International Journal of Science and Engineering Applications
Volume 15-Issue 09, 42 – 45, 2026, ISSN:- 2319 - 7560
DOI: 10.7753/IJSEA1509.1006

Research and Development of Hardware-in-the-Loop Testing Platform for Autonomous Vehicles

Yibo Yang
School of Automobile and Low-Altitude Vehicle
Zibo Polytechnic University
Zibo, Shandong, China

Abstract: Addressing the industry pain points of high cost, significant risk, incomplete scenario coverage, and poor repeatability in real-world autonomous driving testing, this paper develops a highly adaptable, high-precision, and scalable Hardware-in-the-Loop (HIL) testing platform for autonomous vehicles. The testing platform integrates real-world vehicle braking systems, steering systems, sensor systems, and network communication systems, providing a complete hardware-in-the-loop simulation environment for the entire vehicle.

Keywords: autonomous driving; hardware-in-the-loop; test platform

1. INTRODUCTION

With the rapid iteration of intelligent connected vehicle technology, Level 2 (L2) assisted driving has achieved large-scale mass production, and Level 3 (L3) and Level 4 (L4) high-level autonomous driving have gradually entered the stage of implementation and verification[1]. The autonomous driving system integrates multi-module functions including perception, decision-making, planning and control, with complex operating conditions and extremely high safety redundancy requirements. Its performance and reliability directly determine vehicle driving safety. The implementation and application of autonomous driving functions rely on massive test and verification work. The traditional testing method is dominated by real-vehicle road testing, which can restore real road conditions, but has obvious limitations: first, extreme dangerous scenarios and rare traffic conditions are difficult to reproduce on site, leading to insufficient scenario coverage; second, real-vehicle testing is interfered by weather, road conditions and driver status, resulting in poor test repeatability and low data consistency; third, the test cycle is long, the labor and operation & maintenance costs are high, and there are significant safety risks, which cannot adapt to the test requirements of rapid iteration of autonomous driving algorithms[2-3].

Hardware-in-the-loop simulation testing, as a semi-physical simulation technology between pure virtual simulation and real-vehicle testing[4], connects real on-board hardware into the closed-loop virtual simulation system. It takes into account both simulation efficiency and test authenticity, can efficiently complete repeatable tests for multiple scenarios and multiple working conditions, and has become the core means for the development and verification of autonomous driving systems.

2. Overall Technical Scheme

The self-developed autonomous vehicle hardware-in-the-loop test platform takes dSPACE (Matlab/Simulink) as the core to build a controller rapid prototyping platform. Based on the PreScan software, it provides virtual reality interfaces and environment perception sensor modules, uses the CarSim software to run the vehicle dynamics model in real time, and integrates the real-vehicle braking system, steering system, sensor system and network communication system, providing a rapidly verifiable platform for autonomous driving algorithm testing. This test platform can be applied to the development and testing of upper-level autonomous driving control algorithms and underlying actuators, the development and testing of Advanced Driving Assistance Systems (ADAS) such as ACC/AEB/LKA, driver behavior characteristic research, and human-machine co-driving system development. The overall architecture is shown in Figure 1.

Figure 1 Autonomous driving hardware-in-the-loop platform framework

The autonomous driving hardware-in-the-loop platform framework is mainly divided into five parts: the upper computer (PreScan), the perception and decision-making computing platform (PX2 & Linux), the domain controller, the lower computer and the hardware platform. The upper computer mainly runs the PreScan software and human-machine operation interface. PreScan, on the one hand, provides a virtual reality interface to generate approximate real test working condition scenarios for autonomous driving, and on the other hand, provides environment perception modules including millimeter-wave radars and cameras for autonomous driving. PreScan sends raw sensor data to the perception and decision-making computing platform (PX2 & Linux) through the CAN network. The perception and decision-making computing platform processes and calculates the raw sensor data and carries out path planning. The domain controller receives path planning signals, conducts decision judgment, and sends braking, steering and throttle signal commands to the bottom layer through the CAN network. The hardware part of the domain controller is dSPACE MicroAutoBox, which receives signals collected by underlying sensors, provides real-time vehicle state parameters to the algorithm module, and can realize rapid controller prototyping. The lower computer is dSPACE MicroAutoBox, which runs the CarSim vehicle dynamics model in real time, and realizes real-time signal communication between underlying hardware and software. The hardware platform is mainly the underlying actuators, namely the real vehicle, which is based on the hardware part of the original vehicle braking system and steering system, to realize the steering and braking system hardware-in-the-loop.

