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Self-Configuration in Cyber-Physical Systems: Enhancing Autonomy and Adaptability

Hua Wang
School of Information and Electronic Engineering, Zhejiang University of Science and Technology, Hangzhou, CHINA
Corresponding Author: Hua Wang

ABSTRACT: *Cyber-Physical Systems (CPS) are the integration of computation, networking, and physical processes. These systems are ubiquitous in modern technologies such as autonomous vehicles, smart grids, industrial automation, and healthcare systems. One of the key features that make CPS scalable and efficient is their ability to self-configure. Self-configuration refers to the system's capacity to automatically configure its components and adapt to changing conditions without human intervention. This paper explores the concept of self-configuration in CPS, the challenges involved, and the benefits it offers in terms of autonomy, flexibility, and robustness. Additionally, it highlights current approaches and future directions in the development of self-configuring CPS.*

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I. INTRODUCTION

Cyber-Physical Systems (CPS) are sophisticated integrations of computation, networking, and physical processes, enabling applications such as autonomous vehicles, industrial automation, smart grids, and healthcare monitoring systems. CPS fundamentally relies on the seamless interaction between cyber components (software, algorithms, and networks) and physical entities (sensors, actuators, and processes). As these systems evolve, they must dynamically adapt to changing environments, unpredictable conditions, and emerging user requirements, necessitating advanced self-configuration capabilities.

Self-configuration in CPS refers to a system's ability to autonomously modify its components, behavior, or architecture without human intervention. This process is crucial in real-time applications, where rapid changes in operating conditions render manual reconfiguration impractical. For example, in a smart grid, self-configuration enables the rerouting of power flows in response to faults or integrating new renewable energy sources dynamically [1]. Similarly, in autonomous vehicles, self-configuration allows the system to adapt to traffic conditions, road infrastructure changes, or sensor failures [2].

Recent advancements in distributed algorithms, machine learning, and model-based systems have paved the way for self-configuration in CPS. Machine learning methods, particularly reinforcement learning, are increasingly used to optimize system configurations in dynamic environments [3]. Distributed approaches further enhance system scalability and robustness, allowing large-scale CPS deployments to handle complex scenarios efficiently [4]. These methods are especially vital for CPS with resource constraints, such as those in the Internet of Things (IoT), where self-configuration must balance adaptability with energy efficiency [5].

Despite these advancements, challenges remain. Key issues include ensuring security and privacy in self-configuring systems, handling limited resources in embedded devices, and achieving interoperability in heterogeneous CPS architectures [6]. Moreover, developing fault-tolerant mechanisms that enable systems to recover from unexpected failures during the self-configuration process is an active area of research [7].

This paper explores the state of the art in self-configuration for CPS, with an emphasis on recent advancements, current challenges, and potential solutions. By addressing these issues, we aim to provide a comprehensive perspective on the role of self-configuration in enabling robust and autonomous CPS.

II. The Concept of Self-Configuration

Self-configuration is a key concept in the realm of Cyber-Physical Systems (CPS), referring to the ability of a system to autonomously adapt and modify its structure, behavior, or resources in response to changes in the environment or the system’s internal state. This concept is particularly important in the context of CPS due to their dynamic nature, where components often interact with each other in real time, and the system must maintain optimal functionality despite uncertainties and environmental changes.

2.1 Definition and Characteristics

In the context of CPS, self-configuration enables systems to make decisions about how to reconfigure themselves without human intervention. The process typically involves several stages: detecting a change or anomaly, deciding the necessary changes to system configuration, and applying those changes in a way that minimizes disruption to the system's overall function [8][9]. Self-configuration may involve reconfiguring system topology, reallocating resources, adjusting operational parameters, or switching communication protocols based on the evolving requirements. Key characteristics of self-configuration in CPS include:

1) Autonomy: The system can independently determine the necessary actions to take in response to internal or external changes, without requiring external control or human input.

2) Adaptability: The system is capable of modifying its configuration in response to varying conditions, ensuring that it continues to operate efficiently in dynamic environments.

3) Scalability: Self-configuration mechanisms should scale effectively as the size and complexity of the system grow, ensuring that large-scale systems can adjust their configurations without performance degradation.

4) Real-time Operation: Given that many CPS are deployed in time-critical environments (e.g., autonomous vehicles or industrial automation), self-configuration must occur in real-time to prevent system failure or degraded performance.

