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Automated vulnerability detection and firmware hardening for industrial IOT devices

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Abstract
The rapid proliferation of Industrial Internet of Things (IIoT) devices has revolutionized industrial systems, but it has also introduced significant security challenges, particularly in firmware protection. This review examines the critical vulnerabilities associated with IIoT firmware, highlighting the pressing need for automated detection tools and robust hardening strategies. Foundational work in firmware security is discussed, alongside technological advancements such as static and dynamic analysis, machine learning, and policy-based frameworks. The paper evaluates emerging approaches to securing IIoT firmware, emphasizing their effectiveness in addressing real-world challenges. Practical recommendations for researchers and industry practitioners are provided, focusing on scalable solutions and collaborative efforts to bridge existing gaps. By exploring future directions, including integrating advanced tools and standardization efforts, this review aims to contribute to developing a resilient and secure IIoT ecosystem.

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1. Introduction

The Industrial Internet of Things (IIoT) represents a transformative paradigm in modern industries, redefining how physical devices, sensors, and machinery interact within connected ecosystems (Munirathinam, 2020) [20]. By integrating advanced data collection, processing, and real-time analytics, IIoT enables industries to optimize operations, reduce inefficiencies, and enhance decision-making (Peter, Pradhan, & Mbohwa, 2023) [31]. From manufacturing and energy to healthcare and logistics, the adoption of IIoT has led to unprecedented operational advancements, making these systems indispensable in critical infrastructure. However, this increased interconnectivity introduces significant vulnerabilities, particularly within firmware, which serves as the operational core of these devices (Austin-Gabriel, Hussain, Ige, Adepoju, & Afolabi, 2023) [2].

Firmware, a specialized type of software embedded in hardware, is essential for controlling device behavior and ensuring system functionality. It acts as the intermediary between the hardware and higher-level software applications, dictating how a device operates and interacts within the IIoT ecosystem (Qasem *et al*., 2021) [32]. Despite its critical role, firmware often remains a vulnerable entry point for cyberattacks. Many IIoT devices rely on outdated or inadequately secured firmware, creating opportunities for attackers to exploit these weaknesses to gain unauthorized access, disrupt operations, or compromise sensitive data. These vulnerabilities are exacerbated by the resource constraints of many IIoT devices, which limit the implementation of robust security protocols (Tan, Mohamad-Saleh, Zain, & Aziz, 2017) [35].

The consequences of firmware vulnerabilities in IIoT systems are profound, with potential impacts ranging from operational

disruptions and economic losses to threats to public safety. Cyberattacks targeting IIoT devices, such as the infamous Mirai botnet, have demonstrated the devastating potential of exploiting poorly secured firmware.

As industries increasingly depend on interconnected devices, the stakes for addressing these vulnerabilities continue to rise, necessitating a proactive and comprehensive approach to firmware security (Xenofontos *et al*., 2021) [36].

This review paper addresses the urgent need for securing IIoT devices by focusing on two critical aspects: automated vulnerability detection and firmware hardening. Traditional methods of identifying and mitigating vulnerabilities are often reactive, time-consuming, and insufficient in the face of rapidly evolving cyber threats. Automation, by contrast, offers a scalable and efficient solution for proactively identifying vulnerabilities and implementing security measures. By leveraging advanced technologies such as machine learning and artificial intelligence, automated tools can enhance vulnerability detection's speed, accuracy, and effectiveness, enabling industries to stay ahead of emerging threats.

The scope of this review encompasses the challenges, foundational research, and recent advancements in IIoT firmware security. It begins by exploring the unique security challenges posed by IIoT systems, highlighting the limitations of existing approaches and the need for innovation. The paper then delves into the foundational work that has shaped the field of firmware security, offering insights into key developments and their implications for IIoT devices. Building on this foundation, the review examines cutting-edge solutions, including automated vulnerability detection tools and firmware hardening techniques, emphasizing their potential to revolutionize IIoT security.

