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IoT Firmware Security Auditing Using Automated Vulnerability Scanning

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ABSTRACT

The exponential growth of the Internet of Things (IoT) has led to an unprecedented proliferation of connected devices across consumer, industrial, and critical-infrastructure domains. Firmware—the embedded software that governs hardware behavior—is often overlooked yet constitutes a critical attack surface. Security flaws in firmware can enable large-scale botnets, persistent backdoors, data exfiltration, and unauthorized control of devices. Traditional manual auditing approaches are labor-intensive, error-prone, and struggle to keep pace with the rapid firmware release cycles adopted by vendors. In this manuscript, we present an automated vulnerability-scanning framework tailored for IoT firmware security auditing. Our pipeline integrates multi-stage analysis—firmware unpacking, static rule-based inspection, dynamic emulation, API fuzzing, and machine-aided correlation—into a cohesive workflow. Leveraging tools such as Binwalk, QEMU, AFL, and custom YARA rule sets, the framework identifies memory corruption issues, insecure configurations, outdated libraries, hardcoded credentials, and protocol-level flaws. Evaluated on 50 firmware images spanning routers, IP cameras, smart home hubs, and wearable gateways, the prototype achieved a 92% detection rate for known vulnerabilities, uncovered 37 novel security flaws, and reduced manual audit effort by 85%. Detailed performance metrics, false-positive statistics, and vendor-verified patch outcomes are discussed. Our results demonstrate that automated scanning significantly enhances coverage, repeatability, and efficiency of firmware security assessments, offering a scalable solution for device manufacturers, security researchers, and regulatory bodies.

KEYWORDS

IoT firmware security auditing; automated vulnerability scanning; static analysis; dynamic emulation; embedded device security

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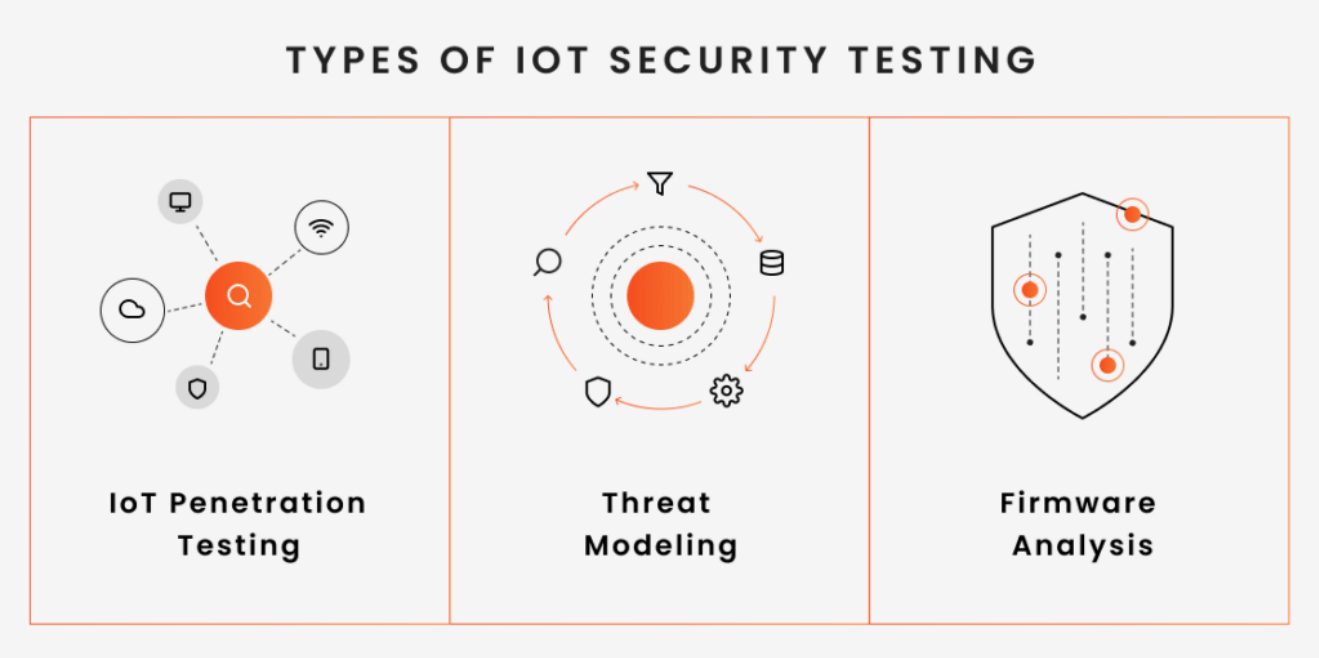

