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Secure, Scalable Infrastructure for Hardware-in-the-Loop Testing

WHITE PAPER

In this whitepaper, nVent SCHROFF explores the evolving role of HIL in modern system design, with a focus on the essential infrastructure that supports reliable, scalable, and high-performance test environments.



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Embedded systems are becoming increasingly complex, integrating advanced electronics, control logic, and interconnected software components. At the same time, engineers are designing for a broadening range of real-world conditions. Traditional methods of product development and validation struggle to match the speed and sophistication required to keep pace with modern innovation.

Simulation-based testing rises to the challenge, offering engineers smarter, faster, and safer ways to evaluate system performance. Hardware-in-the-Loop (HIL) testing is a powerful methodology that bridges the gap between purely virtual simulations and full physical prototypes.

HIL testing allows physical hardware, such as embedded controllers or electronic control units (ECUs), to interact with real-time simulated environments for early validation of functional behavior, control logic, and system integration under highly realistic conditions.

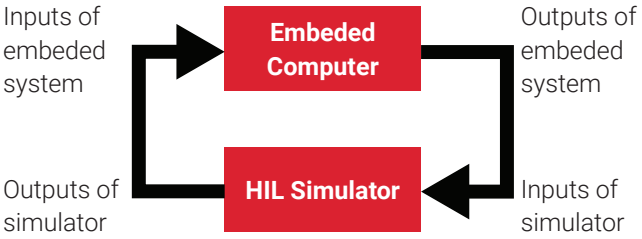
With growing demand for high-fidelity testing across industrial sectors, HIL testing is emerging as a critical component of advanced product validation. This paper explores the foundations of HIL testing, its growing relevance, and how system infrastructure decisions can help engineers unlock the full potential of their HIL testing systems. It also outlines how infrastructure choices, often overlooked, directly impact reliability, test coverage, and scalability in modern HIL testing.

Understanding HIL Testing in Modern Embedded System Validation

At its core, HIL testing is a simulation-based methodology that enables physical hardware to operate within a real-time virtual environment. The simulated environment includes the rest of the system that the hardware would normally interact with in a finished product. For example, an automotive ECU may be tested using HIL while "driving" through a simulated terrain with real-time weather and road conditions. The goal is to ensure that the physical hardware reacts correctly and consistently to the stimuli it would encounter in a real-world scenario.

HIL testing ensures that embedded systems behave as intended, even under edge-case conditions or stress states. This is especially important for safety-critical applications in autonomous driving, aerospace flight control, medical device development, or industrial automation, where malfunction can lead to catastrophic consequences. HIL testing detects faults or deviations and helps to isolate issues early, preventing costly recalls and reputation damage.

Core Elements of HIL Testing Systems



A complete HIL testing setup involves a combination of hardware and software that work together to simulate, monitor, and analyze the behavior of a device under test (DUT).

The key components typically include:

- **Real-Time Computer System:** Executes the simulation model with sub-millisecond latency and ensures deterministic, repeatable behavior for accurate validation.
- **Device Under Test (DUT):** Represents the hardware being evaluated, typically an embedded controller, sensor suite, or subsystem.
- **I/O Interfaces:** Provides real-time communication between the DUT and simulation system via channels such as CAN, LIN, or Ethernet.
- **Signal Conditioning and Power Infrastructure:** Delivers and distributes the appropriate power levels and conditions signals for safe and accurate interaction between components. This is especially important when simulating sensors or actuators under varying load conditions.
- **Fault Injection:** Simulates abnormal conditions to evaluate system resilience and verify safety-critical responses.
- **Human-Machine Interface (HMI) and Data Acquisition:** Enables operator interaction, test monitoring, and logging of simulation results.

