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Original Paper

Optimized Design of Instrument Test Platforms for Industrial Sites

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Abstract

Instrument test platforms for industrial sites are key means to improve product quality, shorten R&D cycles, and support reliability verification. This paper systematically elaborates on the overall architecture and functional modules of such platforms, proposes an optimized design strategy based on virtual instrumentation, parameter optimization, multi-physics simulation, and remote monitoring, and discusses the implementation paths of key technologies such as fault injection, power management, and digital twin integration. Through engineering cases of power equipment and automotive ADAS test platforms, the effectiveness of the platform in improving testing accuracy, efficiency, and safety is validated. Looking ahead, test platforms will continue to evolve toward intelligence, digitalization, and modularization, becoming essential support systems for industrial intelligent testing and collaborative verification. The research presented in this paper provides a theoretical basis and practical reference for the design and implementation of test platforms under complex operating conditions.

Keywords

Instrument test platform, Virtual instrument, Multi-physics simulation, Parameter optimization, Industrial automation

1. Introduction

With increasing demands on product performance and reliability in industries such as power systems and automotive engineering, on-site testing and verification have become increasingly critical. Traditional testing methods often rely on single instruments or manual operations, resulting in limitations such as single functionality, low efficiency, and poor scalability (Yang, 2009). To ensure stable operation of equipment under real working conditions, it is necessary to develop integrated instrument test platforms that combine sensing, measurement and control, and data analysis, enabling parameter acquisition and design optimization. Practical applications have demonstrated that such platforms significantly improve efficiency and data reliability in testing motors, power electronics, and automotive components.This paper focuses on the system architecture, functional design, and optimization methods of test platforms, verifies their effectiveness through engineering applications, and discusses future development trends.

2. System Architecture and Functional Module Design

Industrial test platforms typically adopt a modular and layered architecture, consisting of the unit under test (UUT), measurement and control units, data management systems, and human–machine interfaces. As shown in Fig. 1, the system generally includes an upper-level control/algorithm layer, a lower-level execution and measurement layer, and an environmental/working-condition simulation layer (Sun, Ding, Li et al., 2019). The upper layer executes control algorithms and issues commands, while the lower layer—comprising loading mechanisms and sensors—performs control and measurement tasks. The environmental layer simulates real loads and operating conditions, enabling reproduction of real-world scenarios in laboratory settings.This architecture integrates the concept of Hardware-in-the-Loop (HIL), combining real hardware with virtual models to form a closed-loop testing system. The platform is typically centered on an industrial computer or programmable measurement and control chassis, using high-speed acquisition cards and bus interfaces to manage input/output signals of various instruments.

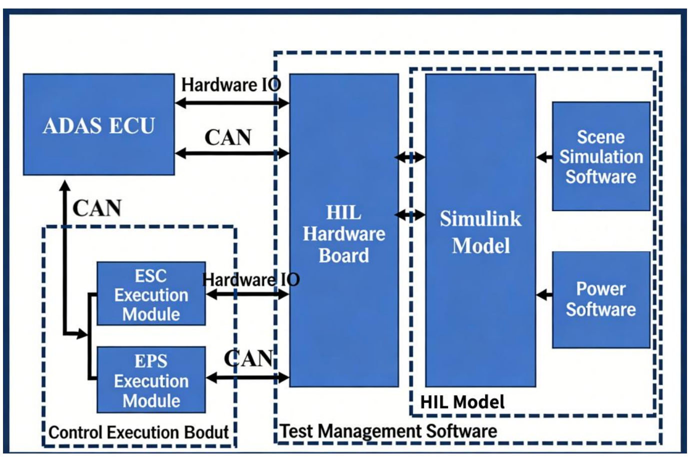

Figure 1. Schematic Diagram of the System Architecture of an Industrial Test Platform

Main Functional Modules

A typical instrument test platform includes the following core modules:

1) **Unit Under Test (UUT)**: the equipment to be tested, such as motor prototypes, switchgear, automotive components, etc. Its parameter range determines the measuring range and load configuration of the platform.

2) **Measurement and data acquisition module**: composed of sensors, measuring instruments and acquisition systems, which measure key indicators such as voltage, current, temperature, rotational speed, force/torque in real time. To avoid aliasing distortion, the sampling rate should satisfy the Nyquist theorem, that is, the sampling frequency f_s should satisfy $f_s \geq 2f_{max}$.

