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Autonomous Vehicles Testing Methods Review

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Abstract—**Driving test is critical to the deployment of autonomous vehicles. It is necessary to review the related works since the methodologies summaries are rare, which will help to set up an integrated method for autonomous driving test in different development stages, and help to provide a reliable, quick, safe, low cost and reproducible method and accelerate the development of autonomous vehicle. In this paper, we review the related autonomous driving test works, including autonomous vehicle functional verification, vehicle integrated testing, system validation in different architectures. This review work will be helpful for autonomous vehicle development.**

I. Introduction

Autonomous driving systems are becoming increasingly complex and must be tested effectively before deployment. The assurance of autonomous driving system safety in critical situations is a challenging task, and the concepts and testing process have to be discussed in order to cope with this [1~6]. Currently, there are lots of related works been carried out, from ADAS to automated and autonomous driving tests [7~10]. However, a complete profile for autonomous vehicle testing methodologies is still highly needed during the whole development process, including functional development and testing, system integration and verification, test drive and validation etc.

The virtual or real approaches testing methods used in ADAS and automated driving systems are good references for autonomous driving tests [11,12]. One of these approaches is virtual simulation testing, from simulated sensors, vehicle dynamic model and controller, virtual driver, to simulated comprehensive traffic environment. The function modules are tested by software in the loop (SIL), hardware in the loop (HIL), vehicles in the loop (VEHIL) or mixed simulation methods [13,14]. Another approach is real traffic driving tests. Automated or autonomous driving systems must be secured with hundreds of thousands of FOT kilometers testing [15]. The advantage of the simulation testing is simple, low-cost, and easy to reproduce. However, the testing results reliability is highly depended on the accuracy of simulated sensors, vehicle and environment models. Although on-road testing is very representative, its limited ability to test all critical scenarios due to safety and costs involved is well established and its low efficiency is known[16,17]. Some specific testing centers, like M-City of Michigan University MTC, are ready to test autonomous driving. However, they are closed, simulated, with several selected traffic scenarios and limited testing vehicles. It is difficult to reproduce or simulate the real complex traffic with lots of vehicles or pedestrian interaction.

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With the advantages of these existing testing methods, it is possible to test autonomous vehicles in dangerous situations or failure modes where real traffic testing would be hard; and also possible to test in scenarios that would be difficult to generate or rarely happened in real world; and also some key parameter spaces traversers can be used to find boundary values at which certain failure occurs can be applied in the testing.

This paper reviews the existing methods of autonomous driving functional testing, verification and validation. It will be helpful to set up some reliable, quick, safe, low cost and reproducible testing methods, and accelerate the development. It consists of five sections. The first section is introduction, and the second is autonomous driving testing related methods introduction. The third section is autonomous vehicle functional testing. The fourth section is autonomous vehicle evolutionary testing method. The last is the conclusion.

II. Autonomous Driving Testing Related Methods

Integrated tools suites and methods supported process is crucial to enable cost and time efficient full coverage autonomous driving test, by an effective process with linking available tools from the Intelligent Vehicle related testing technologies [18].

A. Software Testing

The million lines codes in autonomous vehicle require automation functional test on source code level and also require enhanced security of permanently online safety-critical systems. The testing practices could be used, which requires automatically created test cases, hardware-in-the-loop (HIL) testing, change-based testing and the mapping of tests cases to requirements, with aerospace DO178C, ASIL-D level, and ISO26262, similar testing specifications with lots of available test tools, such as revision of Google Test [19].

B. Simulation Testing

High-fidelity simulation is required in autonomous vehicle testing. The dedicated software containing mathematical representation of the subsystems should be used in order to achieve realistic system dynamic, which can be validated with hardware-in-the-loop techniques. High level algorithms for trajectory planning, vision based processing, and multi-vehicles interactions are examples of suitable fields based on game engines [20~22].

