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An IoT-Based Cyber-Physical Framework for Turbine Assembly Systems

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ABSTRACT Turbines are typical engineering-to-order products which can be highly customized. This paper considers the final assembly control under uncertainty in turbine assembly workstations. A cyber-physical framework based on Internet of Things (IoT) is proposed for the turbine assembly, which consists of physical components, cyber components and an IoT-based monitoring system. The IoT-based monitoring modules capture real-time data of the physical components, including the workers, tools, parts and the actual assembly process. These cyber modules can generate the original scheduling for the assembly tasks, re-sequence the assembly tasks, re-assign the workers and control the logistics when an unexpected event occurs. Physical activities are undertaken in a turbine assembly workstation based on assembly instructions and guidance from the cyber components. The proposed framework can be implemented in the large turbine assembly system, which can facilitate real-time information driven assembly process monitoring and collaborative control of the task sequence, the worker assignments and logistics in a closed-loop environment. The experimental results show that our method can significantly improve the quality and the efficiency of a turbine assembly system.

INDEX TERMS Internet of Things, cyber-physical systems, engineering-to-order, production control, assembly process.

I. INTRODUCTION

With the rapid development of new information and communication technologies, such as cyber-physical systems (CPS), Internet-of-Things (IoT) and cloud computing, advanced manufacturing is undergoing a revolution, which is referred to as the fourth industrial revolution or Industry 4.0. A CPS can be described as a system of collaborating computational elements that can control physical entities to enhance manufacturing in cyber-physical production systems for process automation and control [1]–[3]. An IoT emphasizes the interconnection and information exchange between distributed cyber and physical components using a wireless network and sensing identification of the physical entities, in which cyber components interact, interface and integrated seamlessly with the physical world of sensors and things [4], [5]. Physical entities are the ‘‘things’’ referred to in the term ‘‘IoT’’ which can collaborate with similar entities across the Internet. IoT alongside CPS can provide support to handle assembly system complexity, increase information visibility and improve production performance [6], [7].

In this paper, an IoT-based cyber-physical framework is proposed which is used in the final assembly of a turbine with a value of hundreds of million RMBs, which is a typical engineering-to-order (ETO) product. ETO products are manufactured and assembled at a low volume to satisfy individual customer specifications, allowing companies to position themselves to respond to rapid market shifts through the production of one-of-a-kind products [8]. Since these products are often used in large projects, it is not unusual for their customers to impose large cost penalties for any delays [9], [10]. Thus, the final assembly process control of the ETO product is important to ensure that the manufacturing company can deliver the product by the due date as per their customer contract. Since ETO environments require a high level of customization and long flow times, the production

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plans often need to be defined before information on product customizations and detailed production activities are completely disclosed. There can be some level of uncertainty in executing assembly processes, for example, assembly process modifications, equipment failures, quality problems and delivery delays of parts and sub-assembly components, which can cause unavoidable delays in the existing assembly schedule [11], [12]. Therefore, substantial deviations from the original schedule may occur over the course of its execution and the existing schedule may need to be modified for unanticipated disruptions, which is generally referred to as rescheduling or dynamic scheduling [13].

ETO production planning and scheduling have already been previously addressed in the literature [14]–[16]. However, only a few approaches have been proposed which address dynamic scheduling problems resulting from unexpected event occurrence. Hicks *et al.* [17] developed a heuristic method and evolution strategy to reschedule new orders and minimize the sum of the work-in-progress holding costs, as well as product earliness and tardiness costs. Alfieri *et al.* [12] proposed a two-stage stochastic programming formulation of the resource constrained project scheduling problem for production planning under uncertainty in ETO systems. Hu and Wan [10] proposed a data-driven reallocation of workers in an ETO assembly system to meet specified due dates by efficient use of human resources when unexpected events occur.

However, the previous research has focused on using rescheduling algorithms to respond to unexpected disruptions but do not consider collection of real-time assembly process information. In ETO environments, unexpected events can gradually spread due to a lack of timely, accurate and consistent manufacturing information that is shared between related workstations. Frequent changes to the assembly process can cause significant disruptions of assembly systems. Therefore, it is essential that there is a seamless flow of information between the various cyber-physical components to ensure that there is a collaborative control strategy for the assembly processes, which includes the workers, tools, parts logistics and assembly activities, in order to accommodate unexpected events.