3) **Control and execution module**: composed of industrial controllers, drivers and actuators, used for load control, working condition switching, etc., to ensure the stable execution of the test process.

4) **Data analysis and management software**: realizes test configuration, real-time monitoring, data recording and visualization, and supports remote/local storage, abnormal alarm and automatic report generation functions.

Typical Characteristics: The optimally designed test platform has the characteristics of multi-function, high precision and good scalability. Its modular design supports flexible switching of different test objects and interfaces; high precision is guaranteed by advanced sensing and high-speed acquisition technology; the platform is equipped with safety mechanisms such as emergency stop, limit protection and electrical isolation to meet the long-term stable operation requirements of industrial sites.

3. Optimal Design Method and Key Technology Implementation

The optimal design of industrial test platforms needs to balance performance, cost and reliability, usually through software-hardware coordination and integration of key technologies to achieve overall optimization. The following explains from four aspects.

3.1 Virtual Instrument and Software-Defined Testing

Modern test platforms widely adopt the virtual instrument architecture, which constructs general measurement hardware into a configurable system through graphical programming environments (such as LabVIEW) and standard buses (such as GPIB, PXI) (Zhang, Wang, & Sun, 2008). This method realizes convenient function expansion, simplified operation and later upgrade, supports the addition of test items and optimization algorithms on demand, and improves the flexibility and automation of testing.

3.2 Key Parameter Optimization Design

In the design of the test platform, it is necessary to optimize key parameters such as sampling frequency, controller parameters, load configuration and test sequence to balance accuracy and efficiency. Common methods include orthogonal experimental design, response surface analysis and intelligent optimization algorithms. For example, Gao Ge et al. used orthogonal design to optimize the parameter combination of the electric shock test platform and reduce the incidence of malfunction. Such methods analyze the influence of factors through a small number of representative test combinations, and then construct an objective function to achieve multi-objective optimization:

$$\min_{x} F(x) = \omega_1 T(x) + \omega_2 C(x) - \omega_3 Q(x)$$

where $\min_{x} F(x)$ represents the set of design parameters (such as sampling rate, control algorithm parameters, etc.), $T(x)$ is the time consumption of a single test, $C(x)$ is the cost overhead, $Q(x)$ is the test quality or accuracy index, and $\omega_1, \omega_2, \omega_3$ is the weight coefficient used to balance efficiency, cost and accuracy. When focusing on reliability, a life index can be introduced. For example, the reliability $R(t)$ in the life cycle T satisfies:

$$R(t) = \exp(-\lambda t), \quad \text{MTBF} = \frac{1}{\lambda}$$

where λ is the constant failure rate. This optimization framework supports controlling costs and improving platform durability while meeting accuracy requirements.

3.3 Multi-Physics Simulation and Digital Technology

To accurately simulate complex working conditions, multi-physics simulations such as electromagnetic-thermal-mechanical and digital twin technology are introduced in the design stage. Through finite element modeling, sensor layout and control strategies can be optimized to improve platform adaptability. The platform is usually equipped with a high-performance computing unit, which supports data filtering, spectrum analysis and fault diagnosis, realizes real-time prediction and feedback of equipment operating status, and assists product iteration and reliability evaluation.

3.4 Key Technology Implementation

The optimally designed test platform integrates a number of key technologies to improve the comprehensiveness and effectiveness of testing. Among them, fault injection and safety testing technologies are particularly important. The platform has a built-in fault injection module, which can simulate typical fault modes (such as short circuit, open circuit, sensor failure, etc.) to verify the fault tolerance of the tested object and diagnosis algorithms. As shown in Figure 2, an automotive electronic test platform switches circuits through a relay matrix to realize open-circuit and short-circuit simulation of ECU input/output, and detects the protection response of the controller. Such technologies are widely used in automotive electronics and power protection equipment test platforms, which can effectively expose potential defects under abnormal working conditions and provide a basis for product improvement.