2.2 The Role of Self-Configuration in CPS

Self-configuration plays a crucial role in ensuring the robustness and resilience of CPS, particularly in situations where human intervention is impractical or impossible. In the case of autonomous vehicles, for example, self-configuration may involve adjusting sensor parameters or switching between communication channels when there is a failure or change in the environment [10]. Similarly, in smart grid systems, self-configuration can enable the grid to automatically reroute power flow in response to faults or integrate new renewable energy sources seamlessly into the network [11].

One of the key motivations for implementing self-configuration in CPS is the inherent complexity and heterogeneity of these systems. As CPS increasingly rely on diverse sensors, actuators, and computing devices, the need for seamless integration and communication among these components grows. Self-configuration offers a solution to this challenge, allowing systems to adapt their components and communication protocols to accommodate new devices, handle network failures, or adjust to fluctuating resource availability.

2.3 Techniques for Enabling Self-Configuration

Several techniques have been proposed to enable self-configuration in CPS, often drawing from fields such as distributed computing, machine learning, and network theory.

1) Distributed Algorithms: One of the foundational techniques for enabling self-configuration is the use of distributed algorithms. These algorithms allow individual system components to make decisions locally based on their observations and interactions with other components. The decentralized nature of these approaches ensures that the system can continue to operate even if some components fail or become isolated from the rest of the network [12].

2) Machine Learning and Artificial Intelligence: Machine learning techniques, particularly reinforcement learning (RL), are increasingly being employed to enable self-configuration in CPS. RL allows the system to learn from experience and optimize its configurations over time. For example, in autonomous vehicles, RL can be used to adjust driving strategies based on real-time traffic data, sensor inputs, and environmental factors [13]. In industrial automation, RL algorithms can optimize resource allocation and scheduling, improving both efficiency and robustness.

3) Model-Based Approaches: In some cases, model-based reasoning is used to predict the outcomes of different configuration choices and guide the system's decision-making process. These models can be based on mathematical representations of system behavior or learned from data. For example, in smart grids, models of power flow and demand can help the system decide how to reconfigure the network in response to changing conditions [14].

4) Self-Healing Mechanisms: Self-healing is closely related to self-configuration and is used to ensure system reliability and resilience. In CPS, self-healing mechanisms enable the system to detect and correct faults or failures autonomously, minimizing downtime and maintaining system performance. For instance, in industrial CPS, self-healing mechanisms may detect a faulty sensor and automatically switch to a backup sensor or recalibrate the system [15].

5) Security and Privacy Considerations: As CPS become more autonomous, ensuring their security and privacy during the self-configuration process is critical. Self-configuring systems must be robust against cyberattacks that could disrupt their operation or compromise sensitive data. Techniques such as secure communication protocols, cryptographic methods, and anomaly detection are essential for maintaining trust in the system [16].

2.4 Applications in CPS

Self-configuration has numerous applications across various CPS domains.

1) Autonomous Vehicles: In autonomous driving, self-configuration allows vehicles to adapt to environmental changes, adjust sensor settings, and optimize communication with other vehicles and infrastructure. Self-configuration is vital for maintaining safe and efficient operation in complex, dynamic environments [10].

2) Smart Grids: In power systems, self-configuration enables smart grids to adjust power distribution dynamically, respond to energy demands, integrate renewable energy sources, and recover from faults in real time. The ability to self-configure in a decentralized manner enhances grid resilience and efficiency [11].

3) Healthcare Systems: In healthcare CPS, self-configuration enables adaptive patient monitoring systems to adjust their sensing and data processing strategies based on patient needs, environmental conditions, and resource availability. This is particularly important in emergency or remote healthcare applications where quick adaptation is required [17].

Despite the promising potential of self-configuration, several challenges remain. These include ensuring the scalability of self-configuration methods for large-scale CPS, maintaining security and privacy during autonomous reconfiguration, and developing mechanisms for fault tolerance and system recovery in the face of component failures or environmental disturbances [18]. Further research is needed to explore hybrid approaches that combine the benefits of centralized and decentralized techniques, and to develop more sophisticated machine learning algorithms that can handle the complexities of real-world CPS applications.