A modern assembly system can be considered a composition of physical, cyber and human components, and IoT is used to connect their integration across cyber interfaces [18]. IoT technologies have been widely used in assembly systems. Wireless information networks integrated with radio frequency identification (RFID) and auto ID sensors have been developed to collect and synchronize real-time data for walking-workers and track moving objects in a flexible assembly line [19]–[21]. Cecil *et al.* [7] developed an Internet of Things (IoT) based cyber-physical framework in the field of micro-device assembly. The framework uses cyber modules that can perform assembly planning, path planning, virtual reality-based assembly simulation and physical command generation. The physical assembly activities are accomplished using micro assembly work cells. Krishnamurthy and Cecil [22] designed and developed an IoT-based CPS for PCB assembly. The outputs from a virtual reality-based simulation was compared and analyzed against the production data of the physical shop floors provided from sensors and cameras to facilitate agile product and process design. A CPS framework that integrates a set of computational tools with various physical machines was proposed to support personalization design and on-demand manufacturing, which was demonstrated using the example of a personalized bicycle [23]. Tan *et al.* [24] analyzed the requirements of industrial robot assembly and proposed a four-level decentralized dynamic closed-looped cyber-physical interaction architecture for a shop-floor assembly system to handle the planning and scheduling problem. Liu [25] proposed a guaranteed cost control design procedure for model-based cyber-physical assembly systems, which provides support to control closed-loop assembly systems with a guaranteed cost and responds to disturbances. The effectiveness of the proposed control method is demonstrated by a single-axis servo drive. Mayer *et al.* [26] presented a framework composed of three elements: a simulation model representing a modular assembly system, a multi-agent system incorporating centralized or decentralized control logic, and an interface for data-exchange. Centralized and decentralized control algorithms were developed to manage a specified flexibility and coordinate the cyber-physical entities of the modular assembly system. These studies focus on assembly process planning support and quality control in assembly lines for mass production. However, none of these studies consider assembly control when unexpected events occur in ETO environments.

Effective control of the turbine assembly process depends on accurate, detailed and real-time assembly process information. In this paper, IoT technologies are adopted to realize the CPS framework, which can support the effective control of the moving workers, fixtures, parts logistics and assembly activities in the turbine assembly workstation. The rest of the paper is organized as follows: the assembly system of the steam turbines is provided in Section II, Section III describes the CPS framework for the ETO products, Section IV provides the detailed cyber-physical components and Section V provides a real case of large turbine assembly. The conclusion is presented in Section VI.

II. ASSEMBLY SYSTEM OF STEAM TURBINES

Steam turbines used in the large power generation industry are too large, bulky and heavy to move during final assembly, as the length, width and height of these turbines can each be several meters. The weight of its main parts (e.g., the cylinder and rotor) is several dozen tons and they have very complex and irregular structures. Therefore, a bridge crane is necessary to move heavy parts and assemble the turbine (as shown in Fig. 1).

Furthermore, these turbines are typical ETO products, which are manufactured and assembled in low volume to satisfy individual customer specifications. The ETO strategy means that every turbine is unique and is ordered by a specific

FIGURE 1. Final assembly system of a steam turbine.

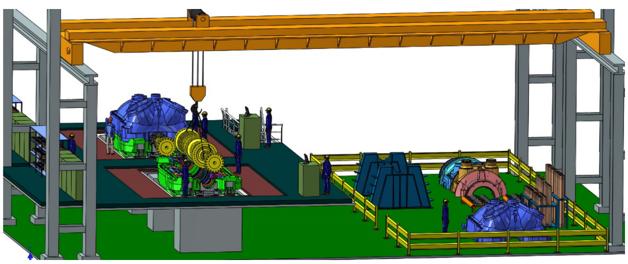


FIGURE 2. Turbine assembly workstations with fixed position layouts.

customer, and each part and sub-assembly from both internal and external sources is also unique [17]. The final assembly process is performed with a one-piece flow, and the assembly system will be reconfigured for the next unique product after each product assembly is completed.