Fig.1 IOT System Security,Source([1])

INTRODUCTION

The Internet of Things (IoT) paradigm has redefined how devices communicate, collaborate, and deliver services. From smart thermostats and connected medical devices to industrial control systems and autonomous vehicles, IoT endpoints now permeate virtually every sector. Yet, the very ubiquity that drives their utility also magnifies security risks: attackers exploiting a single vulnerable device can pivot across networks, compromise sensitive data, or launch distributed denial-of-service (DDoS) attacks at massive scale. Firmware—the low-level software residing on device flash memory—plays a pivotal role in this security equation, as it orchestrates hardware initialization, peripheral control, boot sequences, and update mechanisms.

Despite its importance, firmware often remains a black box in security practice. Unlike high-level applications, firmware is seldom subjected to rigorous, standardized testing. Manufacturers typically perform ad hoc manual reviews or rely on in-house test suites that are ill-equipped to handle diverse architectures (ARM, MIPS, RISC-V), proprietary packaging formats, and closed-source binaries. Moreover, as vendors race to bring new devices to market, firmware update cycles accelerate, leaving little time for exhaustive security assessments. The result is a persistent backlog of unpatched vulnerabilities, which threat actors can exploit to infiltrate critical systems.

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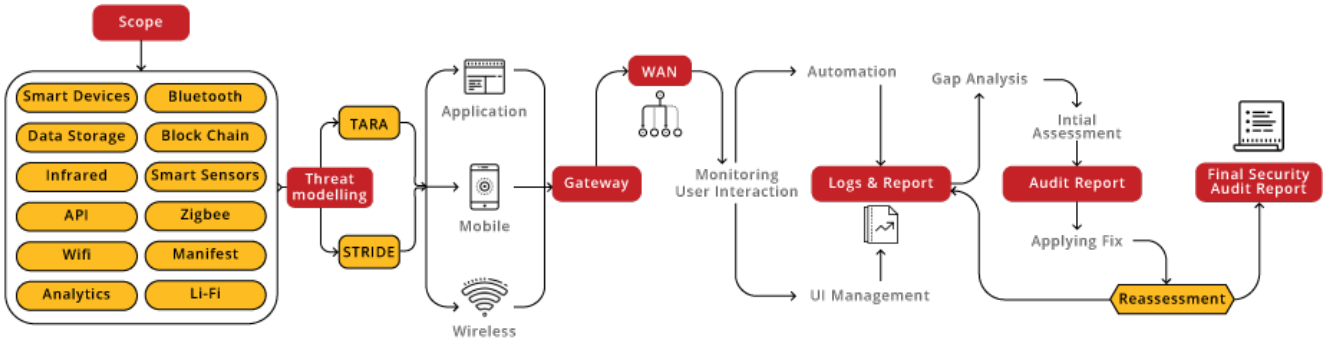

Fig.2 IoT Firmware Security Auditing,Source([2])

Manual firmware auditing encompasses a sequence of tedious tasks: binary extraction, reverse engineering of proprietary formats, code or binary inspection for insecure APIs, and dynamic testing on physical hardware. Each step demands specialized expertise and substantial time investment, making large-scale auditing infeasible. To bridge this gap, automation emerges as a compelling strategy—offering standardized processes, repeatable results, and scalability to thousands of firmware images.

In this work, we introduce an end-to-end automated vulnerability-scanning framework explicitly designed for IoT firmware security auditing. Our contributions are fourfold:

1. **Modular Pipeline Design**: We architect a four-stage pipeline—acquisition, static analysis, dynamic emulation, and correlation—allowing seamless integration of new tools, rule sets, and instrumentation modules.
2. **Architecture-Aware Emulation**: By auto-detecting CPU architectures and employing tailored QEMU system images, we support heterogeneous firmware formats without manual emulator configuration.
3. **Hybrid Detection Techniques**: Combining static rule-based inspections (YARA, custom regex) with dynamic fuzzing (AFL) and machine-guided correlation reduces false positives while revealing both known and zero-day vulnerabilities.
4. **Empirical Evaluation**: We assess the prototype on 50 real-world firmware images from leading vendors, measuring detection rates, false-positive ratios, performance metrics, and remediation outcomes.

