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Original Article

Cyber-Physical Resilience in Mission-Critical Facilities: Integrating Security, Reliability, and Safety Engineering

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Abstract - *The advent of additional cyber and physical infrastructures has created a high demand in the establishment of resilience systems capable of sustaining functionality in the adverse and unforeseen conditions. As a convergence of computational intelligence and physical processes, Cyber-Physical Systems (CPS) of modernity are experiencing mounting pressure due to cyberattacks, system failure, and environmental interference that threaten the survival of the operation. In this paper, I have thoroughly presented the resilience strategies in mission critical facilities considering the dimensions of absorption, recovery and adaptation in the three aspects of security, reliability and safety engineering. During the analysis, such advanced methods as AI/ML-based modelling, cyber-physical emulation, and robust control frameworks that may be implemented to enhance the system dependability, protection, and performance efficiency are mentioned. Besides, the paper will discuss central cybersecurity challenges, such as insider threats, supply chains vulnerability, compliance limitations, and regulatory divergences. Integrating the operations that have been employed in the fields of data center, energy systems, healthcare and defense infrastructure, the review might see significant gaps in the development of an all-inclusive and sustainable resilience. The findings show the value of adaptive, self-healing, and intelligent architectures towards offering secure, reliable and sustainable operations in contemporary mission critical environments.*

Keywords - *Cyber-Physical Systems, Resilience, Mission-Critical Facilities, Security, Reliability, Safety Engineering.*

1. Introduction

The design of industrial systems was traditionally based on the isolation model, in which the operational technology and the information technology were physically apart. In the modern world, the integration of operational and information technology is taking place [1]. The Cyber-Physical Systems (CPS) [2] that have been operating in recent years have necessitated the development of resilience the capacity of a system to prepare, absorb, recover, and adapt to maintain an acceptable level of functionality in the face of adversity. The high-visibility events of recent years [3], including cyberattacks on energy infrastructure, failures in industrial control systems, and so on, have revealed that such systems must develop resilience to respond to adversity.

Resilience in mission-critical infrastructures goes beyond traditional notions of reliability or robustness [4]. The moderation of the critical infrastructures (CIs) is crucial to society. CI as cyber-physical-social systems (CPSS) is also impacted by end-user behavior, particularly with regard to the effects of user behavior, to be proactive in identifying and responding to any possible attacks using data-driven responses in the form of modeling resilience of systems in digital twins. CIs are physical resources and systems that deliver a service required nationally, regionally and locally [5]. The resilience of the critical infrastructures must exist on every level including governance and operational level. To model the resilience of the complex systems whose components are physical, cyber-based, and social in nature, it is necessary to determine helpful criteria. The German government advocates for the Cyber-Physical System (CPS), the most crucial idea of the 4th industrial revolution, in order to build smart factories and capture market share.

Industry 4.0 [6] is intended for distributed engender through shared amenities in the combined global industrial structure for on-demand manufacturing to succeed personalization and resource efficiency [7]. Industry 1.0 dealt with mechanization and steam power; Industry 2.0 dealt with mass production and assembly lines; Industry 3.0 dealt with digitalization and automation. The Cyber-Physical System is a fundamental idea of Industry 4.0. CPS are cutting-edge technologies that link network and computer infrastructure with physical reality activities. CPS concentrates on linking several devices, although normally integrated gadgets are meant to operate as separate units. Historically, one form of protection against external threats has consisted of system isolation.

System security[8] is not guaranteed due to limited communication interaction with external devices and users, or partially connecting systems and limiting the communication access points. Worst, some CPS, such as legacy systems, do not implement internal security controls for system interconnection threats. Because of the convergence of the physical and cyber domains in CPS, these systems' attack surfaces[9]. Increases, and traditional security defence techniques against cyberattacks cannot be applied to CPS straightforwardly. Moreover, in the physical domain, CPS components are under the influence of the effects of environmental noise, such as electromagnetic, acoustic,

magnetic, electrical, and power changes. The main goals include examining the evolution of phishing attacks from their beginning to the present, paying special emphasis to methodological and technological advancements [10]. The study looks at upcoming threats and existing trends to find patterns in the evolution of attacks and forecast future developments.