Through this exploration, the paper aims to provide a comprehensive understanding of the current state of IIoT firmware security while identifying gaps and opportunities for future research and development. By emphasizing automation and advanced security measures, this review seeks to contribute to the ongoing effort to fortify IIoT systems against evolving cyber threats, ensuring their resilience and reliability in an increasingly interconnected world.

2. Challenges in IIoT Security

2.1 Key Vulnerabilities in IIoT Devices

IIoT devices are distinct in their architecture and function, often operating in environments where security has historically been secondary to performance and reliability. At the heart of these vulnerabilities lies firmware, the embedded software that governs device operations (Demertzi, Demertzis, & Demertzis, 2023) [10]. Firmware is often static and seldom updated after deployment, leaving it susceptible to exploitation through known vulnerabilities. Attackers capitalize on this immutability to infiltrate devices, gaining unauthorized access or persistence within industrial networks.

One of the most critical issues is the absence of secure boot processes in many devices. Without these safeguards, attackers can modify firmware, injecting malicious code that remains undetected during routine operations. Additionally, the widespread use of hardcoded credentials, default passwords, and insufficient authentication protocols exacerbates the problem. Such weaknesses provide attackers with straightforward entry points, allowing them to manipulate devices or pivot to other systems within the network (Chalapathi, Chamola, Vaish, & Buyya, 2021) [9].

Another persistent vulnerability is the lack of encryption between IIoT devices. Unencrypted data transmission enables attackers to intercept sensitive information or carry out man-in-the-middle attacks. These risks are further magnified by the increasing use of edge computing, where decisions are made closer to the device, introducing new attack vectors that target both hardware and firmware (Khujamatov, Reypnazarov, Khasanov, & Akhmedov, 2021) [16].

2.2 Current Security Threats

The consequences of these vulnerabilities are evident in numerous real-world incidents, demonstrating the tangible risks to IIoT systems. One notable example is the Mirai botnet, which exploited insecure firmware in connected devices to launch one of history's most significant distributed denial-of-service attacks. By leveraging default credentials and weak authentication protocols, the attackers created a network of compromised devices capable of overwhelming major online services. This incident underscored the scale at which firmware vulnerabilities can be weaponized, causing widespread disruption (Adepoju *et al*., 2022; Austin-Gabriel *et al*., 2023) [7, 1].

In another high-profile case, a German steel mill was targeted by attackers who exploited vulnerabilities in industrial control systems. The attackers gained access through IIoT devices, ultimately causing physical damage to the plant's operations. This event highlighted how firmware weaknesses can bridge the gap between cyber and physical realms, resulting in tangible harm (Onoja & Ajala, 2022) [27].

These examples illustrate the evolving threat landscape, where attackers are increasingly sophisticated and capable of exploiting firmware vulnerabilities to achieve digital and physical objectives. As industries continue to expand their reliance on IIoT, the potential for catastrophic incidents grows, making it imperative to address these risks proactively (Oladosu *et al*., 2022b) [23].

2.3 Obstacles to Securing IIoT Environments

Securing IIoT systems is a complex undertaking, hindered by several technical and systemic obstacles. A primary challenge is the resource constraints inherent in many devices. Unlike traditional computing systems, IIoT devices are often designed with limited processing power, memory, and energy capacity, leaving little room for implementing robust security features. Encryption, real-time monitoring, and automated patching mechanisms are often considered too resource-intensive, resulting in minimal security measures (Oladosu *et al*., 2022c) [22].

Legacy systems further complicate the security landscape. Many industrial environments rely on equipment that predates modern cybersecurity practices. Integrating these legacy systems with new IIoT devices creates compatibility issues, widens the attack surface, and introduces challenging vulnerabilities. In many cases, replacing legacy equipment is cost-prohibitive, leaving organizations to work with inherently insecure systems. The lack of standardized security protocols across manufacturers presents another significant barrier. IIoT devices are often developed by diverse vendors, each with its own design philosophy and security practices. This lack of uniformity results in

fragmented security measures that fail to provide consistent protection across devices and networks (Ike *et al*., 2021; Oladosu *et al*., 2022a) [22].