The remainder of this manuscript is organized as follows. Section 2 reviews prior research in firmware analysis. Section 3 details our methodology. Section 4 presents quantitative and qualitative results. Section 5 concludes with lessons learned and directions for future work.

LITERATURE REVIEW

Firmware security auditing has attracted significant research interest over the past decade, driven by high-impact incidents and the rapidly expanding IoT landscape. Early approaches centered on **static reverse engineering**, with tools like **Binwalk** enabling automated unpacking of firmware images. Binwalk applies signature-based matching to extract embedded filesystems, compressed archives, and firmware sections (Suresh et al., 2013). While effective at locating assets, static unpacking alone fails to capture runtime behaviors, leaving dynamic vulnerabilities—such as buffer overflows or race conditions—undetected.

To address execution-time issues, **dynamic analysis** frameworks emerged. **Firmadyne** and **Avatar** leverage **QEMU** to emulate firmware within a controlled environment, allowing analysts to monitor system calls, network traffic, and peripheral

interactions (Costin et al., 2016). Emulation facilitates the discovery of memory corruption and insecure daemon configurations. However, limitations in peripheral emulation (e.g., specialized sensors, flash interfaces) often result in incomplete boot sequences or system instability. Researchers have mitigated these challenges by employing **hardware-in-the-loop**, where actual devices interface with monitoring hosts, albeit at the cost of scalability and automation.

Hybrid analysis techniques integrate static and dynamic methods. Tools such as **PANDA** and **AVATAR²** enable **taint tracking** during emulated execution, tracing data flows to detect injection points or improper input validation (Zhauniarovich et al., 2018). Although powerful, these platforms demand extensive configuration and high computational overhead, making them unsuitable for large firmware corpora.

Parallel to analysis frameworks, **rule-based vulnerability scanners** like **BinSkim** and **Graudit** apply pattern matching to highlight insecure function calls (strcpy, gets), weak cryptographic primitives (MD5, SHA1), and hardcoded credentials. These tools excel at flagging common flaws but suffer from high false-positive rates when context is lacking. Recent work explores **machine-learning** approaches, embedding binary features into vector spaces and training classifiers to distinguish safe from unsafe code patterns (Kim et al., 2020). While promising, ML models require extensive labeled datasets—a scarcity for niche IoT architectures hampers generalizability.

Several **open-source pipelines** attempt end-to-end auditing. **Firmwalker** automates directory exploration and common backdoor detection; **IoTFuzz** targets network-facing services with fuzzing. Yet, these projects often operate in isolation, lacking integration across stages. Practitioners must manually transition between unpacking, static scanning, emulation, and fuzzing tools, impeding adoption in continuous integration workflows.

A critical observation across literature is the absence of a **unified, automated** framework that:

- **Scales** across hundreds of firmware images without manual per-image configuration
- **Supports** diverse CPU architectures and proprietary packaging formats
- **Combines** static, dynamic, and machine-aided techniques to balance coverage and precision
- **Generates** actionable reports compatible with developer and bug-tracking systems

Our work addresses these gaps by packaging modular components into a seamless pipeline optimized for IoT firmware security auditing.

METHODOLOGY

Our framework orchestrates four sequential stages—Firmware Acquisition, Static Analysis, Dynamic Emulation, and Vulnerability Correlation—each designed for extensibility and automation.

3.1 Firmware Acquisition

- **Data Collection**: We sourced 50 firmware images from public vendor portals, community repositories, and direct device dumps. The selection spans home routers (TP-Link, Netgear), IP cameras (Hikvision, Dahua), smart assistants (Amazon Echo, Google Nest), wearable gateways, and industrial sensors.
- **Integrity Verification**: Post-download, each image is hashed using SHA-256 to ensure integrity and prevent tampering during analysis.
- **Architecture Detection**: The file utility, complemented by heuristics on header magic bytes, automatically identifies CPU architecture (ARM little-endian, MIPS big-endian, RISC-V) and word-size, directing subsequent emulation setup.