III. APPROACHES TO SELF-CONFIGURATION

Self-configuration in Cyber-Physical Systems (CPS) involves a variety of methods and techniques that enable systems to autonomously adjust their internal structures, behavior, or resources in response to changes in their environment or operational conditions. Several approaches have been proposed to realize self-configuration in CPS, each focusing on different aspects of system behavior, from decision-making mechanisms to the integration of adaptive algorithms. These approaches can be broadly classified into the following categories.

1) Distributed Algorithms

Distributed algorithms are foundational to the concept of self-configuration in large-scale CPS, particularly those that operate in environments where centralized control is impractical or inefficient. In these systems, each component or node operates independently but collaborates with neighboring nodes to achieve system-wide reconfiguration.

One popular approach is consensus-based algorithms, where nodes in a distributed system exchange information and reach a consensus on how to configure themselves based on local observations and requirements. These algorithms enable decentralized decision-making, which is crucial for scalability and fault tolerance in dynamic environments. For instance, in a network of smart sensors or autonomous vehicles, nodes can dynamically adjust their configurations (such as communication parameters or sensor ranges) to adapt to varying network conditions or changes in the physical environment.

Another key distributed technique is gossiping protocols, where nodes periodically exchange messages to share information about system status and configuration. Through these interactions, nodes can gradually converge to a globally optimal configuration. These protocols are particularly useful in large-scale, decentralized CPS like industrial IoT systems, where rapid adaptation is needed in real-time.

2) Machine Learning-Based Methods

Machine learning techniques, especially reinforcement learning (RL), are increasingly being applied to self-configuration in CPS due to their ability to optimize decision-making over time based on continuous feedback. In reinforcement learning, an agent interacts with its environment by making decisions (such as changing configuration parameters) and receiving feedback on the effectiveness of those decisions. The agent learns to improve its configuration strategies based on cumulative rewards or penalties, eventually converging to an optimal policy.

RL has been particularly effective in environments where system behavior is complex and not easily modeled with traditional rule-based approaches. For example, in autonomous driving, RL can be used to adaptively adjust the vehicle’s configuration based on real-time traffic data, sensor inputs, and environmental conditions. Similarly, in industrial automation, RL can enable machines to self-optimize their operation by learning from past actions and adjusting their behaviors accordingly.

Supervised learning techniques are also used in self-configuration tasks where labeled data is available. These methods can be applied to predict the best configuration based on historical data. For example, supervised learning can be used to forecast the optimal configuration for resource allocation in CPS, ensuring that the system is always operating at peak efficiency without manual intervention.

3) Model-Based Techniques

Model-based approaches leverage mathematical models or simulations to predict the outcomes of different configuration choices before actually applying them to the system. These models can represent system behavior, performance metrics, or environmental interactions, and are often used to optimize configurations or verify system stability under different conditions. Model-based self-configuration helps ensure that the system's adaptation is not only effective but also safe and reliable.

A common model-based technique in self-configuration is system identification, where a system's dynamic behavior is modeled based on input-output data. The model is then used to simulate potential configurations and determine the best course of action. This approach is particularly useful in systems that require precise control, such as autonomous robotics or smart grids, where changes in system behavior must be carefully considered to avoid performance degradation or failure.

Another model-based approach is constraint-based optimization, where the system configuration is determined by solving optimization problems subject to constraints such as power consumption, resource availability, or safety limits. For example, in a smart grid, optimization techniques can be used to reconfigure the power distribution network in response to changing demand, ensuring that the grid operates efficiently while adhering to safety and stability requirements.

4) Hybrid Approaches

Hybrid approaches combine elements from different self-configuration techniques to leverage the strengths of each. For example, a hybrid approach might combine distributed algorithms with machine learning to achieve both decentralized decision-making and adaptive optimization. In such systems, the distributed algorithm could handle communication and coordination between nodes, while machine learning techniques continuously optimize the system's configuration based on feedback.

Another hybrid approach involves integrating model-based techniques with machine learning. In this case, machine learning models can be used to improve the accuracy and efficiency of the system's models, or to generate more accurate predictions about future system behavior. These hybrid methods can be particularly useful in complex CPS applications, where both real-time adaptability and long-term performance optimization are crucial.

5) Security and Fault-Tolerant Strategies

Security and fault tolerance are critical considerations in the self-configuration of CPS. As systems become more autonomous, they become vulnerable to attacks, failures, and unexpected disruptions. To ensure robust self-configuration, it is essential to incorporate mechanisms that allow the system to recover from faults and ensure secure communication during the reconfiguration process.

