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An Open Vehicle-in-the-Loop Test Method for Autonomous Vehicle

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***Abstract*—Aiming at the safety verification problems of autonomous vehicles in complex environments, this paper proposes a novel vehicle-in-the-loop test method and discusses the key technologies of the method. The test system consists of simulation environment, control center and automatic test vehicle. Firstly, it can map the virtual scene in the simulation environment to the real test environment through the control center and drive the automatic test vehicle to complete the test cases. Secondly, performance indicators such as intelligent perception and behavioral decision-making of the tested self-driving car can be quickly collected through sensor and data fusion. Then a closed loop system is built based on the virtual simulation scene, control center, automatic test vehicle and the tested vehicle. The virtual scene can meet the requirements of testing the performance of the autonomous vehicle under various scenarios.**

Keywords—VIL, autonomous vehicle, test method

I. Introduction

At present, mainstream automobile enterprises and Internet companies at home and abroad are actively developing autonomous driving technology. However, several unmanned vehicle driving accidents in recent years have caused people to question the safety of autonomous vehicle, especially in complex traffic scenarios. How to ensure safety of autonomous driving is a challenging task, so full, systematic and rigorous testing of autonomous vehicles must be carried out before leaving the factory.

A lot of related work has been carried out from ADAS testing to autonomous driving testing, such as virtual simulation testing, hardware-in-the-loop(HIL) testing, vehicle-in-the-loop (VIL) testing and real-car testing, all of which are important means for autonomous vehicle testing[1]-[6]. The software-based virtual simulation test method has the advantages of low cost and high test efficiency. However, many practical factors are neglected when establishing the simulation model, it is not easy to guarantee the accuracy of the simulation results, nor can the hardware performance test and calibration of the autonomous vehicle be realized. HIL-based simulation methods are widely used in automotive testing[7]-[9]. HIL technology combines mathematical models with physical hardware devices to introduce gravity, resistance and friction when simulating vehicle dynamics and stability control, these key physical parameters improve the confidence of the model. Compared with the actual vehicle test, the method has low construction cost, short development cycle and good reproducibility. VIL simulation is a special type of HIL simulation[10]. It integrates the autonomous driving system into real vehicles and builds simulated roads, traffic scenarios and environmental factors under laboratory conditions. Function and performance testing of autonomous vehicle based on multiple scenarios can be systematically implemented.

Although the above methods have their own advantages, they all belong to tests conducted in the laboratory, not road tests. The road test has the characteristics of authenticity and reliability, which directly reflect the performance of the autonomous vehicle in the commercial environment. It is an indispensable part of the self-driving vehicle before going on the road. Road tests are mainly divided into closed field tests and open road tests[11][12]. Closed field tests have higher security, but the test scenarios are too simple and the site investment cost is high. although the road tests have a rich test scenario, the test security is low, and all traffic scenarios cannot be exhausted[13]. In addition to road and environmental conditions are limited, Road tests require a lot of manpower time. For the complex environment of different road conditions, weather, and adjacent stationary and moving entities, it is difficult to manually set and reproduce some unexpected situations, which makes it difficult to repeat the test and verification. Therefore, it is necessary to solve the problem of test adequacy of the automatic driving system in complex environment.

This paper proposes an open vehicle-in-the-loop test method for road tests in closed fields. The method establishes different traffic scenarios by remotely controlling the unmanned test vehicle. It can track and test the driving performance of the tested vehicle, and collect real-time data of the tested vehicle for analysis and evaluation. Compared with traditional road test, this method has better safety, higher repeatability and lower labor cost. In addition, compared with the traditional virtual test, it is more authenticity practical.

II. Design of Automatic Driving Test System

The automatic driving test system consists of test field, control center and automatic test vehicle, see Fig.1 for an illustration. The test field is a fully networked test environment. Equipped with vehicle-connected communication facilities, roadside units, intelligent basic transportation facilities and differential GPS base stations to form an intelligent ecosystem of "vehicle-road" real-time interaction[14]. The key elements include: communication elements, such as LTE-V, 5G and other communication equipment; facilities elements, such as traffic signal lights, traffic signs, road marking lines etc. transportation elements, such as pedestrians, animals, two-wheeled vehicles, motor vehicles etc. functional elements, such as vehicle-road collaboration, vehicle-vehicle collaboration, Internet of vehicles and so on.

The control center mainly plans, simulates, monitors and remotely controls the automatic driving test vehicle through the human-computer interaction interface in the networked vehicle environment, so as to reproduce the complex traffic environment. The functions of the control center include:

- Software simulation, synchronously reproduce the real scene test process under the virtual environment.
- Test case design, select test cases under different test scenarios according to test requirements and generate specific control instructions.
- Remote control, in the control mode, control the automatic test vehicle in real scene through the driving simulator and simulation software.

