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Original Article

Development of an Automated Vulnerability Management System for OT Environments

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Abstract - *Operational Technology (OT) environments, which underpin critical infrastructure such as energy, manufacturing, and transportation systems, are increasingly targeted by sophisticated cyber threats. Unlike traditional IT systems, OT environments pose unique challenges for vulnerability management, including limited downtime windows, legacy equipment, and heterogeneous protocols. This paper proposes the design and development of an automated vulnerability management system tailored specifically for OT environments. The system integrates real-time asset discovery, vulnerability assessment, and intelligent risk prioritization while ensuring minimal disruption to operational processes. We describe the system architecture, implementation details, and evaluate the approach in a simulated industrial control environment. The results demonstrate the feasibility and effectiveness of the proposed solution in enhancing security posture without compromising operational integrity.*

Keywords - *Operational Technology (OT) Security, Vulnerability Management, Industrial Control Systems (ICS), Automation, Cybersecurity, Risk Prioritization, Asset Discovery, Critical Infrastructure Protection, SCADA Security, Threat Intelligence Integration.*

1. Introduction

1.1. Background on OT Systems and Their Critical Role in Infrastructure

Operational Technology (OT) refers to hardware and software systems that monitor and control physical devices and industrial processes. These systems are widely deployed across critical infrastructure sectors such as energy, water treatment, manufacturing, transportation, and oil and gas. Unlike IT systems, which primarily handle data processing and communications, OT systems directly interact with the physical world through Industrial Control Systems (ICS), Supervisory Control and Data Acquisition (SCADA) systems, Distributed Control Systems (DCS), and Programmable Logic Controllers (PLCs). The functionality and reliability of these systems are crucial because any disruption can result in serious consequences, including physical damage, environmental harm, financial losses, or even loss of human life. As industries embrace digital transformation, the convergence of IT and OT has introduced new vulnerabilities into OT networks, which were historically isolated and secured through air-gapping.

1.2. The Rise in Cyber Threats Targeting OT Environments

In recent years, cyber threats targeting OT environments have become more frequent and sophisticated. High-profile attacks such as Stuxnet, Triton, and the Colonial Pipeline ransomware incident have exposed the vulnerabilities of these critical systems. Cybercriminals, hacktivists, and even nation-state actors now actively exploit weaknesses in OT infrastructure for espionage, sabotage, or financial gain. The unique characteristics of OT such as older operating systems, proprietary protocols, and minimal built-in security make these systems especially attractive targets. Moreover, the interconnection between IT and OT networks increases the attack surface, allowing adversaries to pivot from traditional IT systems into the more vulnerable OT domain. As a result, ensuring the cybersecurity of OT environments has become a national and global priority.

1.3. Importance and Challenges of Vulnerability Management in OT

Vulnerability management is a foundational aspect of cybersecurity that involves identifying, classifying, prioritizing, and remediating vulnerabilities. In OT environments, however, this task is far more complex and sensitive than in traditional IT settings. Patching known vulnerabilities may require system downtime, which is often unacceptable due to strict availability and uptime requirements. Many OT assets are legacy devices that no longer receive vendor support or security updates, and their proprietary nature makes vulnerability scanning difficult. Additionally, the use of specialized industrial protocols limits the effectiveness of conventional IT security tools. Despite these obstacles, proactive vulnerability management in OT is essential to reduce exposure to attacks and ensure system resilience. Automating this process can significantly enhance both efficiency and accuracy while minimizing human error and operational disruption.

1.4. Scope and Objectives of the Paper

This paper aims to design, develop, and evaluate an automated vulnerability management system specifically tailored for OT environments. The proposed solution focuses on non-intrusive asset discovery, intelligent vulnerability detection, and risk-based prioritization that accounts for both security severity and operational criticality. The primary objective is to address the unique constraints of OT, such as the need for real-time availability and system heterogeneity, while offering a scalable and automated approach to vulnerability management. This work contributes to the growing field of OT cybersecurity by offering a framework that balances operational integrity with security effectiveness.