1.1. Structured of the paper

This paper is structured as follows: Section II discusses mission-critical facilities, their definition, characteristics, and operational significance, Section III describes the idea of cyber-physical resilience of contemporary systems, Section IV provides the major cybersecurity issues in the mission-critical CPS systems, Section V is a literature review, and Section VI a concluding of the paper that present the key findings and research directions.

2. Mission-Critical Facilities: Definition and Characteristics

The mission-critical facilities are important systems that guarantee organizational survival. They are made to be very dependable and outage proof. The typical aspect ratio operating point and its surrounding operating space are determined by systems analysis, with an emphasis on the plasma and technical restrictions. The significant uncertainty when achieving required parameters demands robustness as a solution Engineering approaches that deliver mission-critical facilities and their management combine expertise from electrical and mechanical fields together with software-defined systems and operational optimal methods [11]. Key ratifies include the deployment of redundant power and cooling systems, advanced fire suppression mechanisms, seismic-resistant structural designs, and geographically dispersed backup sites. The advent of AI, and predictive analytics has also transformed the way such facilities work due to the ability to quickly detect anomalies in real time, predictive maintenance and automatic response to incidents the types shown in Figure 1.

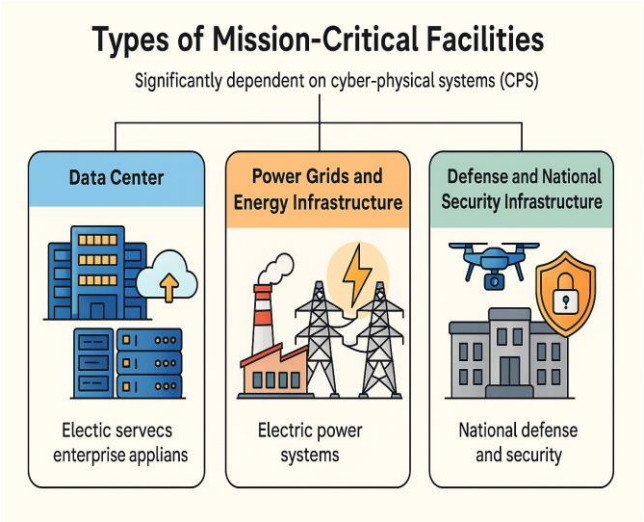

Fig 1: Types of Mission-Critical Facilities

2.1. Types of Mission-Critical Facilities

Mission-critical facilities refer to environments that need to deliver continuous function, data integrity, and operational reliability for the purposes of organizational or national goals. The failure or disruption of these facilities can have catastrophic impacts that range from a loss of financial value or service interruption, to physical threats to human life or national security. The following examples represent mission-critical infrastructures that depend significantly on cyber-physical systems (CPS) [12]:

2.1.1. Data Center

Data centers are a fundamental part of the digital economy, providing cloud services, enterprise applications, and data repositories that must always be available. Their mission-critical nature is predicated on continuous availability, data protection, and reliability of service for users and organizations around the world [13]. Any unavailability - even only briefly may cause a loss of economic revenues, reputation, or a loss to service-level contracts (SLAs).Cyber-physical data centre resilience is the overall coordination of redundant power and cooling systems, automated fault-tolerant controls, or cybersecurity measures against ransomware or distributed denial-of service (DDoS) attacks [14], and self-adaptive load-balancing policies to maintain performance in the face of unfavourable conditions.

2.1.2. Power Grids and Energy Infrastructure

Electric power systems, which consist of transmission networks, distribution control centres, and power producing facilities, are classic instances of cyber-physical systems. Using Industrial Control Systems (ICS) or Supervisory Control and Data Acquisition (SCADA) systems [15][16][16], grid operations are monitored and automated remotely [17] and in case system disruptions (e.g., malware attacking control logic) or physical disruptions (e.g., transformer faults, natural disasters) occur, this may lead to blackouts spreading to large areas [18]. Consequently, electric power sector resiliency implies a regular real-time detection of anomalies or isolating (islanding) disruption, self-healing grids, and communications to achieve continuity of service in the face of partial shifts in the system, or physical degradation of the system.

