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Advancing Smart Cyber Physical System with Self-Adaptive Software

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Abstract

The proposed integration of DevOps and Digital Twins presents a ground-breaking approach to enhancing the resilience and adaptability of Cyber-Physical Systems in the context of Industry 4.0 and the forthcoming Industry 5.0 era. This research explores the synergistic potential of DevOps principles in fostering collaborative and efficient development and maintenance processes for embedded systems and distributed control systems within CPS. Concurrently, the utilization of Digital Twins offers real-time monitoring and simulation capabilities, heralding a shift towards a human-centric approach to CPS operation. The emphasis on self-adaptive systems within CPS anticipates the ability to address dynamic conditions and unforeseen challenges, paving the way for the evolution of resilient and responsive industrial systems. This research explores the integration of DevOps and Digital Twins in the context of Industry 4.0 and anticipates the requirements of Industry 5.0, emphasizing the need for resilient and human-centric Cyber-Physical Systems. This study investigates the integration of DevOps and Digital Twins to enhance the resilience and adaptability of Cyber-Physical Systems in the context of Industry 4.0 and Industry 5.

Keywords: CPS, Human-Centric Approach, Industrial Internet of Things, Resilience Adaptability.

Introduction

The continuous integration of revolutionary technologies, exemplified by Industry 4.0 and the upcoming shift to Industry 5.0, has introduced a new era of interconnected and intelligent Cyber-Physical Systems (CPS). This evolution requires a thorough reassessment of system design and operation to fulfil the requirements of dynamic, intricate, and cooperative ecosystems (1). This study aims to enhance the robustness and flexibility of Cyber-Physical Systems (CPS) by including two crucial concepts: DevOps and Digital Twins. DevOps, which is based on collaborative practices and agile approaches, plays a crucial role in efficiently coordinating interdisciplinary teams that are involved in the creation, deployment, and maintenance of CPS. Simultaneously, the inventive application of Digital Twins brings about a fundamental change, generating virtual duplicates that provide instantaneous monitoring, analysis, and simulation capabilities. This methodology promotes a viewpoint that prioritises human needs, enabling a more detailed comprehension of CPS behaviour and aiding adaptive decision-making. This research specifically concentrates on the advancement of self-adaptive systems within CPS, which include embedded systems and distributed control systems. The projective is to successfully respond to dynamic conditions and unexpected problems that may arise. As the industrial sector advances towards Industry 5.0, this study explores the impact on distributed control systems in the Industrial Internet of Things (IIoT) (2). This project aims to establish the foundation for robust, flexible, and user-focused smart Cyber-Physical Systems (CPS) by combining the advantages of DevOps and Digital Twins. The ramifications of this research on the advancement and execution of sophisticated CPS are profound.

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By demonstrating the practical benefits of integrating software agents into CPS, the study paves the way for more intelligent, self-adaptive systems that can respond in real-time to environmental changes and user demands. This can lead to significant improvements in various domains, such as smart manufacturing, healthcare, and transportation, where CPS are increasingly prevalent. Moreover, the research provides a foundation for developing more robust and scalable systems, which can drive further innovations and applications in CPS technology. These systems will be well-equipped to succeed in the changing landscape of industrial needs and technological progress. The following investigation seeks to make a substantial contribution to the existing discussion on the future direction of CPS in Industry 4.0 and beyond (3, 4). This study establishes a well-defined framework for designing sustainable and intelligent Cyber-Physical Systems (CPSs). It outlines a research plan and methodology using an industry case study. Sections 2 and 3 do a comprehensive examination of the most advanced technology in Digital Twins and delineate the necessary specifications for embedded control software enhanced by Digital Twins. Section 4 presents a design that utilises micro-services to better control services in embedded devices with limited resources. Sections 5 to 8 demonstrate many experiments and capabilities, such as sub-millisecond real-time twinning, closed-loop control, self-protection, and architecture-based asset adaptation. The showcased DevOps features (Section 6, 7, and 8) emphasise the dependable remote monitoring, adaption, deployment, and runtime experiments. Section 9 explores the Results and analysis, while Section 10 provides a conclusion. This work significantly enhances the current understanding of CPS and software engineering by introducing new integration methodologies that leverage software agents for improved system autonomy and adaptability. It also provides empirical evidence on the effectiveness of these methodologies in real-world applications, thereby offering practical insights that bridge the gap between theoretical concepts and operational realities. The research contributes to the body of knowledge by highlighting the potential of advanced algorithms and architectures to address the dynamic nature of CPS environments, ultimately fostering more resilient and efficient systems.

