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RESEARCH ARTICLE

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Towards a next-generation production system for industrial robots: A CPS-based hybrid architecture for smart assembly shop floors with closed-loop dynamic cyber physical interactions

Abstract Given the multiple varieties and small batches, the production of industrial robots faces the ongoing challenges of flexibility, self-organization, self-configuration, and other "smart" requirements. Recently, cyber physical systems have provided a promising solution for the requirements mentioned above. Despite recent progress, some critical issues have not been fully addressed at the shop floor level, including dynamic reorganization and reconfiguration, ubiquitous networking, and time constrained computing. Toward the next generation production system for industrial robots, this study proposed a hybrid architecture for smart assembly shop floors with closed-loop dynamic cyber physical interactions. Aiming for dynamic reorganization and reconfiguration, the study also proposed modularized smart assembly units for the deployment of physical assembly processes. Enabling technologies, such as multiagent system (MAS), self-organized wireless sensor actuator networks, and edge computing, were discussed and then integrated into the proposed architecture. Furthermore, a multijoint robot assembly process was selected as a target scenario. Thus, an MAS was developed to simulate the coordination and negotiation mechanisms for the proposed architecture on the basis of the Java Agent Development Framework platform.

Keywords cyber physical system, robot assembly, multiagent system, architecture

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1 Introduction

Industrial robots that carry out automatic carrying, welding, spaying, and assembly functions are becoming remarkably important nowadays in manufacturing industries. In recent years, the demands of industrial robots have increased rapidly due to Industry 4.0-oriented renovation investments. Moreover, the industrial robot applications have ranged from the automobile industry to almost all manufacturing domains. Recently, the International Federation of Robotics has estimated that more than 1.7 million new industrial robots will be deployed in factories worldwide by 2020, with an average annual growth rate of 14% between years 2018 and 2020 [1].

Industrial robots are complex mechanical and electronic products. Generally, a typical industrial robot is composed of 4 to 6 joints and arms, recreational vehicle or harmonic gears, servo motors, sensors, other mechanical components, and electrical accessories. Traditionally, given the process complexities and precision requirements, assembling such devices mainly relies on manual operations. However, the manual assembly mode constrains the efficiency and quality consistency of final products. As the demand grows, several leading robots companies have lately introduced automatic assembly lines into robot production, which are characterized as "manufacturing robots by robots". Although automatic assembly lines will dramatically increase the output of robot production, the flexibility and adaptability issues are remained in the context of fluctuant demands, mass customization, and rapid product iterations. Furthermore, in small and medium enterprises, the automatic assembly paradigm is not economically applicable due to huge investment and low capacity utilization. Therefore, like other industries, novel assembly paradigms are desperately needed to cope with internal and external requirements.

For the past few years, the cyber physical system (CPS) has been immerged as a promising paradigm to address aforementioned issues in the manufacturing domain. CPS can be defined as a closed-looped system that integrates dynamic physical processes with communication, controlling, computing and other novel information technologies [2]. In the context of the manufacturing domain, CPS is a scalable concept ranging from field equipment to the supply chain system. Studies have claimed that CPS combined with the internet of things (IoT), cloud computing, and Big Data will enable “smart manufacturing” in the Industry 4.0 era. Several CPS-based architectures were presented for the implementation of smart manufacturing. An architecture with 5C levels for the CPS production systems was presented in Ref. [3], namely, connection, conversion, cyber, cognition, and configuration. Industrial network, cloud, supervisory control terminals, and smart objects could be integrated with Big Data analysis to construct a smart factory for Industry 4.0 [4]. In the shop floor field, interoperability among different devices is a type of issue that has respect to CPS architectures [5]. On the basis of micro service technology, a cyber physical framework was proposed with IoT resources as the “glue” for system integration and interoperability [6]. Despite recent progress to construct a flexible, scalable, and feasible shop floor CPS system, several critical problems remain to be elucidated from the perspective of architecture design. These problems range from dynamic reorganization and reconfiguration and ubiquitous networking to time constrained computing and controlling (Section 3).

The contribution of this research includes the following:

1) A hybrid architecture for smart assembly shop floor level is proposed, which is first introduced in industrial robots smart assembly. The integration and interoperation of enabling technologies within the architecture are studied.

2) The concept of smart assembly units (SAUs) is introduced to encapsulate the modularized physical process. Dynamic assembly processes are modelled and mapped in the cyberspace.

3) The implementation of the multiagent system (MAS) as the key enabling technology in architecture is further studied and discussed in the field of dynamic process planning and coordination.

This article is organized as follows. Section 2 presents the hybrid architecture for smart assembly shop floors with closed-loop dynamic cyber physical interactions. Section 3 discusses the key technologies and their interactions in the proposed architecture. Section 4 proposes a multijoint robot general assembly scenario to demonstrate the architecture. An MAS prototype is developed to simulate coordination and negotiation mechanisms on the basis of the Java Agent Development Framework (JADE) platform. Lastly, Section 5 concludes the research and discusses the future work.

2 Hybrid architecture for smart assembly shop floors with closed-loop dynamic cyber physical interactions

The shop floor assembly system is dynamically complex with machinery, equipment, robots, sensors, and human operators interacting in real time. In traditional tight-coupled shop floor assembly systems, such as automobile assembly lines, assembly resources, and procedures, are rigidly predefined which make building a centralized assembly architecture convenient. However, given that the centralized assembly system lacks dynamic reconfiguration, scalability, reorganization, and optimization abilities, it is less adaptable in the context of product orders fluctuations, supply chain disruptions, product type iterations, or equipment malfunctions.