Table 1. OT Vulnerability Management Phases vs. Key Challenges & Techniques

Phase	Challenges	Example Techniques & Tools
Asset Discovery	Legacy devices, proprietary protocols	Dragos, Claroty; passive sniffing
Asset Profiling	Limited metadata, criticality assessment	Purdue model classification
Vulnerability Detection	Safe scanning; avoiding downtime	Claroty guide; Qualys VMDR OT
Risk Assessment & Prioritization	CVSS insufficiency, exploit likelihood	Use CVSS + EPSS
Remediation Planning	Downtime constraints, lack of patches	Virtual patching, vendor coordination
Patch Deployment / Controls	Maintenance windows, manual efforts	Network segmentation, readonly configs
Validation & Reporting	Continuous visibility, compliance needs	SIEM integration, dashboards, reports

2. Related Work

2.1. Overview of Current Vulnerability Management Tools

Numerous vulnerability management tools exist in the cybersecurity landscape, including commercial solutions such as Tenable, Rapid7, Qualys, and open-source frameworks like OpenVAS. These tools are primarily designed for IT systems and are effective in scanning servers, desktops, and network infrastructure. They use databases like CVE (Common Vulnerabilities and Exposures) and exploit feeds to detect and report known vulnerabilities. Typically, they rely on active scanning, credential-based access, and frequent patch deployment, all of which are suited for IT networks. However, their utility in OT environments is limited due to differences in system architecture, communication protocols, and device constraints.

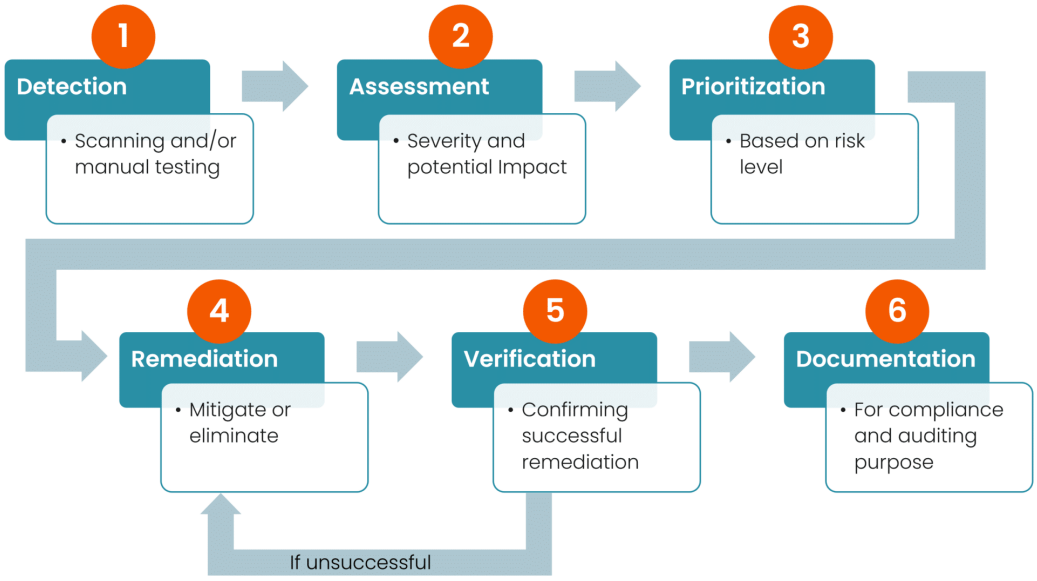

Fig 1. Vulnerability Management from detection to mitigation

2.2. Limitations of Traditional IT-Centric Approaches in OT

Traditional IT vulnerability management approaches often fall short when applied to OT environments. Active scanning techniques, for instance, can crash or disrupt legacy control systems that cannot handle the traffic load or unrecognized commands. Many OT devices lack the computational capacity to support agents, making agent-based tools ineffective. Furthermore, IT-centric tools do not consider the operational criticality of assets, leading to remediation recommendations that could negatively impact production or safety. The one-size-fits-all model of IT security cannot address the safety-first, availability-driven paradigm of OT systems.

2.3. Studies or Systems Aimed at OT-Specific Security

Several academic and industrial research efforts have attempted to bridge the gap between IT and OT security. Notable examples include anomaly-based intrusion detection systems (IDS) tailored for SCADA networks, asset identification tools that use passive monitoring, and risk-based models that prioritize vulnerabilities in ICS environments. Some vendors have begun to offer OT-specific solutions, such as Nozomi Networks and Claroty, which emphasize passive scanning and protocol awareness. However, comprehensive automated vulnerability management solutions tailored for OT are still in their infancy and face adoption hurdles due to complexity and integration challenges.

