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Enhancing Verification Strategies for Modern Embeded Systems

Laila DAMRI
ENSA of Berrchid, First Hassan University, Morocco
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Abstract: *Achieving high-quality software during development is more effective than attempting to correct defects post-production. Verification and validation (V&V) are essential throughout the software lifecycle, ensuring that development outputs meet design specifications and that the final product satisfies user requirements. Verification confirms adherence to functional and structural standards, while validation ensures correct behavior in real-world scenarios. Early integration of V&V reduces errors, lowers development costs, and enhances reliability. This paper reviews recent research on verification techniques and outlines strategies to improve the process. Key approaches include model-based design, formal verification, automated testing, hardware-in-the-loop simulation, and continuous integration, which collectively enable early defect detection and robust system validation. Emphasis is placed on systematic feedback, coverage metrics, and performance monitoring to strengthen verification outcomes. By adopting these methods, developers can ensure software correctness, efficiency, and alignment with user expectations. The discussion provides practical insights for both practitioners and researchers seeking to optimize verification practices, ultimately contributing to the production of dependable, high-quality embedded and general-purpose software systems.*

Keywords: *Assertion Monitoring, Embedded Software, Formal Verification, High-Level Testing, System Validation*

I. INTRODUCTION

Embedded systems are specialized computing systems designed to perform dedicated functions within larger mechanical, electrical, or electronic systems. They typically combine hardware components such as microcontrollers, microprocessors, and embedded computers with software components that provide functional and logical control. Hardware provides the computational capacity and interfaces to interact with sensors, actuators, and communication networks, while software governs the system's behavior, processes inputs, executes control logic, and produces outputs. In many embedded applications, the software component represents the most complex aspect of development in terms of time, cost, and integration challenges.

Embedded software can be divided into two main layers. The basic or low-level software is responsible for hardware initialization, configuration, communication with peripherals, and real-time task scheduling. It ensures that all hardware components operate reliably and cohesively. The application-level software processes sensor data, applies control logic, executes algorithms, and generates outputs that define the system's observable behavior. Both layers must work together seamlessly to ensure correct system operation.

Developing real-time, large-scale embedded systems introduces numerous challenges, including strict timing constraints, concurrent task management, fault tolerance, resource limitations, and the need for high reliability and safety. Verification and validation (V&V) are critical throughout the software development lifecycle to ensure the system meets functional requirements, complies with industry standards, and behaves correctly under all operational scenarios. V&V strategies include formal verification, model-based design, hardware-in-the-loop testing, automated test suites, and continuous integration.

The complexity of embedded system design and integration underscores the need for comprehensive development frameworks and tools that link all stages of software development. Such frameworks reduce interface and integration complexity, enhance traceability, and improve overall system reliability. This paper synthesizes research in embedded software development and verification, highlighting techniques and best practices to enhance efficiency, correctness, and robustness in real-time embedded applications.

II. Challenges in Embedded Software Verification

Embedded software verification presents unique challenges due to the tight interaction between software and hardware, real-time constraints, and system complexity. Unlike general-purpose software, embedded systems often operate under strict timing requirements, where delayed or missed responses can lead to system failure. Ensuring that tasks execute within deadlines requires rigorous real-time verification and precise timing analysis.

Concurrency is another major challenge. Embedded systems often run multiple tasks simultaneously, including sensor data acquisition, control logic execution, and communication with external devices. Verifying the correct behavior of concurrent processes requires careful modeling and analysis to detect race conditions, deadlocks, or priority inversion issues.

Large-scale systems introduce additional complexity. As systems grow, the number of modules, interfaces, and dependencies increases exponentially, making integration testing and system-level verification more difficult. Ensuring traceability from requirements to implementation becomes critical to identify and resolve errors efficiently.

Resource limitations, such as limited memory, processing power, or energy constraints, further complicate verification. Software must be optimized to meet functional and performance requirements while remaining reliable under resource constraints.

Finally, safety-critical and high-reliability applications, such as automotive, aerospace, or medical devices, require compliance with strict industry standards (e.g., ISO 26262, DO-178C, IEC 62304). Verification must not only detect functional errors but also ensure adherence to regulatory requirements.

Addressing these challenges requires a combination of formal verification, model-based design, automated testing, simulation, and hardware-in-the-loop approaches, supported by tools that enable traceability, reproducibility, and comprehensive coverage across the development lifecycle.