Recent research has proposed that the introduction of the CPS will be able to deal with the aforementioned issues in the manufacturing domain. However, to model and analyze CPS-based manufacturing, noting that the CPS is not the simple union of physical and cyber worlds is important, but the real time intersection and interaction of both. Consequently, introducing the CPS will notably increase the degree of complexity where production management and control systems interoperate with physical entities on the basis of real time data acquiring, transferring, and computing [5]. Thus, the new CPS-based manufacturing architecture must accommodate such complexities. At the shop floor level, problems are much complicated as this level of manufacturing is critical for CPS implementation. Several implementation issues are listed as follows:

• Dynamic reorganization and reconfiguration. The reorganization of CPS-based assembly shop floors requires decentralized facilities and strategies supporting the plug and play functions, e.g., adding or removing an assembly equipment or station in real time. Moreover, the dynamic planning and scheduling of reorganized processes should be achieved accordingly, making the implementation in some centralized and hierarchical CPS architectures difficult.

• Ubiquitous sensing and communication network. The network, which has the ability to integrate heterogeneous legacy communication networks and software systems, serves as the “tube” connecting cyber and physical world. Ubiquitous sensing and data acquisition must be supported as fundamental functions. In addition, the topology of the network must be reconfigurable.

• Time constrained controlling and computing. Most assembly processes at the shop floor level are time- or latency-sensitive with controllers and actuators interacting in real time. Thus, controlling and computing these processes must be carried out timely. Cloud computing is regarded as a promising computing paradigm for data processing and storage in some CPS architectures. However, transferring all data to the cloud will occupy tremendous bandwidth and cause undesirably latency. As heterogeneous data are generating exponentially in the IoT era, cloud computing may not be sufficient for shop floor computing.

This paper proposes a novel CPS-based hybrid assembly shop floor architecture to address the aforementioned issues (Fig. 1). The main frame of the proposed architecture is based on the general concept of the CPS as the fusion of computing, communication, and control. Furthermore, toward the implementation concerns for shop floor assemblies, novel enabling technologies are integrated and interoperated within the architecture.

From the bottom to the top, the architecture comprises three layers, namely, physical interaction, field networking, and computing and controlling layers. In the physical interaction layer, assembly entities and processes are encapsulated by SAUs, which perform assembly activities along with heterogeneous networks and human machine interfaces (HMI). In the field-networking layer, wireless sensor actuator networks (WSANs) acquire data through heterogeneous networks and physical processes by multiple sensor and actuator nodes. Thereafter, the data are transferred to the computing and controlling layers where the MAS of shop floors can be constructed to simulate the physical process. Cloud computing together with edge computing (EC) resources provides timely computing and efficient storage services for the simulation, controlling, and optimization of assembly processes. The optimization results, such as process planning and scheduling instructions, are sent to the field for executing. Section 3 details the specifications and interactions of integrated technologies in the proposed architecture.

3 Key technologies and their interactions in the proposed architecture

3.1 SAUs for modularized physical assembly processes

In rigidly coupled assembly processes, such as automobile assembly lines, materials, energy, and information flows, are preconfigured in the design phase. However, when the production processes should be altered, the previous configuration must be reset to meet new requirements. Under this circumstance, changing the rigidly coupled

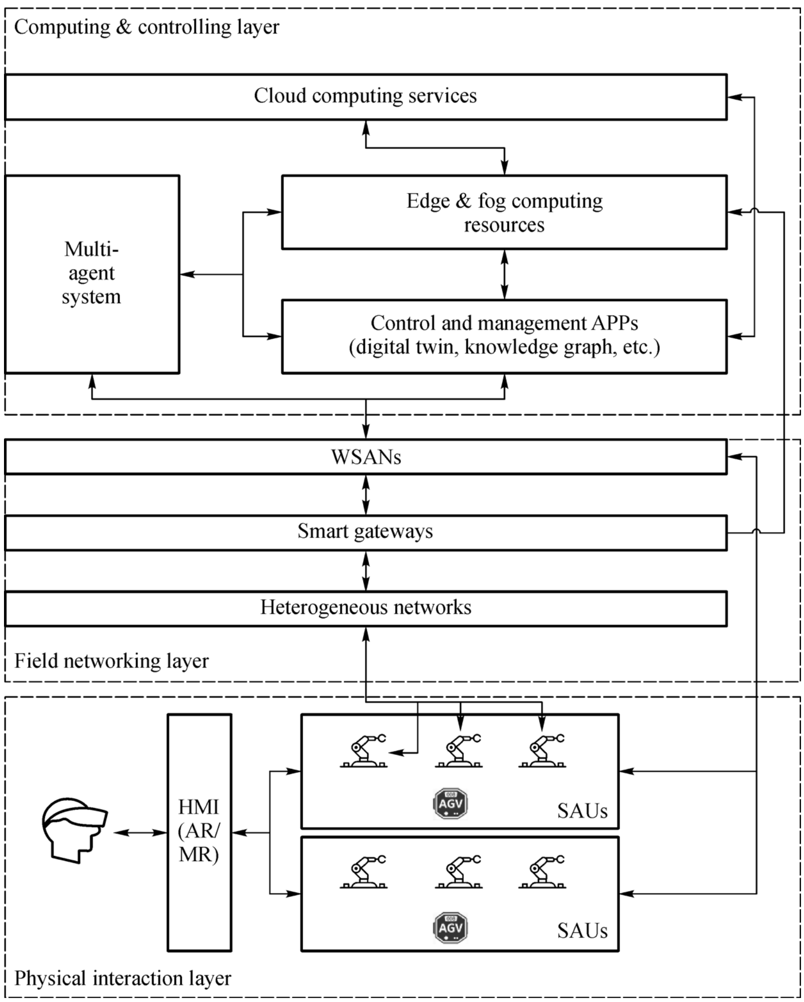

Fig. 1 Hybrid architecture of CPS based smart assembly shop floors.

processes will be inconvenient and cost considerable switching time. Therefore, dynamic modularity is a critical aspect to implement a reconfigurable assembly system in the CPS environment.