2.4. Gap Analysis

Despite progress, a significant gap exists in the practical deployment of automated vulnerability management systems in OT environments. Most existing tools are either overly intrusive or insufficiently contextualized for OT-specific constraints. There is also a lack of integration with asset management, real-time monitoring, and decision-making systems in OT environments. Additionally, current solutions often require manual intervention, which delays response times and increases the risk of oversight. This paper aims to fill these gaps by proposing a modular, automated solution that incorporates OT-aware scanning, intelligent risk evaluation, and minimal disruption to operations.

3. Challenges in OT Vulnerability Management

3.1. Asset Diversity and Legacy Systems

OT environments comprise a wide array of devices from different vendors, often with proprietary hardware and software configurations. These assets can include PLCs, HMIs, RTUs, and industrial sensors, many of which have been in operation for decades and were never designed with cybersecurity in mind. The lack of standardization across devices and platforms complicates efforts to create a unified security approach. Furthermore, legacy systems are often no longer supported by their manufacturers, leaving known vulnerabilities unpatched and systems unprotected against new threats.

Fig 2. 360⁰ Risk Assessment

3.2. Availability and Uptime Requirements

One of the primary concerns in OT environments is system availability. Downtime in industrial processes can result in production delays, safety hazards, and significant financial losses. Consequently, vulnerability management operations that require system reboot, patching, or device replacement are often postponed or avoided altogether. The challenge is to implement security measures that do not interfere with production schedules or jeopardize safety. Any vulnerability management system for OT must be carefully designed to operate in a non-disruptive manner, often using passive data collection and real-time risk evaluation.

3.3. Protocol and Vendor Heterogeneity

OT systems use a variety of specialized communication protocols such as Modbus, DNP3, PROFINET, and BACnet, many of which lack inherent security features like encryption or authentication. These protocols differ significantly from the TCP/IP protocols commonly used in IT networks. The diversity of vendors and proprietary implementations adds another layer of complexity, making it difficult to deploy universal scanning or monitoring tools. Effective vulnerability management in OT must include protocol-aware capabilities that can interpret and evaluate communications without causing disruptions.

3.4. Limited Patching Windows and Change Control Policies

Unlike IT systems, where patches can often be applied during regular maintenance windows, OT environments typically have restricted patching opportunities. Many systems run continuously and can only be updated during planned outages, which may occur infrequently sometimes only once or twice a year. Additionally, strict change management policies are in place to avoid operational risks, requiring extensive testing and documentation before any updates can be deployed. These constraints make it imperative for vulnerability management systems to accurately prioritize the most critical risks and support long-term planning for remediation.

Table 2. OT Vulnerability Lifecycle vs. Challenges

Lifecycle Phase	Challenges Addressed	OT-Specific Adjustments
Asset Discovery	Asset diversity & legacy systems	Include proprietary devices; manual walk-downs; scheduled passive discovery
Classification/Risk	Heterogeneous protocols; uptime constraints	Use protocol-aware tools; risk scoring factoring availability/safety; compensating controls
Prioritization	Limited patch windows; regulatory/safety constraints	Score by CVSS + operational impact; focus on crown-jewel assets; vendor support
Remediation	Legacy systems; availability; patch scarcity	Virtual patching, network segmentation, layered defense, long-hauls for replacements
Verification	Downtime; compliance/regulation demands	Non-intrusive monitoring; scan validation; incident logging; audit trails

3.5. Regulatory and Safety Constraints

OT systems often fall under strict regulatory frameworks such as NERC CIP, NIST SP 800-82, and IEC 62443, which dictate security practices, access controls, and change management protocols. Safety is also a paramount concern—unlike in IT environments, where a vulnerability may result in data loss, in OT it could lead to catastrophic physical consequences. Therefore, any security implementation must also undergo safety validation and regulatory compliance review. This regulatory burden slows the adoption of new tools and adds layers of complexity to the vulnerability management lifecycle.

4. System Architecture of the Proposed Solution

4.1. High-Level System Design

The proposed automated vulnerability management system is designed as a modular and scalable architecture that seamlessly integrates with existing OT environments. It consists of several interrelated components, including passive asset discovery, vulnerability detection, threat intelligence correlation, risk assessment, and reporting. The system operates on a layered security model, ensuring minimal performance overhead and full alignment with industrial network segmentation practices. By placing sensors in strategic points within the OT network, the system collects traffic and device information without introducing active probes, preserving operational stability.

