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Cloud-Based Cyber-Physical Robotic Mobile Fulfillment Systems: A Case Study of Collision Avoidance

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ABSTRACT The rapid development and implementation of the Internet of Things (IoT) and Cyber-Physical Systems (CPS) in the engineering and manufacturing field have embraced a virtual identity to ensure nearly real-time adjustment. Warehouses are challenged to reassess its order fulfillment operations while simultaneously being provided with the opportunity to develop its own cloud-based CPS with the aid of IoT devices. Robotic Mobile Fulfillment System (RMFS) is a system controlling mobile robots, mobile storage rack, putaway and picking workstations, charging stations, and wireless communication infrastructure in the context of robotic-assisted warehouse. This paper addresses the value creation utilizing cloud-based CPS in RMFS. By providing an analysis of cloud services and IoT enhancement, theoretical concepts from the literatures are consolidated to solve the research que-stions on how RMFS offering better order fulfillment can gain benefits in terms of operational efficiency and system reliability. The paper also proposes a cloud-based CPS architecture, providing a comprehensive understanding on conflict avoidance strategy in the multi-layers multi-deeps warehouse layout. This research presents six conflict classifications in RMFS and provides a case study in the real-life context. Dock grid conflict is a new type of conflict appearing in multi-deeps RMFS. A scenario analysis with real customer orders is applied to present the collision detection and solution.

INDEX TERMS Robotic mobile fulfillment system, Cyber-physical systems, Internet of Things, collision avoidance.

I. INTRODUCTION

The technological evolution in the Warehouse Management System (WMS) that foster the e-logistics efficiencies has gained the attention of industrial practitioners and researchers. The Amazon KIVA system is the pioneer of Robotic Mobile Fulfillment System (RMFS) in e-Commerce order fulfillment system. **Figure 1** shows a conceptual diagram of the RMFS including the autonomous mobile robot, wireless charging station, mobile storage rack, positioning identifier (e.g. QR code), putaway and picking station, wireless communication infrastructure, and real-time swarm robots control center. All mobile robots receive information, such as their robot dwell coordinates and operational status, to identify the robots' location. With the aid of ICT advancement, near/real-time capture of sensing data, and operation activities, the item location and order status can be obtained, and the decision-making environment under the framework of Cyber-Physical Systems (CPS) is further supported. Manufacturers, retailers, and customers

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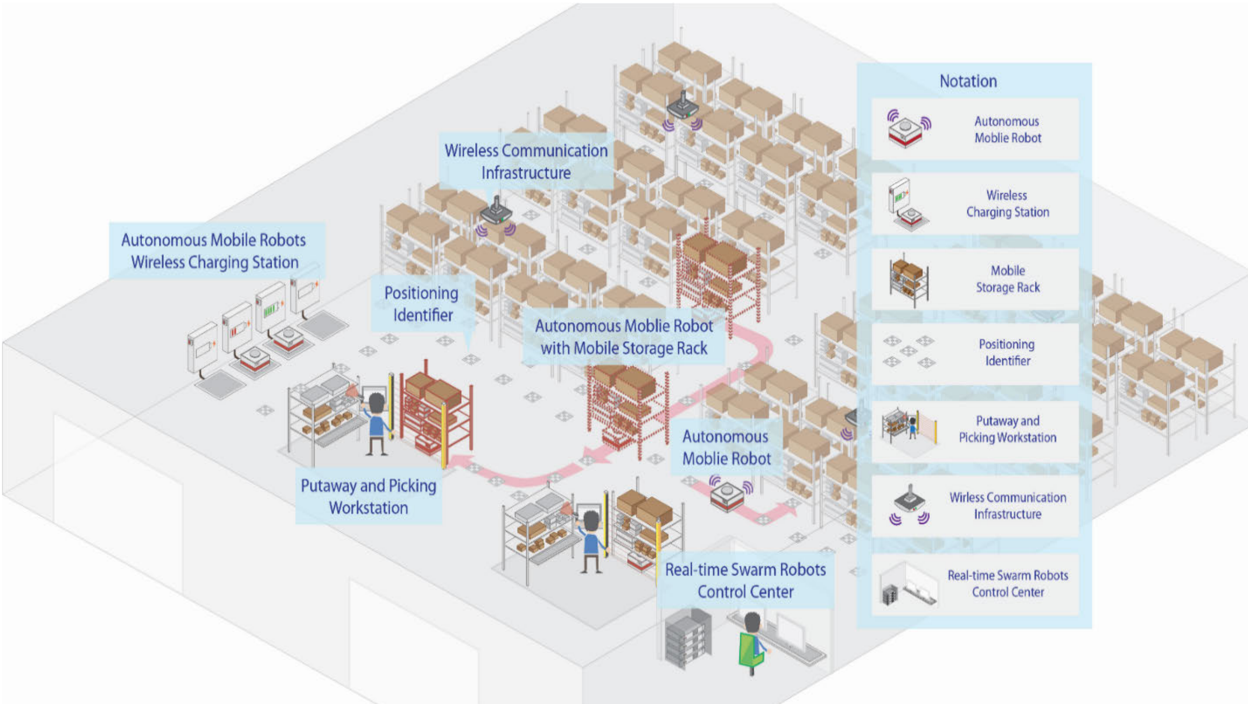


FIGURE 1. **A Conceptual Diagram of the Robotic Mobile Fulfillment System [13].**

are now seeking a digital-twin-enabled service innovation on smart logistics service [1]. Logistics Service Providers (LSPs) act as third-party agencies for data acquisition and service providers in the logistics process and have to not only satisfy the logistics requirements of the firms but also meet customers' expectations by gauging customers' needs. The smartness of real-time information systems is a critical factor in the management of customer relationship between firms and customers. The Internet-of-Things (IoT) solution in smart warehouse offers an opportunity to gain knowledge from customer requirements and support the communication of real-time market data to firms through an agile supply chain management [2]–[7]. The smartness of the warehouse system could provide a value-added service, such as real-time dispatch monitoring and estimation of delivery procedure, and further support value co-creation along the supply chain, such as last-mile logistics, responsiveness logistic design and flexibility in logistics arrangement, in the context of e-Commerce service innovation [8]–[11].

The integration of cloud computing and CPS real-time control and management allows us to closely monitor material, activity, and information flow in the WMS. The computational capacity of cloud computing offers expendable computational and storage resources. Furthermore, practitioners can also offer an API (Application Programming Interface) to external parties for information extraction. A more complementary information flow in the WMS side can further support the real-time tracking of the online sale platform and last-mile delivery. In such cases, customers can have a seamless order tracking with the recent advancement of cloud-based CPS and digitalization of e-Commerce activities. Cloud-based CPS in WMS not only increases customer satisfaction but also provides data visualization and an analytics platform to evaluate the warehouse efficiency and operational performance.

Moreover, practitioners can gain advantages by adopting a cloud-based CPS to evaluate and monitor the activities of physical objects in the RMFS. The control system of the RMFS is comprehensive as the back-end system has the authorities to control the mobile robot's actions and determine the path for order fulfillment. However, precise control of the physical mobile robots in RMFS can be challenging due to the time lag problem in wireless communication, information overload, and lack of accuracy of multiple criteria decision making from vague and incomplete data. The emerging cloud-based CPS architecture can capture all the activities and events in the RMFS and consolidate the data in a centralized data sink, which offers a more efficient and effective platform to reduce the discord between the physical events and virtual machine via the Digital Twin.

This paper contributes a border discussion on the cloud-based CPS in RMFS as well as a method to improve its operational efficiency and error-free operation in the context of cloud-based CPS. Zhang *et al.* [12] and Lee *et al.* [13] propose a CPS-related architecture in the traditional Automated Guided Vehicles (AGV) warehouse and in RMFS. Lee, *et al.* [13] illustrated the research gap in this area, since the current literature hints only at the significant role of RMFS to handle operation problems. A cloud-based CPS architecture is needed in various situations, such as real-time conflict-free path, collision avoidance and charging scheduling [14]. The adoption of cloud-based CPS can reduce the local warehouse computational power and combine the Enterprise Resource Planning (ERP) in the cloud platform.

The conflict-free path planning problem through AGV in the traditional warehouse has been widely discussed in the literature [15]–[20]. However, the subjects of collision avoidance and cloud-based CPS in the RMFS remain somewhat unexplored. This is relevant to both theoretical and practical research and is the inception motivation for the research introduced in this paper. Therefore, this paper explores value creation through cloud-based CPS in the RMFS to visualize the potential physical mobile robotic collision via IoT. The latest development in the field of the IoT and CPS show the advantages of real-time control management while alleviating the costs incurred by the collision of mobile robots.

The research objective is to propose a cloud-based CPS architecture applied to RMFS for value creation through a virtual prototype. Value creation is approached from the perspective of the difficulties of real-time control and monitoring; therefore, it takes the advantages of CPS and IoT to figure out the new types of collision appearing in RMFS. Dock grid conflict is a new type of conflict appearing in multi-deeps RMFS. This objective is achieved with a comprehensive literature review, a real-life case study in traditional warehouse transferred into the RMFS, as well as by proposing a conceptual framework that integrates relevant literature with the operational evidence from a RMFS's company.

Zhang, *et al.* [21] and Lee, *et al.* [13] outlined three types of collision in traditional warehouses; they are head-on collision, cross collision, and stay-on conflict. In our case scenario, we found several conflicts that have not yet been discovered before in literature. Furthermore, a cloud-based CPS architecture offers a more efficient and effective solution for the practical operations in RMFS, such as reducing the space in the warehouse by storing the data in a cloud system.

After describing the general background of IoT, cloud-based CPS, and RMFS, the state-of-the-art is presented in Section 2 for the ease of architecture and collision illustration. Section 3 illustrates the cloud-based CPS in RMFS. Section 4 describes a case study on RMFS and proposes a new type of collision that appeared in the RMFS. The description of the simulation results is also illustrated in Section 4. The summary of the research and the concluding remarks are given in Section 5.

II. LITERATURE REVIEW

A. ROBOTIC MOBILE FULFILLMENT SYSTEM

The literature review presented in this section reviewed the most significant developments in the field of RMFS in the context of recent research on the CPS, which is important to the realization of the research objective.

Along with the rapid development of IoT technologies and robotic intelligence, RMFS has entered the accelerated development period [13]. Swarm intelligence has been widely developed and adopted in the warehouse to enhance operation efficiency and shorten the picking time. Most research studies are focusing on operations, except for Lee, *et al.* [13] who are providing a CPS system to solve the dynamic conflict problem in RMFS and Mourtzis and Vlachou [22] who included the contents for adaptive shop-floor scheduling and condition-based maintenance.

The research areas can be divided into mobile robots' path planning and scheduling problems, ordering assigning and picking problems, charging problems, collision and deadlock problems, and mobile storage rack assignment and reposition problem.

In a traditional warehouse, inbound operation, cross-docking with value-added services, and outbound logistics are the three aspects of activities. The different types of queuing networks adopted in researches are continuing to estimate the storage systems' performance and minimize the total throughput time in shuttle-based compact systems, automated storage and retrieval systems, and autonomous vehicle storage and retrieval systems [23]–[26]. This method has also been adopted to evaluate the performances of RMFS. Zou *et al.* [27] presented a semi-open queueing networks and adopted a two-phase approximate approach based on the handling speeds of workstations for performance estimation of the RMFS. Lamballais *et al.* [28] used a cross-class matching multi-class semi-open queening network to find out the throughput performance while the inventory is spread across the mobile storage racks in RMFS. Roy *et al.* [29] analyzed the robot assignment strategies for multiple storage zones based on multi-class closed queueing network models and developed a two-stage stochastic model. Yuan and Gong [30] built queue network models to describe the RMFS with two protocols for sharing robots among pickers by evaluation under the throughput time.

Despite evaluating the performance of RMFS by adopting the queuing network, the charging efficiency is crucial in RMFS. Zou *et al.* [31] identified three types of charging strategies including plug-in charging, battery swapping, and inductive battery charging. Different charging strategies result in execution time and operational cost differences. Zou, *et al.* [31] concluded results found that battery swapping is cheaper than plug-in charging, battery costs are relatively low, and inductive charging generates the best retrieval throughput time in RMFS. Weidinger, *et al.* [32] formalized the rack assignment as a specific interval scheduling problem and proposed a matheuristic-dubbed adaptive programming to solve the assignment problem in RMFS. Krenzler, *et al.* [33] formulated a deterministic model to solve the mobile storage rack repositioning problem under a multiple pick station. Merschformann *et al.* [34] simulated the pick and replenishment process and studied the order assignment, mobile storage rack selection, and assignment problems by evaluating multiple decision rules per problem.

Xie, *et al.* [35] proposed an efficient order picking method through split orders in RMFS. Merschformann, *et al.* [36] introduced an RMFS simulation framework, RAWSim-O, for supporting real-time decision problems, and Xie, *et al.* [37] elaborated on the RMFS simulator connected to the enterprise resource planning system and connected with the mobile robots and workstations through an XOR-bench. Jin *et al.* [38] proposed a dynamic scheduling of the Amazon Kiva System. Merschformann, *et al.* [39] presented a collection of path planning algorithms for real-time movement of multiple mobile robots across the RMFS.

B. CLOUD-BASED CYBER-PHYSICAL SYSTEMS

The cloud-based CPS is the extension of the CPS. The CPS, as a connection between the cyber layer and physical layer, was first defined by the US National Science Foundation in 2006 [12], [13], [40]–[47]. Lee [43] interpreted the CPS definition as integrations of computation and physical process. Poudel, *et al.* [48] introduced a real-time CPS for power system security and control. Ma, *et al.* [49] applied CPS in energy manufacturing industries. Schulze, *et al.* [50] combined cooling tower management and CPS in manufacturing companies. Kong, *et al.* [51] proposed a CPS-enabled platform for solving the virtual e-Commerce logistics chains. Lins, *et al.* [52] applied the CPS for the monitoring of tool wear in the machining process. Liu and Wang [53] studied a CPS application under a hazardous manufacturing environment.