Due to safety, lead-time and cost considerations, assembly workstations are adopted with fixed position layouts for turbine assembly, as this can provide several advantages including the reduced movement of work items, minimized damage or movement costs and more continuity with assigned workers since the item does not move from one workstation to another. As shown in Fig. 2, there are two final assembly workstations in turbine assembly workstations which are both independently operated in parallel. During the entire assembly period, the turbine being assembled is located at the fixed workstation, while the workers, tools and parts for each assembly task are moved to the given workstation according to a higher assembly plan.

Since each turbine in a customer order is unique, the main parts and sub-assemblies are irreplaceable components for each specific turbine. Due to limited space, a workstation only contains the turbine being assembled. Other parts, sub-assembly and specific tools for the forthcoming assembly task are delivered to a buffer area, which is close to the assembly workstation. After the current assembly task is completed, the heavy pallets, sub-assemblies and tools required for the next task are moved to the workstation using a bridge crane. The crane will have limited time windows for availability for both assembly workstations, due to other moving services in the shop floor.

The final turbine assembly of turbines requires skilled and unskilled workers in different fields, including mechanical engineering, electronic engineering, welding, and quality engineering. All workers can walk between workstations and each worker is responsible for one assembly task at each workstation before moving to the next. Workers are assigned to perform related tasks depending on the work content defined in the processes and the starting time of tasks in the given schedule. The operating time of each task is dependent on the skill level and the number of assigned workers.

In the turbine assembly workstation, the workers, tools, parts and sub-assemblies all dynamically move, since the turbine does not move while it is being assembled. Unfortunately, in these environments, unexpected disturbances frequently happen that can delay the existing assembly schedule, for example, worker absence, unavailability of tools, delayed delivery of parts and sub-assemblies and variations in operating times. To address this problem, the assembly processes of the turbines must be dynamically controlled, which requires the following problems to be solved:

(1) Due to the lack of effective information collection and communication between turbine assembly workers, required tools and components, the assembly plan and any adjustments may not reach the turbine final assembly workstation in time. The occurrence of unexpected events will cause the existing turbine assembly plan to be changed and temporary modification information should be transmitted by telephone or paper. In turbine assembly, the workers and the foreman are dynamically moved to the workstation which makes it extremely difficult for them to immediately receive the updated information, causing disorder to the moving parts and tool preparation of the turbine assembly.

(2) Logistic and information flow are not synchronous in the turbine assembly workstation. Since there is no monitoring system, information on the progress of the assembly plan execution and the real-time status of available workers and tools cannot be collected and transferred to the foremen and the manager synchronously. Thus, decision-making of the turbine assembly planning and control lacks real-time data support.

(3) There are frequently errors made in the turbine assembly. A steam turbine is a typical ETO product, which is highly customized to satisfy individual customer specifications. The ETO production and the walking-workers require visual operation guidance. However, it is inconvenient for the ambulatory workers to consult paper-based assembly instructions in the turbine assembly workstations. This leads to

frequent quality problems in the turbine assembly, requiring disassembly and reassembly of the turbines.

III. IoT-BASED CPS FRAMEWORK

The aim of the paper is to dynamically provide exact assembly task information to the assigned workers in the turbine assembly workstation to achieve real-time guidance, assembly progress monitoring and assembly procedure control by rescheduling the existing task sequence, reassigning the workers and controlling the parts logistics when unexpected events occur.

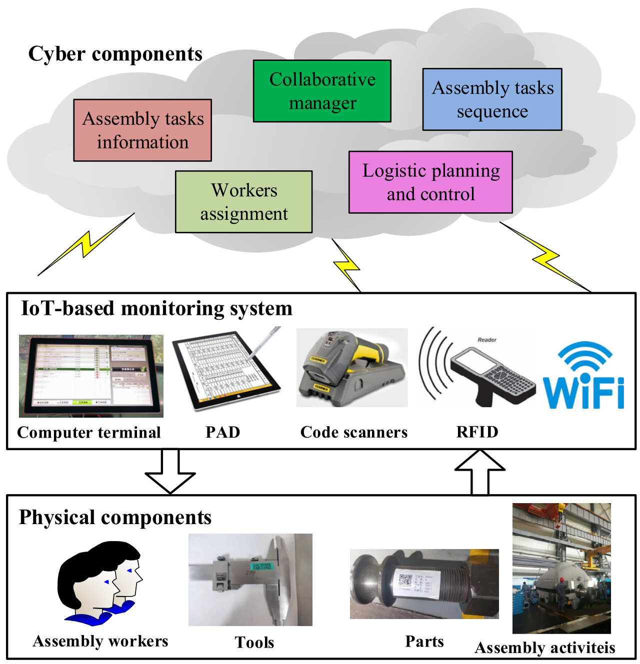


FIGURE 3. Overview of IoT-based CPS framework for turbine assembly.