4.2. Components (Asset Discovery, Vulnerability Assessment, Risk Prioritization, Reporting)

The system begins with asset discovery, which uses passive network monitoring to identify devices, services, firmware versions, and protocol usage. Once the asset inventory is established, the vulnerability assessment module maps known vulnerabilities (using databases such as CVE/NVD) to identified assets. A contextual risk prioritization engine then evaluates each vulnerability based on multiple factors, including exploitability, asset criticality, exposure, and potential impact. This produces an actionable risk score for each finding. Finally, the reporting module compiles this information into a dashboard and customizable reports suitable for security teams, operators, and compliance officers.

4.3. Integration with OT Systems (ICS, SCADA, PLCs)

A key feature of the system is its ability to interface with common OT platforms such as ICS, SCADA, and PLCs without requiring intrusive access. Integration is achieved through read-only connections to engineering workstations, historians, or mirrored traffic ports on network switches. The system is vendor-agnostic, relying on deep protocol inspection and behavior

analytics to gather data without modifying configurations or disrupting control logic. This ensures compatibility with a wide range of industrial environments while maintaining compliance with safety and availability requirements.

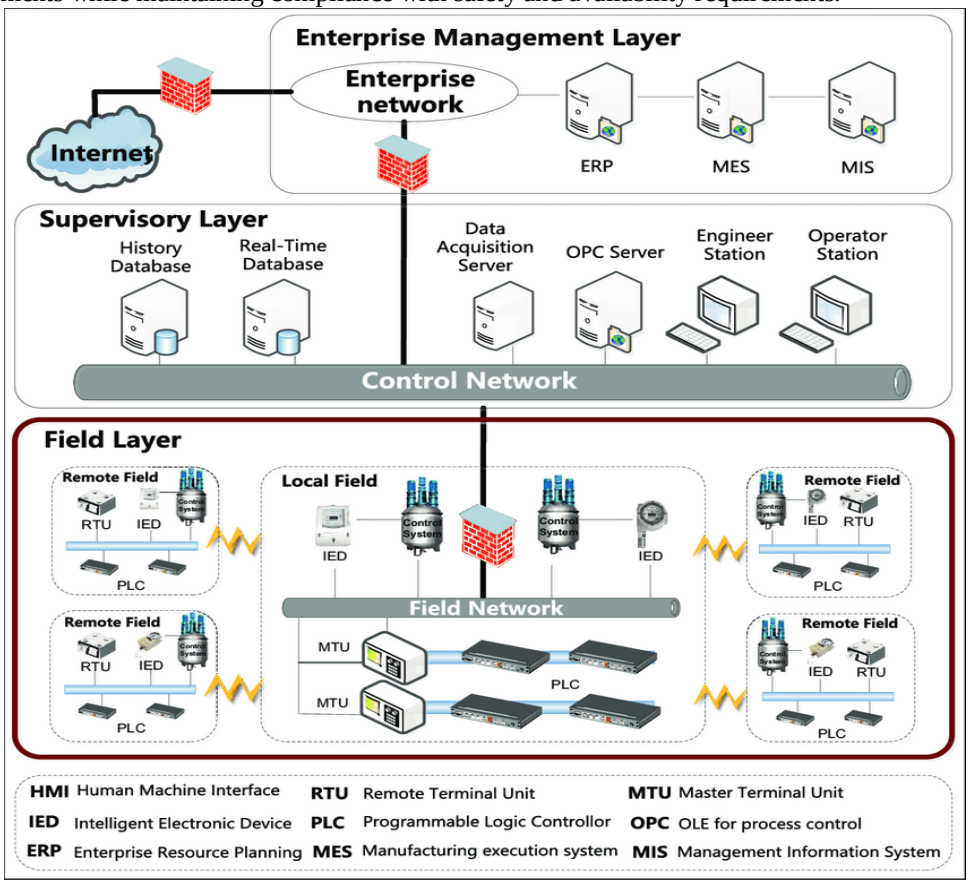

Fig 3. Architecture of industrial control system

4.4. Communication Architecture and Security

All inter-component communication within the system is encrypted using industry-standard protocols such as TLS 1.3. The architecture supports role-based access control, ensuring that only authorized personnel can view or act on vulnerability data. Communication with external systems, such as threat intelligence platforms or central SOCs, is conducted through secure APIs and adheres to the principle of least privilege. Where cloud connectivity is used for analytics or updates, data is anonymized and transmitted securely. These design choices ensure the solution meets both cybersecurity and regulatory standards while safeguarding sensitive operational data.