The distributed nature of IIoT environments also poses unique challenges. Devices are frequently deployed in remote or hard-to-reach locations, making physical security and timely maintenance difficult. Attackers can exploit these distributed networks to carry out lateral attacks, compromising multiple devices and systems. Furthermore, the global supply chain for IIoT components introduces risks of tampering during manufacturing or transport, creating vulnerabilities even before devices are deployed.

Human factors remain a significant challenge to securing IIoT systems. Many organizations lack the necessary expertise to manage and secure these devices effectively. This skills gap often results in poor security practices, such as failing to update firmware, neglecting password policies, or misconfiguring devices. Attackers frequently exploit these oversights, as they provide an easy pathway into otherwise secure networks (Afolabi, Ige, Akinade, & Adepoju, 2023; Onoja & Ajala, 2023b) [2, 28].

Overcoming these challenges requires a multi-pronged approach that combines technical innovation with organizational best practices. On the technical front, automated tools for vulnerability detection can play a transformative role, enabling organizations to identify and address firmware vulnerabilities in real time. These tools, often powered by machine learning, can analyze vast amounts of data to detect anomalies and predict potential threats, enhancing the resilience of IIoT systems (Hussain, Austin-Gabriel, Ige, Adepoju, & Afolabi, 2023) [2].

Manufacturers must prioritize security during the design phase, incorporating features such as secure boot mechanisms, encrypted communication protocols, and the ability to perform over-the-air updates. Standardizing security practices across the industry can also help establish a baseline level of protection, ensuring consistency and reducing fragmentation. Organizationally, investing in workforce training and awareness programs is essential. Empowering personnel with the knowledge and skills to manage IIoT security effectively can reduce the likelihood of human error. Collaboration between stakeholders—manufacturers, regulators, and end-users—is equally important for developing comprehensive strategies and fostering a security culture (Afolabi, Hussain, Austin-Gabriel, Adepoju, & Ige, 2023; Onoja, Ajala, & Ige, 2022) [7, 1].

In conclusion, while the challenges to securing IIoT environments are significant, they are not insurmountable. Industries can build more secure and resilient systems by addressing firmware vulnerabilities, understanding evolving threats, and overcoming systemic obstacles. The stakes are too high to ignore, and proactive measures are critical to safeguarding the future of industrial operations in an increasingly interconnected world.

3. Foundational Work in Firmware Security

The growing prevalence of Industrial Internet of Things (IIoT) devices in critical operations has spurred significant research into firmware security, focusing on understanding vulnerabilities and developing mitigation strategies. As firmware is the foundational layer for device functionality, its security is paramount in protecting IIoT ecosystems. Foundational work in firmware security has been instrumental in advancing the field, but critical gaps must be addressed to ensure comprehensive protection.

3.1 Landmark Studies and Key Innovations

Landmark studies in firmware security have laid the groundwork for understanding its vulnerabilities and protection methods. Early research primarily focused on reverse engineering firmware to identify vulnerabilities. Tools and methodologies developed during this phase enabled researchers to deconstruct firmware binaries, analyze their structure, and detect security flaws. These studies revealed critical issues, such as the use of hardcoded credentials, unencrypted data storage, and insecure update mechanisms, which made firmware a prime target for attacks.

One pivotal study introduced the concept of firmware binary analysis to uncover vulnerabilities without requiring access to source code. This work demonstrated that attackers often exploit firmware that lacks encryption or verification during the boot process. The insights gained from this research have influenced subsequent developments in secure boot processes and digital signature validation (Akinade, Adepoju, Ige, & Afolabi, 2023; Oladosu *et al*., 2021b) [1, 22].

Key innovations in firmware security also include dynamic analysis techniques, which involve observing firmware behavior during execution to identify potential threats. Dynamic approaches complement static analysis by capturing runtime vulnerabilities, such as buffer overflows and memory corruption. This dual-layered approach has become a cornerstone of modern firmware security research, enabling more comprehensive vulnerability detection.