An IoT-based CPS framework has been proposed to assemble turbines, which involves cyber components, an IoT-based monitoring system and physical components, as shown in Fig. 3. The physical components include operating workers, used tools, assembly parts, assembly workstations and assembly activities. The IoT-based monitoring systems are composed of a computer terminal, a PDA terminal, two-dimensional code scanners, an RFID reader and WiFi. Depending on the given work content and schedule of the assembly tasks, workers perform assembly activities using the specified tools on the given parts. IoT-based monitoring systems provide real-time feedback as the specific assembly activities progress, along with notification of any specific unexpected events encountered during the realization of assembly activities, such as a prolonged operating time or the delayed delivery of parts.

The cyber components include the assembly task information, task sequence, worker assignment, logistic planning and control. The task information component manages the work content obtained from the manufacturing process planning and the original schedule of the assembly tasks determined by the high-level production plans, including the task sequence, the worker assignments for every task and the corresponding logistic plan. The IoT-based monitoring component links the cyber and physical worlds. Assembly information is sent to the appropriate physical workers in the assembly workstation where the assembly tasks are performed. The real-time assembly information that is collected is used to compute any deviations between the original schedule and the real assembly progress, which serves as an input to the task re-sequencing and worker re-assignment module. The cyber components use the assembly task information and the collected real-time assembly progress to re-sequence the assembly tasks, re-assign the workers to forthcoming tasks and control the logistic system of the parts and special tools to rapidly respond to a disturbance. The various cyber and physical components collaborate in order to accomplish the overall objective of assembling turbines in uncertain environments.

IV. CYBER-PHYSICAL COMPONENTS

This section describes the main cyber-physical components in the framework. When unexpected events occur, the real-time information captured in the turbine assembly process is used for operating guidance, collaborative control of the task sequence, worker assignment and logistic planning and control.

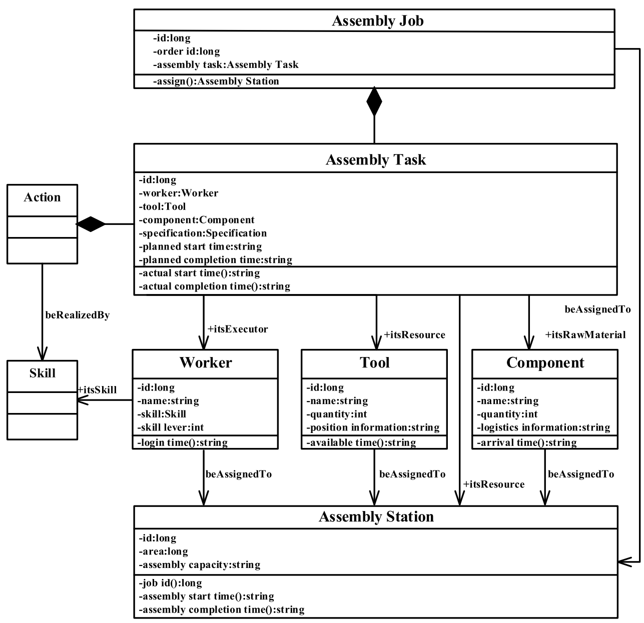


FIGURE 4. Assembly task information model.

A. ASSEMBLY TASK INFORMATION

Fig. 4 shows the proposed assembly information model of the turbine. The description of each notation in the UML is presented as follows to define the required workers, tools and components for the task execution. An assembly job is an order booked by a customer and assigned to an assembly workstation to assemble a specific turbine, which can generally be decomposed into a series of sequential assembly tasks. An assembly task is defined in terms of its actions, which are the smallest reusable units of behavior. Each action is undertaken on components of the turbine by the assigned workers in the turbine assembly station. A component is a constituent part of a turbine. For the turbine assembly process specification, the required tools and the skilled workers are deployed to perform the actions in the workstation. Therefore, the assembly tasks must dispatch the corresponding tools and workers according to the given schedule.