3. Upper Computer (PreScan)

PreScan can realize scene construction, including environment models, road models, weather and sunlight[5]. Among them, the environment models include pavement and roadside facility databases, traffic signs, buildings and so on; the road models include moving vehicles, pedestrians and the like; the weather and sunlight section covers weather conditions, light sources and other related parameters, as shown in Figure 2.

Figure 2 Scenario Setting

PreScan can provide sensor simulations, mainly including single-binocular cameras, millimeter-wave radars, LiDARs and lane line sensors with different precisions. These sensor models provide accurate environment perception modules for the verification of autonomous driving algorithms, and improve the authenticity of test working condition environments for the autonomous driving hardware-in-the-loop test platform, as shown in Figure 3.

Figure 3 Sensor module

4. Perception and Decision-Making Computing Platform

NVIDIA Drive PX2 is selected as the perception and decision-making computing platform, with a data processing capacity of 24TOPS. It is based on the 16nm FinFET process, with a maximum power consumption of 250W, adopts a water-cooled heat dissipation design, and supports 12 channels of camera input, laser positioning, radar and ultrasonic sensors.

5. Domain Controller

This technical scheme includes a chassis integrated domain controller based on multi-objective optimization, which aims to establish a transmission mechanism from decision-making and planning in autonomous driving to actuator control commands.

The hardware of the domain controller is based on dSPACE MicroAutoBox, which can realize rapid controller prototyping. The controller is equipped with a 1401 single-core processor with a frequency of 900MHz, supporting DS15113 module, DS1514 module and DS4342 module, and is configured with 6 CAN channels, 32 analog input (AI) ports, 8 analog output (AO) ports, 24 digital input/output (DIO) ports and 2 CAN FD channels.

Figure 4 Micro AutoBox

The domain controller is implemented based on Matlab/Simulink, delivered in the form of independent Simulink program modules with open source codes, and has complete definitions of input and output interfaces.

The list of input signals for the domain controller is as follows:

Table 1 Domain controller input signal

Input Interface	Signal Source	Signal Communication Type	Remarks
Target Path	Decision-Making and Planning Layer	CAN	
Safety Domain	Decision-Making and Planning Layer	CAN	The safety area based on the target path
Path Deviation	Perception Layer	CAN	Lane curvature, heading angle, lateral deviation, etc.
Driver Takeover Signal	Perception Layer	CAN	Identify whether the driver intervenes
Vehicle Absolute Coordinates X, Y	Perception Layer	CAN	GPS signals
Vehicle Speed Signals Vx, Vy	Perception Layer	CAN	Sensor measurement / state observation
Acceleratio	Perception	CAN	Integrated

n Signals a_x, a_y, $\dot{\varphi}$	Layer		sensors
Vehicle Body Pose	Perception Layer	CAN	Gyroscopes / inertial navigation

The list of output signals from the domain controller is as follows:

Table 2 Domain controller output signal

Output Interface	**Signal Target**	**Signal Communication Type**
Target Braking Pressure	Brake-by-wire System	CAN
Target Torque	Engine Control System	CAN
Target Steering Wheel Angle	Steer-by-wire System	CAN

6. CarSim

The CarSim software conducts modeling based on vehicle assembly characteristics, and the simulation data has high credibility. It mainly provides the vehicle dynamics model for testing for the autonomous driving hardware-in-the-loop test platform. Users can customize and set vehicle parameters, including tire parameters, vehicle parameters, dynamic performance parameters and other related parameters.