CPS in Industrial 4.0 is a dominant change in the manufacturing industry, as an enhancement of visibility, transparency, predictability, and adaptability [44]–[46], [54], [55]. But still, a cloud-based CPS including cloud computing facilitates the provision of a pliable stack of enormous computing, storage, and software services in an economical and scalable manner [56]–[59]. Most works of literature on cloud and CPS have made a great contribution considering the view of separation except Wan, *et al.* [56], Wan, *et al.* [60], Shu, *et al.* [59], and Zheng, *et al.* [61]. Wan, *et al.* [56] considered a context-aware vehicular CPS with cloud support and proposed an application scenario on context-aware dynamic parking services. Wan, *et al.* [60] designed a new CPS, which was adopted in vehicular networking, with the aid of mobile cloud computing. Shu, *et al.* [59] proposed a cloud-based CPS for complex industrial applications based on life cycle management and included the industrial wireless networks while virtualizing resource management. Zheng, *et al.* [61] proposed a smart and connected product co-development in a cloud-based environment through a data-driven CPS.

The functionality of CPS or the looked over trajectory planning for a traditional warehouse system has been explored by numerous researchers [16], [19], [21], [62]–[65]. Combining cloud computing and CPS with the adoption of RMFS will facilitate the handling of massive data through IoT sensors generated from a multi-layers warehouse or multiple warehouses for real-time monitoring and control, for example, a nearly real-time collision avoidance.

Mainly, the CPS theoretical study is explored by the researchers instead of applying real-life applications in warehouse operations. Some conflict resolutions are found on mathematical modeling and with high computational complexity. For a long period of computational time, some solutions may not well fit in a real-life situation. In summary, in the context of cloud-based CPS, RMFS allows the monitoring, control, and centralization of the mobile robot and mobile storage rack in support of IoT sensors during the physical layer and assist with a digitalized environment for real-time control and planning for enhancing the operation efficiency in the cyber layer.

III. CLOUD-BASED CYBER PHYSICAL ROBOTIC MOBILE FULFILLMENT SYSTEM

A. FRAMEWORK OF A 5C CPS-BASED ROBOTIC MOBILE FULFILLMENT SYSTEM

Lee, *et al.* [45] proposed and developed a CPS 5C level architecture to provide a guideline for deploying CPS for manufacturing applications. The 5C architecture showed how to construct a CPS from initial data acquisition to analytics and the final value creation. Each layer of the 5C architecture represents its responsibilities and cooperates with other layers to input and output information and data, as shown in **Figure 2.**

In the smart connection level, data acquisition for multiple hardware devices were considered as the bottom layer. Mobile robots, charging stations, mobile storage racks, and workstations are embedded with sensors such as QR codes in the RMFS. The selection of an appropriate sensor is important for condition-based monitoring and helps obtain accurate and transmittable data for real-time control. For the sensor networks, the RMFS usually selects the Industrial Wireless Networks (IWNs), wireless network, and Wi-Fi Network for building up a tether-free communication. The sensor network allows physical devices to self-connect and self-sense.

The second level is the conversion level, which brings self-awareness to IoT devices in the case of RMFS. The functionality of this layer is to convert the raw data, such as status log, mobile robots' speed, the mobile storage rack location, the condition of workstations, and charging stations, to useful information for obtaining device-related knowledge.

The cyber layer is to adopt virtualization, most likely combined with the concept of Digital Twin (DT), to connect the massive data gathering from the physical world to the cyber world. The idea of constructing a "twin" refers to creating multiple copies of a physical device in a virtual form in cyberspace [66]–[69]. Simulations and predictions can be conducted in a parallel virtual space to obtain invaluable source of information.

The fourth level is the cognition level which provides additional analytic knowledge to probable users through the decision support system. The system is used for selecting the best alternatives based on the information transmitted from the third layer. Rational decisions are also made regarding prioritizing and optimizing decisions from the cyber layer for different situations. Collaborative diagnostics from historical data and real-time data can be beneficial for better

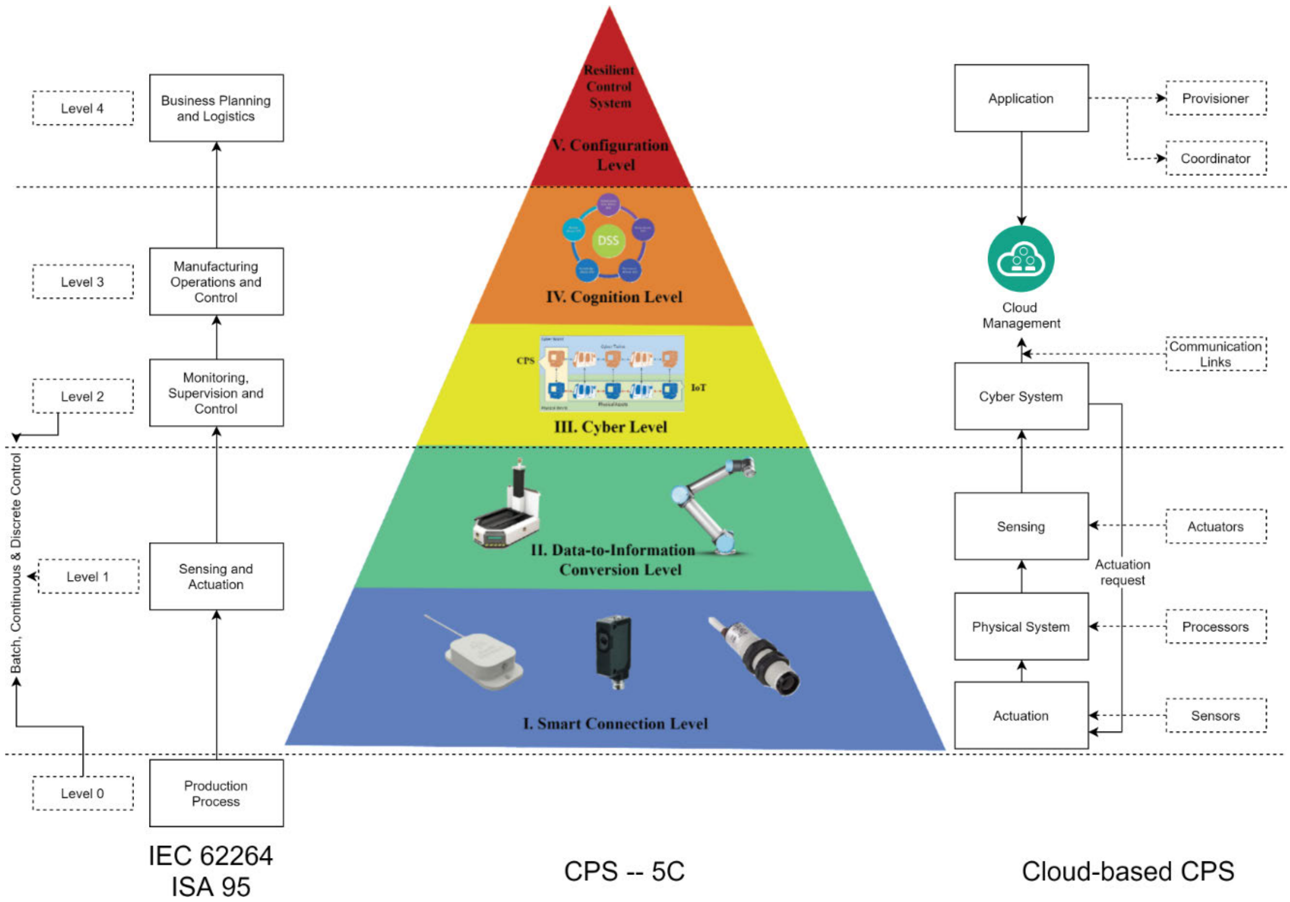


FIGURE 2. A Conceptual Framework of CPS, cloud-based CPS, and IEC 62264/ ISA 95.

human decision making, integrated simulation, and synthesis in RMFS.

Finally, at the configuration level, the application of a corrective and predictive judgment should be made as a supervisory control from the cognition layer. Actions should be made through a feedback loop system from the cyber world to the physical world to avoid operational disruption in the RMFS. This stage also performs as a resilience control system.

B. AN IMPROVED FRAMEWORK OF A 5C CPS, CLOUD-BASED CPS AND IEC 62264/WWWWW/ISA 95

The IEC 62264 international standard, named as the enterprise-control system integration for manufacturing operations management, enables the enterprise system to control the system integration and is proven by the International Organization for Standardization (ISO); moreover, the ISA 95 international standard, by the International Society of Automation, named it the international standard for the integration of enterprise and control systems, which was proven by the American National Standards Institute (ANSI). Both of these standards define a manufacturing operations management model that includes the production control, scheduling, maintenance management, or quality control [70].

Nagorny, *et al.* [71], Delsing, *et al.* [72], Mazak and Huemer [73], and Cupek, *et al.* [74] contributed and built up their research foundations on the IEC 62264 and ISA 95. Nagorny, *et al.* [71] proposed a service and multi-oriented manufacturing automation architecture under IEC 62264. Delsing, *et al.* [72] discussed a service based on automation architecture under ISA 95. Mazak and Huemer [73] proposed an integrated modeling framework spanning over production chains and value networks, based on ISA 95 and IEC 62264. Cupek, *et al.* [74] presented an agent-based manufacturing execution system based on ISA 95 standard with the aid of CPS. A production system model has been developed for controlling, and the conceptual levels of ISA 95 and IEC 62264 architecture address different aspects via the five layers, as shown in **Figure 2** [70]–[72], [74].

A cloud-based CPS architecture can be classified based on the 5C layer and included one aspect named cloud management through the cyber layer [75]. A cyber layer provides a communication link for cloud management as well as cloud computing. Normally, the communication link is in the form of standard network protocols such as Internet Protocol Version 4 (IPv4), Internet Protocol Version 6 (IPv6), Transmission Control Protocol (TCP), User Datagram Protocol (UDP), Message Queuing Telemetry Transport (MQTT), Constrained Application Protocol (CoAP), Advanced Message Queuing Protocol (AMQP), and HyperText Transfer Protocol (HTTP).

C. THE PHYSICAL LAYER OF CLOUD-BASED CPS IN THE RMFS

The physical layer in the cloud-based CPS is defined as the considerations of the RMFS system and includes the mobile robots, mobile storage rack, charging station, and workstation with its inherent information and activities as discussed previously and shown in **Figure 3**. A multi-sensor system is acquired in the RMFS. The physical system provides information through the QR code. The QR code is used for mobile robot navigation, stored goods information for the mobile storage rack, and recorded the responsible workers in the workstation.

Mobile robots depend on data collection to transform real-time data and to watch over the surrounding environment. Data acquisition is the foundation for mobile robots to process data. A camera is equipped on the bottom edge of the mobile robot to scan the QR code that clings to the ground. Therefore, the mobile robot can locate its own position in the RMFS. Lidar is adopted to avoid emergencies and unexpected collisions by observing the lengths between the mobile robot and obstacles. A motor board commands the motion of the mobile robot and surveils the simultaneous motion speed. The Programmable Logic Controller is applied in normal and extreme cases and embedded to handle the input and output of sensors. All output of the sensors, including the sensors embedded to the mobile storage rack, charging station, and workstation, are consolidated to a micro-controller in each physical item. All the data from the micro-controllers are transmitted to the cloud server through a gateway. Edge computing and Wireless Sensor Networks (WSNs) are preferred for use in an RMFS multi-sensor system before being transmitted to the cloud server.

1) EDGE COMPUTING

Edge is defined as any computing and network resources along the path between data sources and cloud data centers [76]. Edge computing indicates an open platform with numerous features such as networking, computing, storage, and application, which are implemented at the network edge near a device or data source and provide intelligent services for smart manufacturing for an agile connection, real-time processing, data cleaning, and privacy protection [76]–[82]. The reasons for adopting edge computing are ''Push from Cloud Services'', ''Pull from IoT'' and ''Change from Data Consumer to Producer'' [76]. The bandwidth of transmitting the information is paused to compare it with the rapidly developing data processing speed through IoT devices. In this context, the raw data produced by IoT will be consumed at the edge of the network rather than transmitted to the cloud. For example, Georgakopoulos, *et al.* [82] proposed to manufacture and IoT and edge cloud computing roadmap. The edge data centers support smart manufacturing plants for larger storage capacity. The centers could shorten the processing time, which saves unnecessary network bandwidth consumption. Edge computing combines different information from the physical layer's IoT devices for centralized uploads to cyberspace.

The monitoring and controlling of the physical operations and offloading of workloads from the cloud system are done by means of edge computing in RMFS. All the raw data from sensors are consolidated into a micro-controller in each device. All the data from the micro-controllers are transmitted through the edge. The edge of the network acquiesces computing offloading, data storage, caching, and processing in a working environment of physical devices that automatically sense and react in the RMFS so that the cloud system can reduce its computing complexity, especially the multi-levels RMFS. A centralized upload procedure can further ensure a higher autonomy, security, and robustness that can be applied in the RMFS system, including through multi-levels RMFS.

2) WIRELESS SENSOR NETWORK

The Wireless Sensor Network is set to transmit the data obtained from the physical devices. With the recent advancement of WSN and its applications, academicians and industrial practitioners have enabled the development of low-cost, low power, multifunctional sensor nodes that are small-scale and communicate unbound within a particular distance [83]–[91]. WSN consists of a large number of sensor nodes providing raw data and various gateways centralized for collecting data. The sensor nodes have the ability to receive data and route the data back to the sink. In the RMFS, sensor nodes are spatially appropriated for a demonstration in the warehouse environment. The nodes are available for self-organization and local computing. Mobile robots and other physical devices in the RMFS serve as sensor nodes in the WSN. The physical devices share information through the embedded sensors with wireless communication devices. An event-driven protocol is adopted in sensor nodes' data collection. Therefore, the overall picket sizes will be declined, and the consumption of energy will also fall off. In the physical layer, a hierarchical topology is selected to organize the nodes and gateways for getting a handle on the dynamic structures in warehouses. The sink may liaise with the task allocation node via the Internet.