Among the vehicle simulators, the most known is probably Racer which is with a very realistic and real time vehicle model, but not with complex sensor models, hard to setup reference scenarios in order to evaluate and validate embedded algorithms. The USARSim high-fidelity open-source simulator is fully compatible with the Player frameworks and Mobility Open Architecture Simulation and Tools (MOAST)

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[23], which implements the Real-time Control System (RCS) reference model architecture, mainly for software-intensive, real-time control robots, hard to manipulate. The CarMaker from IPG is too complex for a real time autonomous driving prototyping in a complex situation with several vehicles and traffic management, or the scene rendering is not realistic enough.

The SUMO and USARSim simulators are used to simulate autonomous vehicle in a traffic environment. However, this software architecture is for the prototype of autonomous vehicle simulation and lacks detailed testing methods elements, especially in driving environmental perception. The PreScan platform from TNO is a typical used in ADAS prototyping [24]. However, it is not enough realistic for control/command applications. The SiVIC platform interconnected with RTMaps platform offers an easy and efficient way to respond to the ADAS prototyping, tests and evaluation and many features are still under development [25,26].

C X-in-the-loop Simulation Testing

The integrated X-in-the-loop simulation testing tool suite includes state-of-the-art simulation platforms for autonomous vehicle, focusing on modelling of phenomenological sensor models, the vehicle with its actuators, the definition of driving scenarios, as well as autonomous driving functions, which provides a novel approach and test architecture to validate the perception systems, planning and control logic of such autonomous vehicles using simulation and virtual techniques.

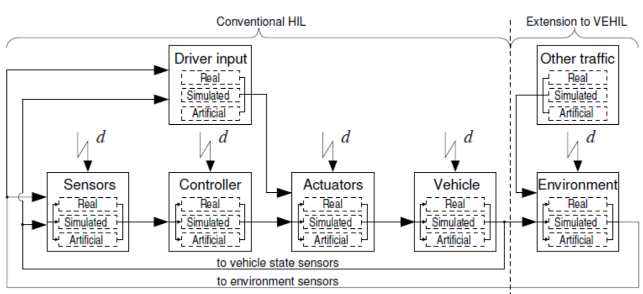

Figure 1. Possible configurations for HIL and VEHIL simulations

Hardware-in-the-loop (HIL) testing is provided for sensor, communication systems, and function modules. The real code can then be verified with Software-in-the-loop (SIL) simulations, where the remaining hardware components, vehicle dynamics, and environment are simulated in real-time [27]. There are different concepts of combining measurements and simulations, X-in-the-loop, as Figure 1 shown, hardware components are connected to the virtual environment, measured and simulated environmental aspects are augmented and aligned in order to test autonomous vehicles on both worlds. Vehicle-in-the-loop (VEHIL) simulations provide a solution for testing a full-scale autonomous vehicle in a HIL environment [28,29].

4) Driving Test in Real Traffic

Autonomous Vehicle driving tests can be carried out in real, open environments. Google driverless cars are mostly tested in real traffic. There are several autonomous vehicle proving ground or testing centers, such as M-City from MTC and iVPC from China [3,30], as Figure 2 shown, used to test new technologies in possible traffic situations and road types. These proving grounds facility consist of several test environments, including urban and rural area, high-speed area, where scenario-based tests can be carried out in a repeatable and structured manner.

Figure 2. M-City and iVPC Overview

Test drives with prototype vehicles are always the final link in the validation chain to evaluate the system's performance in the real world environment that it will finally be used in. Google reports its driverless car testing every month, which is available here [1]. All the existing autonomous vehicles road testing are similar to the way we proposed in this paper [17], test driving by a certain mileage in the typical environments, assess the autonomous driving quality.

Autonomous driving operation depends on interaction with real world physical infrastructure. The road tests can investigate how current transportation infrastructure can be optimized to maximize the potential benefit of the autonomous driving technologies.

