A Blockchain Enabled Cyber-Physical System Architecture for Industry 4.0 Manufacturing Systems

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A blockchain enabled Cyber-Physical System architecture for Industry 4.0 manufacturing systems

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ABSTRACT

Cyber-Physical Production Systems (CPPSs) are complex manufacturing systems which aim to integrate and synchronize machine world and manufacturing facility to the cyber computational space. However, having intensive interconnectivity and a computational platform is crucial for real-world implementation of CPPSs. In this paper, the potential impacts of blockchain technology in development and realization of real-world CPPSs are discussed. A unified three-level blockchain architecture is proposed as a guideline for researchers and industries to clearly identify the potentials of blockchain and adapt, develop, and incorporate this technology with their manufacturing developments towards Industry 4.0.

1. Introduction

Industry 4.0 initiative has introduced the manufacturing industry to new paradigms of Cyber-Physical Systems, Internet of things (IoT), big data analytics, cloud manufacturing, fog computing, etc. [1]. It is anticipated that these technologies would bring along many benefits and potential opportunities, such as self-awareness, self-prediction, self-comparison, self-reconfiguration, and self-maintenance [2]. However, these paradigms still use a centralized industrial network and a third-party trust operation [3]. As a result, current manufacturing suffers from issues related to flexibility, security, privacy, transparency, efficiency, data integrity, resilience, the trustworthiness of data, etc. [2,4–8].

Recently, blockchain technology [9] has received significant attention in financial technology. However, it possesses the capability and significant potential to sustainably support the Industry 4.0 initiative and eliminate problems related to it. In [1] a 5 level architecture, namely 5C-CPS has been proposed for developing CPSs in manufacturing. However, there are many challenges associated with data security, privacy, centralization, networking, etc. which require further development and progress. Therefore, in this research, a three-layer blockchain structure, namely BCPS, is proposed for addressing these challenges. A desired set of roles and functionalities are proposed for each blockchain layer and their key impacts are discussed in details.

2. Blockchain

Blockchain is a distributed ledger which is simulated and shared between the members of a peer to peer (P2P) network [10]. Recently, blockchain concept has drawn lots of attention in technologies with distributed nature like IoT because it enhances security and privacy [11], increases system's fault tolerance [12], provides a faster settlement and reconciliation [13], creates a scalable network [2,12,14], and helps in saving cost and time by removing intermediaries [15]. Blockchain technology has taken off in several industries, such as, machine to machine communication in the electrical grid system [16], food supply chain traceability system [17], decentralized logistic operation [18], decentralized data sharing among healthcare applications [19], and financial services for banking industry [20]. However, there is no systematic study on the incorporation of blockchain technology in manufacturing systems.

A distributed ledger must have some key features to be successfully used in IoT/CPS applications, namely, the energy consump-

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tion, the ability to execute orders automatically (e.g. smart contract), the type of network access (permissioned or permissionless), and the type of network (public or private). A study conducted by [21] identifies the three most suitable distributed ledgers for IoT/CPS applications: Ethereum [22], Hyperledger Fabric [23] and IOTA [24]. Structural architecture of blockchain technology inherently can create several key features as described below [25,26]:

A. **Immutable** – Advanced cryptography (hash functions) – cannot be changed.
B. **Transparent** – Each computer in the network has a copy of the ledger.
C. **Authentic** – All parties in the transaction have accurate, timely, consistent and complete data.
D. **Decentralized** – There is no single controlling entity.
E. **Distributed** – Spread over different location and/or organization.
F. **No intermediaries**– self-executable algorithms– e.g. Smart Contract.
G. **Anonymous** – Public and private keys may use for interaction with no need for private information

3. A Blockchain enabled CPS (BCPS) structure

BCPS (Fig. 1) aims in resolving the challenges associated with the real world implementation of 5C-CPS structure by addressing (a) Interoperability, (b) Data integrity, (c) Security and Privacy, and (d) Resilience. Table 1 summarizes the key requirements for each layer of 5C-CPS and the potential impacts of blockchain technology. The detailed BCPS architecture is outlined as follows:

3.1. Connection Net

Advanced connectivity, data management, integrity, and security are the major characteristics in this level. The most important factor for this global connectivity and integration is 'Interoperability'. There are eight aspects for establishing a successful 'technical interoperability': security, privacy, accessibility, multilingualism, subsidiarity, multilateral solutions, the use of open standards, and open source software [31,32]. Blockchain helps in addressing security and privacy by using advanced cryptographic algorithms and global consensus mechanism. Subsidiarity improves through decentralized framework presented by blockchain. Multilingualism and multilateral solutions can be enhanced through improved interconnectivity between Nodes (computers, sensors, actuators, etc.). Generally, Nodes with higher capacity (Master Nodes) might be used as a local server (Micro-Cloud) for resource restricted Nodes to store their data, perform computational tasks, and interact with other Nodes. A public key can be assigned to each Master Node for direct communication with other Nodes. Therefore, all Nodes would be able to interact with each other, share data, and even share their computational and networking capacities with each other. It is expected that incorporating distributed storage and shared networking would increase redundancy and enhance network resilience.

3.2. Cyber Net

This layer is responsible for the conversion of data to meaningful information and managing Cyber-Physical and Cyber-Cyber interactions in order to achieve integrity, fault tolerance, and resilience. Cybersecurity [33], big data (Volume, Variety, and Velocity) [34], cloud computing [35], network connectivity, privacy, and transparency [6] are the major characteristics for consideration in this layer. Different techniques like grid and cloud computing are typically used to increase the computation speed, system resilience, network scalability and make an efficient use of idle resources. The role of these techniques is to distribute the computation and storage burden among different computers within the network [36]. A blockchain structure could be essential for this development towards distributed computing [37] by providing data security [2,38], distributed data storage [13,39], and facilitating data access through a P2P network [39-41].

In this layer, integration of AI tools are essential for the conversion of raw data to meaningful information and extending intelligence to individual Nodes. A network enabled with AI is necessary for today's manufacturing systems [42] and more importantly Distributed and Decentralized AI (DDAI) [43,44] will outperform the centralized intelligent platforms [44,45]. With the help of blockchain, AI tools can run, relearn, and coordinate their knowledge in a distributed fashion. As DDAI modules are trained with

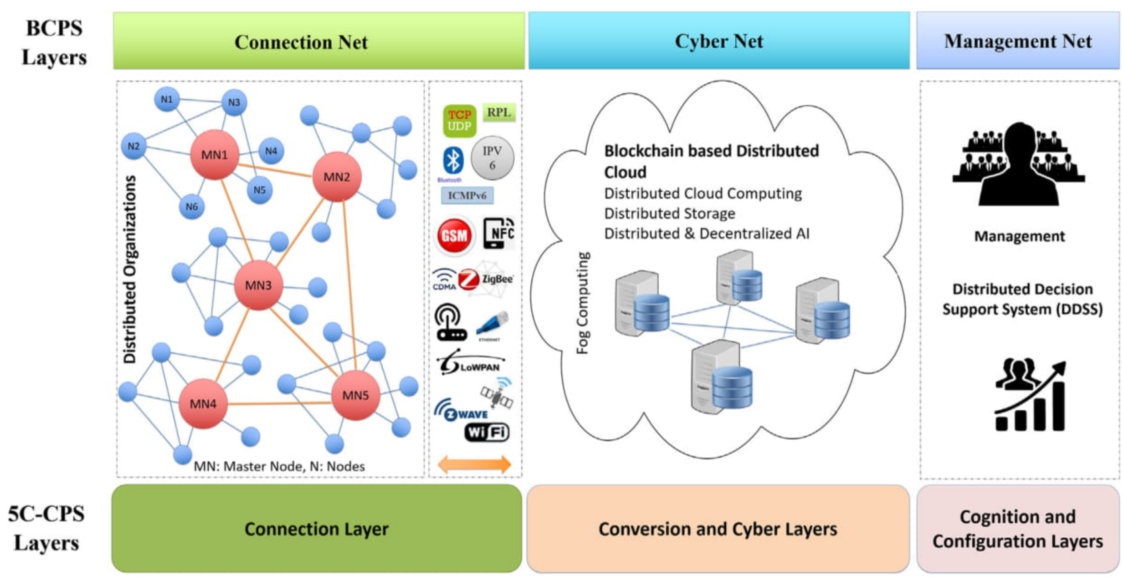

Fig. 1. The proposed three-layer BCPS architecture.