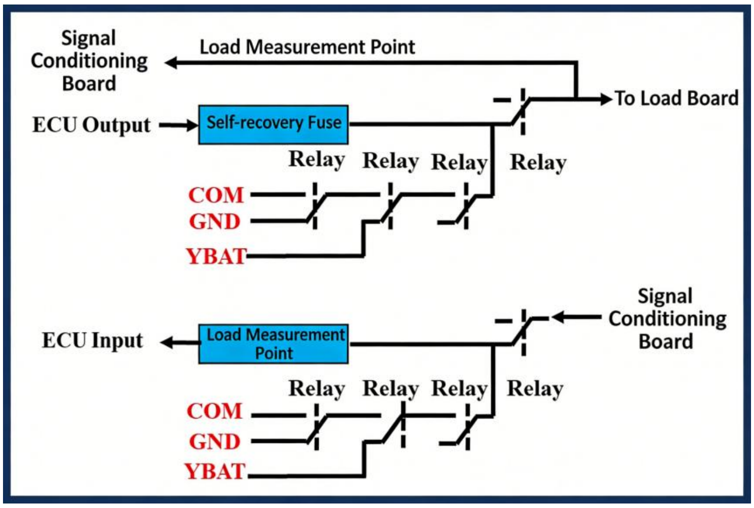

Figure 2. Schematic Diagram of the Fault Injection Module

Another key technology is power supply and load control. The platform needs to provide programmable power supplies and loads for electrical UUTs to meet different voltage and current working conditions and ensure stable and safe power supply. As shown in Figure 3, a power test platform integrates load switches, circuit breakers and multi-channel adjustable DC power supplies, supports automatic switching of power supply configurations, and can provide multiple voltage levels (such as ±15 V, 5 V, 12 V, etc.) to the measurement and control system and the tested equipment at the same time. The system has overload protection and emergency power-off functions to ensure test continuity and safety.

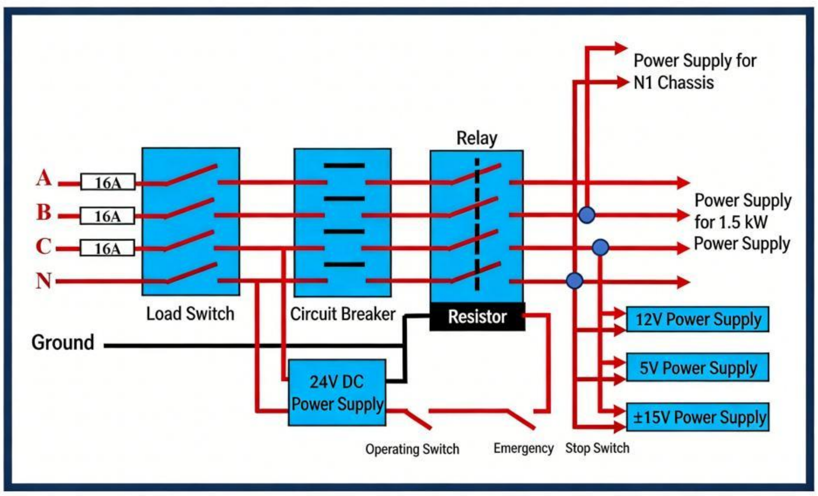

Figure 3. Schematic Diagram of Power Management and Distribution Module Design of the Test Platform

At the same time, the platform has remote monitoring and cloud interconnection capabilities. With the help of industrial Internet of Things technology, test data can be encrypted and uploaded to the cloud, viewed and adjusted in real time by remote engineers, and combined with big data analysis and machine learning to complete equipment performance prediction and maintenance decisions. For example, the on-line power monitoring platform can automatically detect abnormal trends and trigger remote tests, effectively realizing the transformation from passive detection to active prevention.

In summary, with the above optimization methods and integration of key modules, modern instrument test platforms can efficiently cope with complex test tasks and support product R&D, reliability verification and industrial application.

4. Engineering Application Cases and Performance Verification

To verify the effectiveness of the above optimal design, the engineering implementation and performance improvement effects of the test platform are explained below combined with typical application cases in the electric power and automobile industries.