Comprehensive Examination of the Most Advanced Technology in Digital Twins

The study of Digital Twins is a crucial investigation into the cutting-edge of technological technology. Digital Twins have transformed the way virtual representation and real-world interaction are approached, spanning several sectors and applications. This research thoroughly explores the complex aspects of cutting-edge Digital Twin technologies, revealing their influence on several sectors. This study explores the orchestration of embedded services using micro-services and the transformation of Cyber-Physical Systems (CPS) into services. It covers advanced analysis, requirements formulation, design models, and empirical trials. This study examines the application of sub-millisecond real-time twinning for context-aware monitoring and closed-loop control. It focuses on self-protection mechanisms and architecture-based modifications to facilitate ongoing development and evolution (5). The research concludes with an examination of proven DevOps skills, highlighting the dependability and adaptability of remote monitoring, adjustment, implementation, and runtime trials. This analysis explores the significant impact that Digital Twins can have on influencing the future technological landscape, with a specific focus on industrial applications. The research methodologies employed in this study include both theoretical formulation and empirical validation of self-adaptive software. The process begins with the conceptualization of adaptive algorithms designed to enhance system responsiveness and efficiency. These algorithms are then implemented using state-of-the-art software engineering tools and integrated into CPS prototypes. Validation involves rigorous testing through simulations and real-world case studies to assess performance, scalability, and reliability. The results are analysed using statistical methods to ensure accuracy and generalizability, providing a comprehensive evaluation of the proposed methodologies. The standards for Digital Twin-enhanced embedded control software include a number of important requirements designed to assure smooth integration, real-time monitoring, and adaptive capabilities. Figure 1 shows the most advanced technology in Digital twins and Figure 2 shows the key challenges and obstacles in the embedded systems domain. These criteria are required to fully realise the potential of Digital Twins in the world of embedded systems. The selection of software engineering approaches and tools in this study is driven by the need to address specific challenges associated with CPS, such as real-time processing, scalability, and system interoperability. Advanced algorithms are chosen for their ability to provide adaptive and intelligent responses to dynamic environments. Tools like edge computing platforms are employed to reduce latency and enhance data processing capabilities. Additionally, modular design principles are adopted to ensure flexibility and ease of integration with various CPS components. These approaches and tools are selected based on their proven effectiveness in similar contexts and their alignment with the study's objectives of enhancing CPS functionality and reliability.

The following are critical features of the required specifications:

Monitoring and simulation in real time:

- Using Digital Twins, you may monitor physical processes in real time.
- Facilitate simulation capabilities for a virtual depiction of the behaviour of the embedded system.

Adaptability Under Resource Constraints:

- Design for resource-constrained contexts, ensuring optimal computing resource utilisation.
- Implement adaptive features that optimise performance while taking into account processing power and memory constraints.

Architecture Based on Micro-services:

- Adopt a micro-service based architecture to improve modularity and scalability.
- Through well-defined interfaces, enable the orchestration of native embedded services.

This research has broad applicability across several fields, including urban areas with advanced technology, automated industrial processes, and the medical sector. In smart cities, self-adaptive CPS can optimize traffic flow, enhance energy management, and improve public safety through real-time monitoring and adaptive responses to changing conditions. In manufacturing, self-adaptive systems can increase efficiency, reduce downtime, and enhance quality control by dynamically adjusting to variations in production processes and machinery conditions. In healthcare, CPS with self-adaptive software can enhance patient monitoring, optimize the allocation of medical resources, and improve the accuracy and efficiency of diagnostic and therapeutic procedures.

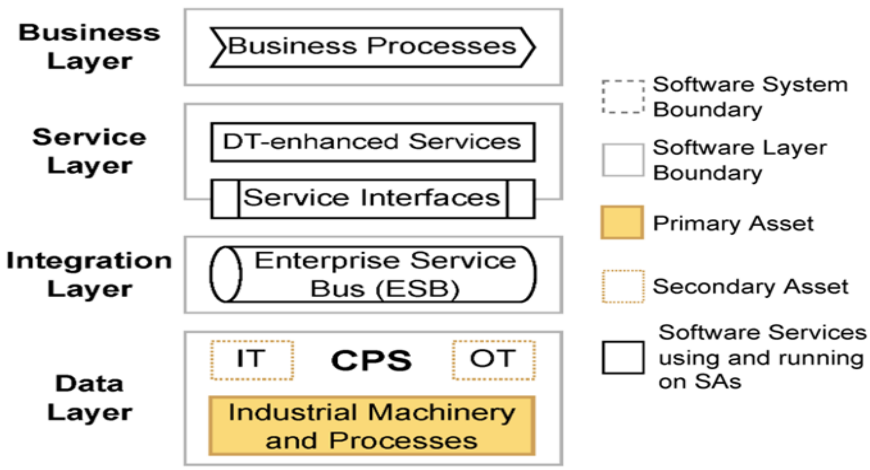

Figure 1: The Most Advanced Technology in Digital Twins

Model of Secondary Asset Digital Twin

- Create a supplementary Digital Twin model to control and reflect the embedded system's Information and Communication Technology (ICT) attributes and states.