The automatic test vehicle is equipped with an independent data acquisition system with a high-precision positioning system. It can carry out real-time and synchronous collection of the driving data, upload to the control center, Then, data analysis is made base on the test conditions and evaluation standards to obtain the test results.

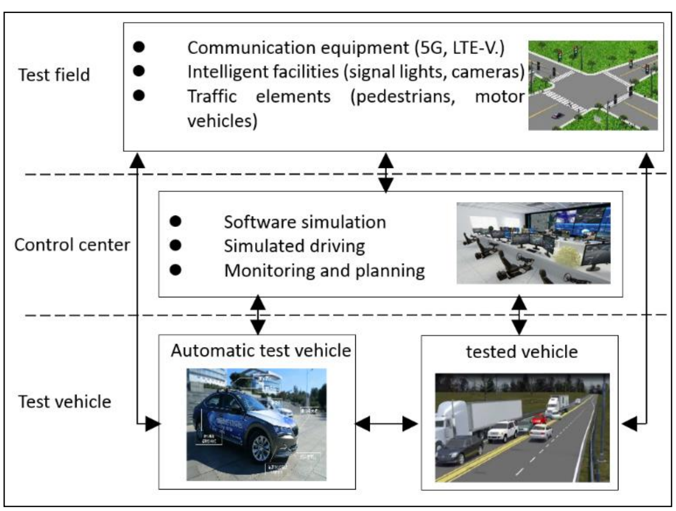

Fig. 1. An illustration for open VIL test system of autonomous vehicle

III. Automatic Driving Test Method

The goal of the open VIL autonomous vehicle test method proposed in this paper is to solve the problem that testing the autonomous vehicle in a complex environment. Using this method to model simulation for the test requirements of the tested vehicle. And then map the simulation environment and the control instruction to automatic test vehicle in the physical world. Through the coupled modeling of automatic test vehicle and the control center, and the synchronous interaction of the control commands with the vehicle state, which will act together on the autonomous vehicle being tested. Through the flexible set of simulation scenarios and test cases, the vehicle performance can be fully tested, and the individual functions of the tested vehicle can be repeatedly verified.

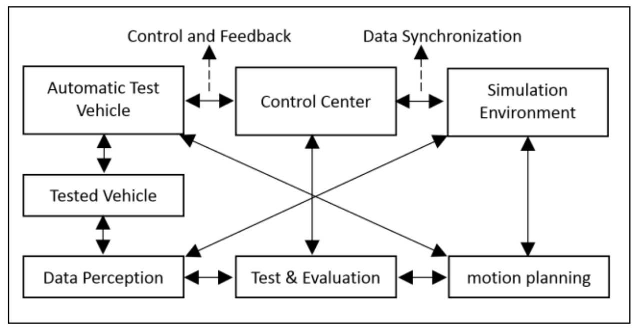

Fig. 2. the basic structure of open vehicle-in-the-loop test method

The Fig.2 is the basic structure of vehicle-in-the-loop test method. The specific operation can be divided into three steps:

Firstly, construct test scenario corresponding with the actual traffic environment to simulate the actual traffic environment. There is no uniform definition about the description of test scenarios in the industry, but the elements contained in test scenarios are basically consistent. A test field usually can cover urban roads, highways, rural roads and other kinds of roads. It has relatively perfect transportation facilities, intelligent networking equipment and multiple type of communication facilities. The signal can cover closed test area by 5 G, LTE -V2X and DSRC, which can provide a basic environment for the testing, verification and demonstration of relevant technologies of autonomous vehicle, so that self-driving cars can be tested under rich conditions. The satellite positioning base station can provide accurate positioning services for the internal vehicles to meet a variety of automatic driving and V2X test scenarios.

Construction elements of automatic driving test fields can be divided into static and dynamic elements. Static elements include traffic signal lights, badges, roadblocks, etc. Dynamic elements include pedestrians, non-motor vehicles, motor vehicle, etc. Since it is difficult to realize the long time and long distance dynamic control of motor vehicles, therefore, this paper adopts an unmanned test vehicle with a replaceable shell for the test. The test vehicle has a power chassis and a motor vehicle shaped shell. The platform is equipped with cameras, radar, differential GPS and various sensors. It not only can drive automatically according to a predetermined trajectory, but also can be taken over by the remote control center. Through monitoring and playback of the motion data of the unmanned test vehicle, the tested vehicle behavior in the real driving environment can be effectively restored to achieve the purpose of repeated test and verification. It provides a reliable and convenient test method for autonomous vehicles.