2.1.3. Defense and National Security Infrastructure

The national defences strategies are also constantly developing to be resistant to both conventional and unconventional threats [19]. The contemporary national defences requires a multilayer approach that would involve the combination of the conventional means (military) and new technologies. Government infrastructure, particularly critical infrastructure, may be targeted in cyber-attack, and autonomous weapon systems, such as drones, have redefined the whole security challenge environment. This therefore demonstrates the crucial and necessary role that security engineering has become as a challenge to such predicaments as a result of the fact that it provides resilient, adaptive and robust systems that pre-empt and counter-act threats. The national defense strategies have also been altered to address the requirements of the activities not only in the conventional

military threats, but also in the unconventional activities, such as the cyberattacks and the espionage Security engineering has offered a multifaceted resolution to safeguard the critical infrastructures and enhance the situational awareness [20].

3. Concept of Cyber-Physical Resilience

The digitization and interconnectedness of almost everything is making an unimaginable impact on all aspects of everyday life. The Internet of Things (IoT) is an essential enabling technology to Cyber-Physical Systems (CPS) [21], through which better actuation/control of peripheral actuators at the network edge and embedded intelligence. Examples of CPS include next-generation mobile devices, smart buildings, and intelligent grids, as seen in Figure 2. Given the growing importance of CPS in society, it must be vigorously protected against any threats that might compromise the system's normal operation and the standard of living. Furthermore, cyber-physical systems, or CPS, are becoming increasingly prevalent in contemporary society [22]. According to these systems, efficiency, reliability, and safety would be improved by combining physical processes with computing, communication, and control systems [23]. CPS can be discussed as medical equipment, smart grids, or driverless cars. The integration of these digital and physical systems, however, also creates new risks and weaknesses, leaving them open to cyberattack.

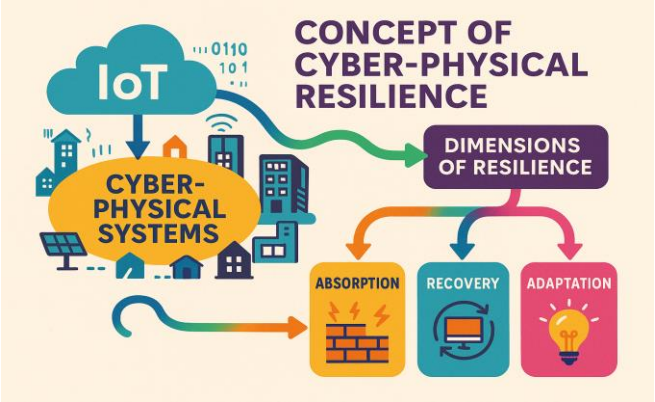

Fig 2: CPR Concepts

3.1. Dimensions of Resilience

The resilience dimensions define the response of the systems to the interruption and recovery at different stages. They summarize the ability of a given system to anticipate potential threats, take in the impact of disturbances to the system, bounce back, and adapt to new threats. These together can provide a comprehensive way to understand and enhance the capacity of mission-critical facilities to respond to both planned and unplanned incidents.

3.1.1. Absorption

Absorption is the ability of the system to withstand the interference and still carry out the essential functions, albeit at a lower level of performance. It puts focus on structural and operational characteristics such as redundancy, fail-safe, and fault-tolerant designs which assist the system to be stable under the influence of shocks [24]. A power grid, which remains partially functioning even when one of its components fails, is an example of a power grid with high absorption capacity.

3.1.2. Recovery

Recovery, once the system has been interrupted, is the process of restoring the system to normal operation. It is concerned with the speed and efficiency with which the system can be restored to a normal or acceptable operation [25]. Repair, resource distribution, backup system activation, and restoration procedures are all included. Fast recovery is crucial in mission-critical environments to reduce downtime and financial loss and guarantee the continuation of vital services.