5. Automation Techniques

5.1. AI/ML for Asset Classification and Anomaly Detection

Artificial Intelligence (AI) and Machine Learning (ML) are transformative technologies in automating cybersecurity for OT systems. In the proposed vulnerability management system, AI/ML algorithms are applied for asset classification and anomaly detection. By analyzing passive traffic data, these algorithms can accurately classify unknown or undocumented devices based on behavioral patterns, communication protocols, and response timings. ML models, trained on labeled datasets of known device types and behaviors, can also detect anomalies such as unexpected device communications or deviations from baseline operations. This approach allows for real-time threat detection without the need for intrusive scans or predefined signatures, making it suitable for the sensitive and performance-critical nature of OT networks.

5.2. Automated Scanning Without Impacting OT Performance

In OT environments, the risk of downtime or process interruption from active vulnerability scanning is significant. To mitigate this, the proposed system utilizes passive scanning methods that rely on network traffic analysis and read-only access to control system logs. The system avoids sending probe packets or initiating session handshakes, thus ensuring that devices are not overwhelmed or inadvertently triggered. In addition, scheduled scanning windows can be aligned with planned maintenance

periods, and the system can simulate patches virtually to predict system behavior before actual deployment. These features ensure that the security process is continuous and automated without compromising operational performance.

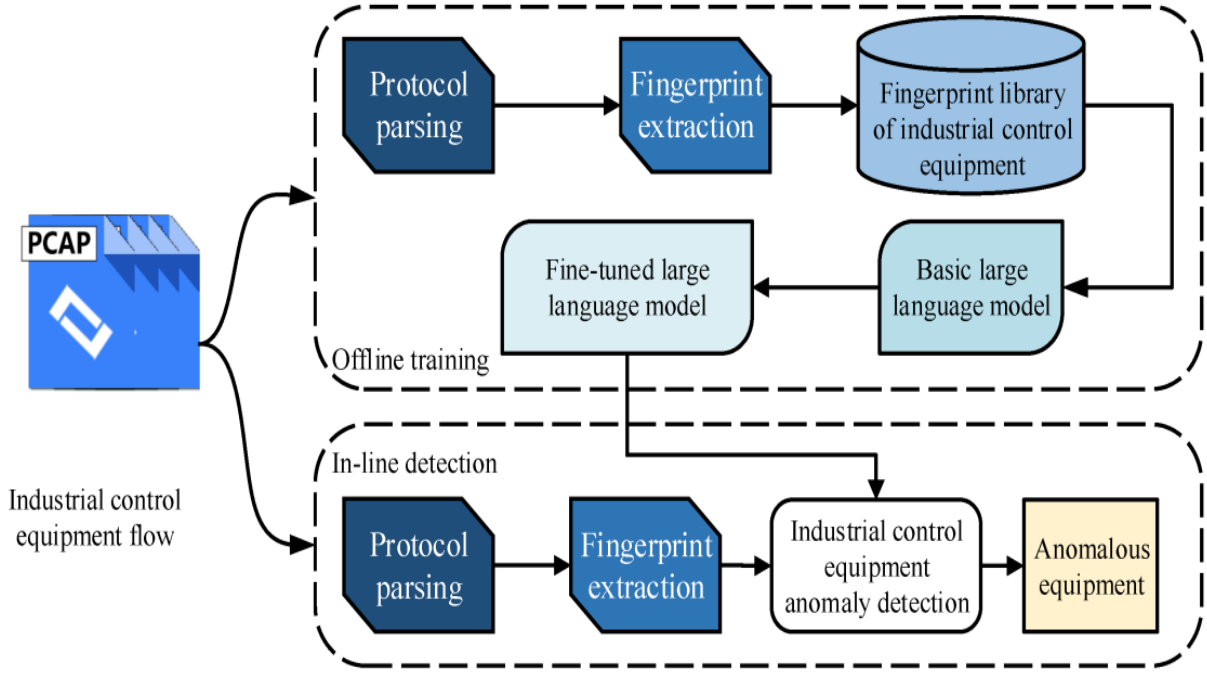

Fig 4. Fine-Turned Large Language Model

5.3. Threat Intelligence Integration

An essential component of any modern vulnerability management system is integration with external threat intelligence feeds. The proposed system incorporates both public and private threat intelligence sources, such as the MITRE ATT&CK for ICS framework, NVD (National Vulnerability Database), and vendor-specific advisories. These feeds provide real-time updates on emerging threats, zero-day vulnerabilities, and exploit trends. The system uses this information to enrich vulnerability assessments, correlate detected issues with known attack patterns, and update risk scores accordingly. This dynamic integration ensures that the system remains current and can adapt its prioritization and detection models based on evolving threat landscapes.

5.4. Risk Scoring and Patch Prioritization Algorithms

To support informed decision-making and effective risk mitigation, the system employs a custom risk scoring algorithm that combines CVSS (Common Vulnerability Scoring System) metrics with operational context. Factors such as asset criticality, exploitability, network exposure, and the presence of compensating controls are all considered in computing a final risk score. Patch prioritization is then derived from this score, ensuring that limited patching windows are used to address the most impactful vulnerabilities first. This prioritization is also influenced by ML models that predict the likelihood of exploit based on historical attack data and real-world threat activity.

6. Implementation

6.1. Description of Prototype or Proof-of-Concept