In addition, with the practice of several years Intelligent Vehicle Future Challenge (IVFC) competition organization works, we found that, a good methodology to test and validate or assess automated or autonomous vehicles is using real pre-crash scenarios based on experimental data [31,32]. For example, Volvo's pedestrian detection system is evaluated based on real-life accidents.

III. AUTONOMOUS VEHICLE FUNCTIONAL TESTING

A. Autonomous Vehicle System Architecture

The architecture of an autonomous vehicle is based on the general driver behavior, and follows a sensor-based and actuator-based autonomous system architecture, consisting of Perception, Decision and Action Layer, as Figure 3 shown [33,34]. Currently, advanced and new capabilities, such as adaptation and learning, the existing test/validation methods are insufficient. These new challenges require considering established technologies like formal verification [35,36].

As Figure 3 shown, a probabilistic methodology for simulating radar, Lidar or other sensors' data is to increase the simulation's level of realism while maintaining both flexibility and adaptability of simulation-based validation strategies. The probabilistic sensor models are compared with real data in order to evaluate the statistical characteristics of both datasets [37,38].

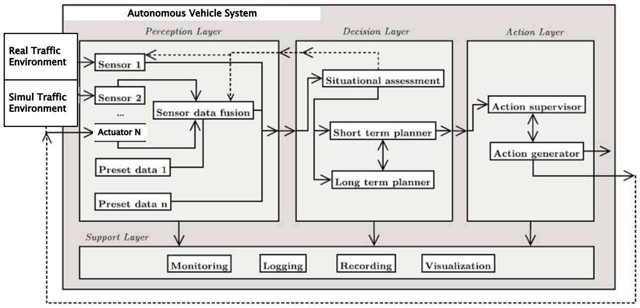

Figure 3. Generic Autonomous Vehicle System Architecture

B. Autonomous Vehicle Functional Testing

1) Perception Layer Functions Testing

The Perception Layer is responsible for the acquisition of all data, from vision, Lidar, or radar based sensors. Then they are merged into a unique fusion map. By physical tests, software test or HIL simulation test, both the various sensors and environment perception layer are tested. The assessment criteria are obtained, including the state and errors of the posture and localization, the detected pedestrians, lanes, traffic signs and lights, other vehicle and other related elements [39,40].

2) Decision Layer Functions Testing

The Decision Layer is fed by the Perception Layer providing feedback data to further optimize the data acquisition and interprets all incoming data from it to generate a reasonable output to the Action Layer. The Situational Assessment provides the input evaluation for short and long term planners; they should influence each other to avoid short term decisions which do not accomplish the overall goal. Artificial Intelligence algorithms are commonly used in the Decision Layer mainly due to the highly non-linear behavior of real environment such as Neural Networks, Machine Learning, etc.

This comprehends the middle level supervision from simple tasks such as follow a line or a path and speed control to more complex tasks such as adjusting speed anticipating a curve or collision avoidance. Evaluation of autonomous vehicle decision making modules is done by way of test drive or simulation test. The driving system reaction characteristic are used for indicators, including reaction time and operating correctness etc.

3) Navigation Layer Functions Testing

The Navigation Layer functions testing are done by test drive or simulation. The navigation level performs higher level tasks related to driving such as controlling the global objectives, trajectory planning, efficiency and commodity, taking into account the driving conditions.

The Path planning error is used for assessment criteria; evaluate the capability of the algorithms to avoid collisions with other objects, at any time.

4) Action Layer Functions Testing

Action Layer receives commands through the Decision Layer into the action supervisor, which sets up the abstract decision into set points to be fed by the actuators' controllers. The action generator denotes the system controllers and performs the low-level actions in the actuators, also monitoring the feedback variables to further process the new actuating variables.

The control level is the lowest level, i.e. the physical control of the vehicle, i.e. the sensors and actuators of the driver's model. It is evaluated by test drive or simulation ways. The vehicle trajectory deviation, acceleration and jitter are used to evaluate this module.