When using CarSim, the first step is to configure the vehicle model: select appropriate model configurations, input operations, simulation environments and conditions according to actual needs. After configuration, the simulation calculation of the model can be carried out. The calculated results are sent to the underlying actuators through the lower computer to perform corresponding actions. The signals collected by sensors are fed back to the CarSim model for data analysis and processing[6]. The simulation results can be stored in multiple data formats for convenient analysis. At the same time, the built-in drawing function of CarSim can easily realize data visualization.

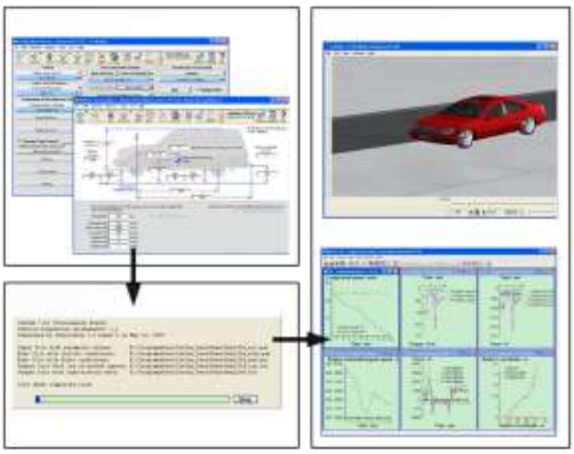

Figure 5 CarSim visualization interface

7. Underlying Actuators

The underlying actuators of the autonomous driving hardware-in-the-loop test platform integrate the real-vehicle braking system, steering system, sensor system and network communication system, which can provide a complete vehicle-level hardware-in-the-loop simulation environment, as shown in Figure 6.

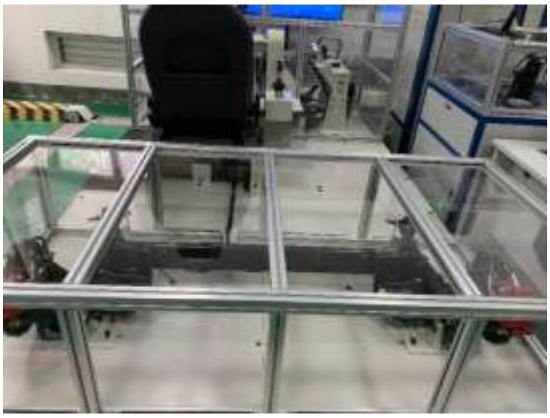

Figure 6 Physical image of the underlying layer of the autonomous driving hardware-in-the-loop testing platform

In this platform, the signal collection of control algorithms mainly relies on its powerful and accurate sensor system, including pressure sensors, angle sensors and other types of sensors. The control instructions calculated in the control algorithm cycle are sent to the underlying actuators through various interfaces, including braking pressure request interface, steering angle request interface and engine torque request interface.

In addition to the real-vehicle platform, the hardware part also includes a high-definition wide screen placed above the engine compartment, which communicates with PreScan and is used for virtual reality interface display. The lower computer, which is dSPACE MicroAutoBox, provides abundant digital, analog and CAN interfaces to realize real-time signal interaction of underlying actuators.

Conclusion

Aiming at the shortcomings of traditional autonomous driving testing methods, this paper independently develops a modular, high-precision and high-real-time autonomous vehicle hardware-in-the-loop test platform. By constructing a four-layer overall architecture and completing the integrated design of software and hardware systems, it solves key technical problems such as multi-sensor signal synchronization, accurate reproduction of extreme scenarios, and real-time interaction of virtual-real closed loops. Experimental verification shows that the real-time performance, stability and test accuracy of this platform all meet the testing and algorithm development requirements of L2-L4 level autonomous driving systems. It can fully cover conventional working conditions and high-risk extreme scenarios. Compared with traditional testing methods, it significantly reduces testing costs, improves test efficiency and scenario coverage, and effectively makes up for the limitations of real-vehicle testing.

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