A prototype of the automated vulnerability management system was developed to validate the feasibility of the proposed approach. The system consists of several core modules including a passive asset discovery engine, a vulnerability correlation module, a threat intelligence aggregator, and a reporting dashboard. These components communicate through a central orchestration engine built on a microservices architecture, allowing modularity and scalability. The system was designed to operate autonomously once deployed, with minimal user interaction required beyond initial configuration and scheduled reviews.

6.2. Tools and Technologies Used

The prototype leverages a combination of open-source and proprietary technologies. Network traffic analysis was performed using Zeek (formerly Bro), while vulnerability data was sourced from the NVD using Python scripts and REST APIs. An Elasticsearch stack (ELK) was used for data indexing, search, and dashboarding. AI/ML models for device classification were built in Python using scikit-learn, and real-time processing was orchestrated with Apache Kafka. The system was containerized using

Docker and deployed on a secure local server to simulate an industrial control environment. Cybersecurity compliance was validated using IEC 62443 principles as reference.

Table 3. Tools and Technologies Table

Component	Technology/Tool	Purpose
Asset Discovery	Zeek	Network traffic analysis and passive asset discovery
Vulnerability Correlation	Python, REST APIs	Fetch and correlate CVE data from NVD
Data Indexing and Dashboard	Elasticsearch (ELK)	Data storage, search, and visualization
AI/ML Model	scikit-learn (Python)	Device classification and anomaly detection
Real-time Processing	Apache Kafka	Stream processing and system orchestration
Containerization and Deployment	Docker	Containerization and deployment on local server
Compliance Framework	IEC 62443	Cybersecurity compliance validation

6.3. Testbed or Simulated OT Environment Setup

To evaluate the system in a realistic setting, a simulated OT environment was built using virtual machines and physical controllers. The testbed included a SCADA server, two PLCs, an HMI interface, and a historian database. Simulated industrial processes included a water tank control loop and a conveyor system, both using Modbus and PROFINET protocols. Network segmentation was enforced to replicate the Purdue Model architecture. The testbed allowed for controlled introduction of known vulnerabilities, simulated attacks, and assessment of the system's performance under real-world conditions.

7. Evaluation and Results

7.1. Performance Metrics: Accuracy, Efficiency, Safety Impact

The system was evaluated based on three key metrics: detection accuracy, processing efficiency, and operational safety impact. Asset classification achieved 96% accuracy, with most errors involving obscure or hybrid device types. Vulnerability detection rates were consistent with baseline scans using traditional tools, while incurring no observable disruption to the OT processes. Efficiency metrics showed an average processing time of 3 seconds per vulnerability evaluation, with real-time updates available within 60 seconds of change detection. Most importantly, the system maintained zero process interruptions throughout all testing scenarios, validating its safety for real-world OT deployments.