III. Research Review

Research on embedded systems verification has evolved significantly over the past two decades, focusing on improving software reliability, reducing verification time, and addressing the increasing complexity of real-time systems. Many studies emphasize that traditional testing alone is insufficient for ensuring system dependability; instead, a combination of formal verification, model-based approaches, and automated validation techniques is required.

Formal verification methods

Formal verification methods, including model checking, theorem proving, and abstract interpretation, have been extensively studied and applied to embedded systems to ensure correctness and reliability at the design level. These techniques rely on mathematical models to verify that a system satisfies its specifications, rather than relying solely on empirical testing. Clarke et al. [1] introduced model checking as a formal approach to automatically explore all possible system states using state-transition models. This allows engineers to detect logical inconsistencies, deadlocks, or timing violations early in the development process, well before hardware integration or field deployment. The method has proven particularly effective for verifying control logic, communication protocols, and safety-critical behaviors in real-time systems.

Similarly, Kroening and Strichman [2] expanded the scope of formal verification by integrating symbolic model checking and SAT/SMT-based decision procedures, enabling more efficient exploration of complex state spaces. These advancements have made formal verification more practical for embedded software, where timing precision and determinism are essential. However, despite their precision and exhaustiveness, formal methods remain computationally intensive, as the state-space explosion problem limits their scalability for large or highly concurrent systems. Therefore, recent research has focused on combining formal verification with simulation and testing to achieve both completeness and feasibility in real-world applications.

Model-Based Design (MBD)

Model-Based Design (MBD) has emerged as one of the most effective approaches to improving verification and validation in embedded system development. It allows engineers to design, simulate, and verify system behavior at a high level of abstraction before implementation. According to Baresi et al. [3] and Piziali [4], MBD integrates specification, simulation, and testing within a unified framework, reducing the gap between system requirements and implementation. Instead of writing code first, developers construct executable models that represent both the functional and temporal behavior of the system. These models can then be simulated to validate performance, logic, and timing under a variety of operating conditions.

A major advantage of MBD is its ability to identify design flaws early in the development cycle, thus minimizing costly errors discovered during later stages. By using tools such as Simulink, Stateflow, and SystemC, designers can create accurate models of control systems, communication interfaces, and real-time operations. These models support automatic code generation, ensuring consistency between the verified model and the final embedded software. Furthermore, integrating formal verification techniques with MBD enables automatic checking of model properties such as safety, liveness, and timing constraints.

Research has shown that MBD significantly improves productivity and quality while reducing development time. It provides traceability from requirements to implementation and promotes early validation

through simulation-based testing. As Baresi et al. [3] highlight, combining MBD with continuous integration and automated testing can form a robust framework for developing complex embedded systems that are both reliable and maintainable.

Hardware-in-the-Loop (HIL)

Hardware-in-the-Loop (HIL) Testing has become a vital component in the verification and validation of embedded systems, bridging the gap between simulation and real-world implementation. It enables developers to test embedded software in real time by connecting it to actual hardware components or their emulated counterparts. This approach allows for comprehensive system evaluation under realistic conditions without exposing the physical system to risk. As Chen et al. [5] explain, HIL testing integrates real hardware interfaces such as sensors, actuators, and communication buses into the simulation environment, providing a controlled yet dynamic platform for system verification.

Through HIL simulation, engineers can observe how embedded software responds to real-time stimuli, validate timing constraints, and evaluate system performance under different operating scenarios. It is particularly effective in safety-critical domains, such as automotive systems, aerospace control, and industrial automation, where early-stage hardware faults or software timing errors can have severe consequences. According to MathWorks [6], HIL environments using tools like Simulink Real-Time and dSPACE platforms allow continuous iteration between model simulation and physical testing, ensuring consistency and early fault detection.

Furthermore, HIL testing supports regression analysis, automated fault injection, and robustness evaluation, making it a key technique for verifying embedded controllers and communication protocols. It also complements Model-Based Design (MBD) by enabling seamless transition from simulated models to hardware-integrated validation. In recent studies, combining HIL with continuous integration pipelines has been shown to significantly accelerate verification cycles and enhance overall system dependability.

Automated Testing and Continuous Integration (CI)

Automated Testing and Continuous Integration (CI) have emerged as essential practices in modern embedded software development, significantly improving reliability and reducing verification time. Traditional testing methods for embedded systems often involve manual execution, hardware setup, and result analysis processes that are time-consuming and prone to human error. To address these limitations, Gao et al. [7] proposed an automated testing framework that integrates simulation-based testing, unit testing, and regression analysis within a CI pipeline. This framework allows developers to execute multiple test suites automatically whenever code changes are committed, ensuring immediate detection of integration faults and functional regressions.