HIL testing is a vital quality assurance tool across multiple high-stakes industries, each with unique performance and safety demands:

- **Automotive:** For validating ECUs, Advanced Driver Assistance Systems (ADAS), battery management systems (BMS), and motor and inverter controllers.
- **Aerospace:** In avionics testing, including radar platforms, flight control systems, and navigation and communication systems.
- **Industrial Automation:** For Programmable Logic Controllers (PLCs), robotic controllers, and safety-critical machinery.
- **Energy and Renewables:** In power inverter testing, grid-interactive systems, and smart metering.
- **Medical Devices:** For validating embedded systems in patient monitoring systems, infusion pumps, imaging equipment, and surgical automation.

Key Benefits of HIL Testing in Development and Design Verification Testing

With HIL testing, engineers can validate functionality and compliance earlier in the development cycle by safely and repeatedly simulating real-world conditions that are difficult, dangerous, or impossible to reproduce using prototypes. This proactive approach helps teams uncover hidden issues and refine system behavior before field deployment.

HIL testing offers several critical advantages that enhance product readiness:

Risk Reduction

By allowing teams to detect faults like timing mismatches or control anomalies, HIL testing prevents these issues from becoming deeply embedded in larger, more complex systems. It also empowers engineers to simulate rare but critical failure scenarios (e.g., signal dropout, intermittent sensor behavior, or power disruptions) without putting physical hardware or test operators at risk. These fault injection capabilities are essential for stress-testing safety mechanisms under conditions that would be difficult or dangerous to reproduce in the real world.

HIL testing contributes to safer and more efficient validation by replacing high-risk physical trials with controlled, repeatable virtual tests. For instance, simulating a failure in braking logic during a virtual drive removes the hazard of live testing while still validating system performance. These tests also support compliance with rigorous industry standards, like ISO 26262 for automotive functional safety and IEC 61508 for industrial control systems, to help organizations meet regulatory demands and streamline certification processes.

Enhanced Testing Fidelity and Coverage

HIL testing elevates the quality and completeness of validation with complex, multi-variable scenario modeling. With the help of real-time operating systems (RTOS), optimized simulation software (e.g., MATLAB/Simulink), and high-speed modular platforms (such as PXI/PXIe) for latency management, HIL testing allows engineers to observe and analyze how a DUT will perform in near-real-time. Meeting strict real-time constraints is essential for accurately replicating time-dependent interactions where a millisecond-level response can impact overall system stability.

Scalability and Flexibility

As mentioned above, modularity gives engineers the flexibility to tailor test systems precisely to their current goals without overcommitting resources or rebuilding infrastructure from the ground up. Whether engineers are validating a single ECU or orchestrating tests across a network of interconnected subsystems, HIL setups can be scaled accordingly. For example, an automotive test bench might begin with a single powertrain ECU and scale to include ADAS controllers, battery management systems, and multiple sensor interfaces across a distributed test rack. Teams can integrate new communication protocols or channels, fault injection tools, and environmental simulation modules without requiring a complete redesign.

A well-designed HIL testing system can also be replicated across sites, reused for future projects, or shared between teams to maximize investment, improve consistency, and reduce redundant setup efforts.



Cost Efficiency

This virtual-first approach to testing lowers the financial and logistical burden traditionally associated with system integration and iterative testing and enables high-throughput testing.

Engineers can execute thousands of test cases, including edge and environmental scenarios, in rapid succession. This includes varying voltage inputs, extreme temperature profiles, signal jitter, and mechanical stress simulations. HIL systems can also be scaled over time by adding new channels, cases, or modules to support growth without major reinvestment.

Faster Time to Market

HIL testing accelerates product development by enabling thorough validation during hardware-software integration and design verification. This insight allows for faster iteration and more efficient debugging throughout development. In later stages, HIL also supports the verification of hardware revisions and late-stage updates to maintain momentum without compromising reliability.

Modern HIL platforms streamline this process with real-time data logging, automated test execution, and standardized reporting, reducing manual setup time and accelerating issue resolution across the test cycle.

The Role of Infrastructure in Effective HIL Testing Systems

While much of the focus around HIL testing systems centers on simulation models and software platforms, the physical infrastructure is critical. Without robust and adaptable infrastructure, even the most advanced simulation logic can be hindered by integration issues, overheating, inconsistent power delivery and distribution, or physical layout constraints.