Due to the limited space in the turbine assembly workstation with a fixed position layout, there is no buffer to store large components and tools. Therefore, workers, components and tools associated with each specific task can only be moved to each corresponding workstation after the previous task has been completed and the corresponding tools have been removed. As a result, while each task is being realized, if an unexpected event occurs, it is necessary to jointly re-sequence tasks, control component logistics and re-assign workers and tools. However, more data is required with respect to the turbine being assembled, including the real-time status of the task being executed, the available workers, the tools specified in the assembly process and the logistical information of the components.

Task data can be seen as a stream of tuples in the form <No., Workers, Tools, Components; Planned starting time, Planned completion time; Real starting time, Real completion time >. The given scheduling of assembly tasks describes the required workers, tools, parts and their arrival times, which determine the planned starting time and the expected completion time. For a real turbine assembly process, the arrival time of each item is collected by the IoT-based monitoring system. This time may deviate from the planned time, thus delaying the completion time of the turbine assembly.

B. IoT-BASED MONITORING SYSTEM

The IoT-based monitoring system collects real-time information about the workers, tools and parts in order to identify unexpected events requiring task rescheduling in the turbine assembly workstation. All collected data is transferred to the collaborative manager module for analysis of the current scenario. Completion time delays in the turbine assembly can be detected and will trigger assembly task re-sequencing, worker re-assignment and logistics control.

The monitoring system provides vital feedback from the physical world to each of the collaborating partners. The workers each have RFID staff cards, and RFID readers are deployed at the portal gate of each assembly station. When the assigned workers enter an assembly workstation, the readers can detect their RFID and record their arrival time. All pallets holding the small-sized subassemblies and components are attached with metal RFID tags. Smart RFID bolts are attached directly to other large-sized fixtures and components, such as the turbine cylinder. Their arrival time can be recorded using other RFID readers deployed on the hooks of the crane which is used to move the heavy pallets and large-sized items. Other precise measuring tools, such as a micro caliper, are affixed with two-dimension (2D) data matrix codes on metal paper. Workers carry a handheld machine vision system (PDA terminal) to read data matrix codes. After the deployment of the 2D data matrix vision system and RFID devices, all workers, tools and components are converted into smart objects, which can sense and communicate with each other. Therefore, the final assembly of turbines can be performed according to either predefined scheduling or revised scheduling in response to arrival time delays of each related item and the starting time of each assembly task, as detected by the IoT-based monitoring system.

C. COLLABORATIVE CONTROL IN TURBINE ASSEMBLY PROCESS

The collaborative manager is initialized when a user submits a booked turbine to be assembled. The sequence of assembly tasks is subsequently generated using a task scheduling algorithm, and the corresponding logistics plans and the worker assignments of each task are determined simultaneously based on the task related-information, such as the assigned workers and the required tools and parts. The physical assembly commands associated with each specific assembly task is downloaded to an electronic Kanban in the physical assembly workstation, where the booked turbine will be assembled by the assigned workers. During the physical turbine assembly, the assembly status can be monitored and shared over the cloud with users in different locations, such as logistics operators, mechanical assembly operators, electronic assembly operators and supervisors. When unexpected events occur, such as delivery delays of main components or disassembly and re-assembly of components due to assembly quality problems, the task sequence, worker assignment and item delivery are adjusted. This temporary information adjustment can then be transmitted to related workers, thus improving collaboration between different workers in the assembly workstations.

Fig. 5 shows an operator overview of turbine assembly execution using Workstation Explore. Since the large turbine remains in the assembly workstation over its entire assembly period, different workers, tools and parts are moved to their corresponding workstation according to the generated sequence of assembly tasks. At the start of each task, the assigned workers for the next assembly task are informed of the current status using their smart phones (as shown in Fig. 6) Workers then enter their designated assembly workstation and login to the Workstation Explore in the electronic Kanban using their staff card. Task related information is then downloaded from the cloud to the electronic Kanban in the workstation, including the task sequence, the required parts, the tools and the assigned workers. Any absence of assigned workers or lack of required tools, parts and sub-assemblies will delay the start of the turbine assembly task.