Fault-tolerant strategies often involve the design of self-healing systems, where the system can detect failures and autonomously reconfigure itself to bypass the failed components or switch to backup systems. For example, in autonomous vehicles, if a sensor fails or malfunctions, the vehicle should be able to adjust its configuration by relying on other sensors or reconfiguring its processing algorithms to compensate for the loss of data.

In terms of security, ensuring that the self-configuration process does not introduce vulnerabilities is vital. Secure self-configuration requires the use of cryptographic protocols, secure communication channels, and robust authentication mechanisms to prevent unauthorized access and manipulation of the system during reconfiguration. Techniques such as anomaly detection and intrusion detection systems can be incorporated into self-configuration strategies to ensure that only legitimate and secure configuration changes are implemented.

The diverse approaches to self-configuration in CPS provide a wide range of strategies for enabling autonomous adaptation to changing environments and operational conditions. While distributed algorithms and machine learning-based methods have garnered significant attention for their ability to support real-time decision-making and optimization, model-based techniques and hybrid approaches are increasingly being adopted to provide more sophisticated and reliable configurations. As CPS continue to evolve and scale, it is likely that a combination of these approaches will be necessary to meet the demands of complex, dynamic, and resource-constrained environments. Additionally, ensuring the security and fault tolerance of self-configuring systems will be crucial to their successful deployment in mission-critical applications.

IV. APPLICATIONS OF SELF-CONFIGURATION IN CPS

Self-configuration in Cyber-Physical Systems (CPS) enables the systems to autonomously adapt to changing conditions, making them more resilient, efficient, and flexible in a variety of applications. As CPS become more integrated into daily life, their ability to self-configure plays a pivotal role in ensuring their continued functionality and performance in dynamic environments. Below are several key applications where self-configuration is essential:

1) Autonomous Vehicles

Autonomous vehicles rely heavily on CPS to perceive their environment, make decisions, and navigate roads without human intervention. Self-configuration is crucial in ensuring that these vehicles can adapt to changing traffic conditions, road surfaces, and potential sensor failures. For instance, in the event of a malfunction or degradation of a sensor, such as a LiDAR or camera, the vehicle's system may reconfigure by switching to alternative sensors or adjusting sensor settings to ensure continued operation.

Moreover, self-configuration allows autonomous vehicles to adjust their behavior based on real-time traffic data, weather conditions, or road hazards. The vehicle might reconfigure its navigation path, speed, or driving strategy to optimize for safety, fuel efficiency, or travel time. This ability to adapt quickly in real-time is crucial to ensuring the safety and efficiency of autonomous vehicles in diverse and unpredictable environments.

2) Smart Grids

Smart grids are an excellent example of CPS where self-configuration is key to optimizing power distribution, integrating renewable energy sources, and ensuring grid stability. In a smart grid, self-configuration mechanisms allow the system to autonomously adjust the distribution of electricity based on demand fluctuations, power supply conditions, and the integration of distributed energy resources like solar panels or wind turbines.

Self-configuration enables the grid to reroute power in response to faults, such as a transformer failure, or during periods of peak demand. This adaptability is particularly important in regions with a mix of renewable energy sources that are subject to fluctuations. The grid can dynamically adjust its configuration to balance supply and demand, prevent blackouts, and improve overall efficiency.

Additionally, in response to emergencies, such as natural disasters, self-configuring systems in smart grids can automatically isolate faulted sections of the grid, prioritize power delivery to critical areas, and integrate backup power sources to restore service quickly.

3) Industrial Automation and Manufacturing

In industrial automation, CPS are used to control and monitor production lines, machinery, and equipment. Self-configuration in such environments ensures that production systems remain efficient and resilient to failures or changes in the production process. For instance, if a piece of machinery breaks down or experiences degraded performance, the system can autonomously reconfigure itself by rerouting tasks to other machines, adjusting production schedules, or recalibrating machinery to restore optimal operation.

Additionally, self-configuration in industrial settings can optimize the use of resources. For example, in a factory with automated robots and conveyor belts, the system might adjust the speed and coordination of robots based on real-time data to maintain throughput while minimizing energy consumption. This ensures continuous operation and reduces downtime, improving overall productivity.