C. Autonomous Vehicle System Validation Approach

Task-Specific autonomous vehicles System validation approach is modeled in functional levels, avoiding the complexities of tremendous algorithms evaluation, similar to Grey-Box testing [17], shown as Figure 4.

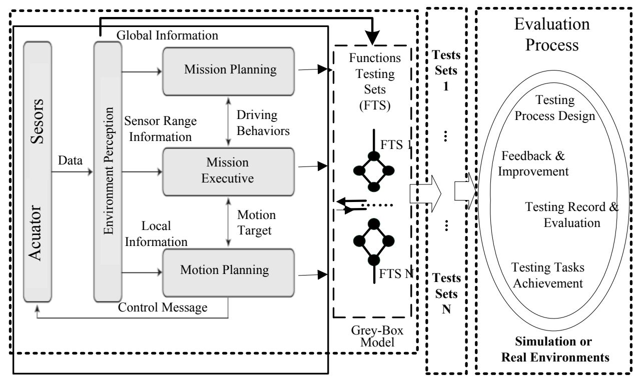

Figure 4. Autonomous vehicle System validation model

By analyzing autonomous driving functions, lists of simple function test cases are selected and assembled into different testing processes, which are further abstracted as driving tasks sets. By analyzing specific driving tasks sets, autonomous driving functions can be evaluated. Autonomous driving tasks tests are carried out under different simulation or real environments. By a formal evaluation process, including tests design, recording and evaluation and completion verification, all driving tasks completion are finally evaluated with different task complexity property and different environment complexities.

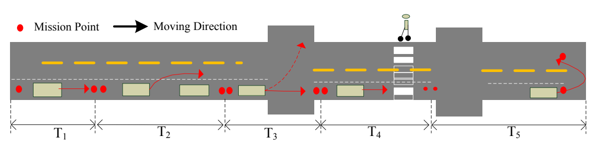

Figure 5. As an example, T1 (On-road Driving), T2 (Overtaking), T3(Turn Left), T4 (Pedestrian Avoidance), T5 (U-TURN) are set along the competition route and divided by mission points.

IV. Autonomous Vehicle Evolutionary Testing Method

A. Autonomous Vehicle Evolutionary Design and Testing Flow

Based on these autonomous driving testing practices and other related works [17], we summed up an Autonomous Vehicle evolutionary design and testing comprehensive flow, as Figure 6 shown.

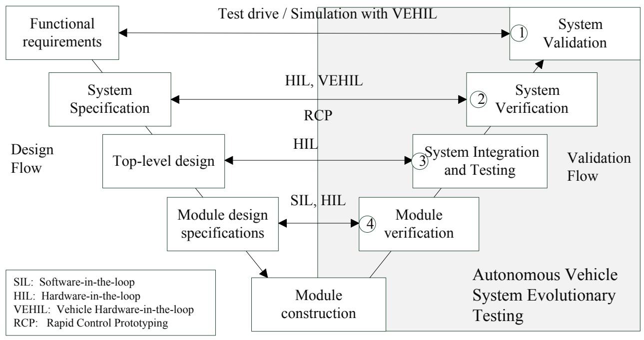

Figure 6. Autonomous Vehicle evolutionary design and testing flow

1) Autonomous vehicle design and system validation

The autonomous vehicle development starts with a definition of the functional requirements in terms of the desired functions, from the basic autonomous driving functional requirements to handle short term and long term planning, avoid dangerous collision and driving safety obey the traffic rules, and with further constraints or requirements on safety, mobility, passenger comfort, and intelligent operational.

The autonomous vehicle validation methods include Test Drive and VEHIL simulation, and the combined evolutionary testing, with feedbacks between the development and testing.

2) Autonomous vehicles system specification and system verification

Autonomous vehicles are safety-critical systems that require a high level of dependability, a term covering reliability, fail-safety, and fault-tolerance. In addition to the system safety, it requires driving safety, identify the safety requirements, with criteria indicators of driving gaps, velocity and trajectory control. At the same time, autonomous vehicles should compliant with the operating efficiency, driving comfort requirements, with criteria indicators of lateral and longitudinal velocity, acceleration and jitter.