HIL infrastructure encompasses the enclosures, chassis, power systems, cooling solutions, and physical interfaces that house and protect the sensitive electronics running real-time simulations. When HIL systems grow more modular and denser, the supporting infrastructure must provide flexibility, reliability, and safety without adding unnecessary complexity.

With decades of experience in electronic infrastructure, nVent SCHROFF brings proven technical expertise to HIL testing environments. We don't supply the simulation software or write the test logic, but we specialize in the systems that surround them. This deep expertise positions us to help engineering teams recognize what to look for in high-performance HIL infrastructure.



Enclosures

HIL testing systems often involve a mix of PXIe chassis, embedded controllers, signal conditioning modules, and DUT interfaces. These demand physical space, structured cable routing, and proper airflow to ensure safe and stable operation.

Modular cabinet architecture allows users to select cabinet dimensions, including height, width (e.g., standard 19" or extended 800 mm), and depth, around the specific size and density of their hardware configuration. Further, cable management accessories reduce clutter, protect cables from damage, and optimize the use of available space within the enclosure. Modularity is especially beneficial for complex, multi-module HIL testing systems, where traditional rackmounts may fall short.

HIL test cabinets are typically open by design to support easy hardware access, airflow, and maintenance. While this open configuration may reduce system-level shielding, shielding is handled at the chassis level within PXIe platforms or individual case enclosures. This approach prevents external interference from compromising test results or creating safety risks.

Equally important is long-term availability and support. HIL testing infrastructure designed today should accommodate tomorrow's scaling needs. nVent SCHROFF's mechanical platform consistency ensures that replacement parts and accessories remain available years into the future.

Integrated Power Solutions

HIL testing power infrastructure must provide reliable, safe power distribution across a range of DUT types, from low-power sensors to high-current motor controllers. In scenarios involving safety-critical systems (e.g., automotive braking ECUs, energy storage controllers), HIL testing may include edge-case fault injection, overload simulation, or high-throughput cycling. Without a robust, well-isolated power backbone, these tests can yield misleading results or even allow a flawed unit to pass undetected.

With support from the right power supply, nVent SCHROFF's Power Distribution Units (PDUs), equipped with integrated safety functions, can support loads up to 63 A. This makes them well-suited for power-demanding procedures like battery cycling, while protecting the DUT and test hardware for repeated use. These can include short-circuit conditions, power supply drops, or overcurrent events, all of which help validate how the system responds under stress without damaging connected components. Additionally, nVent SCHROFF's PDUs are designed to support multiple power connection interfaces for different power connectors, including C14 and C20.

Thermal Management

HIL testing often involves high-duty cycles and continuous runtime. Simulation computers, real-time I/O systems, and DUTs generate significant heat, particularly in dense or compact builds. Left unchecked, thermal load can degrade performance, reduce hardware lifespan, or trigger test instability.

The Role of Infrastructure in Effective HIL Testing Systems

Effective thermal management begins with cabinet design. nVent SCHROFF enclosures support equipment-level cooling and fan modules that deliver targeted airflow where it's needed most. In some use cases, and particularly for HIL platforms validating high-speed processors or sensitive circuitry, chip-level cooling solutions may be required. These can include localized heatsinks, directed airflow ducts, or liquid cooling loops.

Without adequate cooling, heat buildup can distort signal timing, degrade power integrity, or cause thermal drift in sensitive measurement circuits. nVent SCHROFF's compatibility with a variety of component cooling strategies ensures that thermal considerations don't impact test results.

Integration and Brand Consistency

Pre-configured enclosure and power systems can reduce setup time and lower engineering overhead. Look for a range of pre-integrated solutions that combine enclosures, power, cooling, and cable routing into a custom turnkey package to simplify system-level integration.



When visual presentation and system branding matter, consider customizing your HIL testing infrastructure with relevant logos and color schemes for a polished and unified system appearance.