The concept of SAU is proposed in this research to achieve such modularity at the shop floor level. An SAU is a physical assembly workstation or cell, which encapsulates certain assembly functions with data acquiring and transferring abilities and corresponding interfaces. Figure 2 illustrates the prototype of SAUs. Assembly processes in shop floors can be decomposed into multiple SAUs. SAUs can be special purpose machines, robot workstations, or manual operating units. Each SAU encapsulates and performs certain assembly procedures, e.g., wielding components or connecting bolts. However, unlike traditional workstations, SAUs must have the capability of sensing its status and communicating with other entities bidirectionally through digital interfaces integrated within the SAUs. In addition, the plug and play functions are important the aspects of SAUs, in which field networks can identify and configure new SAUs automatically with minimal manual interventions.

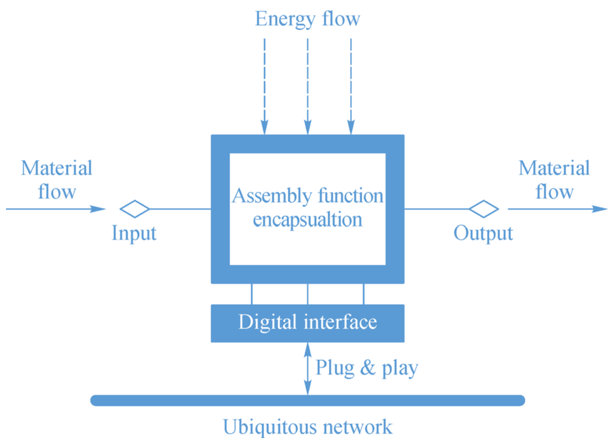

Fig. 2 Prototype of smart assembly unit (SAU).

By combining the different types of SAUs with specific functions, the overall assembly process and layout can be constructed. After that, material and information flows will be determined and configured. However, when the assembly process changes, SAUs should be reorganized accordingly, which further cause the alterations of previous material and information flows. In this case, a self-organized decentralized ubiquitous network is crucial to address such modularity and reconfigurability for SAUs and physical entities, such as automated guided vehicles (AGVs), which are applied to transport materials among them.

3.2 Self-organized WSAN for ubiquitous networking

In the proposed CPS architecture, the ubiquitous networking framework is integrated on the basis of WSANs. WSANs, derived from wireless sensor networks (WSNs), are wireless networks with several sensor nodes and executable actuator nodes. Similar to WSNs, WSANs often adopt multihop wireless mesh network topology, such as ZigBee with IEEE 802.15.4 protocol [7]. In a wireless mesh network, all nodes can send and receive signals to other nodes. When the nearest node is unable to communicate because of jammed traffics or malfunctions, data packets will be rerouted and hopped to other available nodes to guarantee the reliability of communication. Moreover, in the mesh topology, nodes can be added and removed in a self-organizing and self-configuration manner, which are suitable for build a scalable distributed network for the physical processes proposed previously.

In WSANs, sensors should choose optimal actuators to which the data shall be sent. Actuators can communicate with one another to exchange information [8]. In the presented architecture, actuator nodes in WSANs can be switches, machines, tools, radio frequency identifications, robots, or even humans. For example, assembly robots or SAUs in shop floors can be deployed as integrated sensor and actuator nodes in WSANs. AGVs, which transport materials between SAUs, act as another mobile hybrid nodes. These networked nodes communicate and collaborate with each other to perform certain assembly tasks. Material flow routes in shop floors can be reorganized and reconfigured according to process variations. Real-time process data, such as videos and images, acquired by sensors in WSANs with augmented reality (AR) or mixed reality (MR) technologies can be further rebuilt and mapped in virtual space. Therefore, humans as actuators can perform enhanced operations with the help of AR or MR. Information flows are routed through sensor nodes, actuator nodes, and hybrid nodes (with both sensing and actuating abilities) in WSANs as listed in Table 1.

Given that WSANs are distributed and self-organized when a new node is added, the network can automatically discover topology alterations and correspondingly reconfigure new multi-hop paths. Therefore, the material flows and information can be reconfigured to adapt physical process changes.

Table 1 Node types in WSANs

Node type	Functionality	Mobility	Routing mode	Instances
Sensor node	Sense	Yes	Multi-hop	Temperature/humidity sensors
Actuator node	Actuate	Yes	Multi-hop	Pneumatic actuators
Hybrid node	Both sense and actuate	Some yes	Multi-hop	SAUs/AGVs

3.3 Autonomous MAS for dynamic coordination and optimization

The reconfigurable, modularized SAUs with decentralized, self-organized WSANs presented above make material and information flows dynamically changeable. Therefore, modeling, planning, and scheduling such dynamically changing processes are critical to accomplish overall assembly tasks. The proposed architecture introduces MAS to deal with a such problem.

Recent studies have indicated that agents play an important role in the smart manufacturing domain that requires heterogeneous integration, reconfigurable architecture, timely communication, and system robustness [9–11]. In MAS, agents perform autonomous, cooperative, proactive, and adaptive actions with one another to solve dynamic problems [12]. The applications of an agent-based approach in shop floor level manufacturing range from the field control to process planning and scheduling [13–15]. Under these circumstances, agent technology is suitable for describing and modeling next generation manufacturing paradigm such as CPS [16].