Table 1
Key characteristic and requirements of the 5C-CPS structure and their corresponding blockchain impacts.

5C-CPS Architecture	Characteristics	Requirements	Blockchain Impact A	B	C	D	E	F	G
Configuration	• Intelligent Decision Making • Supervisory Control (ERP, MES, SCM CMM, and PLM) • Intelligent Business structure	• Self-Configure, Self-Adjust, Self-Optimize Sustainable Business Plans		✓	✓	✓	✓	✓	
Cognition	• Decision Support Systems • Integrated simulation and Synthesis	• Real-Time Data Access					✓	✓	
		• Trustworthy of Data Source	✓	✓	✓				
		• Availability of Structured Data [27]				✓	✓	✓	
Cyber	• Big Data • Digital Twins • Cloud Computing • Similarity Modeling • Data Warehousing (DW) • Cyber-Cyber Interactions	• Redundancy in storage, bandwidth, and computation [28]				✓	✓		
		• Efficient Connectivity: Bandwidth, Latency, availability, robustness				✓	✓	✓	
		• Cross-Domain Integration and Interoperability [29]		✓		✓	✓	✓	
		• Handling Design complexity [30]						✓	
		• Security and Privacy	✓	✓	✓	✓	✓		✓
Conversion	• AI Analytic Tools • AI/Machine Learning Models/PHM Tools • Distributed and decentralized Intelligence • Fog/Edge Computing • Deep Learning	• Resilience				✓	✓		
		• Adaptive, Reliable and Robust	✓	✓	✓	✓	✓		
		• Fast Computation				✓	✓	✓	
Connection	• Networking: Physical-Physical Interactions, Physical-Human Interactions • Smart Nodes (Sensors, Actuators, Process, Machine, etc.)	• Efficient Connectivity: Bandwidth, Latency, availability, robustness				✓	✓	✓	
		• Security and Privacy	✓	✓	✓	✓	✓		✓
		• Interoperability				✓	✓	✓	

Table 2
Blockchain impacts on the stakeholders' needs and requirements.

BCPS Layers	Stakeholder Needs and Requirements	Blockchain Contribution
Management Net	• Trustworthiness, resilience, security, and efficiency of decision support systems	• Advanced cryptography, Distributed, Decentralized
	• Overhead cost reduction	• Smart contract, P2P interactions
	• Bureaucracy reduction	• Smart contract, P2P interactions
	• Data security and Privacy	• Advanced cryptography
	• Supervisory control, resource management	• P2P interactions- transparency
	• Ownership as a Service (OaaS)	• Assets tokenization [51,52], smart contract
Cyber Net	• Conversion of data to meaningful information	• Training AI models on more data available through shared datasets, Distributed & Decentralized AI
	• Elimination of single point of failures	• Load and resource (computation, storage, networking) distribution among Nodes
	• Data security and Privacy	• Advanced cryptography
	• Efficient Data storage	• Micro clouds, data storage in each Node
	• Data as a Service (DaaS)	• Smart contract, P2P interactions
Connection Net	• Transparency in the supply chain	• Tracking components from their origin step by step – Transparency
	• Interconnectivity between devices	• P2P interactions, Master Nodes
	• Automation	• Smart contract, P2P interactions
	• Efficient connectivity (Bandwidth, Latency, robustness, etc.)	• Shared resources, Master Nodes, P2P interactions
	• Data security and Privacy	• Advanced cryptography

more reliable and global data, their robustness and reliability increases, trustworthiness improves through receiving direct feedback from operations, and implementation cost reduces significantly due to the adaptation of P2P resources sharing and automatic machine learning (AutoMl) [46,47].

3.3. Management Net

In this level, comprehensive information from cyber level is used in a data-driven decision support system (DSS) [48] in order to achieve informed and rapid decision making, productivity, resilience, and finally manufacturing sustainability. In current manufacturing systems, DSS components and/or its users are dispersed geographically, and they require a reliable and distributed platform for enterprise information integrity with the objective of achieving competency, efficiency, and competitiveness [49,50]. A DSS based on blockchain would be decentralized and distributed, meaning decisions are made by achieving a global agreement and by considering all restrictions within a decentralized network. Therefore, all Nodes can participate in the decision-making process. Due to the core advantages of blockchain technology, such a design would be location independent, fault-tolerant, secure, autonomous, and extensible.