Due to limited space of the assembly workstation and the large size of turbine components, it is not feasible to deliver large components any earlier than required. However, a late

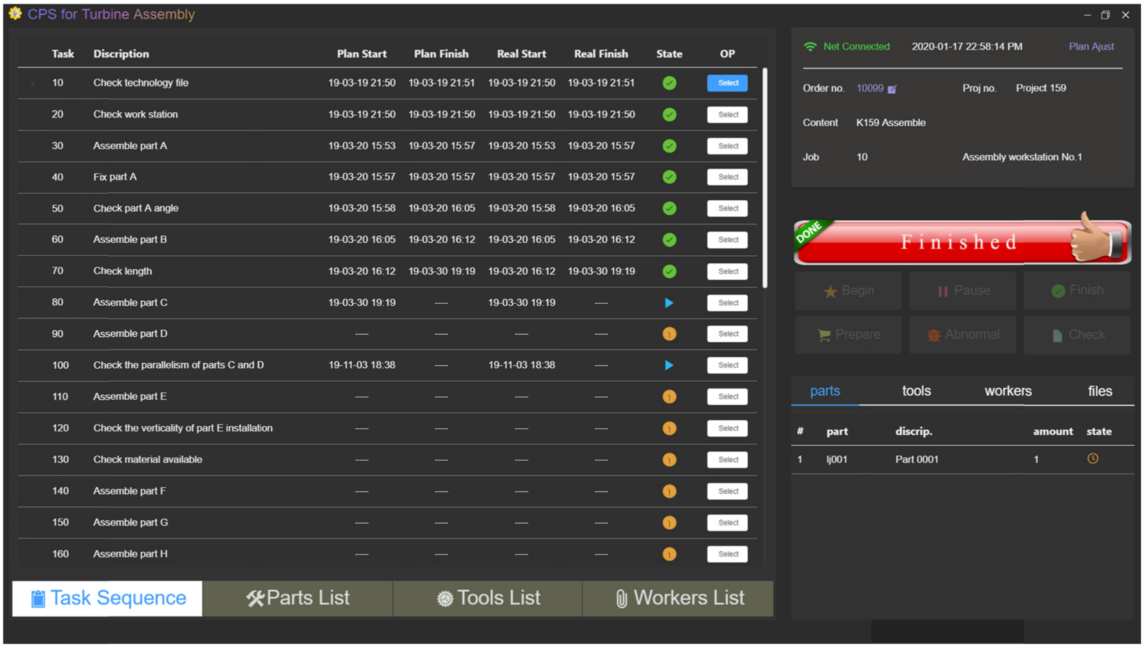


FIGURE 5. Overview of turbine assembly execution with Workstation Explore for operators.

TABLE 1. Average number of errors and quality issues of 10 turbine assemblies.

Performance	Not CPS	CPS	Decreased percentage
Quality issue	3.6	1.2	66.7%
Assembly error	2.8	0.8	71.4%
Matching part error	2.0	0.2	90.0%
Delivered tool error	1.4	0.2	85.7%