Capabilities for Servitization

- Allow for the providing of services connected to embedded control functions by facilitating asset servitization.

- For comprehensive functionality, ensure smooth connection with the larger Cyber-Physical System (CPS).

Real-Time Sub millisecond Twinning

- To provide instantaneous updates and reflections of the physical system's state, achieve sub-millisecond latency in twinning.

Control in a closed loop

- Use the Digital Twin to implement closed-loop control mechanisms that allow for real-time modifications and responses to changing situations.

Mechanisms of Self-Protection

- Integrate self-protection measures into the Digital Twin to reduce risks during continuous development (CD) and continuous evolution (CE).

Adaptation with Zero Downtime

- Implement architecture- and parameter-based adaptive techniques to provide zero-downtime during embedded control software upgrades and changes.

Integration of DevOps

- Integrate with DevOps methods to enable dependable and flexible remote monitoring, adaption, deployment, and runtime experiments.
- These requirements form a solid foundation for embedded control software improved by Digital Twins, enabling a harmonious blend of real-time responsiveness, adaptability, and seamless integration within the larger CPS system.

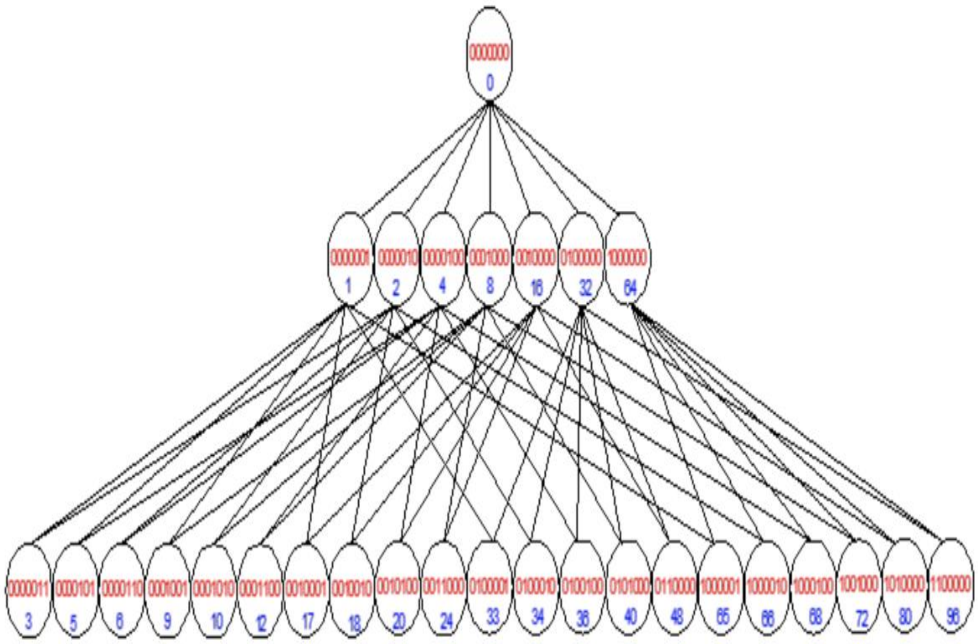

Figure 2: The Digital Twins Cutting Edge Technologies

A micro-services architecture is crucial in the development of a Cyber-Physical System (CPS) designed specifically for embedded devices that have restricted resources. The method entails breaking down the CPS control system into modular micro-services, each optimised to function within the limitations of embedded settings (6). These micro-services, which are conscious of available resources, enable immediate communication using efficient protocols and adjust dynamically to the changing requirements of the Cyber-Physical Systems (CPS). Edge processing is utilised to efficiently spread computational workloads, hence optimising the constrained computational capabilities of embedded systems. The design features fault-tolerant methods and utilises an event-driven architecture to improve responsiveness and enable asynchronous communication, hence separating micro-services (7). Data integrity and confidentiality are guaranteed in resource-constrained circumstances through the incorporation of security features in each micro-service. Micro-services are dynamically adjusted based on resource usage patterns using integrated continuous monitoring and optimisation technologies. The inherent scalability and compatibility of micro-services make them suitable for embedded Cyber-Physical Systems (CPS), enabling effortless integration with tangible operations. Ultimately, the combination of thorough documentation and version control guarantees lucidity and ease of management in this meticulously crafted system. In general, this design for cyber-physical systems (CPS) effectively tackles the difficulties caused by restricted resources, enhancing flexibility, effectiveness, and robustness in the setting of embedded devices. Figure 3 shows the Conceptual Framework for a CPS Design that optimally utilizes micro-services in the context of embedded systems (8). Self-adaptive software is crucial for the effective operation of Cyber-Physical Systems (CPS) as it enables these systems to dynamically respond to changes in their environment and evolving user demands. This capability is essential for maintaining optimal performance, ensuring reliability, and enhancing system resilience. Self-adaptive software leverages real-time data and advanced algorithms to make autonomous adjustments, which allows CPS to handle unexpected scenarios, optimize resource usage, and improve overall efficiency. This flexibility is particularly important in complex and dynamic environments where pre-programmed responses are insufficient.