The second step is to build a simulation environment based on artificial scene data, real-time data of automatic test vehicle and tested vehicle to conduct various experiments. Because autonomous vehicle may encounter dangerous driving, extreme driving, dense vehicles, mixed traffic and other conditions in actual traffic scene, even special weather will also have different effects on sensors of autonomous vehicle. However, these conditions are difficult to reproduce in field tests. it is almost impossible to fully verify the safety and reliability of autonomous vehicle based on field or road tests. Therefore, it is necessary to carry out the finite mapping to the infinite driving environment, so as to extract the typical test scenarios through the driving scenarios database to carry on the simulation test, this method is highly reproducible and can be used for automated testing and accelerated testing.

However, the test scenario alone could not reflect the autonomous vehicle's understanding and adaptability to the scenario, and test cases need to be introduced. The test case is a quantification of the autonomous vehicle's ability to cope with test scenarios, which can evaluate the driving ability of the autonomous vehicle. When developing test cases, as many driving indicators as possible should be quantified according to the design of test scenarios and the driving ability of expected evaluation, so as to establish a more comprehensive test system.

In the third step, the virtual scene in the simulation environment is executed synchronously with the actual scene in the test field. see Fig. 3. The main work of this part is to convert the test cases running in the software simulation environment into the control commands for driving the automatic test vehicle, so that the automatic test vehicle can collect scene data while executing the instructions. Then the performance data of the tested vehicle are also together fed back to the simulation environment through the network layer, so as to realize the closed-loop feedback test effect of virtual-real synchronization.

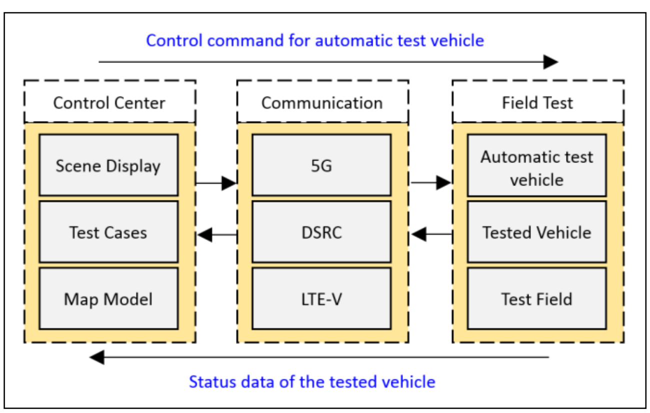

Fig. 3. an illustration of simulation scene displays and synchronous actual test process for autonomous vehicle.

IV. KEY TECHNIQUES OF OPEN VIL TEST

A. construction of typical traffic scenarios

The traffic scenario generally refers to a traffic system composed of traffic participants and a specific road environment. Constructing typical traffic scenarios for autonomous vehicle test can significantly improve the test efficiency, which is an important means for autonomous vehicle testing. At present, the traffic scenario database for the autonomous vehicle test is still not perfect, and the coverage of the test cases is insufficient. The establishment of the scenario database requires many processes, such as scenario data collection, scenario classification extraction, scenario statistical analysis, virtual scenario transformation, etc. Finally, a scenario set that meets the requirements of virtual simulation testing such as HIL, VIL, and MIL should be generated. The data source of traffic scenario should include natural driving data, standard regulations, traffic accident data, etc. It can be seen that the establishment of a typical scenario database is a complex and time consuming project. Part of the process is shown in Fig. 4.

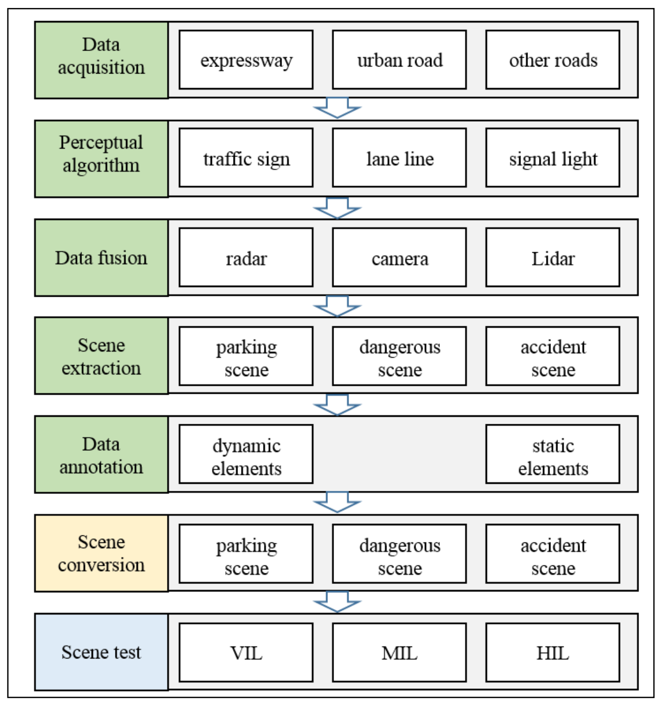

Fig. 4. an illustration of part of the steps in scenario database production process.