From the functional, safety, efficiency and comfortable requirements, an autonomous vehicle system specification is produced to define the precise operation of the autonomous driving system. For example, according to the traffic laws and regulations, as well as traffic conditions, based on the driving safety requirements to make standardized spec. A Model-based testing (MBT) can be used to verify the system, and Rapid Control Prototyping (RCP) method can be used to make rapid prototyping system verification.

3) Autonomous vehicle top level design and system integration testing

The system specification is used as the basis for the top-level design of the system architecture, followed by detailed perception, planning and control modules design with environment sensor, controller, actuator, driver autopilot etc. After implementation of the individual hardware and software modules, system integration takes place by assembling the complete system from its component modules.

In every integration phase, verification takes place to determine whether the output of a phase meets its specification, as illustrated by the horizontal arrows in Figure 6.

4) Autonomous vehicle modules design and modules verification

On the modules level, every function should be tested, to validate the perception systems, planning and control logic of such autonomous vehicles using simulation and virtual techniques and HIL etc. by different novel test approach. On the sensors and perception level, this means testing the range, accuracy, and tracking capabilities of the environment sensor. On the control level, this means testing the vehicle stability and control accuracy. On the planning level, this means the trajectory evaluation against the obstacles and other vehicles.

The hardware controller can be tested in a HIL simulation for its real-time behavior. This limited HIL setup can gradually be extended to include other modules, as the integration of the vehicle progresses.

B. Evolutionary Autonomous vehicle system testing methods

1) Mixed Reality Autonomous Vehicle Testing Methods

The test drives method has its limited, because test results are hard to reproduce and sometime inaccurate, due to hard to get the 'ground truth' state of the obstacles, pedestrians and the other vehicles involved in the test. And for reason of the complexity of the environment, long test mileages are required to form a full coverage of the scenarios [41,42]. To overcome the shortcoming of this method, a solution to combine the advantages of simulations with the representativeness of test drives, by extending the HIL environment from vehicle level to the traffic level, is needed.

When simulating autonomous driving, a necessary component is the simulation of sensors such as radar, lidar, cameras, infrared etc. VEHIL adds value to the development process of autonomous vehicles, with a number of distinct advantages. Tests with VEHIL are performed in a reproducible and flexible way with high accuracy, safer, allow autonomous vehicles to be tested in safety-critical scenarios, and allow precise and repeatable variation of test parameters.

There are several simulation and test drive mixed methods for reference. The mixed reality platform is built on Marvin autonomous vehicle and the Autonomous Intersection Manager (AIM) simulator. By this approach, the mixed reality autonomous intersection scenario is simulated and tested [43]. The Hybrid simulation tool VIVUS (Virtual Intelligent Vehicle Urban Simulator) consists of both hardware in the simulation loop and/or software simulation in the hardware experimental loop [44].

With these approaches, the costs of the validation process are reduced, because many tests are performed in a short time frame with a high success rate. VEHIL facilitates the transition from simulations to outdoor test drives that are used to evaluate the real performance and dependability on the road. These test drives can be performed with a much higher confidence and less risk, when the autonomous vehicle has already been thoroughly tested in VEHIL model.

2) Using Mixed Reality Methods to Accelerate Autonomous Vehicle Testing

Autonomous highest level validation is to test drive in virtual or real environment for a certain mileage. It is therefore important to perform validation of the integrated system against its requirements. Usually, the development process involves several iterations, where the results of verification and validation are used to modify the system specification and design, after which another test cycle takes place, as Figure 6.