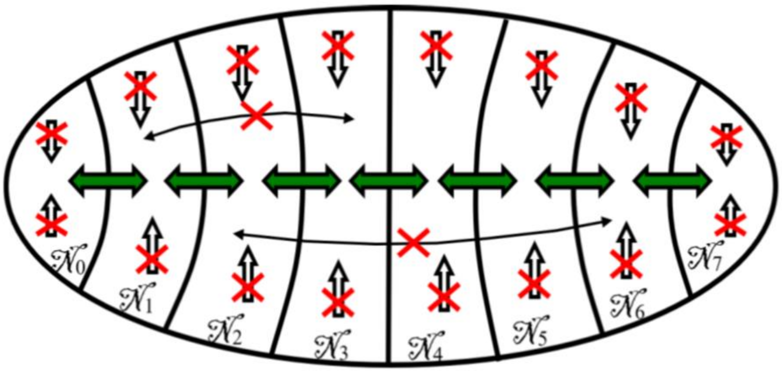

Figure 3: CPS Design

Methodology

Real-time Twinning

Real-time twinning is the act of instantly and dynamically duplicating a physical system or process in a virtual or digital format (9). This notion is frequently linked to Digital Twins, which are virtual depictions of tangible objects, systems, or procedures. Real-time twinning enhances the possibilities of Digital Twins by ensuring that the virtual representation accurately reflects the current state of the physical entity in almost real-time. Real-time twinning refers to the ongoing process of synchronising data between a physical system and its digital representation. The digital twin promptly mirrors any modifications or advancements made in the real system, ensuring a smooth and current depiction. This synchronisation allows for precise monitoring, analysis, and modelling of the physical system, which in turn enhances decision-making, enables predictive maintenance, and improves overall performance. Real-time twinning is utilised in many areas such as manufacturing, healthcare, transportation, and smart infrastructure (10). For instance, in the field of manufacturing, the utilisation of real-time twinning enables accurate surveillance of machinery, enabling the anticipation of probable malfunctions or maintenance requirements before to their occurrence, so preventing any disturbances. In the healthcare field, it can be utilised for the purpose of continuously monitoring patients and medical equipment in real-time. Real-time twinning is typically achieved by the use of sophisticated sensor technologies, Internet of Things (IoT) devices, and reliable communication networks (11). These components work together to facilitate the prompt transfer of data between the physical and virtual domains. The objective is to develop a responsive and precise digital model that accurately reflects the behaviour and condition of the real-world system at the current time. To ensure the software's durability, scalability, and security, several steps are taken. Rigorous testing and validation processes are implemented to identify and rectify potential weaknesses, with continuous integration and deployment practices adopted to maintain and update the software regularly. The software is designed with modular architecture and uses cloud computing and edge computing to handle increased workloads, with load testing and performance benchmarking conducted to ensure the system can scale efficiently. Robust security measures, such as encryption, authentication, and access control mechanisms, are integrated to protect against unauthorized access and cyber-attacks, with regular security audits and vulnerability assessments performed to identify and mitigate potential risks.

Closed-Loop Control in Digital Twin

Closed-loop control in digital twinning is an advanced method for optimising systems. It involves closely monitoring and making adjustments to a real-world physical system using its digital twin counterpart (12). Within this particular framework, a comprehensive digital replica model accurately represents the complexities of the physical system, while sensors collect up-to-the-minute data from the real-world surroundings. Analyse the data using a control algorithm to make decisions that optimise the behaviour of the physical system. Actuators or control mechanisms subsequently execute these judgements in the physical realm, so completing the feedback loop (13). The continual adjustment of the real-world entity to meet desired parameters and respond to changing situations is achieved through the dynamic interplay of the physical system, digital twin, and control algorithm. Applications encompass a wide range of industries including manufacturing, energy systems, smart cities, and healthcare. They provide a revolutionary method for making decisions in real-time, adapting to changing circumstances, and improving efficiency in intricate and interconnected systems. Figure 4 shows the closed loop digital twin (14).