3.1.3. Adaptation:

Resilience is also held by the capacity to modify to crucial circumstances as well as employing change to personal ends. This skill can be defined as post-crisis adaptations [26], which are oriented towards the organizational progress and serves as a primary antecedent of the anticipation [27]. Hence, the ability to adapt is among the most important skills that might assist the organizations in preventing or mitigating the adverse effects of unforeseen circumstances.

3.2. Distinction Between Resilience, Robustness, And Reliability

In engineering and system design, robustness, resilience, and reliability are related, but separate concepts especially in mission-critical systems [28]. Reliability refers to a system's ability to carry out its intended function under defined conditions for a certain amount of time without failing [29]. Reliability is based on established operational environments and predicted failure modes as shown in Figure 3. For instance, the cooling system for a data center is reliable when it performs as expected within its design limitations. However, reliability alone does not mean that the system function despite unanticipated uncertainties and disruption.

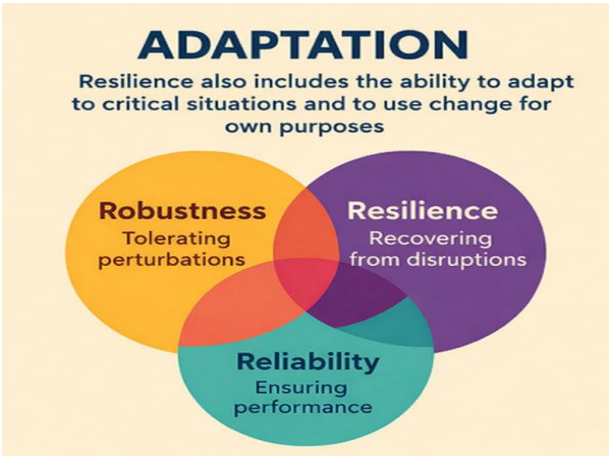

Fig 3: Conceptual Relationship Between Adaptation, Resilience, Robustness, and Reliability in Cyber-Physical Systems

3.3.1. Robustness

The ability to tolerate disturbances is known as robustness, while the ability to adjust to them is known as resilience. An effective method that supports operations when uncertainties arise must be developed for cyber-physical production systems [30]. The case of the prior study looked at the control issue of the nominal situation in the cyber-physical production systems. Nevertheless, the issue of managing the uncertainties in the production system that uses a cyber-physical system has not been addressed. Even though the initial research provided insight into the creation of a methodology to evaluate the effect of resource failures, no detailed analysis has been conducted regarding the study of cyber-physical production systems' resilience and robustness.

3.3.2. Resilience

On the other hand, resilience is a dynamic attribute that shows how well a system can foresee, absorb, recover from, and adjust to unforeseen events. Its main goals are to minimize downtime and restore critical operations following disruptions like cyberattacks or natural catastrophes [31]. Adaptive control, redundancy management, and reconfiguration are used by resilient systems to swiftly recover and change to stop recurrence.

3.3.3. Reliability

Reliability ensures performance under expected conditions, robustness provides stability under known variations, and resilience enables recovery and adaptation under extreme or unknown conditions [32][33]. Together, they define the comprehensive dependability framework for mission-critical infrastructures such as data centers, hospitals, defense networks, and power grids.

4. Cybersecurity Challenges in Mission-Critical Cps

Crucial to the mission Power grids, healthcare systems, transportation networks, and the seamless integration of computer and physical components is essential for highly networked Cyber-Physical Systems (CPS), such as defence infrastructures [34]. Although this integration improves automation and performance, it also introduces a number of cybersecurity flaws that may have an immediate effect on oper ational continuity, safety, and system dependability as shown in Figure 4. Since the development of CPS, physical systems' capabilities have greatly expanded across a range of industries, including manufacturing, transportation, healthcare, and agriculture [35]. The performance and efficiency of the physical systems have significantly increased as the intelligent characteristics have been improved throughout time. However, the establishment of this link between the virtual and real worlds exposes a number of security risks that might have serious consequences [36].