The protocol stack consists of the physical layer, data link layer, network layer, transport layer, and application layer. The IoT networks normally engage in numerous radio technologies. The IoT cannot depend on the Web, which makes use of a single standard messaging protocol, HTTP. After comparing the MQTT, CoAP, AMQP and HTTP, four widely adopted and emerging messaging protocols for IoT systems, the AMQP was chosen as the communication protocol in a WSN to normalize the data exchange in the RMFS, following Naik [92]. The AMQP is a flimsy Machine-to-Machine network protocol developed by John O'Hara at JPMorgan Chase in London, UK, in 2003. The AMQP offers two preliminary levels of Quality of Service (QoS) for the delivery of

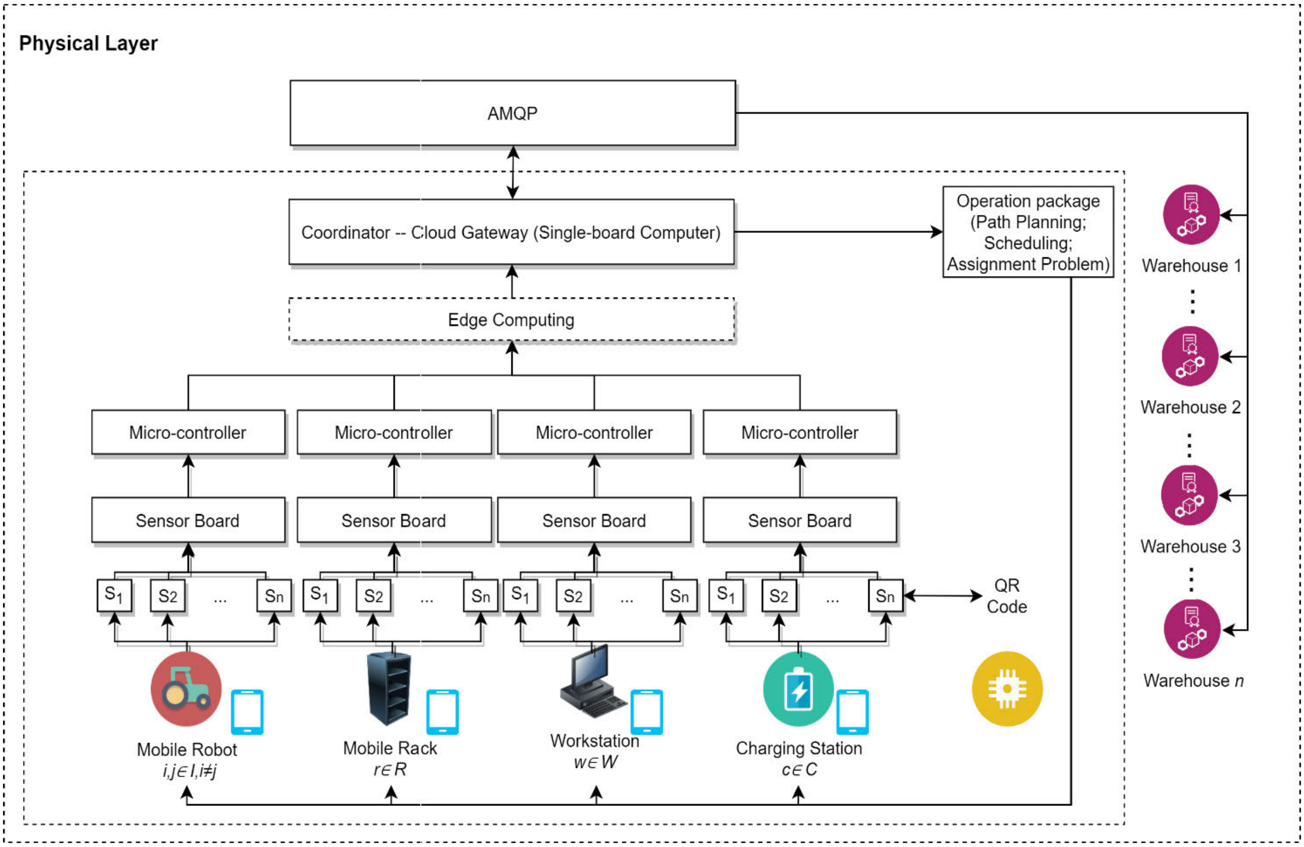


FIGURE 3. A Physical Layer of cloud-based CPS in RMFS.

messages, as follows: Unsettle Format and Settle Format. The AMQP uses TCP as a default transport protocol and TLS/SS and SAS for the security of applications. COAP obtains the highest security with different approaches for TLS negotiation and provisioning when compared to the other three protocols. AMQP is the favorable choice for RMFS because of the broad spectrum of services available for messaging, such as reliable queuing and flexible routing and transactions [92]. Efficient information updation and relatively low power consumption are the advantages of AMQP.

D. THE CYBER LAYER OF CLOUD-BASED CPS IN THE RMFS

The crucial features in cloud computing have been identified as flexibility, scalability of infrastructure, broad network access, location independence, reliability, economies of scale, and sustainability [93], [94]. Generally, the cloud service delivery models are from the core of the cloud and have certain characteristics such as on-demand self-service, multi-tenancy, ubiquitous network, measured service, and rapid elasticity [95]. Traditionally, four deployment models have been described for cloud architecture solutions, including Private cloud, Community cloud, Public cloud, and Hybrid cloud. A hybrid cloud adopted in the RMFS system is beneficial to the private cloud users for its internal warehouse management and public cloud users for its customer order tracking. Cloud management and information security are significant for cloud computing. Security in the RMFS cloud environment refers to a trusted third party that facilitates a cryptographic separation of data and certificate-based authorization. The cyber layer in cloud-based CPS concentrates on the cloud service delivery models, which includes IaaS, PaaS, and SaaS, as presented in **Figure 4**.

1) INFRASTRUCTURE-AS-A-SERVICE

IaaS refers to the cloud service model under the virtualization technology and covers the cloud physical infrastructure layer, virtualization layer, and virtualized resources layer [96]. Digital Twin (DT) is the adoption of virtual simulations and storage in RMFS. DT has been widely adopted in product design, manufacturing, and system simulation [66], [69]. The idea of constructing a "twin" refers to producing a copy of a part or product and using the concept for reasoning out other instances of the same part or product [67], [68], [97], [98]. The main idea of DT is to create multiple copies of a physical object in a virtual form. In RMFS, a cloud-based CPS IoT-based system processes a large amount of data, including the information of mobile robots, mobile storage racks, charging stations, and workstations. Undoubtedly, a transmission time lag appeared in a loop of sending and

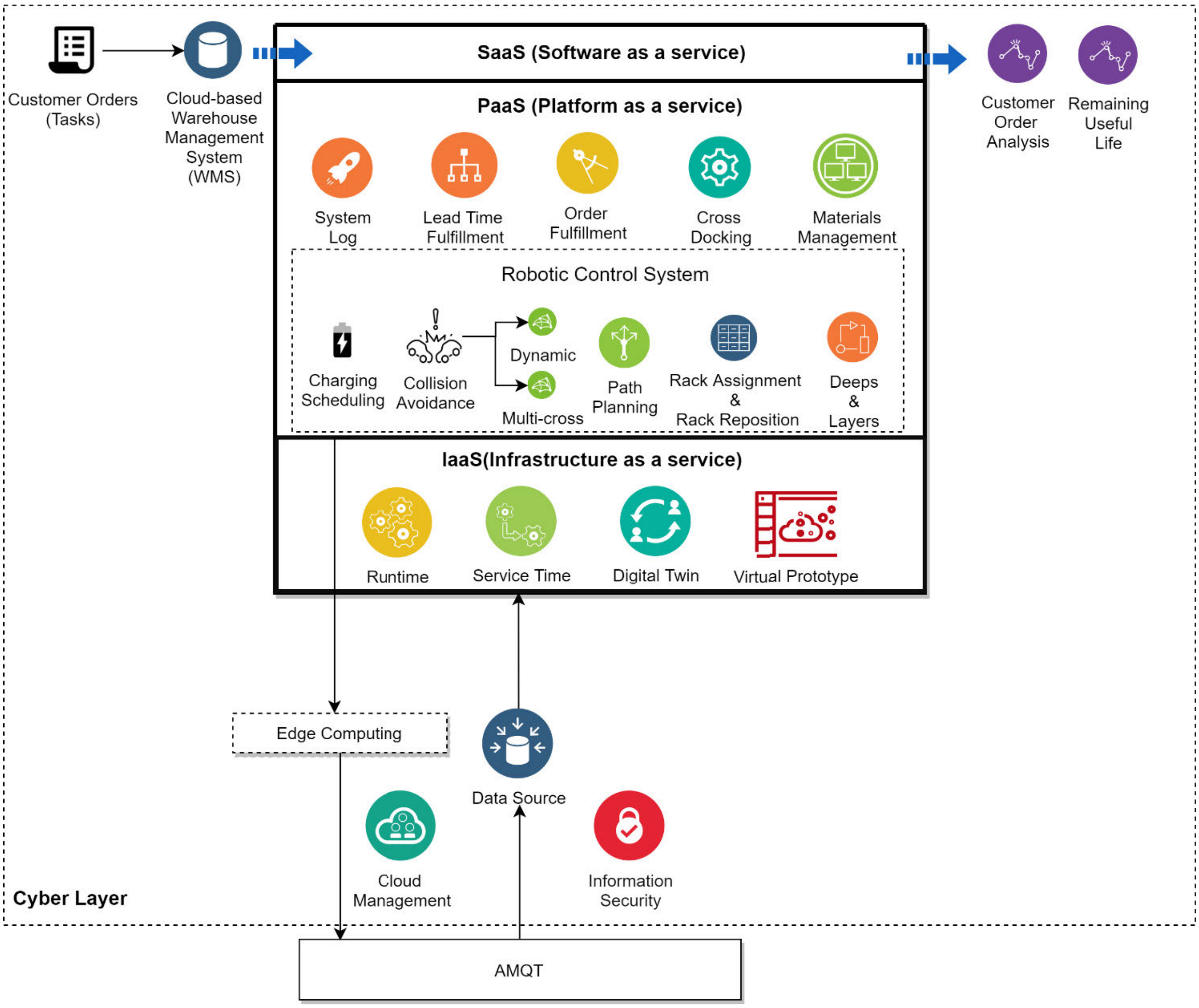


FIGURE 4. A Cyber Layer of Cloud-based CPS in RMFS.

receiving information between the IoT sensor and the cloud-based virtual prototype regardless of the accelerated growth of the sensors and WSN. Therefore, creating a virtual prototype in the cyber layer could simulate the nearly real-time situations for reducing the collision and deadlock accidents that appeared in the RMFS. The virtual prototype will also reveal the service time and the run time using the simulation progress.

2) PLATFORM-AS-A-SERVICE

PaaS refers to the adoption of a platform without installing any supporting tools on its own local machine application. PaaS covers the platform layers, API, and the services layer and relies on the virtualized resources built on the IaaS. After receiving the orders and goods in the RMFS, the PaaS determines several criteria, including the system log, lead time fulfillment, order fulfillment, cross-docking, and materials management. The system log is used to generate virtual outputs for further predictive analysis and management strategies. All the operations are conducted into the cloud system to reduce the power fluctuations that occurred in the local server.

Lead time fulfillment is created based on the time interval between the customer order requirement and the RMFS delivery. This lead time feature is defined by these mechanisms, including the inventory policies and system performances, backorder and lost-sales models, and the lead time information sharing [99]–[102].

Order fulfillment inherits the characteristics of "assemble-to-order", as opposed to conventional "make-to-stock" inventory planning systems [103]–[105]. This action triggers a changed practice in the RMFS. The dynamics-change from suppliers and manufacturers should be estimated for a coping method.

Cross-docking is a function to transfer incoming shipments straight to outbound logistics without storing it in

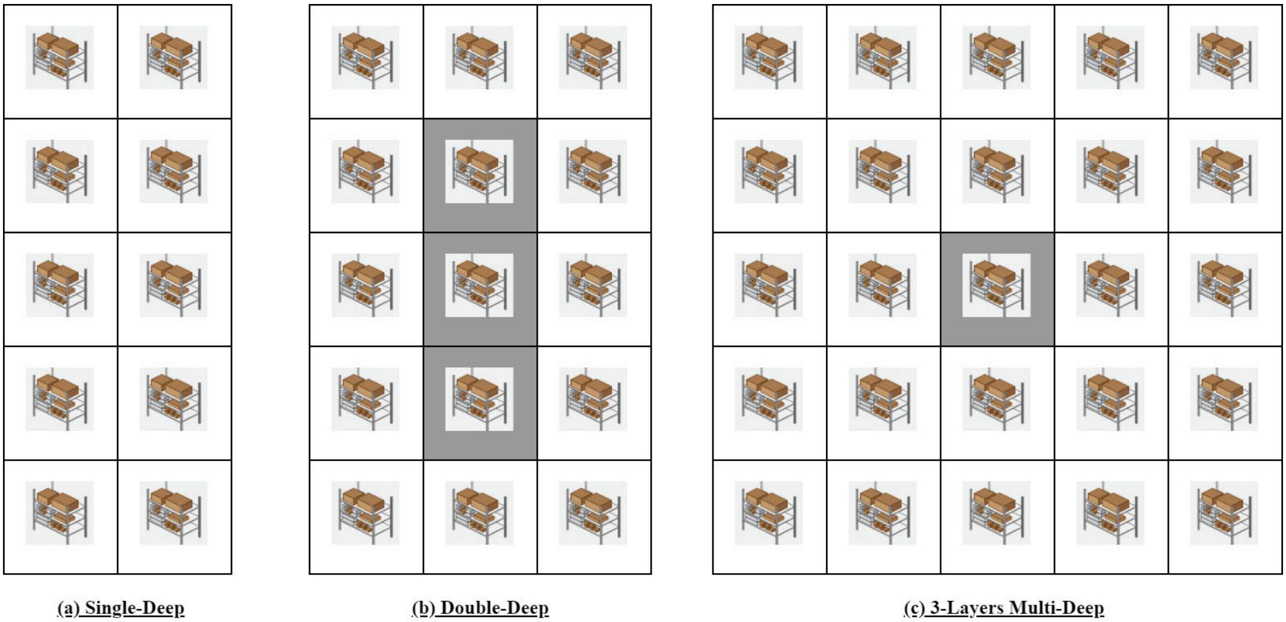


FIGURE 5. An Example of Different Deeps and Layers in RMFS: (a) Single-Deep; (b) Double-Deep; (c) 3-Layers Multi-Deep.

the warehouse. Cross-docking inherited the characteristics of just-in-time manufacturing and electronic data interchange [106]–[108]. This practice will directly influence the operations in the RMFS. According to ABC analysis, category A is the smallest category reserved for the biggest revenues achieved, named as the VIP customer. This move may lead to a cross-docking to reduce the dwell time in the RMFS.