Self- Protection in Digital Twin

Self-protection in Digital Twins refers to a security architecture that is proactive and autonomous. Its purpose is to ensure the integrity, confidentiality, and availability of data and functionality in the digital representation (15). This involves integrating sophisticated security measures into the Digital Twin, such as ongoing threat detection methods, real-time monitoring for abnormalities, and adaptive security features that can adjust to changing circumstances. Secure data handling is ensured by the deployment of powerful encryption, access controls, and data integrity checks. Uninterrupted availability is guaranteed by redundancy and backup procedures (16). Furthermore, the Digital Twin's self-healing characteristics enable it to independently recover from interruptions, so strengthening its resilience. The implementation of secure communication protocols, rigorous user authentication, and robust authorization processes collectively enhance the security of the Digital Twin by preventing unauthorised access. To tackle obstacles and enhance the efficiency of self-adaptive software, several tactics are proposed. Adopting an iterative development approach allows for continuous testing and improvement, helping to identify and address issues early in the development cycle. Utilizing machine learning algorithms enhances the decision-making capabilities of the self-adaptive software, enabling it to better predict and respond to changes in the environment. The implementation of continuous improvement tactics allows the Digital Twin's self-protection capabilities to adapt and develop alongside emerging cybersecurity threats. Through the implementation of these extensive self-defence mechanisms, Digital Twins are transformed into robust layers of confidence in crucial fields, guaranteeing a secure basis for immediate monitoring, analysis, and decision-making (17).

Architecture-based asset adaptation

Architecture-based asset adaptation in the field of Digital Twins refers to a dynamic and intelligent method of enhancing the performance of virtual representations that match physical assets. This adaption is mostly driven by the complexities of the Digital Twin's architecture, which includes the design, modular components, and networked systems. The Digital Twin enables precise modifications by implementing modularity, allowing individual components to react autonomously (18). Parameter tuning in the architecture allows for the precise adjustment of variables and control parameters, optimising their alignment with the changing features of the physical asset (19). The architecture's dynamic reconfiguration capabilities allow it to promptly and flexibly adjust to changing conditions or requirements, ensuring real-time flexibility. Fault-tolerant architectures improve the ability of the

Digital Twin to withstand and manage unanticipated disturbances with elegance and resilience (20). The incorporation of machine learning algorithms enables the architecture to acquire knowledge from data, gradually developing and enhancing its prediction abilities. Sensitivity analysis highlights crucial components, while real-time monitoring and feedback loops guarantee ongoing evaluation and adjustment according to present circumstances (21).