Furthermore, advancements in machine learning have significantly enhanced firmware analysis. By training algorithms on large datasets of known vulnerabilities, researchers have developed predictive models that can identify patterns indicative of security flaws. This innovation has greatly improved the speed and accuracy of vulnerability detection, marking a significant milestone in the field (Ige *et al*., 2022).

3.2 Role of Automated Tools in Vulnerability Detection

Automated tools have played a transformative role in addressing firmware vulnerabilities. As IIoT ecosystems grow increasingly complex, manual analysis is no longer feasible for identifying and mitigating risks. Automated tools provide scalable solutions that can analyze firmware at a pace and depth far beyond human capabilities.

One notable example is the development of static analysis tools that can parse firmware binaries to identify known vulnerabilities. These tools scan for insecure configurations, outdated libraries, and other red flags that could compromise device security. On the other hand, dynamic analysis tools simulate real-world conditions to observe how firmware behaves under various scenarios, uncovering vulnerabilities that might be missed in static analysis (Hussain *et al*., 2021).

Automated tools have also facilitated the integration of vulnerability detection into the development lifecycle. Secure coding practices, coupled with continuous integration/continuous deployment pipelines, enable real-time detection of flaws before firmware is deployed. This proactive approach ensures that devices are equipped with robust security measures from the outset, reducing the likelihood of exploitation. Moreover, the use of artificial intelligence in automated tools has allowed for more

sophisticated detection capabilities. AI-powered tools can analyze patterns, detect anomalies, and predict vulnerabilities with unprecedented accuracy. By automating the labor-intensive aspects of firmware analysis, these tools free up human experts to focus on developing advanced mitigation strategies (Oladosu *et al*., 2023; Onoja & Ajala, 2023a) [24, 28].

3.3 Gaps in Existing Frameworks and Tools

Despite significant progress, existing frameworks and tools for firmware security are not without limitations. One major gap lies in the fragmented nature of the current ecosystem. Many tools are designed to address specific aspects of firmware analysis, such as static or dynamic vulnerabilities, but fail to provide a holistic view of device security. This siloed approach leaves room for undetected threats, particularly those that span multiple layers of the device architecture.

Another critical gap is the lack of standardization across tools and methodologies. The absence of unified standards makes it difficult for organizations to implement consistent security practices. This inconsistency is particularly problematic in IIoT environments, where devices from different manufacturers must work together seamlessly. Ensuring uniform security across diverse systems becomes a daunting challenge without standardized frameworks (Austin-Gabriel *et al*., 2021) [8].

Additionally, many automated tools are not designed to handle the unique constraints of IIoT devices. Resource limitations, such as low processing power and memory, make deploying sophisticated security measures on these devices difficult. Tools that are effective for traditional systems often prove impractical in IIoT contexts, leaving a significant portion of the ecosystem vulnerable. Finally, there is a notable gap in addressing supply chain security. Firmware is often developed by third-party vendors, creating opportunities for tampering or introducing vulnerabilities during production. Existing tools focus primarily on post-deployment security, overlooking the need for robust measures to secure firmware throughout its lifecycle (Akinade, Adepoju, Ige, Afolabi, & Amoo, 2022) [1].

Developing comprehensive frameworks that integrate static and dynamic analysis with real-time monitoring is essential to address these gaps. Such frameworks should be capable of providing a unified view of device security, enabling organizations to detect and respond to threats more effectively. Standardization efforts must also be prioritized, ensuring that tools and methodologies are interoperable and applicable across diverse IIoT environments. Advancing lightweight security solutions tailored to the constraints of IIoT devices is another critical need. Researchers can develop tools that provide robust protection without overburdening device resources by optimizing algorithms and leveraging edge computing. Additionally, enhancing supply chain security through measures such as secure firmware development practices and third-party auditing will help mitigate risks at the source.