Kim et al. [8] demonstrated that adopting CI tools such as Jenkins, GitLab CI, and Bamboo in embedded projects can streamline the development workflow by enabling automated build, deployment, and verification processes. These systems can integrate with hardware simulators and test benches, allowing verification to occur even before physical prototypes are available. The inclusion of automated unit and integration tests helps maintain software quality throughout the development lifecycle, especially in large-scale projects where multiple teams contribute concurrently.

Recent studies reinforce these findings: Klooster et al. [9] showed that fuzzing techniques integrated into CI/CD pipelines improve defect detection efficiency, while Nirek [10] reported that CI/CD pipelines enhance software quality and delivery speed in Linux systems.

Overall, automation and CI provide a systematic, scalable, and traceable verification strategy that supports the growing complexity of embedded systems. When coupled with formal methods and HIL testing, these techniques form a robust foundation for continuous assurance of software correctness and system reliability.

Together, these approaches formal verification, MBD, HIL, and CI/CD form a multi-layered, complementary verification framework. By combining mathematical assurance, simulation, hardware validation, and automated testing, embedded systems developers can ensure reliability, safety, and performance while managing growing complexity and development scale.

Diagnosis in Embedded Systems

Diagnosis plays a critical role throughout the lifecycle of embedded systems, from development to deployment. During the manufacturing phase, diagnostic techniques identify faults related to assembly, calibration, and component quality, enabling improvements in production processes. In the operational phase, diagnostics detect intermittent or latent faults, allowing timely corrections and maintaining system uptime. Moreover, diagnostics reveal errors linked to design or manufacturing imperfections, supporting updates to existing devices particularly software updates for on-board controllers and guiding improvements for future

device versions. The tools, methods, and objectives of diagnostics vary depending on the lifecycle stage and the specific application domain, highlighting the necessity for flexible, scalable diagnostic strategies [11].

Assertion-Based Verification (ABV)

Assertion-Based Verification represents a paradigm shift in embedded system design and verification. Moving from informal, natural-language specifications to mathematically precise and verifiable properties allows automation and improves testbench efficiency. An ABV platform consists of:

Verifiable test plans through property specifications.

Hardware Verification Languages (HVLs) integrated with property specifications to generate higher-abstraction testbenches.

Coverage-driven reactive testbenches based on assertions.

Automated block-level stimulus generation using interface constraints.

Exhaustive or semi-exhaustive formal verification techniques.

Property specification and automatic extraction are central to ABV, enabling intelligent testbenches that systematically check functional correctness and coverage [12].

Proven-Correct Monitors from PSL Specifications

Monitors synthesized from Property Specification Language (PSL) assertions observe input signals and verify conformance to temporal properties. Both weak and strong FL operators of PSL are implemented and formally proven correct using theorem proving. The prototype automatically generates RTL-level VHDL monitors, which can be linked to the Design Under Verification (DUV) for simulation, emulation, or online testing. These monitors allow real-time detection of property violations, storage of signal histories, and waveform analysis for debugging [13].

From Assertion-Based Verification to Assertion-Based Synthesis

Assertion-Based Synthesis extends ABV by transforming temporal properties into correct-by-construction hardware components. Each property becomes an extended-generator, combining monitoring and stimulus generation capabilities. By hierarchically connecting verified components, designs are synthesized directly from PSL specifications, guaranteeing correctness at RTL level. Tools like SyntHorus automate this process, producing efficient reference models suitable for equivalence checking or direct tape-out. This approach significantly reduces design and verification effort while maintaining formal guarantees of correctness [14].

Generation of Hardware Monitors in High-Level Synthesis (HLS)

In HLS, high-level assertions can be projected into synthesizable hardware monitors, integrated into the generated RTL architecture. Assertions are translated into low-level hardware descriptions, preserving functionality during simulation and enabling static verification. Monitors verify block-level behavior and allow early error detection before simulation or emulation. Integrating assertion management into the HLS flow ensures that verification properties are maintained throughout the hardware generation process, improving reliability and traceability [15].

Automated Generation of Checker Units from Hardware Assertion Languages

The research proposed in [16] explores extending assertion-based verification from simulations to runtime hardware monitoring, which is particularly valuable for **safety-critical embedded systems**. By automatically generating checker units from hardware assertion languages, verification can be accelerated and integrated directly into the system's hardware. The study presents existing tools, related approaches, and two practical use cases to benchmark effectiveness. It also discusses challenges, potential pitfalls, and limitations when translating software assertions into hardware implementations. The work concludes with suggestions for future improvements and research directions to enhance automated runtime verification.