Table 2 summarizes the stakeholders' needs and requirements and the potential contribution of the proposed BCPS architecture in addressing them.

4. PHM based BCPS structure

Fig. 2 presents a PHM case study illustrating how each function of BCPS is implemented in health monitoring of manufacturing machines. Accordingly, four different machines have been setup at two different geographical locations; 'Location A' and 'Location B'. Data collected from both machines is pushed to fog computing devices. Meaningful information extracted in the fog layer is pushed to a distributed cloud network for advanced PHM analytics. Blockchain can significantly resolve the problems with the current

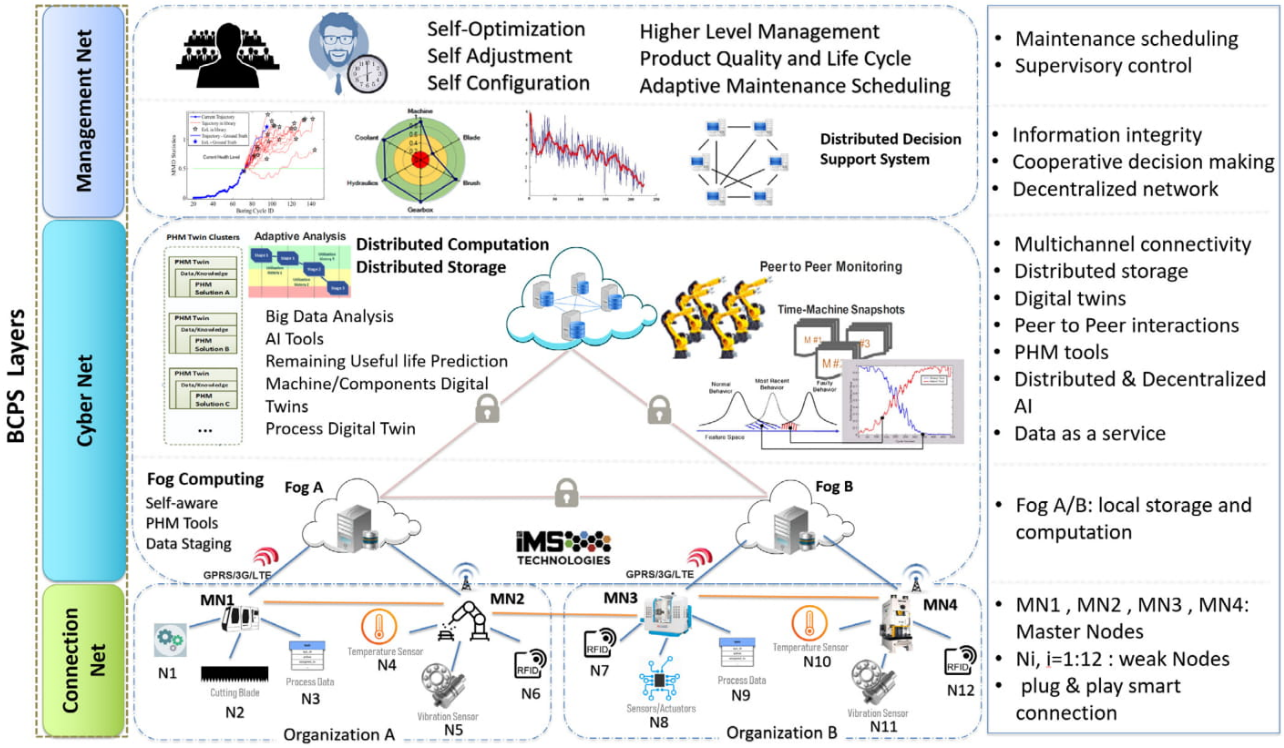

Fig. 2. A case study on the PHM based BCPS Structure.