4. Advances in Automated Vulnerability Detection and Firmware Hardening

4.1 Emerging Technologies for Automated Vulnerability Detection

Automated vulnerability detection has become a cornerstone of IIoT security, driven by the need to analyze firmware at scale without sacrificing accuracy. Emerging technologies in this domain leverage static and dynamic analysis, artificial intelligence, and behavioral modeling to identify weaknesses in device firmware (Lalos *et al*., 2019) [19].

Static analysis tools remain foundational to automated detection, scanning firmware binaries for known vulnerabilities and coding errors. These tools utilize signature-based approaches to detect insecure configurations, unpatched libraries, and hardcoded credentials. While effective, static analysis alone often falls short in identifying runtime vulnerabilities or emergent behaviors caused by external stimuli.

Dynamic analysis addresses these limitations by observing firmware behavior during execution. Tools employing this method simulate real-world conditions, enabling the detection of runtime issues such as memory corruption, buffer overflows, and race conditions. Recent advances have enhanced the efficiency of dynamic analysis, reducing the computational overhead and making it more accessible for resource-constrained environments (Ike *et al*., 2023).

Machine learning has introduced a paradigm shift in vulnerability detection. Machine learning models can identify subtle anomalies and predict potential threats by training algorithms on large datasets of known vulnerabilities and exploit patterns. These systems excel at detecting zero-day vulnerabilities, offering a proactive approach to firmware security. For example, unsupervised learning techniques can identify deviations from normal behavior without requiring prior knowledge of specific threats (Ahmed *et al*., 2023) [4].

Behavioral analysis is another emerging approach that focuses on the operational patterns of IIoT devices. By establishing a baseline of expected behavior, these tools can detect deviations indicating firmware tampering or exploitation. Such methodologies are particularly useful in identifying advanced persistent threats that aim to remain undetected over extended periods (Oladosu *et al*., 2021a) [22].

4.2 Strategies for Firmware Hardening

While vulnerability detection is critical, it must be complemented by robust strategies for hardening firmware against exploitation. Firmware hardening involves enhancing the resilience of embedded systems through secure design principles, advanced protection mechanisms, and policy-based frameworks. One key strategy is the implementation of secure boot processes. Secure boot ensures that only authenticated and unmodified firmware is executed during device startup. This approach prevents attackers from injecting malicious code into the firmware by leveraging cryptographic signatures. Secure boot establishes a trust chain, ensuring that all subsequent software components adhere to predefined security policies.

Policy-based frameworks offer another powerful mechanism for firmware hardening. These frameworks define a set of security rules and constraints that govern device behavior, enabling real-time monitoring and enforcement. For instance, access control policies can restrict unauthorized modifications to firmware, while execution policies can limit the device's ability to perform certain high-risk operations. Policy-based systems provide a flexible and scalable approach to enhancing firmware security across diverse IIoT environments (Koutroumpouchos *et al*., 2019) [18].

Machine learning has also been applied to firmware hardening. Predictive models can identify potential attack vectors and recommend mitigation strategies during development. Additionally, reinforcement learning

techniques have optimized security configurations, balancing protection with performance requirements. These innovations enable a more proactive approach to hardening firmware, addressing vulnerabilities before they can be exploited.

Encryption and obfuscation are further critical components of firmware hardening. By encrypting firmware binaries, organizations can prevent unauthorized access and reverse engineering. Code obfuscation adds another layer of protection, making it more challenging for attackers to analyze and exploit firmware logic. These techniques create a more secure firmware ecosystem, deterring adversaries from targeting IIoT devices (Shwartz, Mathov, Bohadana, Elovici, & Oren, 2018) [34].

4.3 Evaluation of Effectiveness in Industrial Contexts

The effectiveness of automated vulnerability detection and firmware hardening strategies in industrial settings has been a topic of significant research and real-world testing. While these solutions have shown considerable promise, their implementation often faces challenges unique to industrial environments. In highly regulated industries, such as energy and healthcare, the adoption of automated tools is often constrained by compliance requirements. These industries require tools that can provide transparent and auditable results, ensuring alignment with regulatory standards. Automated detection tools have addressed this need by incorporating detailed reporting features, enabling organizations to demonstrate compliance while maintaining robust security.