MAS plays an important role in the proposed architecture. Not only can MAS be applied for the modeling, control, planning, and scheduling of physical manufacturing processes in the shop-floor manufacturing environment, but also effectively solve the dynamic interoperation issues between the physical and information spaces for practical CPS implementations. Therefore, the introduction of MAS brings several advantages. First, MAS is a feasible tool to model the intelligent system. In the proposed CPS architecture, physical entities and computing resources and control processes can be modelled and encapsulated as intelligent agents. Second, MAS realizes knowledge exchange and interpretation among heterogeneous systems. In the CPS environment, knowledge abstraction and application are difficult because heterogeneous processes and devices generate various information with domain-specific semantics. The representation and interpretation of semantics among heterogeneous systems is one core issue regarding physical and cyber interoperability. In MAS, heterogeneous domain specific knowledge can be represented by ontologies. Therefore, the exchange and interpretation of ontologies are possible with the agent communication mechanism. Last but not the least, agent coordination and negotiation mechanisms bring feasible approaches in the context of process planning and dynamic scheduling. Given that agents are proactive and autonomous, dynamic scheduling can be achieved under uncertain manufacturing environment, such as device anomalies. Several types of agents are defined and encapsulated in the proposed MAS:

- Physical agents. Physical agents encapsulate physical entities, such as robots, sensors, and equipment. The entire assembly processes are organized and modularized by SAUs with certain assembly functions; the SAU as a whole can be encapsulated as a physical agent.
- Coordination agents. Coordination agents are introduced as required to coordinate physical processes and physical-cyber interactions. Coordination agents serve as interfaces, which communicate, schedule, and coordinate physical and functional agents to fulfill the overall assembly processes.
- Functional agents. In the cyber level, functional agents are defined as applications (APPs), digital twin (DT), and EC agents. The DT agents are the digital models of physical objects and ongoing processes with dynamic data updating and knowledge evolving during their life cycles. The EC agents act as computing terminals that support timely data processing required in the field control. At last, service agents register these agents in the MAS. Figure 3 illustrates the framework of proposed MAS.

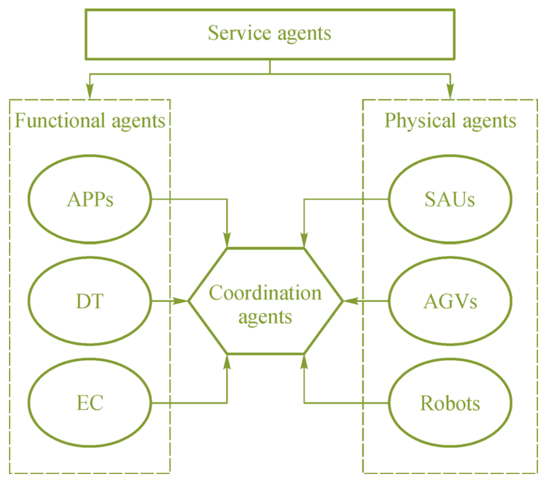

Fig. 3 MAS framework.

WSAN and EC play an important role in the proposed multiagent coordination process. One of the difficulties concerning the implementation of MAS is that processed data cannot be acquired completely and computed timely. In the proposed architecture, with ubiquitous networks, the required data should be able to communicate between agents. Moreover, the EC agents will facilitate and accelerate the planning and scheduling procedure, which makes the reconfiguration of the entire assembly process available in real-time scenarios. Section 4 further discusses the realizations of MAS.

3.4 Edge computing and its synergy with cloud computing

Cloud computing, which provides computing services from centralized clouds, becomes a feasible computing paradigm due to its convenience and huge economic benefit. Now, this paradigm is facing new challenges. As forecasted by Gartner, 20.4 billion devices will be connected to the IoT by 2020 [17]. Under this circumstance, transferring and processing all the data to the cloud will occupy tremendous bandwidth and cost much time. However, in shop floor level assembly applications, such as AR, the required response time is measured in milliseconds. Therefore, it is neither efficient nor economic by only relying on cloud computing paradigms and resources. Moreover, in some critical shop floor assembly processes, transferring all the data to the cloud may not be appropriate for privacy and security reasons.

The presented architecture introduces fog computing and EC as a complementary approach for the time constrained computing. EC, which emerged as a promising computing paradigm in the future IoT world, is now in its initial phase. The common definition of EC has not reached a consensus in the information and communication technology community. Literally, it means that the computing processes take place at the edge of network in close proximity to the physical devices or sensors where data are generated [18]. In the EC paradigm, data acquired from distributed networking devices are selected and processed near the physical assembly process in shop floors. The computing entities range from programmable logic controllers, smart terminals, and smart gateways to cloudlets. Given this physical proximity, compared with cloud computing, EC provides a lower jitter, lower latency, and narrower bandwidth alternative to process the data generated by mass devices and sensors.

Another cloud computing related concept is fog computing. Fog computing is defined as a system-level horizontal architecture that distributes resources and services of computing, storage, control, and networking anywhere along the continuum from cloud to things [19]. Fog computing has similarities to EC, as they both serve at the edge relative to cloud computing. However, compared with EC, fog computing highlights data processing, storage, and transferring mostly above the gateway level. While in EC, especially in the shop floor, computing processes are expected to be carried out by smart devices with fast processing speed and lower latency.

However, the perspective of this paper argues that cloud computing cannot be simply replaced by EC or fog computing in CPS-based smart shop floors. EC, fog computing, and cloud computing can reach a symbiosis in a proposed architecture by cooperating through optimizing workloads to achieve complicated and efficient business functions. For instance, in the collaborative model, the row data are filtered and analyzed on the edge at first, and further processed from fog to cloud services for optimized decisions. Consequently, results provide feedback to the edge to control and adjust the physical processes well.