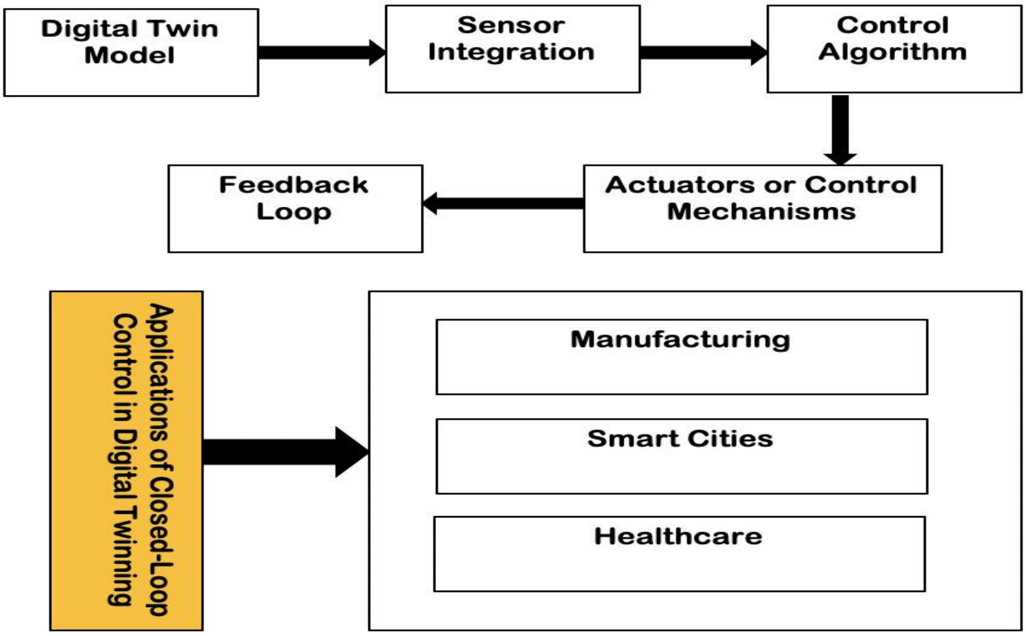

Figure 4: Closed-Loop Control in Digital Twin

Results and Discussion

This Figure 6 depicts the relationship between Cyber-Physical Systems (CPS) functionality and system performance, specifically focusing on scenarios where the parameter N, representing a certain aspect of system performance, varies between 2 and 4. It likely illustrates how the functionality of CPS evolves or responds as the system performance within this range changes. In this Figure 7, the emphasis shifts to CPS functionality in relation to system performance, with a focus on scenarios where the parameter N ranges from 4 to 6. It probably provides insights into how CPS behaviour and capabilities adapt or are influenced by changes in system performance within this range. In Figure 8 delves into the interplay between CPS functionality and system performance, particularly examining scenarios where the parameter N varies from 6 to 8. It likely offers a nuanced understanding of how CPS features and performance characteristics are affected as the system performance falls within this specific range and Figure 9 explores the relationship between CPS functionality and system performance, honing in on scenarios where the parameter N ranges from 8 to 10. It probably provides valuable insights into how CPS capabilities and behaviours are shaped by changes in system performance within this particular range (22, 23). The critical system functionality of Cyber-Physical Systems (CPS) refers to the essential operations, processes, and features that are crucial for the effective and reliable performance of the system (24). CPS integrates physical processes with computational elements and often involves real-time interactions between the physical and digital components (25). Figure 5 Shows the Critical System Functionality of CPS. This concludes that combining self-adaptive software driven by Digital Twins is a revolutionary way to improve Human-Centric Smart Cyber-Physical Systems (26).

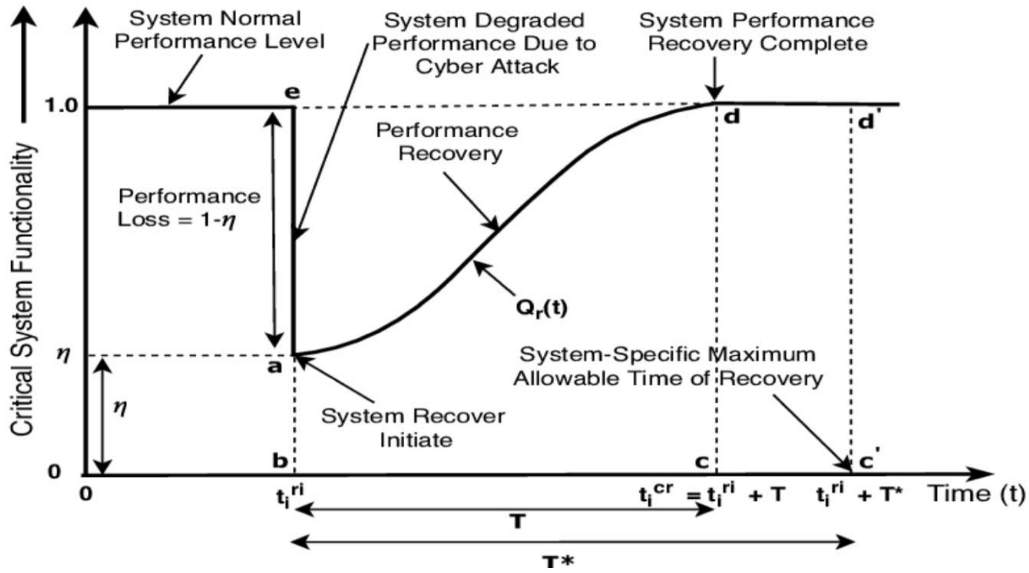

Figure 5: Critical System Functionality of CPS

Table 1: Number of Required Multiplication for the Proposed and Previous Method

N	Number of multiplication operations for the proposed method $8N \times 2^{N_d-1}$	Number of multiplication operations for the previous method $8N \times 2^{N_d-1} \times b$
4	320	800
5	384	960
6	448	1120
7	512	1280

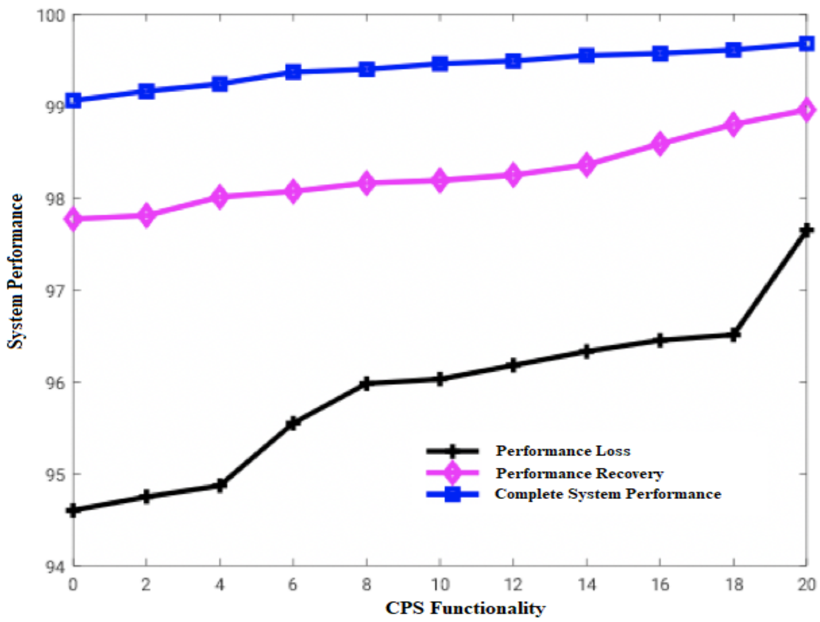

Figure 6: CPS Functionality with System Performance (N=2, 4)