Resource constraints remain a challenge when implementing advanced hardening techniques in IIoT devices. However, recent innovations in lightweight cryptographic algorithms and energy-efficient machine learning models have made these techniques more viable for resource-constrained devices. Field tests have shown that secure boot processes and encryption mechanisms can be implemented without significantly impacting device performance or power consumption (Kornaros, 2022) [17].

The industrial sector has also demonstrated the value of integrating automated detection tools with existing cybersecurity infrastructures. For example, combining behavioral analysis tools with industrial intrusion detection systems has enabled more comprehensive threat monitoring. These integrations allow organizations to correlate vulnerability data with network activity, providing a holistic view of security risks.

Despite these advancements, gaps remain in addressing the long-term maintenance of firmware security. IIoT devices often have extended lifespans, requiring regular updates to remain secure. Automated patch management systems have emerged as a solution, enabling over-the-air updates that address vulnerabilities without disrupting operations. However, ensuring the reliability and security of these updates is an ongoing challenge (Serror, Hack, Henze, Schuba, & Wehrle, 2020) [33].

To maximize the effectiveness of these technologies, continued innovation is essential. Advancements in edge computing promise to enable real-time vulnerability detection and hardening directly on IIoT devices, reducing latency and reliance on centralized systems. Collaborative efforts between manufacturers, researchers, and regulators will also be critical in standardizing best practices and fostering a security culture in industrial settings.

5. Conclusion and Recommendations

5.1 Summary of Insights

The review underscores that firmware vulnerabilities remain a significant attack vector for compromising IIoT devices. The complexity of these devices, combined with their integration into critical infrastructure, amplifies the risks associated with firmware exploitation. Foundational research has illuminated the root causes of these vulnerabilities, from weak authentication mechanisms to insecure update processes. Automated tools have emerged as vital for addressing these challenges, leveraging static and dynamic analysis, machine learning, and behavioral monitoring to detect and mitigate risks effectively.

Furthermore, firmware hardening strategies have been emphasized, with secure boot processes, encryption, and policy-based frameworks offering robust defenses. Despite these advancements, the review identifies several gaps, including the fragmented nature of existing tools, limited standardization, and challenges posed by resource-constrained devices. These gaps highlight the need for continuous innovation and collaboration to ensure comprehensive protection.

5.2 Practical Recommendations

For researchers, the priority should be to develop lightweight and scalable security solutions tailored to the unique constraints of IIoT environments. This includes optimizing algorithms for real-time vulnerability detection and creating holistic frameworks that seamlessly integrate various security techniques. Additionally, addressing supply chain risks by designing secure firmware development and distribution practices is essential to mitigating vulnerabilities at their source.

Industry practitioners are encouraged to adopt automated tools for vulnerability detection and firmware hardening as part of their security strategies. Integrating these tools into the development lifecycle can significantly reduce risks, ensuring devices are secure from the outset. Organizations should also prioritize regular firmware updates and invest in over-the-air patch management systems to address emerging threats proactively. Moreover, fostering a security culture through employee training and adherence to best practices is vital for maintaining resilience in IIoT ecosystems.

5.3 Future Directions

The integration of advanced tools, such as artificial intelligence and edge computing, presents a promising avenue for enhancing IIoT security. These technologies can enable real-time monitoring and protection directly on devices, reducing dependency on centralized systems. Collaboration among stakeholders, including manufacturers, researchers, and regulators, will be critical to standardizing security frameworks and fostering innovation. Joint efforts can ensure that the entire IIoT lifecycle—from design to deployment—is governed by robust security principles.

In conclusion, securing IIoT devices requires a multi-faceted approach that combines cutting-edge technology, proactive strategies, and collaborative efforts. By addressing the gaps identified in this review and pursuing the outlined recommendations, stakeholders can create a resilient and secure IIoT ecosystem capable of withstanding the evolving threat landscape.

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