4 Application in multijoint robot assembly shop floors

4.1 Application scenario description

In this research, a multijoint robot assembly shop floor of a Chinese medium-sized robot manufacturing enterprise is selected as a target scenario to discuss the introduction of the proposed architecture. Generally, the multijoint robot assembly process can be divided into four major steps: First, components are inspected and cleaned for preparation; second, main components, such as robot bases, arms, and gears, are assembled; third, motors, sensors, cables, and other electrical components are installed; lastly, the assembled product is inspected and calibrated before delivery. Figure 4 illustrates the main assembly process of multijoint robots.

Among the four major steps of general assembly process, the mechanical component assembly (MCA) process is crucial for the accuracy and consistency of robots. The arm assembly in MCA is selected for architecture discussion in this research to simplify the procedure. The proposed architecture is introduced for a prototype of smart shop floors for arm assembly. Figure 5 presents the simulation layout of arm assembly in the shop floor.

In Fig. 5, three SAUs with different configurations and capabilities are encapsulated. Each SAU can perform arm assembly process individually. An AGV is responsible for

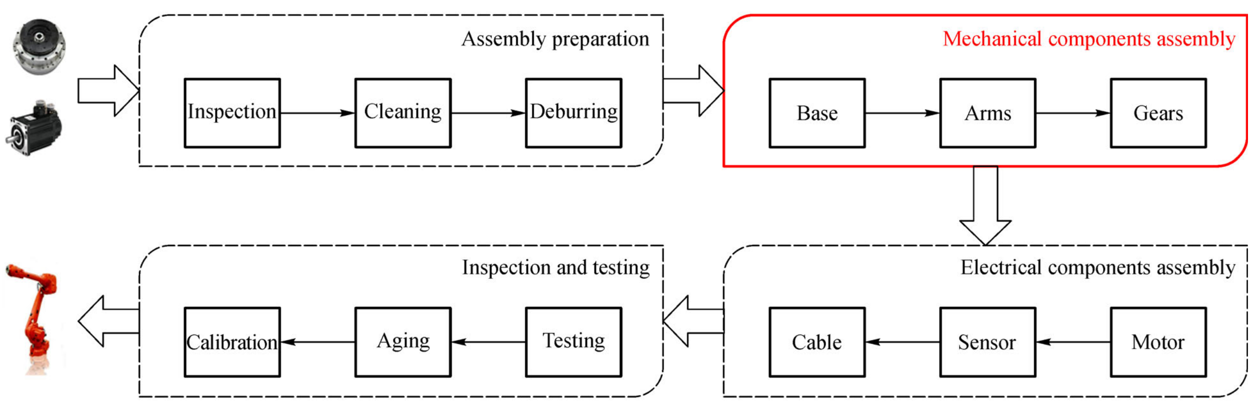

Fig. 4 Main assembly process of multijoint robots.

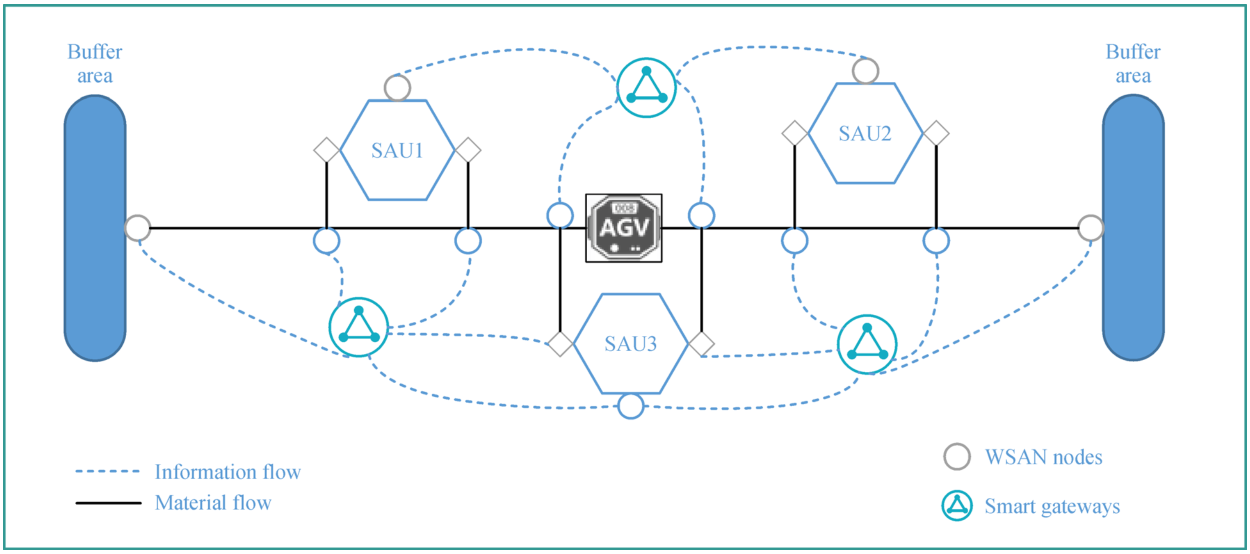

Fig. 5 Simulation layout of arm component assembly shop floors.

material transportation for all SAUs. The WSAN with multiple sensors nodes are deployed correspondingly where ubiquitous production data can be acquired, transferred, and exchanged through scalable communication facilities. Distributed EC resources are configured to support time-constrained computing. MAS is constructed and applied to simulate, schedule, control, and optimize the dynamic assembly process.