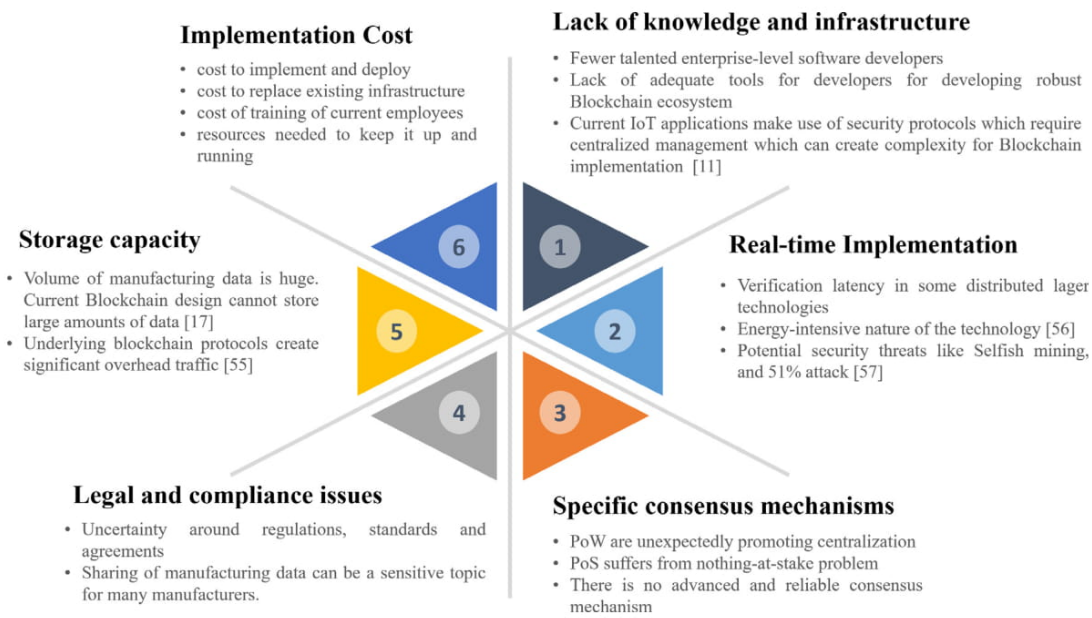

Fig. 3. Challenges in blockchain implementation in manufacturing systems [17,55,11,56,57].

PHM in all levels of the 5C-CPS structure by addressing 1- Data Availability, 2- Intelligent PHM, and 3- Predictive Maintenance Support System (PMSS), as discussed below.

4.1. Data availability

In 5C-CPS architecture; security, privacy, and capacity are major concerns in transferring data from the connection level to the conversion layer and further to the cyber layer. To tackle this shortcoming, incorporation of 'Master Nodes' has been proposed in the first layer of BCPS as an intermediary such that their capacities can be shared with other Nodes in the same local network. Cyber-attacks on sensors and actuators, communication networks, and physical interfaces are major security concerns in the Cyber-Physical interactions [53,54], which potentially can be addressed with the proposed BCPS structure.

4.2. Intelligent PHM

PHM based AI tools need to learn and adapt to the dynamically changing manufacturing environment. However, some of the required data is restricted to public access due to privacy and security. For PHM applications, a blockchain enabled DDAI platform could provide more training data for the learning agents in a secure and private way and increase systems reliability and performance. For example, CNC machines in different factories can take time snapshot of their data, analyze it by an embedded local AI agent and finally encrypt and share the data with interested entities (maintenance people and the CNC or tools manufacturers) through the interconnectivity achieved in the 'Cyber Net' level.

4.3. Predictive maintenance support system (PMSS)

Supplementary information such as manufacturing equipment cost, life cycle, order lead time, replacement downtime, workload distribution, etc. gathered from 'Connection Net' and 'Cyber Net' levels could form an integrated support system for conducting intelligent predictive maintenance. Integration of this information in a DSS operating in the 'Management Net' level would result in an intelligent decision-making system for PHM applications.

5. BCPS challenges for implementation in manufacturing systems

It's worth considering that blockchain is in the early stage of development and there could be some challenges for its implementation in manufacturing systems which require more research and development. Fig. 3 highlights some of the current challenges .

6. Conclusion

This work proposes a systematic blockchain based architecture to mitigate the inherent real-time implementation concerns of cyber physical systems in manufacturing application domain. It is expected that the proposed coupling would incentivize communication and data flow inside of the existing CPPS structure to guarantee the safe and reliable operation of manufacturing systems.

Declaration of Competing Interest

None.

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