Materials management in the warehouse is used to keep enough materials for maintenance purposes for the mobile robots, moveable racks, and charging stations. Furthermore, predictive maintenance could be measured under a long period of operations in the RMFS [109].

The robotic control system is a centralized system to summarize all the information from the physical layer and decide the actions in various RMFS situations, including the following points:

1) *Charging Scheduling:* The differences between the batteries may affect the charging abilities such as the type of materials and the Ampere hour. Adopting different methods for the RMFS charging unquestionably affects the total charging time, operations, and material requirements, including plug-in charging, inductive charging, and swap battery charging. There are three types of battery charging most commonly used in RMFS. Therefore, the action for choosing the charging method in RMFS will affect the charging scheduling. Plug-in charging is required for reducing the inventory of batteries and avoiding a high installation cost in small and medium RMFS. The charging requirement will be induced by the mobile robot at certain residual battery state-of-charge.
2) *Collision Avoidance:* Adaptive collision avoidance is applied in the cloud-based robotic control system for organizing the movements of the mobile robots with or without carrying a moveable rack. In spite of installing a laser sensor for obstacle detection, resource competition still occurs in the contexts of robot-as-a-service and swarm intelligence with the dynamic layouts of multi-deep and layers in RMFS. A conflict prognosis will promptly detect related collisions and adopt specific collision avoidance approaches to solve the competition circumstances. Mobile robots are assumed to be fully equipped to complete customer orders, and the avoidance of collisions, such as the stay-on collision, cross collision, node-occupancy collision, shelf-occupancy collision, and newly collision that appeared in RMFS, is vital for nearly real-time checks and responses in the physical environment [13], [21], [110]–[112].
3) *Path Planning:* The path planning problem in RMFS requires multi-robot cooperation. Different path planning algorithms aim to find paths to manage the customer order without any collision or deadlock during the operations [113]–[116]. Different layouts with a number of mobile robots, moveable racks, workstations, charging stations, and warehouse-size will affect the path planning performance. Normally, the throughput rate, total path lengths, total search time, and computation time are monitored in the RMFS path planning module [39].
4) *Rack Assignment and Rack Reposition:* Rack assignments in the RMFS should be dependent on the order assignment problems. The goods classified from orders

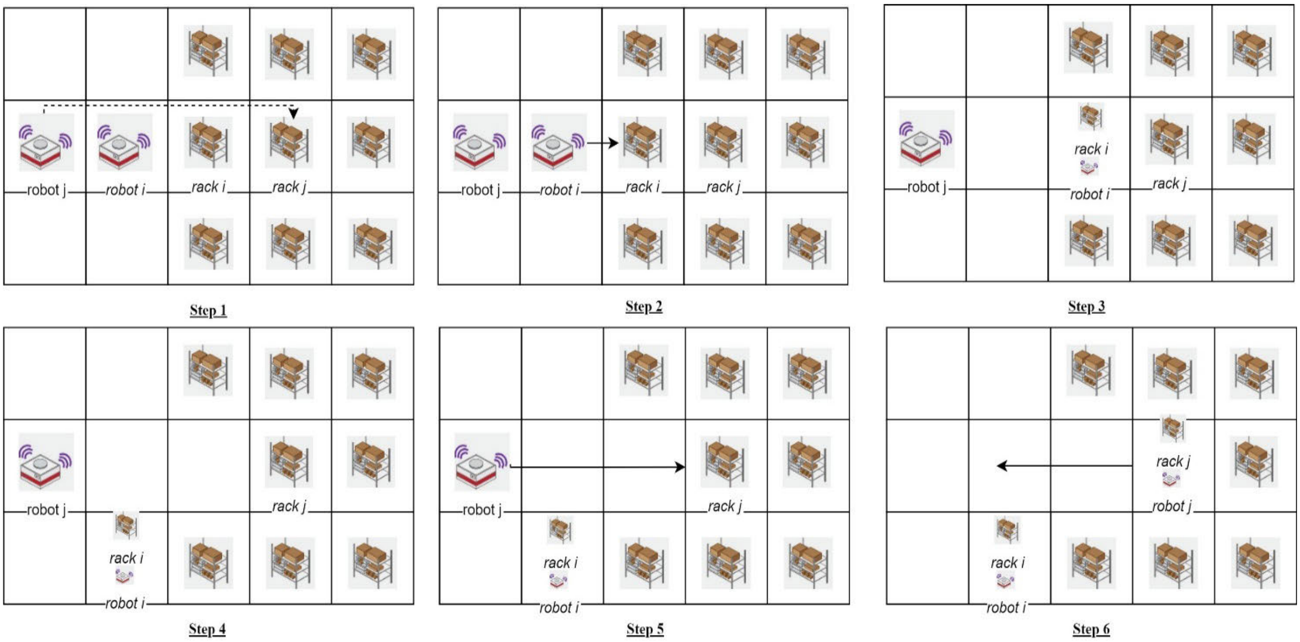


FIGURE 6. **An Operation Logic of Double-Deep in RMFS.**

with a high relevance should be put together or within a close area to reduce the repeated travel commands. For example, a machine learning approach considers the demand correlation pattern for assigning the storage location in the RMFS. Rack reposition is a new approach compared to the AGV traditional warehouse that operates at nighttime without fulfilling any orders. The racks are repositioned the next day during operations preparation.

5) *Deeps and Layers:* In RMFS, there exists different types of deeps and layers as presented in **Figure 5**. The simplest is the single deep **in Figure 5 (a)**. All the mobile robots function without extra help and obtain the moveable rack directly. **Figure 5 (b)** shows the double-deep warehouse structure. The colored area is represented by those moveable racks that require mobile robot cooperation and involve swarm intelligence. In normal cases, the system requires at least two mobile robots to handle the assignment picking up at the colored area rack. **Figure 5 (c)** describes the terms of the multi-layer multi-deep scenario. The colored area is shown as a 3-layer multi-deep scenario. It requires at least three moving steps to pick up that specific rack. **Figure 6** shows the steps to obtain a moveable rack under a double-deep situation. Rack j is assumed for picking up to fulfill the customer requirement. The robot i is ordered to pick up rack i to a specific temporary zone, normally calculated by moving the least distances and without blocking the center path. Then, the robot j picks up the rack j. Rack i will stay at the temporary zone instead of returning to the original place.

3) SOFTWARE-AS-A-SERVICE

SaaS refers to internet-based service for end users that does not require installation of the applications on the customers' computers. This layer covers the applications and services offered as a service for end users with administrative rights in the RMFS. Cloud-based WMS is applied in SaaS and the customer orders are created through the ERP system and transmitted to WMS. WMS is included in the Transportation Management System (TMS) and the Inventory Management System (IMS) in the RMFS for a preferable control through the cloud layer. Based on the historical data stored in WMS, further analysis includes customer order analysis and checking the remaining useful life of the operation tools, which could be done for predictive rack reassignment and reposition.

IV. CASE STUDY

The case study is based on one case company operating within the multi-levels of the RMFS environment. The case study allows researchers to study several new collision occurrences in a real-life context, especially when the collisions differences between the AGV warehouse and RMFS are not well defined in the literature. Since the purpose of this study is to explore the practicalities for improved customer satisfaction with the aid of cloud-based CPS and IoT, the context of the research can be described by purposefully choosing the case company that adopted and implemented the cloud-based CPS and IoT solutions in the RMFS to abet the operation progress. The nature of the investigation, as well as the nature of the studied phenomenon, avoids the potential accidents in the RMFS.

The case company has shifted their current RMFS to a cloud-based CPS. The category of the warehouse items are pure cotton collection and their major customers are textile manufacturers. The case company has also redesigned the warehouse layouts and information storage facilities by adopting the new movable racks, mobile robots, and cloud-based virtual prototypes best suited for the actual RMFS needs after considering how the customer orders are actually fulfilled. The company initially established themselves as Person-to-Goods. Over time, however, their focus shifted towards polishing their offerings with complementary ''Goods to Person'' services that, with the aid of cutting-edge technology, are moderately evolving into IoT-based and cloud-based CPS-aided operations. Furthermore, another significant factor that decided the selection of the particular company was the success of their cloud-based CPS-aided operations in the RMFS in terms of enhanced positive customers' satisfaction through feedback, operation efficiency, and reduced human accidents. The case company has been implementing the cloud-based CPS in multi-levels RMFS over the course of about one year. The case company also initiated a project with a highly reputed university to develop the theoretical and conceptual foundations.

The IoT concept is adopted in the case company's mobile robots, mobile storage racks, workstations, and charging stations as a multi-sensor system. AMQP is chosen as the communication protocol in a WSN to normalize the data exchange in the case company. The data exchange process has two parts: uploading and downloading. Uploading is an action to transfer the physical real-time information to the cyber layer's cloud platform to conduct multiple analyses, including path planning, collision avoidance, charging scheduling and assignment, and rack assignment and reposition. Downloading is an action to provide a nearly real-time reaction to the physical devices, in aid of edge computing. Therefore, a cloud-based CPS in the case company can reduce its own local computational power.

The case company is a large multi-level warehouse storing the goods of the pure cotton collection shown in **Table 1**. The focal areas have consolidated the related cotton to fulfill the needs of the fast-fashion clothing industry through digital content consumption in the context of e-Commerce. Social media has become one of the remarkable platforms used by the young generation to shop fast fashion brands. With an increase in the complexity of customer orders, the warehouse operation requirements have also increased. **Table 2** shows an example of the historical data O.

Previously, cloud storage in the warehouse operations was a standard feature, but it was mainly adopted to support the backup and storage services. The case company has now introduced the cloud-based CPS to build up a robotic control system and a virtual prototype under the cyber layer. The recent development of IoT solutions also offers an opportunity to standardize and consolidate the operations through sensors in the RMFS. This information is transferred to a cloud system, which comes up with a view of both the operations level as well as the case company's strategies management. The crucial value creation logic of the case company regarding the value chain induced by customers is gradually changing. The value creation of the warehouse has switched to include tangible and intangible products and services for RMFS.

TABLE 1. Storing products in the case company.

Product Types	Types	Nanometer (nm) [a]
Everyday	200 Types (E1-E200)	2/36 Nm
Signature	100 Types (S1-S100)	2/28 Nm
Primo	50 Types (P1-P50)	2/54 Nm
Primofine	30 Types (F1-F30)	2/68 Nm
Century	40 Types (C1-C40)	2/50 Nm
Spiral	20 Types (S1-S20)	1/10 Nm
Theory	20 Types (T1-T20)	2/101 Nm

TABLE 2. An example of historical data.

Customer Order	Items
O_1	E1, E3, E55, E64, E100, S5
O_2	S1, S20, F1, S12, T4
O_3	T1, T2, T5
O_4	E10, E10, E32, E33, E34, E40, E100, E100, E127, E127
O_5	F12, C1, S14

Figure 7 shows a rack map example as one of the RMFS levels in the case company. The ones colored in red refers to the moveable rack. The empty area refers to the blocked areas such as for fulfilling the fire safety regulations and limits of construction. The ones colored in green refers to the charging station and the one named as WS represents the picking and replenishing workstation.

The system implementation of the RMFS case company is based on the Java language of the robotic control system through the virtual prototype. The CPS integration in the RMFS includes each type of grid with its ID and coordinates stored in the cloud. Raw data collected through different sensors, including the coordinates, status and current speed of mobile robots, loading and unloading information, and remaining battery level, were transmitted to the cloud-based system through WSN. Customer orders are inputted into the cloud-based WMS and the tasks delivered to the robotic control system for task allocation and path planning. A near-real-time algorithm-designed path was transmitted to the adaptive collision avoidance and other related modules to conduct entire warehouse operations.