4.2 Simulation on dynamic reorganization and coordination

In this research, the proposed prototype is simulated by the JADE platform and Eclipse integrated development environment to discuss the reorganization and coordination characteristics of the constructed architecture. A JADE-based system can be distributed across heterogeneous terminals, which makes it suitable for the ubiquitous networking and distributed computing paradigm proposed in this article. Agents are encapsulated in java classes with deferent behaviors in JADE, which can simulate the heterogeneous features of entities in the presented prototype system. The distributed communication framework between agents in JADE are realized by the agent communication channel (ACC) with agent communication language (ACL)-based messages as illustrated in Fig. 6.

In the proposed architecture, physical agents are smart entities with the ability to provide awareness on their status dynamically. Therefore, on the basis of the communication framework in Fig. 6, two types of dynamic reorganization mechanism for arm assembly coordination are presented:

• Global planning mechanism (GPM). When the new order arrives or the current order changes, the planning and scheduling (PS) agent transforms the processed information, producing patches and series into new assembly plans. These plans were calculated by the support of EC agent and are further assigned to the MCA agents with process data, timelines, and material requirements. The MCA agents communicate and coordinate with the SAU

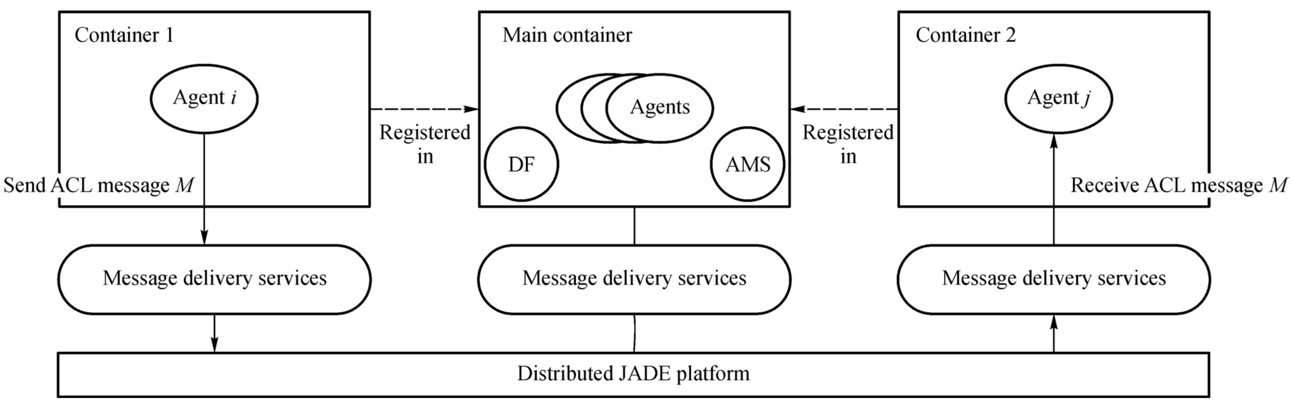

Fig. 6 ACL message communication between physical agents in distributed JADE. DF: Directory facilitator; AMS: Agent management system.

and AGV agents on the basis of bidding algorithms by the EC agents. The winning agent signs the contract with the MCA agents and dispatches the AGV agents for material transportation. When the assembly task is finished, status information will be updated to the upper PS agents. Figure 7 illustrates the sequence diagram of the GPM.

• Local negotiation mechanism (LNM). In the case of equipment malfunctions in the SAU, the corresponding SAU agent will communicate with the available SAU agents nearby to initiate negotiation with the ongoing assembly process (Fig. 8). If the nearby SAU agent is selected, then unfinished assembly missions will be transformed from negotiation initiator to the receiver. The bidding and contracting approaches of LNM are similar to GPM. Without transferring data to the upper coordination agents, the LNM simplifies the coordination process and reduces the communication time cost. However, given the resource constraints, such negotiation may not be successful. Under this circumstance, the MCA agents will coordinate with the PS agents to start another GPM procedure.

In GPM and LNM mechanisms, EC plays an important role for time constrained computing in dynamic process scheduling. EC resources are encapsulated and modeled as the EC agents and do not only store task status and requirements for process scheduling but also carry out computing processes. Thereafter, results are sent to related physical agents for low latency field control.

A simple dynamic shortest time-consuming (DST) rule-based bidding method and algorithm are presented to test the availability of proposed approaches on dynamic communication, coordination, and computing. The application of DST in the proposed scenario is as follows: In real-time t, an arbitrary assembly task s is assigned among available SAU_s. The objective of DST algorithm is to select the shortest time-consuming SAU for task s. Let SAU_i be the ith SAU available for task assignment, and $T_s(i)$ be the total execution time of SAU_i for the assembly task s. Thereafter, SAU_i is selected to execute task s only if its total execution time $T_s(i)$ is the shortest, that is

$$T_s(i) = \min\{T_s(1), T_s(2), ..., T_s(n)\}. \tag{1}$$

In the proposed application scenario, total execution time $T_s(i)$ is relevant to the waiting time, transportation time, and processing time of SAU_i for task s. Therefore, $T_s(i)$ can be calculated by Eq. (2):

$$T_s = T_s^{c}(i) + T_s^{w}(i) + \cdots + T_s^{p}(i), \tag{2}$$

where $T_s^{c}(i)$ is the time for the AGV agents to access and carry the work piece to SAU_i, $T_s^{w}(i)$ is the waiting time for $SAU(i)$, and $T_s^{p}(i)$ is the processing time of the current workpiece in SAU_i.