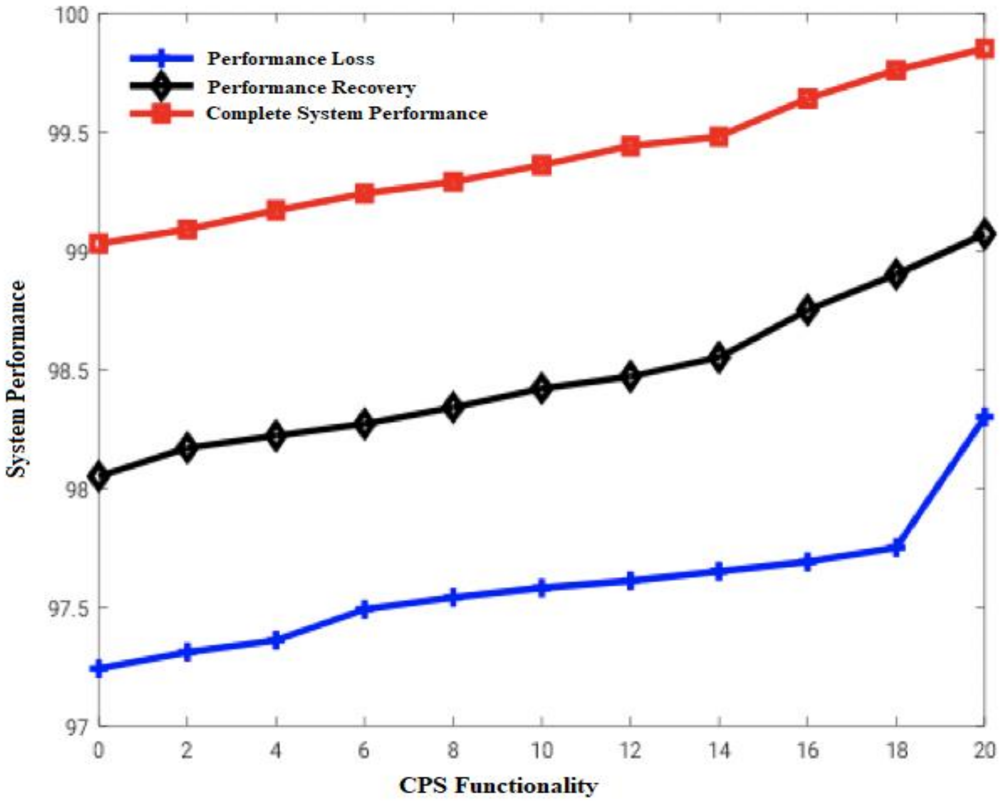

Figure 7: CPS Functionality with System Performance (N=4, 6)