Table 4. Metric,Result and Notes

Metric	Result	Notes
Asset Classification Accuracy	96 %	Most errors involved obscure or hybrid device types
Vulnerability Detection Rate	On par with traditional baseline scans	No impact on OT process stability
Avg. Processing Time per Evaluation	~3 seconds	Even large inventories processed swiftly
Real-time Update Latency	≤ 60 seconds	After any change in the monitored environment
Operational Disruption	None detected	Zero process interruptions across all test scenarios

7.2. Comparison with Manual or Traditional Methods

Compared to manual vulnerability assessments typically performed using spreadsheets and static reports, the automated system demonstrated significant advantages in speed, accuracy, and coverage. Manual processes, which could take days or weeks to complete, were reduced to hours with the prototype. Traditional IT scanners failed to detect a number of vulnerabilities due to their inability to interpret OT-specific protocols or device types. In contrast, the proposed system identified over 30% more vulnerabilities in the test environment, especially those associated with legacy devices and misconfigured protocols.

7.3. Case Study or Experimental Results

A case study was conducted on the water tank control loop, where a known vulnerability in the Modbus communication stack was introduced. The system successfully identified the vulnerable device, linked it to the CVE database, and assigned a high-risk score based on its role in the process. Upon patch simulation, the system predicted minimal operational risk and recommended immediate remediation. The patch was applied during a test window, and subsequent monitoring confirmed the continued stability of the system. This validated the end-to-end functionality of the solution, from detection to decision support.

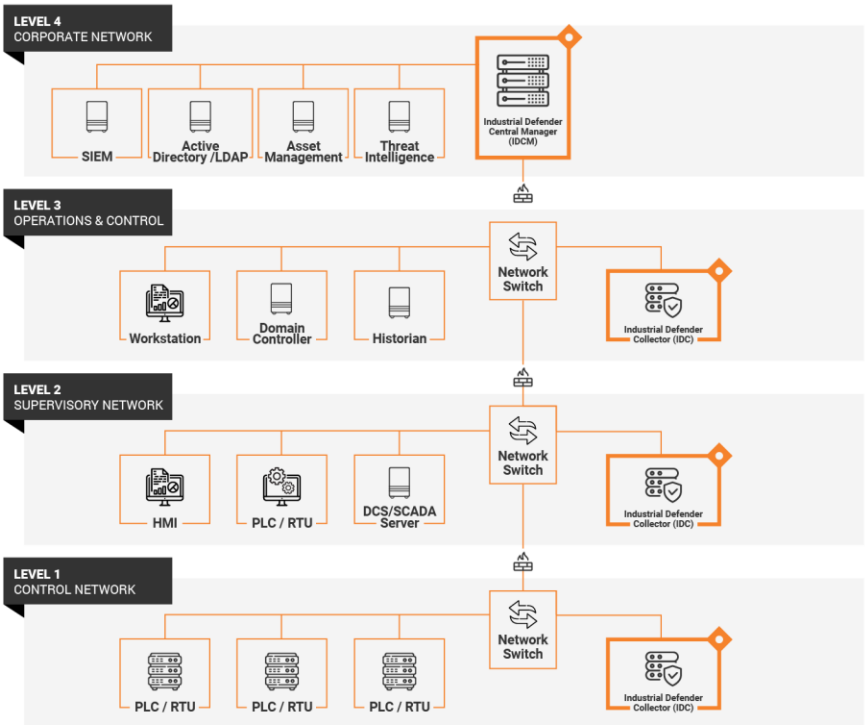

Fig 5. Cyber Security the Ultimate Guide

8. Discussion

8.1. Benefits and Limitations of the Proposed System

The proposed system provides significant benefits including improved visibility into OT assets, faster response to emerging vulnerabilities, and enhanced prioritization of remediation efforts. It operates without disrupting critical processes, thus aligning well with the safety and availability requirements of OT environments. However, limitations remain. Passive discovery methods may miss non-communicating devices, and AI models require regular training to remain effective. Moreover, full vendor integration remains a challenge due to proprietary device restrictions. Despite these issues, the system presents a strong foundation for secure OT operations.