Assuming that: 1) All physical agents have enough buffer spaces; 2) work piece loading and unloading time are negligible. On the basis of these assumptions, $T_s^{w}(i)$

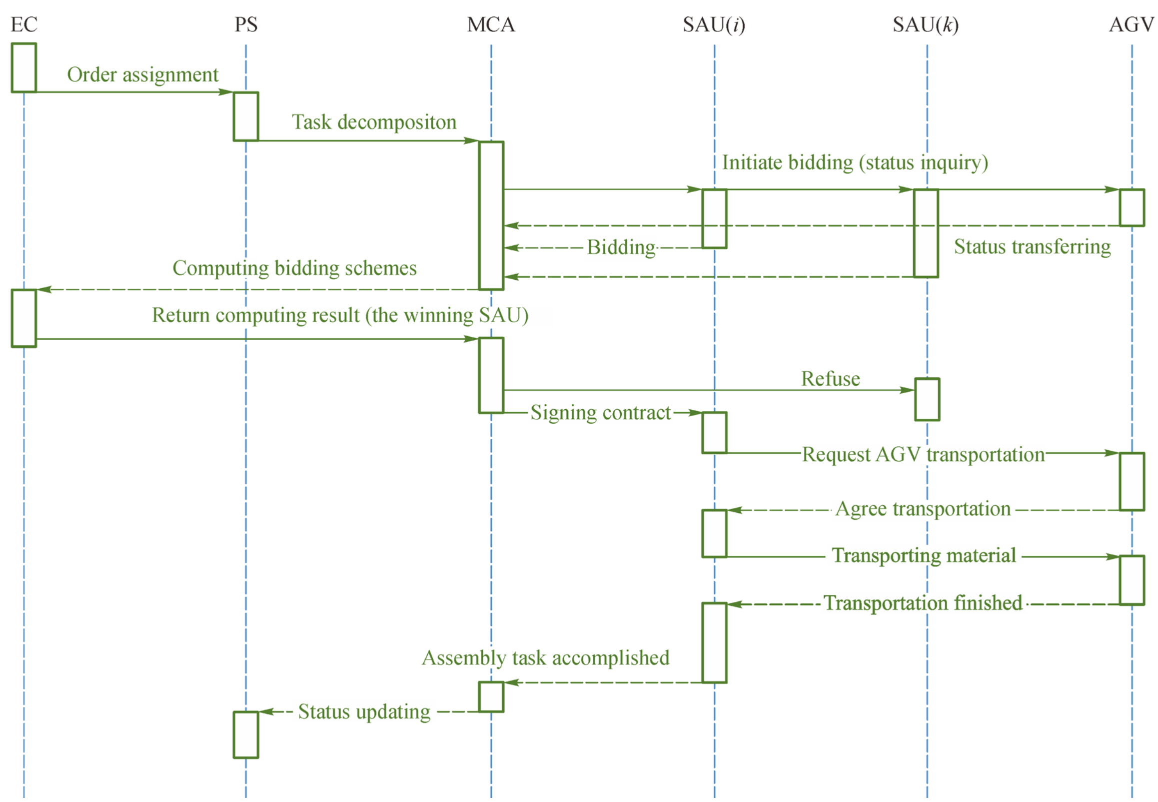

Fig. 7 Communication sequence diagram of GPM.

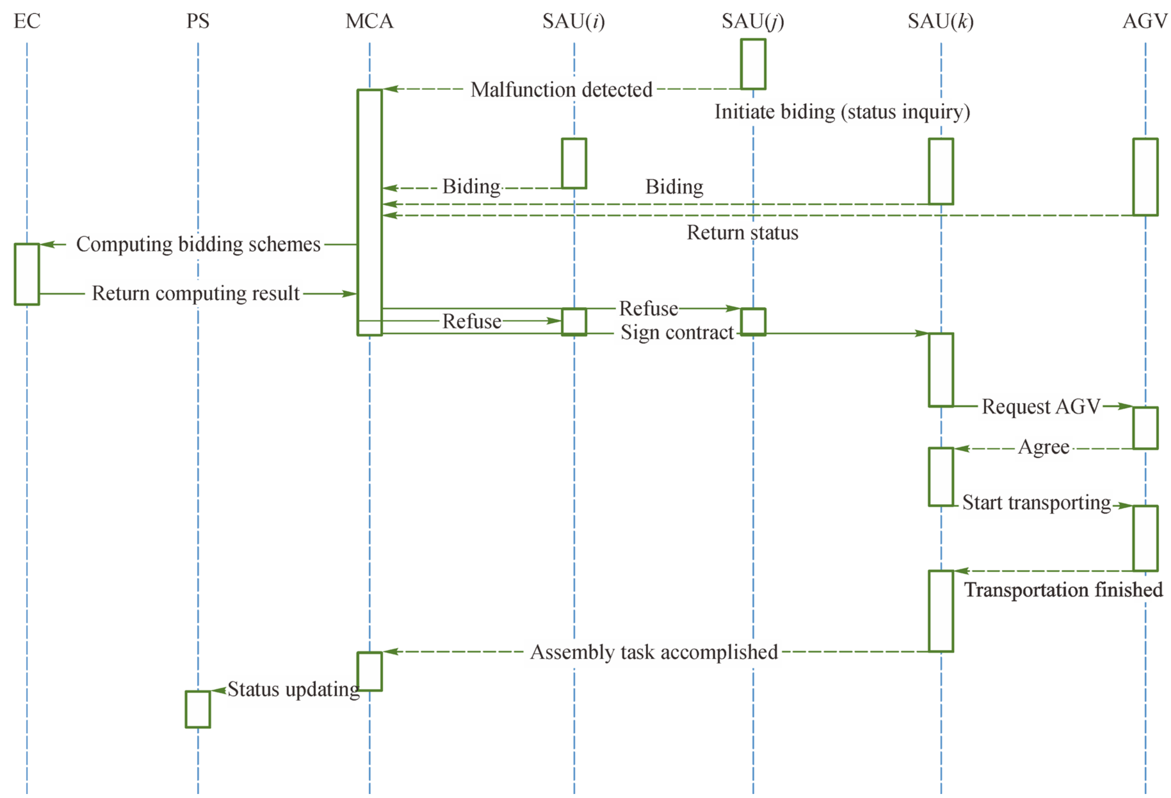

Fig. 8 Communication sequence diagram of LNM.