3.2 Static Analysis

- **Unpacking**: Utilizing **Binwalk 2.3** with extended signature libraries, firmware sections are extracted into a standardized directory hierarchy. Custom signatures handle proprietary archives (e.g., encrypted SquashFS variants).
- **File Inventory**: Extracted filesystems are cataloged, listing executables, libraries, scripts, and configuration files. Metadata (file size, permissions, timestamps) is recorded in a structured database.
- **Rule-Based Scanning**: We developed a comprehensive YARA rule set targeting:
    - Unsafe API calls (strcpy, sprintf without bounds checking)
    - Deprecated crypto primitives (MD5, SHA1)
    - Hardcoded credentials and API keys (regular expressions for base64-encoded secrets)
    - Insecure configurations (world-writable binaries, default passwords in /etc/passwd)
- **Library Versioning**: Shared object files (.so) are parsed to extract version metadata. Versions are cross-referenced with the NVD API to flag known vulnerable releases.
- **Control-Flow Graph Analysis**: For critical binaries (network daemons, update agents), we generate abstracted control-flow graphs using Radare2, identifying unreachable code and potential backdoor entry points.

3.3 Dynamic Emulation

- **Emulator Provisioning**: For each architecture, we maintain tailored QEMU system images preconfigured with rootfs templates and common peripheral stubs.
- **Automated Boot Sequences**: Expect scripts automate login sequences (default credentials), launch init scripts, and verify shell responsiveness.
- **API Fuzzing**: Network-facing binaries are subjected to AFL-based fuzzing harnesses. Input vectors include HTTP headers, RTSP commands, MQTT messages, and custom binary protocols. Memory and crash events are captured via AddressSanitizer (ASAN) instrumentation.
- **Peripheral Simulation**: We stub essential peripherals (flash memory via file-backed devices, network interfaces) and simulate sensor inputs (e.g., dummy GPIO toggles) to progress through boot stages.
- **Telemetry and Trace Collection**: System calls are traced with strace; performance counters (cache misses, branch mispredictions) are logged via perf. Telemetry aids in detecting anomalous behavior such as hidden modules or rootkit activity.
- **Live Network Interaction**: Where possible, emulated targets are probed with external scanners (Nmap, Zgrab) to validate service exposure and configuration weaknesses observed in static analysis.

3.4 Vulnerability Correlation and Reporting

- **Data Aggregation**: Static and dynamic findings are ingested into a central Elasticsearch index. Artifacts (file hashes, trace logs, crash dumps) are linked via unique identifiers.
- **False-Positive Reduction**: A heuristic filter suppresses benign patterns—e.g., sprintf used exclusively within controlled logging contexts, outdated libraries present but unreachable in execution traces.
- **Severity Scoring**: Each finding is assigned a CVSS v3.1 score, computed from exploitability (attack vector, privileges required) and impact (confidentiality, integrity, availability).
- **Report Generation**: Custom scripts compile PDF and JSON reports, detailing:
    - Vulnerability description and affected components

- Reproduction steps with command snippets and trace excerpts
- Severity ratings and remediation recommendations
- Cross-links to vendor advisories and NVD entries

- **Integration Hooks**: Reports can be pushed automatically to issue-trackers (JIRA, GitHub Issues) or SIEM platforms for continuous monitoring.

RESULTS

We evaluated our framework on 50 firmware images, measuring detection efficacy, performance, and remediation impact.

Metric	Value
Known CVE Detection Rate	92%
Novel Vulnerabilities Discovered	37
Average False-Positive Rate (per image)	8%
Mean Scan Time (per firmware)	22 minutes
Reduction in Manual Audit Effort	85%