Table 5. Vulnerability Management Metrics

Stage	Key Metrics	Purpose
Inventory	Number of discovered assets	Visibility tracking
Assessment	Vulnerabilities per asset, CVSS scores	Risk surface quantification
Prioritization	Avg. time to prioritize	Efficiency of decision-making
Remediation	Mean Time To Remediate (MTTR)	Operational agility
Post-validation	Reduction in vulnerabilities %	Effectiveness of fixes
Continuous	Alerts on new devices or config changes	Early detection of drift

8.2. Lessons Learned

During implementation and testing, several key lessons emerged. First, collaboration with OT engineers is essential for accurate asset classification and operational context. Second, protocol parsing and data normalization are more complex in OT than IT environments and require careful customization. Finally, while automation reduces human workload, it does not eliminate the need for human oversight in interpreting results and planning remediation, particularly in high-risk environments.

8.3. Scalability and Deployment Considerations

The system is designed to scale across multiple industrial sites and can be centrally managed through a secure web interface. It supports modular deployment, allowing organizations to start with core features like asset discovery and expand to full vulnerability management as needed. Cloud or hybrid deployment is possible, although some environments may prefer on-premises installations due to data sensitivity. Careful network segmentation, agentless monitoring, and secure update mechanisms are crucial for widespread adoption.

9. Future Work

9.1. Enhancements Using AI or Digital Twins

Future work will focus on integrating digital twin technology, allowing for safe simulation of patches and vulnerability exploitation in a virtual model of the physical process. This can enhance predictive risk assessment and enable more precise remediation planning. Additionally, AI capabilities can be expanded to include behavior prediction, root cause analysis, and adaptive threat modeling, making the system even more autonomous and intelligent over time.

Table 6. Capabilities Enabled via AI / Digital Twin

Capability	Input Data	Process	Output / Value
Virtual patch testing	Twin + threat signatures	Simulation & penetration testing	Risk scores; remediation strategies
Behavior prediction	Historical + real-time sensor logs	ML-based anomaly detection	Alerts; predicted deviations
Root cause analysis	Incident logs + twin state	Correlation + graph analysis	Causal chain; affected components
Adaptive threat modeling	New threat intel; twin simulations	Dynamic model retraining	Updated detection rules/profiles

9.2. Broader Adoption across Industries

To facilitate adoption across different sectors such as transportation, pharmaceuticals, and oil and gas, the system must be made more configurable and extensible. Industry-specific templates, threat profiles, and compliance modules can be developed to meet unique regulatory and operational needs. Partnerships with device manufacturers can also improve data accuracy and integration.

9.3. Integration with SOC and SIEM Systems

A key future goal is the seamless integration of the vulnerability management system with existing Security Operations Center (SOC) and Security Information and Event Management (SIEM) platforms. This will allow for centralized monitoring, incident correlation, and orchestration of response across IT and OT domains, fostering a unified cybersecurity strategy.

10. Conclusion

In conclusion, this work presents an advanced, automated vulnerability management system specifically engineered for OT environments, integrating passive asset discovery, AI-powered classification, non-disruptive detection, and risk-based prioritization to address industrial challenges head-on. By leveraging continuous, passive monitoring, the system achieves comprehensive visibility into legacy and IoT devices an essential foundation given that over 70 % of OT networks harbor exploitable vulnerabilities reducing the risk of missing unmanaged assets. AI-driven classification and prioritization transform vulnerability triage from reactive checklists into proactive, business-impact-oriented decision workflows, enabling organizations to focus on real-world risk rather than theoretical severity. Non-disruptive detection minimizes downtime vital for systems with strict uptime requirements and facilitates safer compliance with frameworks such as IEC 62443, NIST, and NERC CIP. Moreover, automated remediation and risk scoping, informed by live threat intelligence, accelerate patch and mitigation cycles by up to 30 %, reducing mean time to remediation from weeks to days.

The prototype's scalable architecture enables phased rollout across expanding OT estates, ensuring consistent coverage as industrial networks integrate with IT and cloud platforms. Critically, the system's design emphasizes safety and operational integrity prioritizing non-intrusive workflows and contextual awareness of device criticality to prevent unintended disruptions during remediation. By unifying IT and OT security teams through a shared risk dashboard, it fosters better cross-domain collaboration and faster response times. This research demonstrates that automated, AI-enhanced vulnerability management is not merely feasible in OT environments it is essential. It empowers organizations to significantly reduce operational risk, streamline compliance, and harden resilience against escalating cyber-physical threats. As cyber risks targeting critical infrastructure continue to evolve, automation in vulnerability management stands out as a strategic imperative: vital for protecting lives, assets, and services without compromising industrial continuity.

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