The RMFS is divided into different grids. In general, the RMFS is classified into four areas, including picking and replenishing the workstation area, aisle area, storage area, and

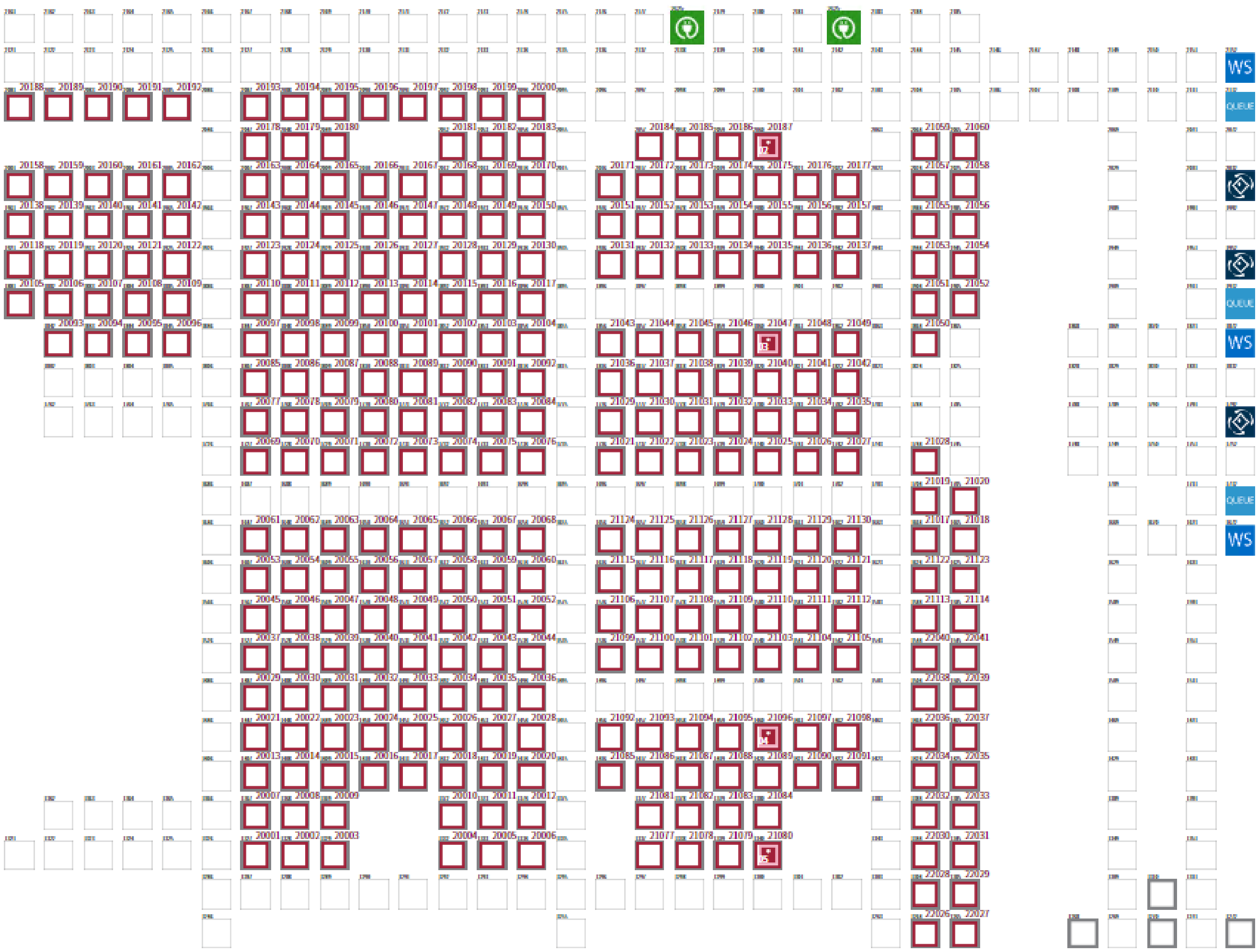


FIGURE 7. A Rack Map for the RMFS: Employ: Blocked Area; Colored in Green: Charging Station; Colored in Write: Empty Path; Colored in Red: Moveable Rack; Named as WS: Picking and Replenishing Workstation; Shape of rotation: Self-rotation area for mobile robot.

charging area. A QR code is used for mobile robot navigation and verifying its own location. Each QR code is clung on the grid. The mobile robot identifies itself by scanning the QR code stuck on the physical floor. The configuration of each robot is assumed as 1030mm*750mm*295mm. The moveable rack bottom is 315 mm from the ground. All the racks have eight levels and the total volume is 32 cartons. Therefore, the mobile robot can pass under the moveable rack when it is free of loads. The specified load of a mobile robot is 500kg. All the racks are within the affordable weights of mobile robots.

The charging stations facilitate plug-in battery charging. The battery is a lithium-based with a 30AH and the battery size is 245mm*175mm*190mm. All the charging stations are standardized with the same charging level. The battery of mobile robots cannot become lower than a certain level, 37% in this case, before the reserved battery is moved to the charge station. The acceptable percentages of mobile robots charged battery state-of-charge is 86%. After completing the charging process, the mobile robot will directly pick up the required rack instead of returning to the queueing from the workstation if there is a new customer order.

RMFS supports the bi-directional movement. All mobile robots can only execute one job at a time. The mobile robot is accountable for two kinds of duties. The first one is to travel from the source grid to the destination grid and lift up the rack. The second duty of the loaded mobile robots is to transport the rack with required goods from the source node to the workstation. The worker in the workstation will pick up the customer requirements and address the rack back to the storage area. The path of a mobile robot occupied by the rack is different from that of an empty mobile robot because of the movement under the rack. The speed of a mobile robot is not constant. The virtual prototype will consider the acceleration and deceleration of mobile robots. Normally, three grids are the standard buffer time for a mobile robot to go from full speed to stop and from the stationary state to full speed state. The rotation of a mobile robot itself is considered for turning purpose. A total of four mobile robots can be operated in the case company.

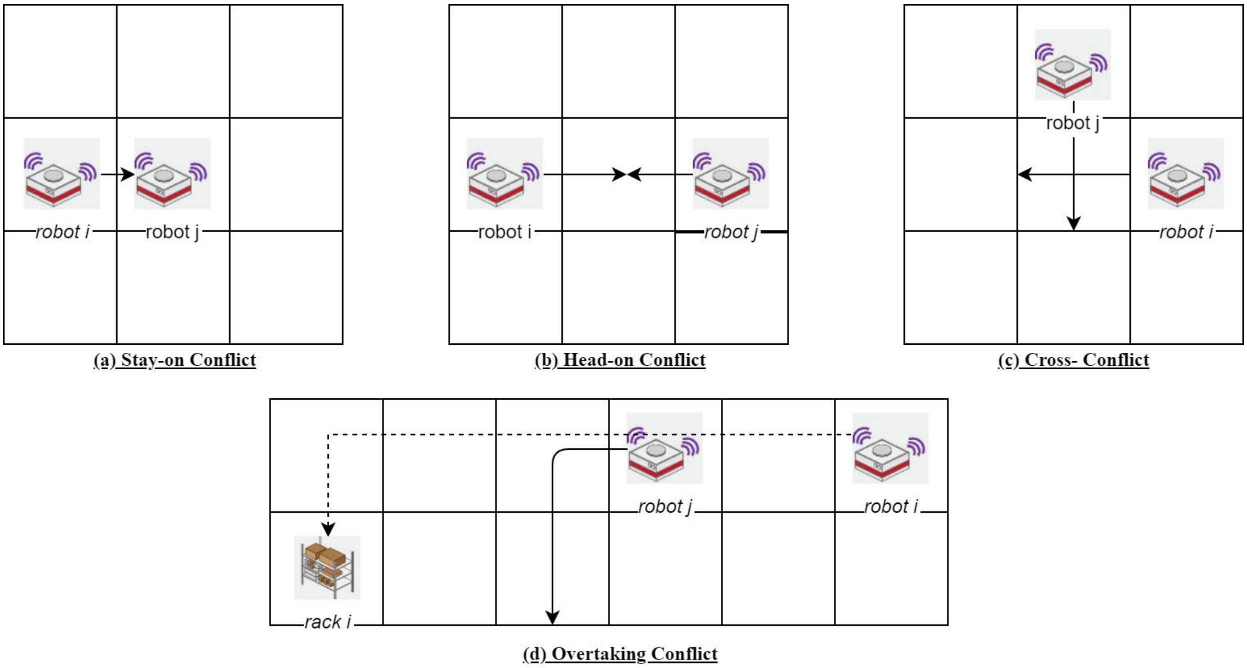


FIGURE 8. An Example of Mobile Robots' Multi-Path Conflict in RMFS: (a) Stay-on Conflict; (b) Head-on Conflict; (c) Cross-Conflict, (d) Overtaking Conflict.

TABLE 3. Specific experiment settings.

Scenario	Orders to fulfill	Number of Robot(s)	Number of Workstation(s)
1	10	2	3
2	10	4	3
3	30	2	3
4	30	4	3
5	60	2	3
6	60	4	3

To find out the different types of collision appearing in RMFS, this paper conducts experiments on real-time operations to fulfill the customer orders. The experiment settings are illustrated in **Table 3.** Six scenarios, which are organized respectively under the different numbers of robots and orders, are complied with the same configurations on a cloud-based virtual prototype. The orders to fulfill are set to 10, 30, and 60 in order to estimate the peak and non-peak seasons in terms of an hour.

A. DISCUSSION

1) TYPES OF COLLISION

The collision detection between every two mobile robots is implemented continually every 0.5 seconds among all the mobile robots based on their priorities. All the conflicts mentioned in the following can be solved by a Go-away strategy for a nearly real-time conflict solution strategy.

There are in total four types of multi-path potential collisions in the RMFS as shown in **Figure 8**: (a) Stay-on conflict, (b) Head-on conflict, (c) Cross Conflict and (d) Overtaking Conflict.

a) *Stay-On Conflict:* The stay-on conflict refers to when two mobile robots rear-end. The most common situation in the RMFS is when robot j stops to rotate and turn and robot i doesn't spare enough time and distances for deceleration.
b) *Head-On Conflict:* As for example shown in **Figure 8**, the head-on conflict happens if two mobile robots that may or may not be carrying racks travel in the same path in the opposite direction. The head-on conflict also includes the path in which the mobile robots travel under the rack.
c) *Cross-Conflict:* The cross conflict happens when two mobile robots are assigned an overlapping path. None of them are prepared for an early deceleration, leading to a crash.
d) *Overtaking-Conflict:* As for example shown in **Figure 8**, robot j is ready to decelerate and robot i is at full speed or acceleration mode to pick up rack i. Therefore, it leads to rear-end.

There exists a new type of conflict in the case of multi-layers multi-deeps circumstance, named as Dock Grid conflict, as shown in **Figure 9**: (a) Dock Grid, (b) Dock Grid conflict, (c) Dock Grid cross-conflict.

a) *Dock Grid:* The dock grid refers to a grid reserved for conducting the mobile robot's cooperation. As shown in **Figure 9**, a double-deep layer is considered. Robot

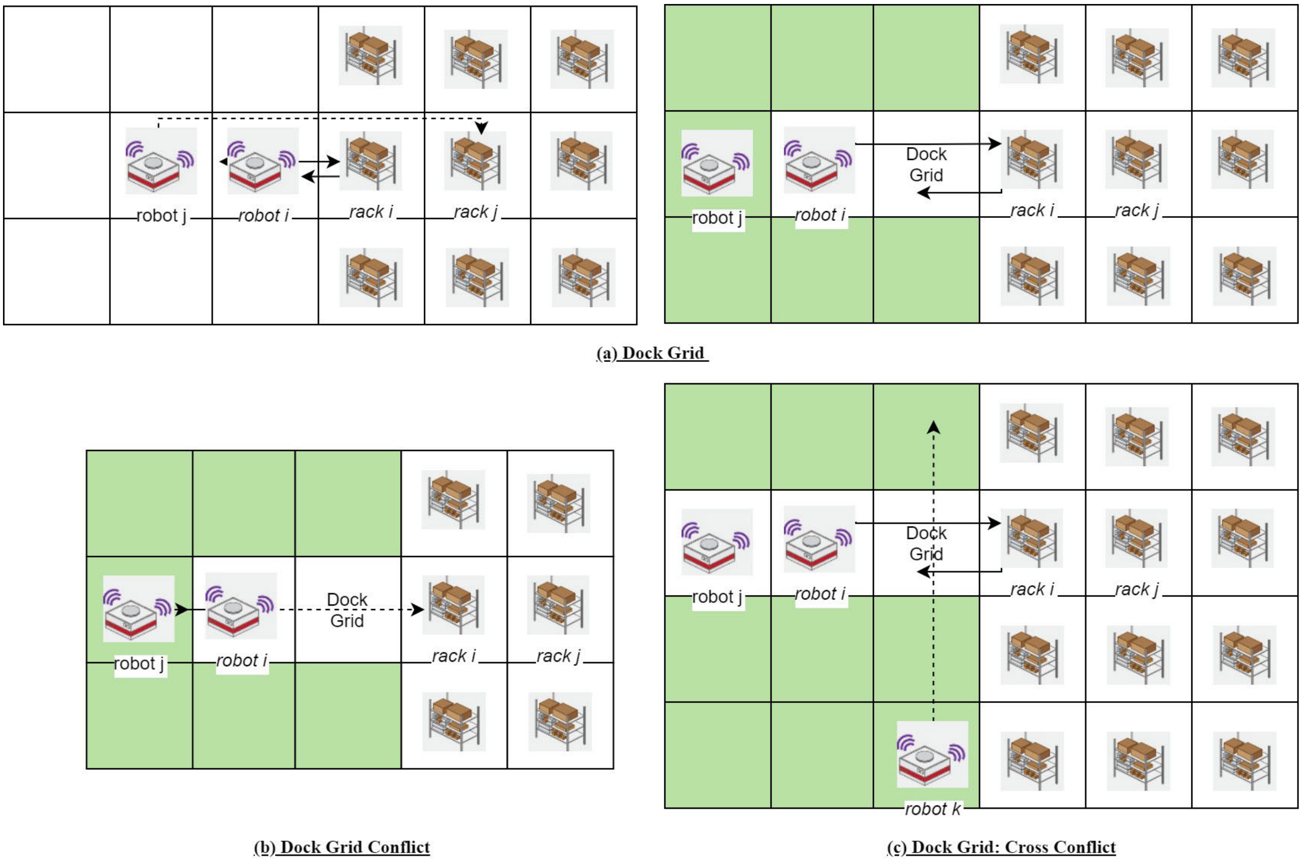


FIGURE 9. An Example of Dock Grid Conflict in RMFS: (a) Dock Grid; (b) Dock Grid Conflict; (c) Dock Grid: Cross Conflict.

j is supposed to pick up rack *j*. Robot *j* can appear and stop at any gird in green color while waiting to move out rack *i*. Still, it needs to put away rack *i* first. Therefore, robot *i* picks up rack *i* to a specific temporary zone.

b) *Dock Grid Conflict:* The dock grid conflict happens when there a dock grid doesn't exist to conduct the mobile robot's cooperation, for example, when robot *i* picks up rack *i* and robot *j* moves to the grid that is supposed to be a dock grid. The traffic then appears to be stuck by robot *j*, which leads to robot *i* not being able to move away.

c) *Dock Grid Cross-Conflict:* The dock grid cross-conflict happens when robot k travels through the dock gird while robot i and robot j are conducting cooperation in a double-deep condition.