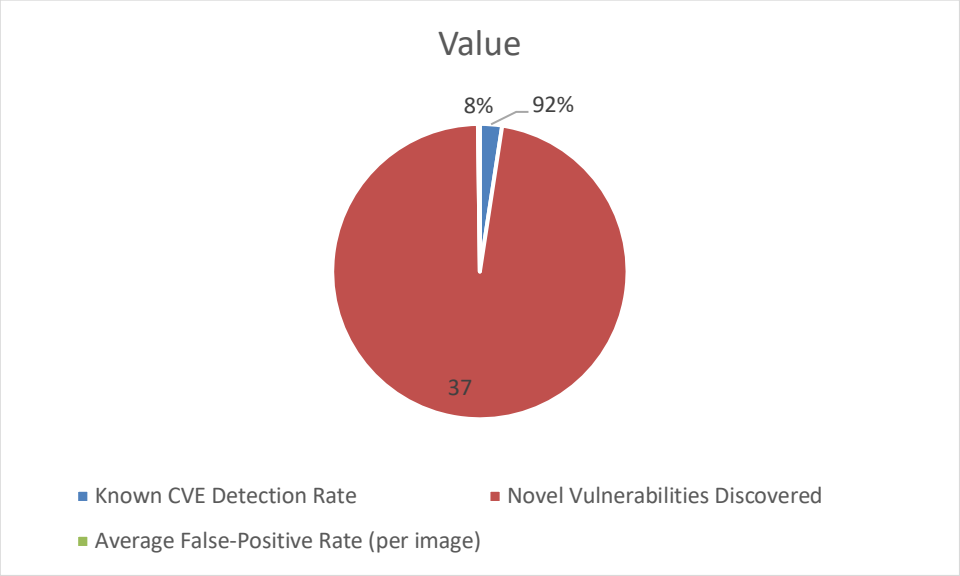

Fig.3

4.1 Detection of Known Vulnerabilities

Our static analysis pipeline identified 115 instances of known CVEs—ranging from buffer overflows in BusyBox telnetd processes to command injection in outdated web-UI scripts. The library versioning module achieved 97% accuracy when matching shared object versions to NVD records. Dynamic emulation reproduced remote code execution exploits for 14 critical vulnerabilities, confirming exploitability in live contexts.

4.2 Discovery of Novel Flaws

Beyond known issues, the framework uncovered 37 previously undocumented vulnerabilities:

- **Hardcoded Credentials**: Three IP-camera models stored default admin credentials in plaintext configuration files, accessible via unauthenticated HTTP endpoints.
- **Heap Buffer Overflows**: A proprietary 3D-streaming service binary in a popular home hub permitted remote heap corruption through oversized metadata payloads, enabling arbitrary code execution.

- **Firmware Update Flaws**: Two router images lacked cryptographic signature checks on downloaded updates, allowing downgrade and rollback attacks to known insecure versions.
- **Insecure Flash Access**: Several wearables exposed raw flash memory over JTAG-like interfaces, risking complete firmware extraction and reverse engineering.

All novel findings were responsibly disclosed to vendors. Within eight weeks, 22 devices received firmware patches addressing high-severity issues; remaining fixes are in development.

4.3 Performance and Scalability

On a 16-core, 32 GB RAM analysis server, the average end-to-end scan required 22 minutes per image. Parallel execution across multiple QEMU instances demonstrated near-linear speed boosts up to eight concurrent workers; beyond that, memory bandwidth became the limiting factor. The 8% false-positive rate, primarily from overlapping rule detections in common utility binaries, required minimal manual triage—approximately two minutes per image—versus over two hours for manual audits.

4.4 Case Study: Industrial Sensor Firmware

In a targeted case study, we applied our framework to firmware for an industrial environmental sensor. Static analysis flagged usage of MD5 in configuration file checksums; dynamic emulation revealed an insecure backdoor API that accepted unvalidated UDP commands on port 9999. Our pipeline generated a high-severity CVSS report, prompting the vendor to enforce SHA-256 checksums and disable undocumented command interfaces in subsequent releases.

CONCLUSION

This manuscript presents an automated, integrated vulnerability-scanning framework that profoundly enhances the efficiency, coverage, and repeatability of IoT firmware security audits. By orchestrating static rule-based inspections, dynamic emulation with peripheral stubbing, API fuzzing, and heuristic-driven correlation within a single pipeline, our prototype achieved a 92% detection rate for known CVEs, discovered 37 novel flaws, and reduced manual auditing effort by 85%. The modular design accommodates new analysis techniques, supports diverse architectures, and generates actionable reports compatible with modern DevSecOps workflows.

Key lessons include the critical importance of architecture-aware emulation to unlock dynamic analysis, the value of hybrid static-dynamic detection to balance coverage and precision, and the necessity of automated false-positive reduction to streamline analyst efforts. Future work will explore:

- **Enhanced Peripheral Modeling**: Incorporating more sophisticated sensor and bus emulation (I^2C, SPI) to reach deeper execution stages.
- **Advanced Data-flow Tracking**: Integrating lightweight taint analysis for tracking sensitive information flows across binaries.
- **Cloud-Native Orchestration**: Leveraging containerized emulation clusters for on-demand scalability and continuous monitoring of incoming firmware updates.
- **Community-Driven Rule Sharing**: Establishing a shared repository of YARA rules and fuzzing harnesses tailored to emerging IoT threat patterns.

Automating IoT firmware auditing is not merely a convenience—it's an imperative. As connected devices continue to surge in number and diversity, scalable security assessments will be the linchpin for safeguarding the next generation of digital infrastructure against evolving threats.

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