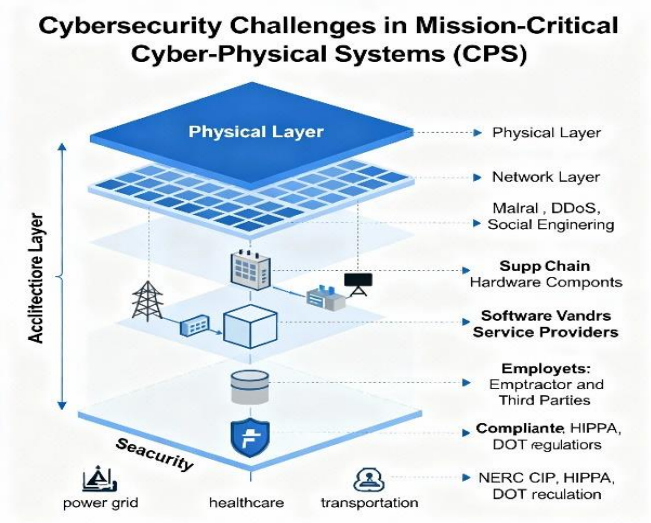

Fig 4: Challenges of CPS

4.1. Real-Time and Safety Constraints

Cyber-Physical Systems (CPS) that are mission-critical have stringent requirements of real-time and reliability. Any slight inconvenience or disruption can cause severe or potentially hazardous repercussions. These types of systems are employed in power grids, healthcare, aviation, transportation and automation in industries. In these regions, the activities in these regions ought to be expeditious, uniform and available every time. The traditional methods of cybersecurity [37] like deep packet inspection, encryption, intrusion detection, and periodic patches to the system, can be slow or unstable to the system activities. This makes it hard to strike a balance between performance and security. A trade-off between ensuring the smooth operation of the system in real time and observing how the system is protected.

4.2. Insider Threats and Human Error

Insider threats are security challenges in a mission-critical environment, whether deliberate or accidental. People having valid access to the system, such as operators, engineers, or administrators, may inadvertently or intentionally cause damage. Technical defences are easily bypassed through human mistakes, including improperly set systems, indiscriminate passwords, or becoming victims of social engineering attacks. This may lead to data attacks, unauthorized access or system interruptions. Human factors are one of the least strong points in the defence of the systems, despite the presence of good security technologies [38]. In order to reduce these risks, organizations should prioritize to access controls, continuous employee training, monitoring of employee behavior, and multi-factor authentication. Also, the implementation of zero-trust [39] architecture and activity auditing may be mentioned as the means of early detection of the appearance of unusual behavior, which enhances resilience and reliability of mission-critical CPS to insider threats.

4.3. Supply Chain Vulnerabilities

The cyber-Physical Systems (CPS) often rely on complex supply chain, which includes different hardware, software, and firmware suppliers. This complicates the fact that any

trade off or ill intent towards the supply chain at any level can pose severe security threats. Issues such as compromised hardware components, malicious code, or compromised firmware can be missed, which affect system performance, integrity and trust later. Such weaknesses may lead to data breach, hacking or system malfunction, particularly in the systems that are of utmost importance and thus reliability and safety is paramount. Due to this fact, the issue of supply chain security [40] has taken the centre stage of CPS. It has to be strictly given, secure parts acquired, observed and safe updating processes done on a regular basis to keep the system secure, intact and resilient.