4) Healthcare Systems

Self-configuration plays a critical role in healthcare CPS, particularly in areas like remote patient monitoring, wearable health devices, and surgical robotics. In such systems, self-configuration enables devices to adapt to the needs of individual patients, respond to changes in their health conditions, and provide continuous, personalized care. For example, in remote patient monitoring systems, wearables such as smartwatches or sensors can automatically adjust their monitoring parameters based on changes in a patient's vital signs or environmental conditions. If a patient's heart rate becomes abnormal, the system might reconfigure by switching to more sensitive sensors or adjusting data sampling rates to provide more accurate readings.

Similarly, in surgical robotics, self-configuration allows robotic systems to adapt their tool sets, sensor configurations, or motion strategies depending on the type of surgery being performed and real-time data from the procedure. This ensures high precision and safety during complex medical procedures.

5) Environmental Monitoring Systems

Environmental monitoring systems, which include applications such as air quality monitoring, wildlife tracking, and disaster management, benefit significantly from self-configuration. These systems are often deployed in remote or hazardous environments where conditions can change rapidly, and human intervention is limited. For instance, in air quality monitoring, sensor networks deployed across a city or region can autonomously adjust their configurations to respond to sudden changes in pollution levels, weather conditions, or equipment failures. The system may reconfigure to activate additional sensors or change the frequency of data collection in response to an event, like a forest fire, to provide more precise information about air quality.

Similarly, in wildlife tracking systems, GPS tags on animals can reconfigure to adjust their data transmission rates or switch to alternative communication methods (e.g., satellite vs. radio signals) depending on location, power availability, or environmental conditions.

6) Smart Homes and IoT Systems

In smart homes, CPS are used to manage lighting, heating, security, entertainment systems, and more. Self-configuration in smart homes allows systems to adapt to the behavior and preferences of the residents. For example, the heating system in a smart home can adjust the temperature based on occupancy, time of day, or even the personal preferences of the individuals present. Similarly, lighting can be reconfigured based on the residents' movements or the time of day, ensuring both comfort and energy efficiency.

Self-configuration also plays a role in energy optimization, where IoT-enabled devices autonomously adjust their power consumption to optimize energy use across the home. For example, smart thermostats, lighting, and appliances can communicate and adjust their settings to reduce energy usage during peak hours or when the house is unoccupied.

7) Robotics and Autonomous Systems

In robotics, particularly in mobile robots or drones, self-configuration is essential for adapting to changing environments, tasks, and operational constraints. A robot may need to reconfigure its sensors, actuators, or processing algorithms to handle new tasks, navigate around obstacles, or operate in varying environments such as indoors, outdoors, or in tight spaces.

For example, a drone performing environmental monitoring may need to adjust its flight path, sensor configurations, or data transmission methods depending on the terrain, weather conditions, or the specific monitoring objectives. Similarly, a mobile robot in a warehouse may need to reconfigure its navigation system or task assignments to accommodate for blocked paths, new inventory, or sudden changes in workload.

The application of self-configuration in CPS spans a wide range of fields, from autonomous vehicles and smart grids to healthcare, industrial automation, and smart agriculture. By enabling systems to autonomously adapt to changing conditions, self-configuration improves system resilience, efficiency, and reliability. As CPS become more pervasive, the need for self-configuring systems will continue to grow, driving innovation across various industries and ensuring that these systems remain capable of operating autonomously in increasingly complex and dynamic environments.

V. CHALLENGES AND FUTURE DIRECTIONS

While self-configuration offers significant benefits to Cyber-Physical Systems (CPS), there are several challenges that must be addressed to fully realize its potential. These challenges arise from both the complexity of CPS themselves and the environments in which they operate. Additionally, the future of self-configuration in CPS will involve advancing existing technologies, overcoming these challenges, and exploring new frontiers in autonomous adaptation. This section outlines key challenges in self-configuration and explores future directions for research and development.

1) Scalability

One of the major challenges in self-configuration for large-scale CPS is scalability. As CPS become more widespread and interconnected, the size and complexity of these systems grow, which can overwhelm current self-configuration mechanisms. For instance, in industrial IoT or smart city applications, the sheer number of devices and sensors that need to be autonomously configured can result in increased computational overhead, communication delays, and inefficient adaptation processes.