According to the test service objects, constructed traffic test scenarios can be divided into functional scenarios, logical scenarios and specific scenarios.

Functional scenarios can be described with natural language, including dynamic traffic participants, static roads and weather elements. Dynamic traffic participants include surrounding traffic participants that have an impact on the vehicle under test, such as motor vehicles and pedestrians. Static road elements mainly include road type, lane number, lane width, road condition, straight, curve, ramp, object lane separation form, line type, traffic signs, special area, etc. Weather elements mainly include sunny days, rain, snow, fog, visibility, day, night, backlight and so on.

Logical scene is the design premise of specific scene. Firstly, according to the statistical analysis of natural driving data, the distribution of relevant parameters of describing scene is obtained. Then, the parameters in the scene are re-sampled to determine the value of key parameters of the corresponding scene, and the specific scene is obtained. It can be obtained through scene extraction, screening and calibration of a large amount of natural driving data, the original scene database adapted to different autonomous vehicle system tests can be obtained.

B. Design of Test Cases

During the test phase, it will be verified that the system meets the specified requirements in the task. This process must be systematically designed, specified, executed, and documented based on the standards.

One difficulty in test case generation lies in the normalization of the input data, Including time sequence of each parameter, Normative description of scenes. and the normative description of the scene is the basis for generating consistent input data. The security requirements need to be specified when defining the scene. first of all, how the system will react to external factors that may affect the safety of the target; secondly, the parameter range that satisfies the system security requirements, in order to generate input data for the test case, the discrete parameter values must be selected from the continuous parameter range of the defined scenario; In addition, the scene must be converted to a normative representation to ensure the enforceability and repeatability of the test case.

In the application, both the simulation and the field test must be used to determine all the parameters needed to execute the test case, and transform the term based on descriptive express into formal expressions based on the system state value. Finally, derive out the parameterized scene systematically. It is used as consistent input parameters to verify the function of the tested autonomous vehicle.

C. The Eastablishment of Test Evaluation Standards

At present, there is no clear standards and methods for the test and evaluation technology of autonomous driving. According to the function range of the evaluation, it can be divided into two stages: single performance evaluation (perception performance, decision-making performance and control performance, etc.) and overall performance evaluation. Through feature extraction, analytic hierarchy process and fuzzy evaluation, the quantitative evaluation of individual performance of autonomous vehicles is realized. Finally, the overall performance of autonomous vehicles is evaluated according to the results of individual evaluation. Here are the specific ideas:

Data mining: the data generated in the automatic driving test is massive, incomplete, noisy and fuzzy. Firstly, data mining method is used to extract the implied effective information and knowledge from the big data. After extracting the effective information of each individual performance of autonomous driving, the machine learning method is used for regression analysis to obtain the regression model of single performance evaluation.

Overall evaluation index weight: according to the results of single performance evaluation of autonomous driving, the weight of single function evaluation index is determined by using extensible analytic hierarchy process. In contrast to analytic hierarchy process, extensible analytic hierarchy process overcomes the ambiguity problem in expert experience judgment and the consistency problem of judgment matrix, which effectively avoids a lot of trial calculation work, and makes the weight of various evaluation indexes of autonomous vehicles more reasonable.

Quantitative evaluation: according to the overall evaluation index weight, the paper adopts the chaotic extensible analytic hierarchy process to conduct quantitative evaluation on the overall intelligence level of autonomous driving vehicles, and then carries out comprehensive evaluation.

V. CONCLUSION

This paper discusses the characteristics of autonomous vehicle test method, and an open VIL test method is proposed on the basis of the VIL test method. It applies the vehicle test of VIL into the real scenes. Firstly, define the test task in the virtual environment, and then map it to actual scenario, finally execute the test cases. Through this process, we can find the most difficult test task. In addition, virtual tests need to be executed synchronously with actual test, which can help us obtain more real test data sets and greatly improve the efficiency and economy of tests.

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