4.4. Compliance and Regulatory Challenges

Ensuring cybersecurity compliance regarding a variety of regulatory standards, such as NIST, ISO/IEC 62443, and IEC 61508 [41][42], has several challenges. Among the main obstacles are:

- Diverse Regulatory Frameworks: Organizations find it challenging to comply with all pertinent compliance obligations because different industries and geographical areas have different standards.
- Operating Constraints: In mission-critical environments, where downtime or system modifications are difficult to accept, strict compliance regulations may clash with real-time operating requirements [43].
- Resource Restrictions: Many organizations struggle to establish and maintain complete compliance across all systems and components due to a lack of funding, staff, or experience.
- Rapid Technological Evolution: The development and the revision of existing regulations very often find themselves outpaced by the fast pace of digital technologies and adoption of new technology [44].
- Complex System Integration: Unified compliance management is made more difficult by the frequent integration of current technologies with ancient systems in mission-critical CPS.
- Continuous Monitoring and Auditing: In order to meet changing requirements, achieving compliance necessitates ongoing monitoring, auditing, and documentation [45].

5. Literature Review

This review is a timely overview of recent developments in the field of cyber-physical system (CPS) resilience and security highlighting methods like AI/ML-based modelling, cyber-physical emulation, robust control, and integrated safety-security systems to improve system reliability, protection, and adaptability to a variety of applications in industries and autonomous systems. Alain et al. (2025) provided a thorough and organized analysis of the state-of-the-art resilience enhancement techniques in CPS, focusing on key elements that characterize the concept of resilience as used in the current work, such as anomaly detection, attack mitigation, fault recovery, and system reconfiguration, as well as the new solutions' responsiveness to threats like hardware failures and cyber physical attacks [46].

Akramul Haque et al (2025)presented a cyber-physical simulation of a University of St. Thomas microgrid that is now in use, with a synthetic cyber network layered over it to evaluate its vulnerabilities and enhance security. Unlike previous testbeds that mainly focus on single-layer analysis or simplified attack models, the framework allows the first systematic evaluation of complex multi-stage attacks on operational microgrids using industry-standard protocols and structured adversarial techniques by combining real-world microgrid specifications with comprehensive cyber network emulation. According to its findings, crucial attack links were found using correlation analysis [47]. Van Bossuyt et al. (2024) examined the application of Large Language Models (LLM) and Artificial Intelligence and Machine Learning (AI/ML) in combination with cyber-security research to create an ongoing resilience study. To do this, the hardware and software of the system are modeled, software vulnerabilities are continuously searched for utilizing LLMs and AI/ML, and the data is fed into resilience models that are updated often. A drone case study is provided to illustrate the potential of the suggested approach [48].

Amiri et al. (2024) These were focused on risk management, system designs, and safe and secure infrastructures and included suppliers, integrators, and asset owners. A comprehensive strategy to integrated security and safety by design that is both economically viable is required since the results indicated a low level of industry knowledge and adoption of the Reference Architecture Model Industries (RAMI) 4.0. Additionally, a comprehensive ontology for safety, security, and operating needs in the IT/OT convergence was provided. Expanding upon previous efforts, provide a model-based engineering methodology for industrial Cyber-Physical Systems (CPS) design that incorporates integrated safety and security [49]. Rani & Kumar (2023) proficient by offering recommendations and potential directions for the dataset generation, improvement, and sharing of intrusion detection datasets to address these challenges. The insights presented in this study aim to direct researchers and practitioners towards better dataset exercise and improved intrusion detection capabilities as the cybersecurity landscape advances [50].

Wu et al. (2022) examined the problem of safe control in cyber-physical systems when malicious data enters the cyberspace and connects directly to the actuators. Provide a new proactive and reactive defensive control strategy based on reinforcement learning and moving target defense (MTD). The MTD control scheme is constructed more easily by first modeling the system (A, B) as a switching system made up of many controllable pairs (A, Bl) [51]. Wang et al. (2022) The difficulty of robust secure consensus control for linear multi-agent systems under random Denial-of-Service (DoS) attacks and external disturbances was investigated. A hostile attacker randomly launches denial-of-service (DoS) assaults on certain network communication channels when agents interact with their neighbours, resulting in a Markovian switching communication topology [52].