To address scalability, distributed self-configuration algorithms must be optimized to handle large-scale networks of devices. Techniques such as hierarchical or decentralized decision-making, where local configurations are handled by smaller sub-systems or clusters, can help manage complexity. Future research will need to focus on making these algorithms more efficient and robust in large-scale settings, ensuring that self-configuration can scale effectively without degrading system performance.

2) Security and Privacy

As CPS become more autonomous and self-configuring, security and privacy concerns grow. Self-configuration often involves dynamic communication between components, potentially exposing the system to cyber-attacks. A malicious actor could attempt to disrupt the reconfiguration process, inject false data, or manipulate system decisions to compromise performance or cause failures.

Ensuring secure self-configuration will require robust security protocols, including encrypted communication channels, secure authentication, and anomaly detection to detect and prevent attacks during reconfiguration. Moreover, privacy concerns must also be addressed, particularly in applications involving sensitive data, such as healthcare or smart homes. Protecting user data while enabling the system to reconfigure autonomously is a critical challenge that will need to be tackled through advanced cryptography, data anonymization, and privacy-preserving techniques. In the future, security measures will need to be integrated into every stage of the self-configuration process, from the design phase to real-time adaptation, to safeguard CPS against increasingly sophisticated attacks.

3) Fault Tolerance and Reliability

CPS often operate in dynamic and unpredictable environments, where the failure of individual components or the system as a whole can have serious consequences. Ensuring fault tolerance and system reliability during self-configuration is a significant challenge. For example, if a critical component fails or behaves unexpectedly, the system must be able to detect the fault and reconfigure itself to mitigate any negative effects, without compromising overall system performance.

To address this challenge, self-configuring systems must incorporate self-healing mechanisms. These mechanisms enable the system to recover from failures autonomously by reconfiguring itself, rerouting tasks, or switching to backup components. Future advancements will likely involve the use of predictive models to anticipate potential failures before they occur and trigger preemptive reconfigurations to prevent system breakdowns.

Moreover, ensuring that self-configuration doesn't inadvertently introduce new vulnerabilities or failures is a key challenge. Research into formal verification techniques for self-configuring systems could help guarantee that reconfiguration decisions do not lead to unintended consequences, ensuring that the system remains safe and reliable at all times.

4) Real-Time Decision Making

Many CPS operate in real-time, where delays in decision-making can lead to catastrophic outcomes. In applications such as autonomous vehicles, robotics, or healthcare, the system must be able to self-configure and adapt within strict time constraints. Real-time decision-making in self-configuration presents a significant challenge, as it requires fast data processing, low-latency communication, and efficient algorithms capable of making decisions under time pressure.

To address these challenges, future systems will need to be designed with real-time operating systems (RTOS) and low-latency communication protocols that ensure fast data exchange and decision-making. Additionally, edge computing could play a pivotal role in reducing latency by processing data locally on devices, thus enabling quicker self-configuration decisions in real-time applications. This will be particularly important in environments like autonomous vehicles, where split-second decisions are critical to safety.

5) Adaptation to Uncertainty

CPS often operate in environments characterized by uncertainty, including unpredictable changes in physical conditions, sensor errors, and varying system workloads. Effective self-configuration must account for this uncertainty, ensuring that systems can maintain optimal performance despite incomplete or noisy data.

To address this, self-configuration techniques will need to incorporate more advanced algorithms for uncertainty modeling and robust optimization. These approaches enable systems to make decisions that are resilient to uncertainty and can adapt to changing conditions without compromising performance. Techniques like probabilistic reasoning or fuzzy logic can help manage uncertainty by providing more flexible decision-making under uncertain conditions.

The future of self-configuration in CPS lies in overcoming the challenges related to scalability, security, reliability, real-time performance, heterogeneity, and uncertainty. As CPS become more ubiquitous and integral to sectors like transportation, healthcare, industry, and smart cities, the need for intelligent, adaptable systems will grow. To meet these demands, future research will focus on developing scalable, fault-tolerant, and secure self-configuration mechanisms that can seamlessly integrate with emerging technologies. The integration of machine learning, edge computing, and explainable AI will be key enablers of self-configuration in the next generation of CPS. By addressing the current limitations and pushing the boundaries of autonomous systems, self-configuration has the potential to significantly improve the performance, efficiency, and resilience of CPS across a wide range of applications.

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