Checklist: Infrastructure Essentials for High-Performance HIL Testing

When evaluating or designing infrastructure for HIL testing systems, look for:

- **Modular Cabinets** – Wide range of enclosure options to support evolving test configurations and to accommodate multiple chassis types, even if they weren't originally designed for a 19" rack integration
- **Shielded Chassis** – PXIe systems, subracks, and cases with integrated EMI protection to ensure equipment compatibility and reliable function
- **Scalable Power Distribution** – PDUs with integrated safety controls and configurable, scalable load handling
- **Thermal Management** – Chassis-level cooling with optional 19" fan trays or chip-level cooling to support demanding thermal requirements
- **Cable Routing** – Organized power and signal paths to save cabinet space, maintain airflow, and simplify troubleshooting
- **Custom Branding Options** – Enclosures and front panels that reinforce a consistent, professional brand appearance
- **Pre-Configured and Custom Options** – Reduce build time and streamline deployment with pre-configured and custom solutions

HIL Workflow Transformation

Remote access and cloud-connected management are transforming traditional HIL workflows. By enabling engineers to monitor, control, and run simulations from geographically distributed locations, organizations reduce the dependency on local lab access and streamline collaboration. In automotive applications, remote HIL setups now support globally distributed software teams, improving test coverage and enabling continuous validation workflows, like the Remote HIL (RHIL) framework pioneered by Ford Motor Company and Mindmotiv.

In energy research, the U.S. National Renewable Energy Lab demonstrated remote HIL for microgrid controller validation in hopes of providing flexible testing access for those looking to test energy technologies at full power in a real-time grid simulation.

Artificial intelligence (AI) is also emerging as a force innovation in HIL testing. AI-enhanced control algorithms and automated anomaly detection reduce manual oversight, optimize test sequences, and adapt simulation parameters in real time. AI models take a dynamic approach to detecting signal anomalies in real time, optimizing test sequences based on failure history, and adjusting simulation fidelity. Researchers are even using HIL testing to help validate AI-enabled control systems, like this example in building system control.

As HIL testing intersects with digital twin technologies, cloud-based orchestration, and evolving compliance frameworks, infrastructure must evolve to support higher data fidelity, interoperability, and continuous operation.

Secure, Scalable, Streamlined HIL Infrastructure

Across all sectors, from automotive and energy to telecommunications, defense, and medical devices, teams that leverage HIL testing face similar challenges: increasing model complexity, tighter real-time constraints, evolving safety standards, and the need for broader test coverage.

Addressing these issues isn't just about simulation software. Without robust infrastructure, even the most advanced HIL environments are vulnerable to inefficiencies, integration delays, and safety risks.

With over 60 years of experience in electronic infrastructure, nVent SCHROFF brings deep domain expertise to the design of high-reliability systems that support evolving HIL testing requirements. From enclosures, subracks, and open-standard system platforms to integrated power distribution and thermal management, nVent SCHROFF infrastructure is engineered for flexibility, customization, and long-term scalability.

We work closely with engineering teams to understand and address system-level constraints such as thermal load, cable routing, and equipment footprint. This proactive approach helps ensure HIL testing systems are compact, efficient, and straightforward to integrate. Whether the challenge involves dense component layouts, high-power DUTs, or AI-enabled validation loops, nVent SCHROFF infrastructure scales alongside innovation to support performance, safety, and system integrity.

nVent SCHROFF's approach supports these demands with configurable, standards-compliant enclosures, scalable power systems, and high-performance thermal management—all engineered for integration into complex, fast-evolving test environments.

By minimizing infrastructure-related bottlenecks and enabling faster configuration changes, nVent SCHROFF helps engineering teams maintain focus on what matters: validating performance, meeting compliance targets, and bringing safer, smarter technologies to market with confidence.

At nVent SCHROFF, we don't just provide enclosures; we create solutions that protect, connect, and make HIL systems possible – so you can test the future.

Is your HIL testing infrastructure ready to support your next production release? Connect with nVent SCHROFF to discuss your specifications and explore infrastructure solutions tailored to your HIL testing environment at:

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