decisions based on sensor information and feeds the decision data back to the test system.

### C. *Real vehicle test*

At this stage, a physical vehicle is used as the device under test. The vehicle data is sent to the virtual simulator through the 4G/5G network. On the basis of the digital simulation test, mixed-traffic flow and self-driving algorithms are added to simulate the real scene, and the real scene will be sent back to the real self-driving vehicle in time. The decision result of the controller will be sent back to the central control simulator, and the test will be completed under the control of the autopilot algorithm.

## V. Digital Twin Applications

Applications variety from automotive uses where telemetry sensors deliver response from vehicles to the DT program. A systemic approach for prototype testing is proposed in [39], to promising intelligent transportation systems for cooperative and unmanned mixed-traffic flow. DT based virtual and physical simulation technology for modern automated braking system is designed in [40], to ensuring safety of active vehicle systems. DTs by GT-Power software, MATLAB/Simulink software, and multi objective evolutionary optimization is pioneered in [41], to improve high performance Atkinson cycle gasoline engine and discover its fuel saving prospective on chain hybrid electric-vehicles. An Intelligent Transport System based on DT and AI is analyzed in [42], to solving the main problems of the transport network and effectively developing it. DT based model of smart electric vehicles are reviewed in [43], to bring these vehicles on mainstream to reduce carbon dioxide emissions up to 43% and SEVs are classified into specific domains such as autonomous navigation control, advanced driver assistance systems, vehicle health observing, battery health management systems, vehicle power electronics, and electrical power drive systems.

Plants where procedures are simulated by DT to deliver improvements in the system. DT towards smart manufacturing industry 4.0 is proposed in [44], to achieve smart manufacturing with greater intelligence, sustainability, and personalization. A new concept of experimental digital twins (EDTs) for the development of future systems in the area of Industry 4.0 is proposed in [45], to structuring element for simulation based systems engineering processes and their interdisciplinary and cross domain simulation in virtual testbeds (VTBs).

Healthcare where sensors can inform a DT model to monitor and forecast the well-being of a patient. A team of human DTs is monitored in [46], where DT initially predicts the physical entity performance through training and, in circumstance of non-optimal result, it proposes modifications in the athlete's performance. Healthcare system using the DT framework is proposed in [47], where this framework is used to contribute in digital healthcare and also improved healthcare operations. Finally, we can say that DT can provide a virtual environment and real dynamics to help developers avoid risks, save time, save manpower and resources, and improve development efficiency.

## VI. Challenges

Through the DT-based linked self-driving test prototype system, we believe that V2X technology can not only support vehicle driving safety, efficiency improvement and other application functions, but also can be used for linked automatic driving tests. In addition, autonomous driving testing can also be considered as one of the important application scenarios of V2X technology. Although the test scheme has been proven to be effective, it is only a basic prototype system and there is still much space for improvement [48-50].

*1)* The auto industry has not yet reached a consensus on the delay in response to autonomous driving. In other words, we are not sure whether the proposed solution can meet the response delay requirements of autonomous driving. With the development of autonomous driving, the corresponding communication performance requirements need to be defined. The DT-based linked autonomous driving test will also be considered as an application of 4G/5G communication network. On this basis, the testing process should continue to be improved [51].

*2)* In this scheme, in vehicle testers cannot see the virtual scenes generated in cyberspace, and the user experience is not good. Therefore, the combination of virtual reality (VR)/augmented reality (AR) can be the future research direction [52].

*3)* It is necessary to ensure that the generated virtual scene is consistent with the real traffic scene. So far, the traffic database is not complete. In other words, there is currently no guarantee that the test scenario can cover and represent the real traffic scenario. With the improvement of the traffic database, the test scenario database will also be continuously improved [53].

*4)* As an application of the communication scenario, the DT-based linked self-driving test must be implemented based on a unified communication protocol, and the data set and data exchange format need to be defined [54]; therefore, we need to formulate the corresponding message layer protocol to ensure that products of different manufacturers can be tested in different test demonstration areas.

## VII. Conclusion

With the development of V2X technology, the automotive industry is considering embedding V2X-related application functions into products. V2X is not only limited to applications such as vehicle driving safety and traffic efficiency improvement, it is also a capable technology in other application fields. The parameterization and generalization technology of traffic scene simulation confirms that the test process and working condition scenes of self-driving simulation are almost unlimited. In the DT-based networked autonomous driving test program, V2X technology plays an important role to connecting virtual space and physical space. This article surveyed a DT-based networked autonomous driving test framework; using 4G/5G networks to establish communication links between virtual and physical spaces, and V2X technology to collect vehicle and road information. Some DT-based applications such as manufacturing sites, autonomous vehicles modeling, and healthcare processing are described and as well as identified some challenges in self-driving systems.

## Acknowledgment

The author(s) wish to acknowledge Yanbing Jia, Shanxi Key Laboratory of Power System Operation and Control, Taiyuan University of Technology, Taiyuan, Shanxi China, for providing the facilities needed for this research work.

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