Figure 4. Hardware Physical Map of an Industrial Field Test Platform (Gao, Li, Zhang et al., 2019)

Case 1: Comprehensive Test Platform for Power Equipment.A power company has built a comprehensive test platform integrating loading, current, temperature rise and remote monitoring according to the on-site test requirements of high-voltage switchgears. The platform supports synchronous testing of mechanical characteristics, electrical performance and temperature rise tolerance: displacement sensors and laser velocimeters measure operating time and speed, current sensors monitor contact temperature rise and voltage drop in real time, and data are centrally displayed and recorded through a remote system. Engineers used orthogonal experimental design to optimize test condition combinations, such as contact pressure, operating voltage and ambient temperature. After multiple iterations of the platform, the measurement accuracy was improved by 5%, the time of a single test was shortened by about 30%, and the overheating hidden dangers that could not be found by traditional tests were successfully identified. All data are centrally managed and traceable queries are realized, which significantly improves test efficiency and automation.

Case 2: Automotive ADAS HIL Test Platform.An automobile manufacturer built an HIL platform based on a PXI real-time system, integrated vehicle actuators and CAN communication modules, and combined with CarSim and PreScan software to build a "driver-vehicle-road" closed-loop simulation environment. The platform supports functional tests such as ACC and AEB, reproduces typical Cut-in scenarios, and realizes the coupling of real vehicle response drive and virtual simulation. Figure 5 shows the vehicle speed and distance change curves during the simulation. Tests show that the platform can accurately evaluate the safety and comfort of the control strategy: when the deceleration is too small, the host vehicle cannot adjust the distance in time, and collisions can be effectively avoided after parameter optimization. Through multiple rounds of simulation and algorithm iteration, the engineering team improved the braking comfort of ACC by about 15%, shortened the test cycle by about 50% compared with traditional road tests, and avoided the safety risks of early road tests (Sun, Zhou, Liu et al., 2013).

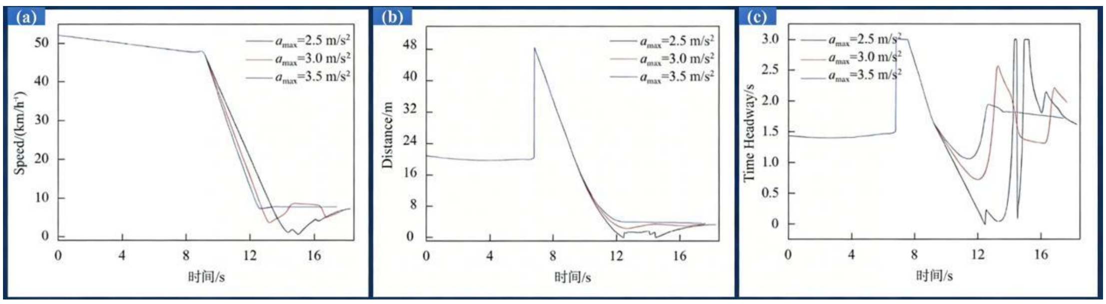

Figure 5. Speed-distance Curves of Vehicle Following Process Obtained by Simulation test [2]: (a) Vehicle speed vs. time curve; (b) Vehicle distance vs. time curve; (c) Time headway vs. time curve

The above cases show that the optimally designed test platform has excellent effects in engineering practice. Whether it is power equipment verification or automotive system testing, the customized platform can provide a high-fidelity environment and accurate data, find problems that are difficult to detect by traditional methods, and promote product improvement and upgrading. Test verification and feedback form a key closed loop in the R&D process, which has become an important part of modern industrial testing.

5. Conclusion and Prospect

The instrument test platform for industrial sites is an important support to improve product quality and accelerate the R&D process. This paper analyzes the system architecture, functional modules and optimal design methods, and combines cases in the electric power and automotive industries to verify its significant advantages in improving test efficiency, data accuracy and automation.

Looking into the future, the test platform will evolve deeply toward intelligence and digitization.First, artificial intelligence and big data analysis will enable the platform to have self-optimization and fault diagnosis capabilities.Second, digital twin will realize virtual mapping and predictive testing and reduce physical costs.Third, the platform will become more standardized and modular, quickly adapting to different products and test requirements.Fourth, relying on 5G/6G and industrial Internet of Things, remote collaborative testing will become the norm, improving cross-regional R&D efficiency.

Overall, the instrument test platform will continue to evolve under the background of Industry 4.0 and intelligent manufacturing, and become a core tool supporting the development and quality assurance of complex systems. By continuously optimizing the platform architecture and introducing new technologies, future testing will be smarter and more efficient, helping engineering innovation to continuously reach new heights.

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