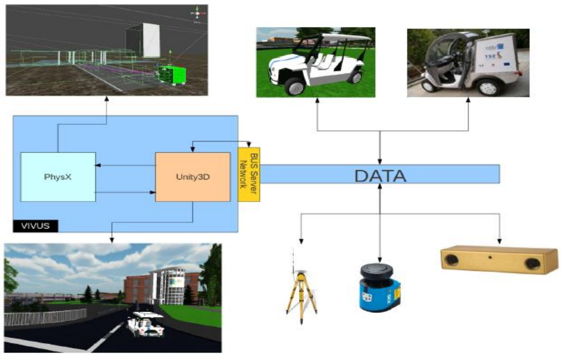

Figure 7. Mixed Reality Testing Methods (VIVUS architecture)

Obviously, there is a need to speed up the process. Because of the need for fast, flexible and reproducible test results, various Mixed Reality Testing Methods are increasingly being used [44], and a new evolutional testing method to accelerate the development process is clarified, as Figure 8 shown, we propose an Evolutionary Autonomous vehicle system testing method.

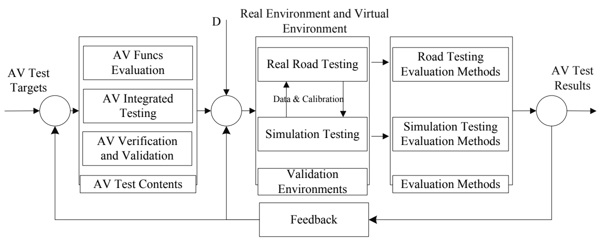

Figure 8. Evolutionary Autonomous vehicle system testing method

The simulation testing environments are based on real traffic environment with 3D data collection and modeling, as Figure 7 shown. But the simulation testing environments can be modified and configured according to the actual testing requirements. And the simulated vehicles are with accurate dynamic model and various types sensor.

Figure 9. Building Simulation testing environments from real traffic

The validation is firstly carried out in simulation environment (built from real traffic, as Figure 9 shown), achieved by mixed simulation testing methods. Then carry out the driving test in the corresponding real environment. Therefore, the simulation models of various components can be corrected with feedback, therefore, overcoming the problem of simulation model inaccuracy. Since the simulation environment can be easily reconstructed and configuration with scenario auto generation tools (as Figure 10 shown), it is a good way to solve the problem of the full coverage of traffic scenarios. Furthermore, autonomous vehicle performance in the traffic accident scenarios can be simulated and evaluated; it is very helpful to autonomous driving development.

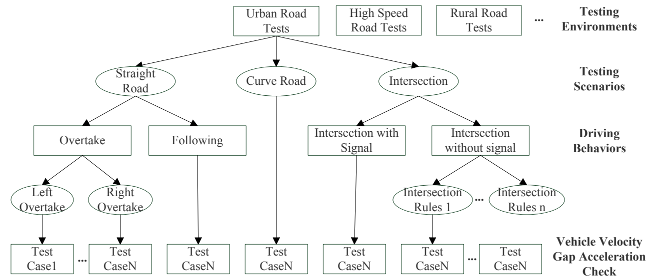

Figure 10. Autonomous vehicle Testing Cases Generation

Traditional testing methods cannot keep pace with the large number of situations required for autonomous driving validation. This method is applied in simulated environments and runs and evaluates thousands of simulated scenarios autonomously. Ongoing classification of the past results and intelligent search methods allow identification of new candidate scenarios that are likely to lead to critical situations that were not adequately covered by past tests. Furthermore, the full coverage testing rate can be proved and the accelerated testing methods can be discussed in this framework.

V. CONCLUSION

Autonomous vehicle testing is critical to the deployment of autonomous vehicles. It is necessary to integrate the existing methods, bring out a set of methods for autonomous driving testing for different stages of development process, and provide reliable, quick, safe, low cost and reproducible testing methods to accelerate the development. In this paper, we review the current related works, and summarize autonomous vehicle functional modules verification and integrated testing, autonomous vehicle system validation methods, and propose an evolutionary autonomous vehicle testing method, which is still under developing. Especially, the proof of full coverage test rate and the accelerated testing methods should be further discussed in our next papers.

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