A dynamic path conflict happens as illustrated in **Figure 10**. Four mobile robots are assigned to pick up different racks. First, robot i is assigned to pick up rack i. Second, robot *j* is assigned to pick up rack *j*. Third, robot k is assigned to pick up rack k. Fourth, robot m is in an acceleration mode or full speed move for traveling. The four actions are assigned nearly at the same time with priorities for fulfilling the customer order. This situation will occur as the four mobile robots are stopped to avoid collisions in the absence of a proper collision solution in the robotic control system.

Go-away strategy redirects robot i or robot j to another adjacent node to allow one of the robots to remain unchanged from its original path. Normally, the system assigns the mobile robot in order of which mobile robot has enough grid distances for deceleration and redirects that mobile robot to the adjacent position for conflict avoidance. If both of the mobile robots are at the same grid distances, this movement will depend on the order placement priorities from the system.

2) SCENARIOS ANALYSIS

Table 4 shows the RMFS under an hour in different scenarios with multiple orders to fulfill. The results obviously show that the virtual prototype in the robotic control system can detect and solve the collision between mobile robots. The experiments suggest mobile robots' deployment. Adopting more mobile robots will lead to an increase in conflicts especially in the context of cross-conflicts. The total completion time may not definitely decrease while applying more mobile robots in the same situation. None of the conflicts happened under the go-away strategies in nearly real-time scenarios.

A cloud-based CPS-enabled RMFS can be well-timed to be in control of the real-time physical operations, as the DT is synchronous with the physical layer in the CPS.

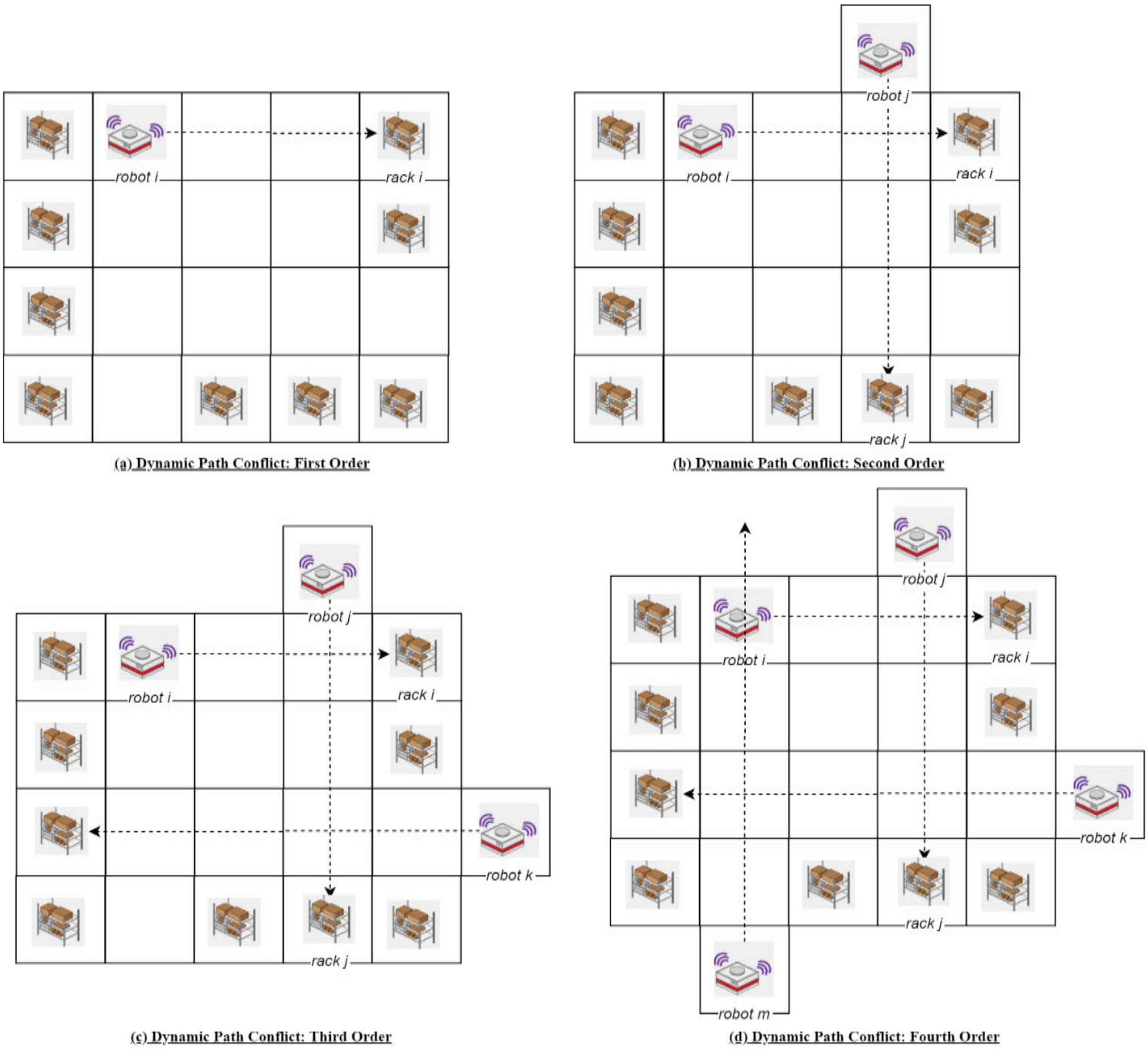


FIGURE 10. An Example of Dynamic Path Conflict in RMFS: (a) First Order; (b) Second Order; (c) Third Order; (d) Fourth Order.

TABLE 4. Results for scenarios.

Scenario	Total Completion Time (min.)	Number of Stay-on conflict(s)	Number of Head-on Conflict(s)	Number of Cross Conflict(s)	Number of Overtaking Conflict(s)	Number of Dock Grid Conflict(s)	Number of Dynamic Path Conflict(s)
1	10.5	1	0	0	0	1	0
2	4.3	2	0	1	1	2	1
3	35.7	1	0	0	0	5	0
4	15.6	5	1	5	2	7	4
5	60.0	3	0	3	0	6	0
6	49.6	9	3	8	1	12	2

Collision detection is operated on the cloud after the path planning module provides a solution for mobile robots. A go-away strategy can directly solve the conflict appearing in the RMFS. The total completion time is included in the charging time of the mobile robots, if needed. Adopting more mobile robots for operations may not be suitable because of the economies of scale and an increase in the chances of a conflict.

V. CONCLUSION

The research presented in this paper explores the authoritative potential behind cloud-based CPS in RMFS achieved via IoT-aided applications and WSN. It primarily introduces and facilitates the integration and deployment of cloud-based CPS through the RMFS, thereby reducing accidents and enhancing the flow of the operation for integration. Connected devices and expeditious interchange of information will eventually lead to increased warehouse efficiency and effectiveness, a shift in economics, and a modified working environment, which will finally evolve and intensify the competitiveness of companies [117].

This paper proposes that cloud-based CPS can serve as an extraordinary implement for the WMS in the future. With a well-planned cloud-based CPS and IoT-aided strategy, companies operating RMFS are able to create a substantial value based on well-grounded data on sensor collections. A customer-driven e-Commerce economy triggers a higher expectation of the delivery of products, which leads to soaring requirements of picking and packing in the warehouse. Moreover, DT in the cloud can be created to enhance customer satisfaction and reduce errors and accidents A cloud-based CPS architecture with physical and cyber operations is explored in this paper, with a particular attention to conflict avoidances. This paper introduces a cloud-based CPS to provide a comprehensive understanding on how warehouses can be better used to avoid conflict under the multi-layers multi-deeps circumstances. The work presents six conflict classifications in RMFS and provides a case study to illustrate how cloud-based CPS helps in conflict avoidance with multi-levels of RMFS.

The research could be extended in the future based on three aspects. A key aspect is a relatively small number of case companies. It is difficult to make a comparison with other RMFS operating different goods for a possibility of generalization. Second, the conflict solution in nearly real-time is solved by a go-away strategy. Still, a detour strategy, wait-before-startup strategy, directly re-modifying the path, and re-dispatching the tasks are methods to solve the conflict mentioned in this paper. However, none of them could solve the conflict in a real-time situation [13]. Therefore, future scope needs to be focused on for modifying the strategies that can be adopted in cloud-based CPS RMFS. Third, this paper combines a study of theoretical considerations and practical evidence from a case company whose RMFS operations and cloud server with CPS adoption were based on IoT devices. Thus, the cloud-based CPS architecture provides a comprehensive blueprint of how a recent cloud system, CPS, and IoT enhance operation efficiency. Artificial Intelligence is a fascinating research area that draws knowledge from different sources. In the context of RMFS, IoT devices generate data that can assist decision-makers facing the dilemma of conflicting criteria, with the aid of AI. Future research on cloud-based CPS and RMFS should focus on uncovering the path planning problem, storage assignment problem, RMFS layout problem and their impacts on path conflicts, and customer satisfaction.

REFERENCES

[1] K.-H. Lai, "Service capability and performance of logistics service providers," *Transp. Res. Part E: Logistics Transp. Rev.*, vol. 40, no. 5, pp. 385–399, Sep. 2004, doi: 10.1016/j.tre.2004.01.002.

[2] A. White, E. M. Daniel, and M. Mohdzain, "The role of emergent information technologies and systems in enabling supply chain agility," *Int. J. Inf. Manage.*, vol. 25, no. 5, pp. 396–410, Oct. 2005, doi: 10.1016/j.ijinfomgt.2005.06.009.

[3] C. K. M. Lee, Y. Lv, K. K. H. Ng, W. Ho, and K. L. Choy, "Design and application of Internet of Things-based warehouse management system for smart logistics," *Int. J. Prod. Res.*, vol. 56, no. 8, pp. 2753–2768, Apr. 2018, doi: 10.1080/00207543.2017.1394592.

[4] C. K. M. Lee, Y. Z. Huo, S. Z. Zhang, and K. K. H. Ng, "Design of a smart manufacturing system with the application of multi-access edge computing and blockchain technology," *IEEE Access*, vol. 8, pp. 28659–28667, 2020, doi: 10.1109/ACCESS.2020.2972284.

[5] C. K. M. Lee, S. Z. Zhang, and K. K. H. Ng, "Development of an industrial Internet of Things suite for smart factory towards re-industrialization," *Adv. Manuf.*, vol. 5, no. 4, pp. 335–343, Dec. 2017, doi: 10.1007/s40436-017-0197-2.

[6] K. L. Keung, C. K. M. Lee, K. K. H. Ng, and C. K. Yeung, "Smart city application and analysis: Real-time urban drainage monitoring by IoT sensors: A case study of hong kong," in *Proc. IEEE Int. Conf. Ind. Eng. Eng. Manage. (IEEM)*, Dec. 2018, pp. 521–525, doi: 10.1109/IEEM.2018.8607303.

[7] A.-R. Sadeghi, C. Wachsmann, and M. Waidner, "Security and privacy challenges in industrial Internet of Things," in *Proc. 52nd Annu. Design Autom. Conf. (DAC)*, Jun. 2015, pp. 1–6, doi: 10.1145/2744769.2747942.

[8] P. Zheng, T.-J. Lin, C.-H. Chen, and X. Xu, "A systematic design approach for service innovation of smart product-service systems," *J. Cleaner Prod.*, vol. 201, pp. 657–667, Nov. 2018, doi: 10.1016/j.jclepro.2018.08.101.

[9] A. Nayyar, *Handbook of Cloud Computing*. New Delhi, India: BPB Publication, 2019.

[10] R. Krishnamurthi, A. Nayyar, and A. Solanki, *Innovation Opportunities Through Internet of Things (IoT) for Smart Cities*. 2019, pp. 261–292.

[11] R. S. Batth, A. Nayyar, and A. Nagpal, "Internet of robotic things: Driving intelligent robotics of Future–concept, architecture, applications and technologies," in *Proc. 4th Int. Conf. Comput. Sci. (ICCS)*, Aug. 2018, pp. 151–160.

[12] Y. Zhang, Z. Zhu, and J. Lv, "CPS-based smart control model for shopfloor material handling," *IEEE Trans. Ind. Informat.*, vol. 14, no. 4, pp. 1764–1775, Apr. 2018, doi: 10.1109/TII.2017.2759319.

[13] C. K. M. Lee, B. Lin, K. K. H. Ng, Y. Lv, and W. C. Tai, "Smart robotic mobile fulfillment system with dynamic conflict-free strategies considering cyber-physical integration," *Adv. Eng. Informat.*, vol. 42, Oct. 2019, Art. no. 100998, doi: 10.1016/j.aei.2019.100998.

[14] K. L. Keung, C. K. M. Lee, and P. Ji, "Mobile robots charging assignment problem with time windows in robotic mobile fulfilment system," in *Proc. IEEE Int. Conf. Ind. Eng. Eng. Manage. (IEEM)*, Dec. 2019, pp. 1329–1333, doi: 10.1109/IEEM44572.2019.8978958.

[15] N. N. Krishnamurthy, R. Batta, and M. H. Karwan, "Developing conflict-free routes for automated guided vehicles," *Oper. Res.*, vol. 41, no. 6, pp. 1077–1090, Dec. 1993, doi: 10.1287/opre.41.6.1077.

[16] S. Maza and P. Castagna, "Conflict-free AGV routing in bi-directional network," in *Proc. 8th Int. Conf. Emerg. Technol. Factory Automat.*, vol. 2, Oct. 2001, pp. 761–764, doi: 10.1109/ETFA.2001.997777.

[17] T. Miyamoto and K. Inoue, "Local and random searches for dispatch and conflict-free routing problem of capacitated AGV systems," *Comput. Ind. Eng.*, vol. 91, pp. 1–9, Jan. 2016, doi: 10.1016/j.cie.2015.10.017.

[18] L. Sabattini, V. Digani, C. Secchi, and C. Fantuzzi, "Optimized simultaneous conflict-free task assignment and path planning for multi-AGV systems," in *Proc. IEEE/RSJ Int. Conf. Intell. Robots Syst. (IROS)*, Sep. 2017, pp. 1083–1088, doi: 10.1109/IROS.2017.8202278.