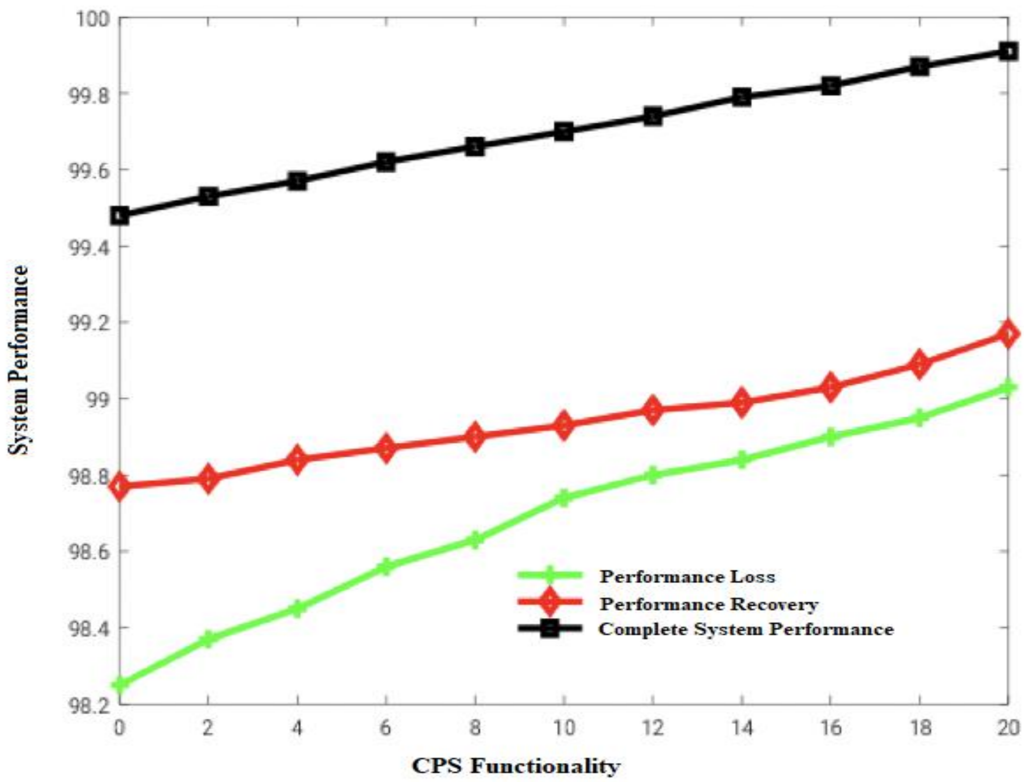

Figure 8: CPS Functionality with System Performance (N=6, 8)

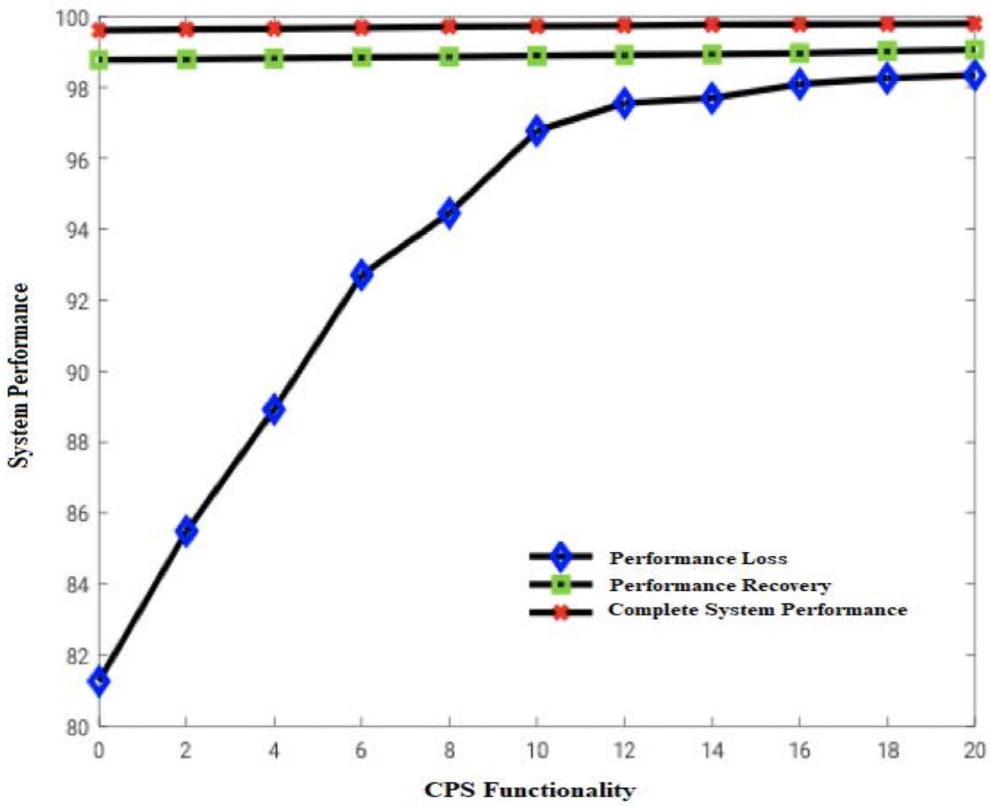

Figure 9: CPS Functionality with System Performance (N= 8, 10)

Conclusion

When self-adaptation and digital twinning technology come together, they create a paradigm shift that makes CPS more resilient, efficient, and able to change. Digital Twins allow for a full, real-time representation of physical things, which helps people make better decisions and improves their general experience in CPS environments. The system's powers are increased even more by the self-adaptive software, which changes with the environment to improve performance and reduce uncertainty. This collaborative method not only makes CPS more reliable and safe, but it also makes it possible for user-cantered applications to be used in healthcare, transportation, and smart infrastructure, among other places. We are still looking into the possibilities of self-adaptive software in the area of Digital Twins. The direction of Human-Centric Smart CPS is set for more progress, leading to a bright future where technology fits in naturally with people's wants and needs.

Abbreviation

CPS: Cyber Physical System
IoT: Internet of Things
DT : Digital Twins
IIoT: Industrial Internet of Things
CD: continuous development
CE: continuous evolution

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Author Contributions

All authors contributed to the study conception and design.

Conflict of Interests

The authors declare that they have no competing interests.

Ethics Approval

Not applicable.

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