Table I outlines recent research on CPS resilience and security, and identifies progress by such techniques as AI/ML modelling, cyber-physical emulation, and defence control. Although such studies enhance system reliability, as well as security, issues like scalability and practical validation still exist. The future undertaking is the development of adaptive and standardized CPS frameworks

Table 1: Summary of Reviewed Literature on Cyber-Physical Resilience in Mission-Critical Facilities

Reference	Study On	Approach	Key Findings	Challenges / Limitations	Future Directions
Alain et al., (2025)	Resilience enhancement in CPS	Examining resilience strategies like as reconfiguration, fault recovery, attack mitigation, and anomaly detection	Cyber-physical dangers are addressed by categorized techniques such as safe state estimation, fault-tolerant design, and robust control.	Integration complexity among resilience mechanisms	Develop adaptive and self-healing CPS architectures
Akramul Haque et al., (2025)	Cyber-physical microgrid emulation for security testing	Real-world microgrid integrated with a synthetic cyber network for attack simulation	Enabled the first methodical assessment of multi-stage assaults against microgrids that are in operation.	Limited scalability and cost of real-world emulation	Expand framework for large-scale industrial microgrids
Van Bossuyt et al., (2024)	Combining reliability and cybersecurity analysis using AI/ML and LLMs	AI-driven continuous resilience analysis for CPS	Demonstrated a drone case study integrating LLM-based vulnerability updates	Data privacy and computational complexity	Broaden application to autonomous and industrial CPS
Amiri et al., (2024)	Integrated safety and security in industrial CPS	Model-based engineering and ontology-driven approach with RAMI 4.0	Revealed limited awareness of RAMI 4.0; proposed integrated design for IT/OT convergence	Low industry adoption and awareness	Enhance practical implementation and standardization of RAMI 4.0
Rani & Kumar, (2023)	Intrusion detection dataset generation and sharing	Analytical review of dataset development for IDS in CPS	Guidelines for better dataset quality and sharing procedures were included.	Lack of realistic, diverse datasets	Develop benchmark CPS datasets for robust IDS training
Wu et al., (2022)	Defense control in CPS against data injection attacks	Reinforcement learning combined with Moving Target Defense (MTD)	Proposed proactive and reactive MTD control for enhanced security	Limited to linear system modeling	Extend scheme to nonlinear and large-scale CPS
Wang et al., (2022)	Secure consensus control under DoS attacks	Sturdy control architecture for Markovian switching topology linear multi-agent systems	Improved consensus control despite random DoS attacks	Restricted to specific attack models	Explore non-linear and adaptive control for resilient CPS

6. Conclusion and Future Work

The concept of reliability, safety and system-wide security control has changed due to the development of Cyber-Physical Systems in terms of mission-based infrastructures. The paper has provided a cogent understanding of cyber-physical resilience in terms of systems' capacity to withstand shocks, resume critical operations, and adapt dynamically to changing threats. A comparative review of the existing research indicates that although the use of AI-based modelling is vital, the digital twins and the cyber-physical emulation as a source of resilience continue to be faced with issues of scalability, interoperability, regulatory uniformity and validation in the environment. Alternative impediments such as the human element, the complex supply chain and poor assimilation of systemic frameworks such as RAMI 4.0 are impediments to resilience implementation and the maturity of operations. Result syntheses indicate that the CPS design needs to evolve in the future in order to cease as a passive protection construct and advance to active adaption, predictive reconfiguration and active situation learning. The system, which implies integration of smart automation, analysis in real-time, and safe layers of communication, is required to enhance mission assurance, stability of the operations and longevity of functions. Better interaction between reliability, safety.

Future studies should target the creation of adaptive and self-healing CPS models with the ability to identify threats and recover quickly. Through Artificial Intelligence, Blockchain, and Digital Twin, it will be possible to monitor

the system in real-time, perform predictive maintenance, and ensure the safety of communication. There will be a greater ease in having standardized resilience benchmarks and simulation platforms to carry out consistent cross-domain tests. Additionally, a behaviour-mindful and regulatory mindset is also likely to assist in overcoming human factors, insider risk and compliance challenges to establish world interoperable and morally regulated mission-critical infrastructures.

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