[19] Z. Zhang, Q. Guo, and P. Yuan, "Conflict-free route planning of automated guided vehicles based on conflict classification," in *Proc. IEEE Int. Conf. Syst., Man, Cybern. (SMC)*, Oct. 2017, pp. 1459–1464, doi: 10.1109/SMC.2017.8122819.

[20] C. K. M. Lee, K. L. Keung, K. K. H. Ng, and D. C. P. Lai, "Simulation-based multiple automated guided vehicles considering charging and collision-free requirements in automatic warehouse," in *Proc. IEEE Int. Conf. Ind. Eng. Eng. Manage. (IEEM)*, Dec. 2018, pp. 1376–1380, doi: 10.1109/IEEM.2018.8607396.

[21] Z. Zhang, Q. Guo, J. Chen, and P. Yuan, "Collision-free route planning for multiple AGVs in an automated warehouse based on collision classification," *IEEE Access*, vol. 6, pp. 26022–26035, 2018, doi: 10.1109/ACCESS.2018.2819199.

[22] D. Mourtzis and E. Vlachou, "A cloud-based cyber-physical system for adaptive shop-floor scheduling and condition-based maintenance," *J. Manuf. Syst.*, vol. 47, pp. 179–198, Apr. 2018, doi: 10.1016/j.jmsy.2018.05.008.

[23] B. Y. Ekren, S. S. Heragu, A. Krishnamurthy, and C. J. Malmborg, "Matrix-geometric solution for semi-open queuing network model of autonomous vehicle storage and retrieval system," *Comput. Ind. Eng.*, vol. 68, pp. 78–86, Feb. 2014, doi: 10.1016/j.cie.2013.12.002.

[24] T. Lerher, B. Y. Ekren, G. Dukic, and B. Rosi, "Travel time model for shuttle-based storage and retrieval systems," *Int. J. Adv. Manuf. Technol.*, vol. 78, nos. 9–12, pp. 1705–1725, Jun. 2015, doi: 10.1007/s00170-014-6726-2.

[25] R. Manzini, R. Accorsi, G. Baruffaldi, T. Cennerazzo, and M. Gamberi, "Travel time models for deep-lane unit-load autonomous vehicle storage and retrieval system (AVS/RS)," *Int. J. Prod. Res.*, vol. 54, no. 14, pp. 4286–4304, Jul. 2016, doi: 10.1080/00207543.2016.1144241.

[26] M. Borovinšek, B. Y. Ekren, A. Burinskienė, and T. Lerher, "Multi-objective optimisation model of shuttle-based storage and retrieval system," *Transport*, vol. 32, no. 2, pp. 120–137, May 2016, doi: 10.3846/16484142.2016.1186732.

[27] B. Zou, Y. Gong, X. Xu, and Z. Yuan, "Assignment rules in robotic mobile fulfilment systems for online retailers," *Int. J. Prod. Res.*, vol. 55, no. 20, pp. 6175–6192, Oct. 2017, doi: 10.1080/00207543.2017.1331050.

[28] T. Lamballais Tessensohn, D. Roy, and R. B. M. De Koster, "Inventory allocation in robotic mobile fulfillment systems," *IISE Trans.*, vol. 52, no. 1, pp. 1–17, Jan. 2020, doi: 10.1080/24725854.2018.1560517.

[29] D. Roy, S. Nigam, R. de Koster, I. Adan, and J. Resing, "Robot-storage zone assignment strategies in mobile fulfillment systems," *Transp. Res. E, Logistics Transp. Rev.*, vol. 122, pp. 119–142, Feb. 2019, doi: 10.1016/j.tre.2018.11.005.

[30] Z. Yuan and Y. Y. Gong, "Bot-In-Time delivery for robotic mobile fulfillment systems," *IEEE Trans. Eng. Manag.*, vol. 64, no. 1, pp. 83–93, Feb. 2017, doi: 10.1109/TEM.2016.2634540.

[31] B. Zou, X. Xu, Y. Gong, and R. De Koster, "Evaluating battery charging and swapping strategies in a robotic mobile fulfillment system," *Eur. J. Oper. Res.*, vol. 267, no. 2, pp. 733–753, Jun. 2018, doi: 10.1016/j.ejor.2017.12.008.

[32] F. Weidinger, N. Boysen, and D. Briskorn, "Storage assignment with rack-moving mobile robots in KIVA warehouses," *Transp. Sci.*, vol. 52, no. 6, pp. 1479–1495, Dec. 2018, doi: 10.1287/trsc.2018.0826.

[33] R. Krenzler, L. Xie, and H. Li, "Deterministic pod repositioning problem in robotic mobile fulfillment systems," Tech. Rep., 2018.

[34] M. Merschformann, T. Lamballais, M. B. M. de Koster, and L. Suhl, "Decision rules for robotic mobile fulfillment systems," *Oper. Res. Perspect.*, vol. 6, 2019, Art. no. 100128, doi: 10.1016/j.orp.2019.100128.

[35] L. Xie, N. Thieme, R. Krenzler, and H. Li, "Efficient order picking methods in robotic mobile fulfillment systems," Tech. Rep., 2019.

[36] M. Merschformann, L. Xie, and H. Li, "RAWSim-O: A simulation framework for robotic mobile fulfillment systems," *Logistics Res.*, vol. 11, 2018, doi: 10.23773/2018_8.

[37] L. Xie, H. Li, and N. Thieme, "From simulation to real-world robotic mobile fulfillment systems," *Logistics Res.*, vol. 12, 2019, doi: 10.23773/2019_9.

[38] X. Jin, M. Zhong, X. Quan, S. Li, and H. Zhang, "Dynamic scheduling of mobile-robotic warehouse logistics system," in *Proc. 35th Chin. Control Conf. (CCC)*, Jul. 2016, pp. 2860–2865, doi: 10.1109/ChiCC.2016.7553799.

[39] M. Merschformann, L. Xie, and D. Erdmann, "Multi-agent path finding with kinematic constraints," in *Proc. 26th Int. Conf. Automated Planning Scheduling*, 2017, pp. 477–485.

[40] B. D. Noble and J. Flinn, "Wireless, self-organizing cyber-physical systems," in *Proc. NSF Workshop Cyber-Phys. Syst.*, Austin, TX, USA, 2006, pp. 1–3.

[41] F. Pasqualetti, F. Dorfler, and F. Bullo, "Attack detection and identification in cyber-physical systems," *IEEE Trans. Autom. Control*, vol. 58, no. 11, pp. 2715–2729, Nov. 2013, doi: 10.1109/TAC.2013.2266831.

[42] L. Wang, M. Törngren, and M. Onori, "Current status and advancement of cyber-physical systems in manufacturing," *J. Manuf. Syst.*, vol. 37, pp. 517–527, Oct. 2015, doi: 10.1016/j.jmsy.2015.04.008.

[43] E. A. Lee, "Cyber physical systems: Design challenges," in *Proc. 11th IEEE Int. Symp. Object Compon.-Oriented Real-Time Distrib. Comput. (ISORC)*, May 2008, pp. 363–369, doi: 10.1109/ISORC.2008.25.

[44] Y. Mo, "Cyber–physical security of a smart grid infrastructure," *Proc. IEEE*, vol. 100, no. 1, pp. 195–209, Jan. 2012, doi: 10.1109/JPROC.2011.2161428.

[45] J. Lee, B. Bagheri, and H.-A. Kao, "A cyber-physical systems architecture for industry 4.0-based manufacturing systems," *Manuf. Lett.*, vol. 3, pp. 18–23, Jan. 2015, doi: 10.1016/j.mfglet.2014.12.001.

[46] R. Rajkumar, I. Lee, L. Sha, and J. Stankovic, "Cyber-physical systems: The next computing revolution," in *Proc. 47th Design Autom. Conf. (DAC)*, 2010, pp. 731–736, doi: 10.1145/1837274.1837461.

[47] J. Lee, H.-A. Kao, and S. Yang, "Service innovation and smart analytics for industry 4.0 and big data environment," *Procedia CIRP*, vol. 16, pp. 3–8, 2014, doi: 10.1016/j.procir.2014.02.001.

[48] S. Poudel, Z. Ni, and N. Malla, "Real-time cyber physical system testbed for power system security and control," *Int. J. Electr. Power Energy Syst.*, vol. 90, pp. 124–133, Sep. 2017, doi: 10.1016/j.ijepes.2017.01.016.

[49] S. Ma, Y. Zhang, J. Lv, H. Yang, and J. Wu, "Energy-cyber-physical system enabled management for energy-intensive manufacturing industries," *J. Cleaner Prod.*, vol. 226, pp. 892–903, Jul. 2019, doi: 10.1016/j.jclepro.2019.04.134.

[50] C. Schulze, S. Thiede, B. Thiede, D. Kurle, S. Blume, and C. Herrmann, "Cooling tower management in manufacturing companies: A cyber-physical system approach," *J. Cleaner Prod.*, vol. 211, pp. 428–441, Feb. 2019, doi: 10.1016/j.jclepro.2018.11.184.

[51] X. T. R. Kong, R. Y. Zhong, Z. Zhao, S. Shao, M. Li, P. Lin, Y. Chen, W. Wu, L. Shen, Y. Yu, and G. Q. Huang, "Cyber physical ecommerce logistics system: An implementation case in hong kong," *Comput. Ind. Eng.*, vol. 139, Jan. 2020, Art. no. 106170, doi: 10.1016/j.cie.2019.106170.

[52] R. G. Lins, P. R. M. de Araujo, and M. Corazzim, "In-process machine vision monitoring of tool wear for cyber-physical production systems," *Robot. Comput.-Integr. Manuf.*, vol. 61, Feb. 2020, Art. no. 101859, doi: 10.1016/j.rcim.2019.101859.

[53] H. Liu and L. Wang, "Remote human–robot collaboration: A cyber–physical system application for hazard manufacturing environment," *J. Manuf. Syst.*, vol. 54, pp. 24–34, Jan. 2020, doi: 10.1016/j.jmsy.2019.11.001.

[54] F. Tao, Q. Qi, L. Wang, and A. Y. C. Nee, "Digital twins and cyber–physical systems toward smart manufacturing and Industry 4.0: Correlation and comparison," *Engineering*, vol. 5, no. 4, pp. 653–661, 2019, doi: 10.1016/j.eng.2019.01.014.

[55] Y. Liu, L. Wang, X. V. Wang, X. Xu, and P. Jiang, "Cloud manufacturing: Key issues and future perspectives," *Int. J. Comput. Integr. Manuf.*, vol. 32, no. 9, pp. 858–874, Sep. 2019, doi: 10.1080/0951192X.2019.1639217.

[56] J. Wan, D. Zhang, Y. Sun, K. Lin, C. Zou, and H. Cai, "VCMIA: A novel architecture for integrating vehicular cyber-physical systems and mobile cloud computing," *Mobile Netw. Appl.*, vol. 19, no. 2, pp. 153–160, Apr. 2014, doi: 10.1007/s11036-014-0499-6.

[57] M. Chen, Y. Zhang, Y. Li, S. Mao, and V. C. M. Leung, "EMC: Emotion-aware mobile cloud computing in 5G," *IEEE Netw.*, vol. 29, no. 2, pp. 32–38, Mar. 2015, doi: 10.1109/MNET.2015.7064900.

[58] L. Wang, R. Gao, and I. Ragai, "An integrated cyber-physical system for cloud manufacturing," in *Proc. ASME Int. Manuf. Sci. Eng.*, 2014, Art. no. V001T04A029.

[59] Z. Shu, J. Wan, D. Zhang, and D. Li, "Cloud-integrated cyber-physical systems for complex industrial applications," *Mobile Netw. Appl.*, vol. 21, no. 5, pp. 865–878, Oct. 2016, doi: 10.1007/s11036-015-0664-6.

[60] J. Wan, D. Zhang, S. Zhao, L. Yang, and J. Lloret, "Context-aware vehicular cyber-physical systems with cloud support: Architecture, challenges, and solutions," *IEEE Commun. Mag.*, vol. 52, no. 8, pp. 106–113, Aug. 2014, doi: 10.1109/MCOM.2014.6871677.

[61] P. Zheng, X. Xu, and C.-H. Chen, "A data-driven cyber-physical approach for personalised smart, connected product co-development in a cloud-based environment," *J. Intell. Manuf.*, vol. 31, no. 1, pp. 3–18, Jan. 2020, doi: 10.1007/s10845-018-1430-y.

[62] N. Wu and M. Zhou, "Shortest routing of bidirectional automated guided vehicles avoiding deadlock and blocking," *IEEE/ASME Trans. Mechatronics*, vol. 12, no. 1, pp. 63–72, Feb. 2007, doi: 10.1109/TMECH.2006.886255.

[63] K. C. T. Vivaldini, J. P. M. Galdames, T. S. Bueno, R. C. Araujo, R. M. Sobral, M. Becker, and G. A. P. Caurin, "Robotic forklifts for intelligent warehouses: Routing, path planning, and auto-localization," in *Proc. IEEE Int. Conf. Ind. Technol.*, Mar. 2010, pp. 1463–1468, doi: 10.1109/ICIT.2010.5472487.

[64] S. A. Reveliotis, "Conflict resolution in AGV systems," *IIE Trans.*, vol. 32, no. 7, pp. 647–659, 2000, doi: 10.1023/A:1007663100796.

[65] M. Saidi-Mehrabad, S. Dehnavi-Arani, F. Evazabadian, and V. Mahmoodian, "An ant colony algorithm (ACA) for solving the new integrated model of job shop scheduling and conflict-free routing of AGVs," *Comput. Ind. Eng.*, vol. 86, pp. 2–13, Aug. 2015, doi: 10.1016/j.cie.2015.01.003.

[66] S. Boschert and R. Rosen, "Digital twin—The simulation aspect," in *Mechatronic Futures: Challenges and Solutions for Mechatronic Systems and their Designers*, P. Hehenberger and D. Bradley Eds. Cham, Switzerland: Springer, 2016, pp. 59–74.