and $T_s^{\mathrm{p}}(i)$ in Eq. (2) can be acquired by the inner task status information of the corresponding SAU agents, while $T_s^{\mathrm{c}}(i)$ is related to the location and speed of AGV, which can be further calculated by Eq. (3):

$$T_s^{\mathrm{c}}(i) = \frac{d(i)}{s_{\mathrm{a}}}, \tag{3}$$

where $d(i)$ is the transportation route distance between AGV and $SAU(i)$, and s_{a} is the average speed of AGV.

On the basis of the DST algorithm, the best SAU_i with minimum T_s can be determined by Eqs. (1)–(3). The DST algorithm considers resource availability, spatial distance, queuing status, and processing capability. Therefore, it is a comprehensive but easy-to-use algorithm to demonstrate real-time dynamic scheduling in this application. On the basis of the proposed DST algorithm and the sequence diagram of agent coordination mechanism presented above, the encapsulation of agents is defined in Table 2.

Table 2 Agent descriptions

Agent name	Encapsulation entity	Type
MCA	Mechanical components assembly	Coordination agent
SAU1	No. 1 SAU for arm assembly	Physical agent
SAU2	No. 2 SAU for arm assembly	Physical agent
SAU3	No. 3 SAU for gear assembly	Physical agent
AGV	AGV for transportation	Physical agent

The parameters of agents, such as $T_s^{\mathrm{w}}(i)$ and $T_s^{\mathrm{p}}(i)$, are predefined as dynamic random values to simulate the real dynamic assembly process. When the MCA agents receive the coordination running signal, they communicate with SAUs and AGV to acquire their status data. After computing, the best SAU agent is contracted and informed. Thereafter, the chosen SAU agent negotiates with the AGV agents for transporting services. Table 3 shows the parameters regarding DST algorithm application in random time t_a and t_b. Parameters are defined in Eqs. (1)–(3).

On the basis of the DST algorithm, the coordination results in t_a and t_b are listed in Table 4.

Table 3 Parameters in random time t_a and t_b

Random time	s_{a} /(m·min^{-1})	$d(1)$ /m	$T_s^{\mathrm{c}}(1)$ /min	$T_s^{\mathrm{p}}(1)$ /min	$T_s^{\mathrm{w}}(1)$ /min	$d(2)$ /m	$T_s^{\mathrm{c}}(2)$ /min	$T_s^{\mathrm{p}}(2)$ /min	$T_s^{\mathrm{w}}(2)$ /min	$d(3)$ /m	$T_s^{\mathrm{c}}(3)$ /min	$T_s^{\mathrm{p}}(3)$ /min	$T_s^{\mathrm{w}}(3)$ /min
t_a	20	20	1	4	5	40	2	6	8	60	3	5	1
t_b	20	20	1	4	1	0	0	6	2	20	1	5	2

Table 4 Coordination results in t_a and t_b

Random time	$T_s(1)$/min	$T_s(2)$/min	$T_s(3)$/min	min(T_s)/min	Contracted SAU
t_a	10	16	9	9	SAU3
t_b	6	8	8	6	SAU1

The simulation results in the JADE platform are consistent with the calculation results, which verify the feasibility of the proposed method and prove that the agent-based scheduling approach is applicable in the CPS architecture. However, as we emphasize the design and description of the proposed architecture in this paper, complex agent-based scheduling algorithms with detailed abstractions are not covered. Furthermore, in the context of the communication latency between agents in the distributed containers with heterogeneous networks are not negligible, which need to be studied in the future.

5 Conclusions and future work

A novel architecture for smart assembly shop floors with closed-loop dynamic cyber-physical interactions toward the next generation assembly system for industrial robots is proposed in this paper. The integration of enabling technologies, including the MAS, WSANs, and EC agents, are discussed in the proposed architecture. Aiming at the dynamic reorganization and reconfiguration, the concept of SAU is presented to model assembly processes. Physical entities including SAUs are connected and communicated by self-organized WSANs. Finally, a multijoint robot assembly application is selected to discuss the implementation of the proposed CPS architecture. A multiagent based dynamic process planning and coordination are established for reorganization at the computational level by the JADE platform.

Compared with the existing general CPS framework, the presented architecture gives an implementation-oriented perspective of CPS architecture at the shop floor level that takes time constrains, dynamic reorganization, and reconfiguration issues into consideration. Therefore, the proposed architecture shows improved characteristics: 1) The reconfiguration and reorganization capabilities of physical assembly processes can be achieved with the introductions of SAUs; 2) heterogeneous field networks in the shop floor can be integrated with WSANs by smart gateways to enable ubiquitous networking; and 3) MAS in the computing and controlling layer supported by EC resources provides timely dynamic modeling and coordination abilities to enhance the real-time controlling performances.

The proposed hybrid architecture can be applied not only in the industrial robot assembly process, but also in other discrete manufacturing systems. Several issues must still be studied in the future work, including the integration and implementation of EC and cloud computing with WSANs, the development ontology framework of the shop floor assembly process, and enhanced algorithms such as reinforced learning for complex multiagent PS to improve the performances of the architecture and facilitate industrial implementation.

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Competing interests The authors have declared that no competing interests exist.

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