IV. Proposed Improvements

Based on the analysis of current verification techniques and their limitations, several improvements can be proposed to enhance the verification of embedded systems, making it more efficient, reliable, and adaptable to increasingly complex designs.

Hybrid Verification Strategy

A flexible verification framework can dynamically select methods based on module importance and system complexity. Critical modules, such as safety controllers or timing-sensitive components, can employ formal verification techniques like model checking or theorem proving to guarantee correctness. Less critical

modules can rely on automated simulation, CI pipelines, or regression testing to reduce computational overhead. This approach balances the need for mathematical assurance in critical areas with efficiency in less sensitive parts of the system.

Adaptive Assertion Management

Assertions are central to detecting errors early, but static assertion sets can become outdated or redundant. An adaptive system would automatically generate and prioritize assertions throughout development based on historical fault data, system changes, and code coverage analysis. Obsolete or low-impact assertions could be retired, while new high-value assertions would be added. This dynamic management improves verification efficiency and ensures that resources focus on the most critical functional checks.

Intelligent Runtime Monitoring

Runtime monitoring can go beyond fault detection to include prediction and early warning of potential failures. By incorporating real-time system data, statistical models, or lightweight AI algorithms, runtime monitors can identify abnormal patterns or early indicators of hardware or software faults. This proactive monitoring reduces unplanned downtime, supports preventive maintenance, and improves system resilience.

Integrated HIL-CI Feedback Loops

Integrating hardware-in-the-loop (HIL) testing with continuous integration pipelines ensures that hardware-software interactions are verified continuously. Feedback from physical tests can automatically adjust simulation parameters, test scenarios, and assertion sets. This integration reduces the gap between simulation and reality, allowing teams to detect and correct interface or timing issues earlier in the development process.

Cross-Domain Verification Dashboard

A centralized verification dashboard can consolidate results from multiple verification techniques, including assertion-based verification (ABV), high-level synthesis (HLS) monitors, CI pipelines, formal verification, and runtime monitoring. This platform provides traceability across verification stages, highlights areas requiring additional attention, and enables more informed decision-making. Such dashboards improve communication across teams and streamline verification management for large, complex systems.

AI-Assisted Formal Verification

Applying AI techniques to formal verification can optimize the exploration of system states and proof paths. For instance, machine learning algorithms can identify high-risk execution paths, prioritize them for model checking, and reduce unnecessary exploration of low-risk scenarios. This approach maintains formal correctness guarantees while lowering computational costs, making it feasible to apply formal methods to larger, more complex systems.

Implementing these strategies collectively can create a verification ecosystem that is scalable, intelligent, and resilient, capable of handling the increasing complexity of embedded systems while reducing verification time, improving fault detection, and enhancing system reliability.

V. Conclusion

The verification of embedded systems is a critical aspect of modern hardware-software design, directly impacting system reliability, safety, and performance. As systems grow in complexity, traditional verification methods manual testing, simulation, and ad-hoc debugging are no longer sufficient. This paper reviewed a spectrum of verification approaches, including assertion-based verification (ABV), high-level synthesis (HLS) monitors, continuous integration (CI) pipelines, runtime monitoring, and formal verification techniques. Each method addresses specific challenges, such as fault detection, functional correctness, hardware-software integration, and timing assurance, but also exhibits limitations when applied independently, particularly in large-scale or real-time systems.

To address these challenges, this work proposes an integrated and adaptive verification framework. Hybrid verification strategies can allocate formal methods to critical components while using automated testing for less sensitive modules, balancing rigor and efficiency. Adaptive assertion management ensures that verification remains focused on the most relevant and high-impact properties. Intelligent runtime monitoring introduces predictive fault detection, reducing downtime and improving system resilience. Additionally, combining CI pipelines with hardware-in-the-loop (HIL) testing creates continuous feedback loops, bridging the gap between simulation and real-world operation. Centralized dashboards consolidate verification results across multiple tools and stages, enhancing traceability and decision-making. Finally, AI-assisted formal verification can optimize the exploration of system states, reducing computational cost while preserving correctness guarantees.

By implementing these improvements, embedded system verification can evolve into a more scalable, proactive, and reliable process, capable of handling complex designs while reducing defect detection time and ensuring compliance with stringent functional, timing, and safety requirements. These strategies collectively lay a foundation for developing sophisticated, high-confidence embedded systems for diverse industrial, automotive, medical, and consumer applications.

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