[67] F. Tao, J. Cheng, Q. Qi, M. Zhang, H. Zhang, and F. Sui, "Digital twin-driven product design, manufacturing and service with big data," *Int. J. Adv. Manuf. Technol.*, vol. 94, nos. 9–12, pp. 3563–3576, Feb. 2018, doi: 10.1007/s00170-017-0233-1.

[68] M. Grieves and J. Vickers, "Digital twin: Mitigating unpredictable, undesirable emergent behavior in complex systems," in *Transdisciplinary Perspectives on Complex Systems: New Findings and Approaches*, F.-J. Kahlen, S. Flumerfelt, and A. Alves Eds. Cham, Switzerland: Springer, 2017, pp. 85–113.

[69] E. Glaessgen and D. Stargel, "The digital twin paradigm for future NASA and US Air Force vehicles," in *Proc. 53rd AIAA/ASME/ASCE/AHS/ASC Struct., Struct. Dyn. Mater. Conf., (Struct., Struct. Dyn., Mater. Co-located Conf., Amer. Inst. Aeronaut.Astronaut.*, 2012, p. 1818.

[70] T. Bangemann, "State of the art in industrial automation," in *Industrial Cloud-Based Cyber-Physical Systems: The IMC-AESOP Approach*, A. W. Colombo Ed. Cham, Switzerland: Springer, 2014, pp. 23–47.

[71] K. Nagorny, A. W. Colombo, and U. Schmidtmann, "A service-and multi-agent-oriented manufacturing automation architecture: An IEC 62264 level 2 compliant implementation," *Comput. Ind.*, vol. 63, no. 8, pp. 813–823, 2012, doi: 10.1016/j.compind.2012.08.003.

[72] J. Delsing, F. Rosenqvist, O. Carlsson, A. W. Colombo, and T. Bangemann, "Migration of industrial process control systems into service oriented architecture," in *Proc. 38th Annu. Conf. IEEE Ind. Electron. Soc. (IECON)*, Oct. 2012, pp. 5786–5792, doi: 10.1109/IECON.2012.6389039.

[73] A. Mazak and C. Huemer, "From business functions to control functions: Transforming REA to ISA-95," in *Proc. IEEE 17th Conf. Bus. Informat.*, Jul. 2015, pp. 33–42, doi: 10.1109/CBI.2015.50.

[74] R. Cupek, A. Ziebinski, L. Huczala, and H. Erdogan, "Agent-based manufacturing execution systems for short-series production scheduling," *Comput. Ind.*, vol. 82, pp. 245–258, Oct. 2016, doi: 10.1016/j.compind.2016.07.009.

[75] D. B. Rawat, J. J. Rodrigues, and I. Stojmenovic, *Cyber-Physical Systems: From Theory to Practice*. Boca Raton, FL, USA: CRC Press, 2015.

[76] W. Shi, J. Cao, Q. Zhang, Y. Li, and L. Xu, "Edge computing: Vision and challenges," *IEEE Internet Things J.*, vol. 3, no. 5, pp. 637–646, Oct. 2016, doi: 10.1109/JIOT.2016.2579198.

[77] Y. Mao, C. You, J. Zhang, K. Huang, and K. B. Letaief, "A survey on mobile edge computing: The communication perspective," *IEEE Commun. Surveys Tuts.*, vol. 19, no. 4, pp. 2322–2358, 4th Quart., 2017, doi: 10.1109/COMST.2017.2745201.

[78] B. Chen, J. Wan, L. Shu, P. Li, M. Mukherjee, and B. Yin, "Smart factory of industry 4.0: Key technologies, application case, and challenges," *IEEE Access*, vol. 6, pp. 6505–6519, 2018, doi: 10.1109/ACCESS.2017.2783682.

[79] W. Shi and S. Dustdar, "The promise of edge computing," *Computer*, vol. 49, no. 5, pp. 78–81, May 2016, doi: 10.1109/MC.2016.145.

[80] P. Mach and Z. Becvar, "Mobile edge computing: A survey on architecture and computation offloading," *IEEE Commun. Surveys Tuts.*, vol. 19, no. 3, pp. 1628–1656, 3rd Quart., 2017, doi: 10.1109/COMST.2017.2682318.

[81] M. Satyanarayanan, "The emergence of edge computing," *Computer*, vol. 50, no. 1, pp. 30–39, Jan. 2017, doi: 10.1109/MC.2017.9.

[82] D. Georgakopoulos, P. P. Jayaraman, M. Fazia, M. Villari, and R. Ranjan, "Internet of Things and edge cloud computing roadmap for manufacturing," *IEEE Cloud Comput.*, vol. 3, no. 4, pp. 66–73, Jul. 2016, doi: 10.1109/MCC.2016.91.

[83] I. F. Akyildiz, W. Su, Y. Sankarasubramaniam, and E. Cayirci, "A survey on sensor networks," *IEEE Commun. Mag.*, vol. 40, no. 8, pp. 102–114, Aug. 2002, doi: 10.1109/MCOM.2002.1024422.

[84] J. Yick, B. Mukherjee, and D. Ghosal, "Wireless sensor network survey," *Comput. Netw.*, vol. 52, no. 12, pp. 2292–2330, Aug. 2008, doi: 10.1016/j.comnet.2008.04.002.

[85] I. F. Akyildiz, W. Su, Y. Sankarasubramaniam, and E. Cayirci, "Wireless sensor networks: A survey," *Comput. Netw.*, vol. 38, no. 4, pp. 393–422, 2002, doi: 10.1016/S1389-1286(01)00302-4.

[86] I. F. Akyildiz, X. Wang, and W. Wang, "Wireless mesh networks: A survey," *Comput. Netw.*, vol. 47, no. 4, pp. 445–487, Mar. 2005, doi: 10.1016/j.comnet.2004.12.001.

[87] G. J. Pottie and W. J. Kaiser, "Wireless integrated network sensors," *Commun. ACM*, vol. 43, no. 5, pp. 51–58, May 2000, doi: 10.1145/332833.332838.

[88] A. Perrig, R. Szewczyk, J. D. Tygar, V. Wen, and D. E. Culler, "SPINS: Security protocols for sensor networks," *Wireless Netw.*, vol. 8, no. 5, pp. 521–534, 2002, doi: 10.1023/A:1016598314198.

[89] C.-Y. Chong and S. P. Kumar, "Sensor networks: Evolution, opportunities, and challenges," *Proc. IEEE*, vol. 91, no. 8, pp. 1247–1256, Aug. 2003, doi: 10.1109/JPROC.2003.814918.

[90] J. N. Al-Karaki and A. E. Kamal, "Routing techniques in wireless sensor networks: A survey," *IEEE Wireless Commun.*, vol. 11, no. 6, pp. 6–28, Dec. 2004, doi: 10.1109/MWC.2004.1368893.

[91] G. Anastasi, M. Conti, M. Di Francesco, and A. Passarella, "Energy conservation in wireless sensor networks: A survey," *Ad Hoc Netw.*, vol. 7, no. 3, pp. 537–568, May 2009, doi: 10.1016/j.adhoc.2008.06.003.

[92] N. Naik, "Choice of effective messaging protocols for IoT systems: MQTT, CoAP, AMQP and HTTP," in *Proc. IEEE Int. Syst. Eng. Symp. (ISSE)*, Oct. 2017, pp. 1–7, doi: 10.1109/SysEng.2017.8088251.

[93] D. Zissis and D. Lekkas, "Addressing cloud computing security issues," *Future Gener. Comput. Syst.*, vol. 28, no. 3, pp. 583–592, Mar. 2012, doi: 10.1016/j.future.2010.12.006.

[94] G. Reese, *Cloud Application Architectures: Building Applications and Infrastructure in the Cloud*. Newton, MA, USA: O'Reilly Media, 2009.

[95] S. Subashini and V. Kavitha, "A survey on security issues in service delivery models of cloud computing," *J. Netw. Comput. Appl.*, vol. 34, no. 1, pp. 1–11, Jan. 2011, doi: 10.1016/j.jnca.2010.07.006.

[96] M. Almorsy, J. Grundy, and I. Müller, *An Analysis of the Cloud Computing Security Problem*. 2010.

[97] Q. Qi and F. Tao, "Digital twin and big data towards smart manufacturing and industry 4.0: 360 Degree comparison," *IEEE Access*, vol. 6, pp. 3585–3593, 2018, doi: 10.1109/ACCESS.2018.2793265.

[98] K. Y. H. Lim, P. Zheng, and C.-H. Chen, "A state-of-the-art survey of Digital Twin: Techniques, engineering product lifecycle management and business innovation perspectives," *J. Intell. Manuf.*, to be published, doi: 10.1007/s10845-019-01512-w.

[99] J.-S. Song, "The effect of leadtime uncertainty in a simple stochastic inventory model," *Manage. Sci.*, vol. 40, no. 5, pp. 603–613, May 1994, doi: 10.1287/mnsc.40.5.603.

[100] Y. Kainuma and N. Tawara, "A multiple attribute utility theory approach to lean and green supply chain management," *Int. J. Prod. Econ.*, vol. 101, no. 1, pp. 99–108, May 2006, doi: 10.1016/j.ijpe.2005.05.010.

[101] S. Nahmias, "Simple approximations for a variety of dynamic leadtime lost-sales inventory models," *Oper. Res.*, vol. 27, no. 5, pp. 904–924, Oct. 1979, doi: 10.1287/opre.27.5.904.

[102] K. Inderfurth, "Simple optimal replenishment and disposal policies for a product recovery system with leadtimes," *Oper.-Res.-Spektrum*, vol. 19, no. 2, pp. 111–122, Jun. 1997, doi: 10.1007/BF01545510.

[103] G. T. M. Hult, D. J. Ketchen, and E. L. Nichols, "An examination of cultural competitiveness and order fulfillment cycle time within supply chains," *Acad. Manage. J.*, vol. 45, no. 3, pp. 577–586, Jun. 2002, doi: 10.5465/3069382.

[104] F. K. Pil and M. Holweg, "Linking product variety to order-fulfillment strategies," *Interfaces*, vol. 34, no. 5, pp. 394–403, 2004, doi: 10.1287/inte.1040.0092.

[105] J.-S. Song, S. H. Xu, and B. Liu, "Order-fulfillment performance measures in an Assemble-to-Order system with stochastic leadtimes," *Oper. Res.*, vol. 47, no. 1, pp. 131–149, Feb. 1999, doi: 10.1287/opre.47.1.131.

[106] J. Van Belle, P. Valckenaers, and D. Cattrysse, "Cross-docking: State of the art," *Omega*, vol. 40, no. 6, pp. 827–846, Dec. 2012, doi: 10.1016/j.omega.2012.01.005.

[107] U. M. Apte and S. Viswanathan, "Effective cross docking for improving distribution efficiencies," *Int. J. Logistics Res. Appl.*, vol. 3, no. 3, pp. 291–302, Nov. 2000, doi: 10.1080/713682769.

[108] W. Yu and P. J. Egbelu, "Scheduling of inbound and outbound trucks in cross docking systems with temporary storage," *Eur. J. Oper. Res.*, vol. 184, no. 1, pp. 377–396, Jan. 2008, doi: 10.1016/j.ejor.2006.10.047.

[109] K. K. H. Ng, M. H. M. Tang, and C. K. M. Lee, "Design and development of a performance evaluation system for the aircraft maintenance industry," in *Proc. IEEE Int. Conf. Ind. Eng. Eng. Manage. (IEEM)*, Dec. 2015, pp. 564–568, doi: 10.1109/IEEM.2015.7385710.

[110] H. Zhang, H. Luo, Z. Wang, Y. Liu, and Y. Liu, "Multi-robot cooperative task allocation with definite Path-Conflict-Free handling," *IEEE Access*, vol. 7, pp. 138495–138511, 2019, doi: 10.1109/ACCESS.2019.2942966.

[111] K. Jose and D. K. Pratihar, "Task allocation and collision-free path planning of centralized multi-robots system for industrial plant inspection using heuristic methods," *Robot. Auto. Syst.*, vol. 80, pp. 34–42, Jun. 2016, doi: 10.1016/j.robot.2016.02.003.

[112] Y. Chen and H. Hu, "Internet of intelligent things and robot as a service," *Simul. Model. Pract. Theory*, vol. 34, pp. 159–171, May 2013, doi: 10.1016/j.simpat.2012.03.006.

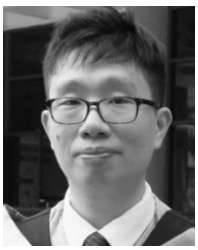
[113] K. K. H. Ng, C. K. M. Lee, S. Z. Zhang, K. Wu, and W. Ho, "A multiple colonies artificial bee colony algorithm for a capacitated vehicle routing problem and re-routing strategies under time-dependent traffic congestion," *Comput. Ind. Eng.*, vol. 109, pp. 151–168, Jul. 2017, doi: 10.1016/j.cie.2017.05.004.

[114] K. K. H. Ng, C. K. M. Lee, F. T. S. Chan, and Y. Lv, "Review on meta-heuristics approaches for airside operation research," *Appl. Soft Comput.*, vol. 66, pp. 104–133, May 2018, doi: 10.1016/j.asoc.2018.02.013.

[115] K. K. H. Ng, C. K. M. Lee, F. T. S. Chan, and Y. Qin, "Robust aircraft sequencing and scheduling problem with arrival/departure delay using the min-max regret approach," *Transp. Res. E, Logistics Transp. Rev.*, vol. 106, pp. 115–136, Oct. 2017, doi: 10.1016/j.tre.2017.08.006.

[116] K. K. H. Ng, C. K. M. Lee, F. T. S. Chan, C.-H. Chen, and Y. Qin, "A two-stage robust optimisation for terminal traffic flow problem," *Appl. Soft Comput.*, vol. 89, Apr. 2020, Art. no. 106048, doi: 10.1016/j.asoc.2019.106048.

[117] A. Rymaszewska, P. Helo, and A. Gunasekaran, "IoT powered servitization of manufacturing–an exploratory case study," *Int. J. Prod. Econ.*, vol. 192, pp. 92–105, Oct. 2017, doi: 10.1016/j.ijpe.2017.02.016.



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