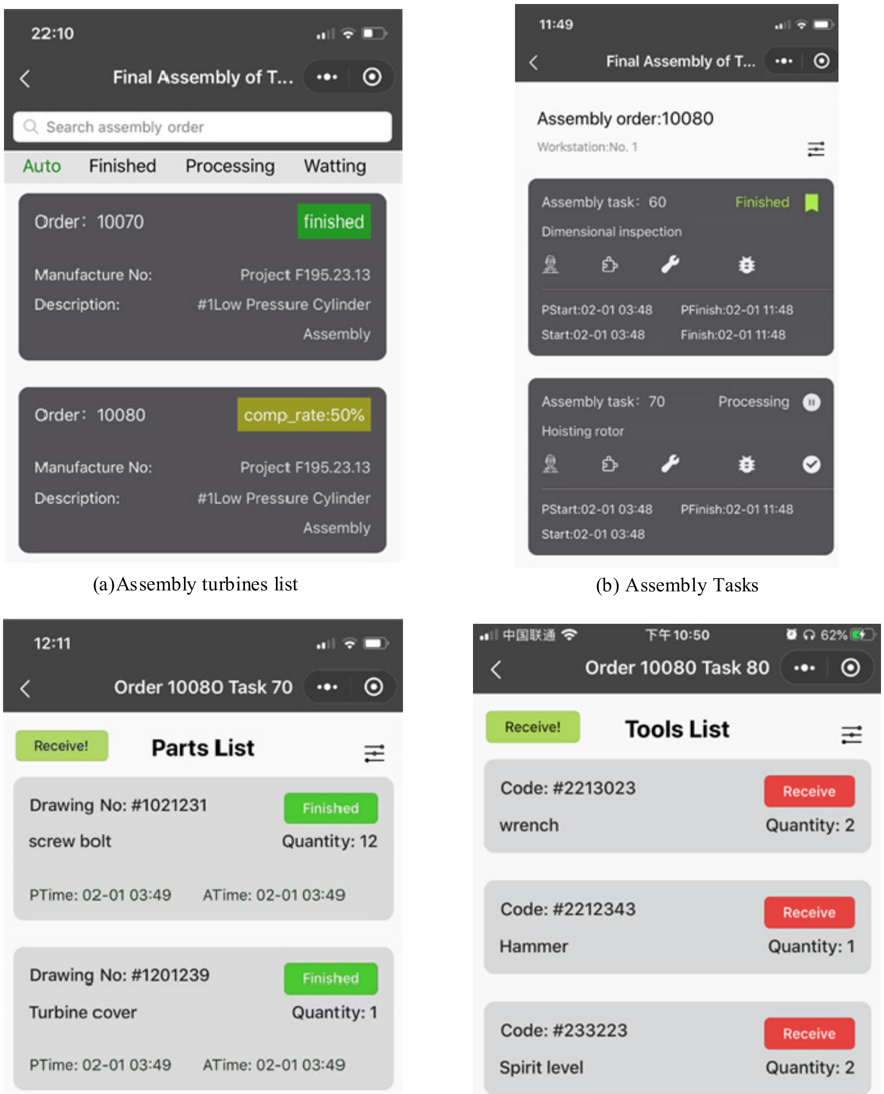
delivery will delay the completion time of the assembly task. The collaborative manager (CM) can inform the driver of the crane to move required tools, parts and sub-assemblies into the workstation as soon as the workers acknowledge that they are ready to start the assembly task. The Workstation Explore prompts workers to check and collect the right tools and parts using a code scanner to read the 2D data matrix codes on large-sized tools and parts, or the RFID in pallets containing the small-sized components. Their arrival times are also recorded and sent to the CM.

Since a steam turbine is a typical ETO product, each turbine will have some differences in products, parts and assembly operations. In this environment, the assembly Workstation Explore must provide instructional assistance using 3D CAD models and videos. Workers can execute their tasks by following the instructions, which can reduce manual assembly errors. When each assembly operation is finished, workers can acknowledge the task completion by clicking the ***Finished*** button on the screen of the electronic Kanban, or on their smart phone. The real-time assembly progress is recorded and shared with the workers for the next incoming task and the driver of the crane.

V. EXPERIMENTAL RESULTS

The purpose of these experiments is to evaluate the performance of the proposed IoT-based cyber-physical framework for turbine assembly. The software was realized on a Windows platform using Java running on the application server of the turbine assembly. The Workstation Explorer was installed on a touchscreen computer with Intel Xeon 2.40 GHz CPU and 16.0 GB RAM and the smart phones of every worker.

Since a turbine is a highly-customized ETO product, experiments were performed using ten similar turbines. The assembly task information was obtained from a PDM system, and the high-level production information of the ordered turbines was derived from an ERP system. The assembly sequence, assigned workers and logistics planning of every task were collaboratively generated by the cyber components, and the assembly commands were transmitted to the workers using their smart phones and the touchscreen computer deployed in the assembly workstation. The assigned workers, specified part tools, and assembly workstation were determined for every turbine assembly task and each related item was given a unique identifier using RFID codes. This allows any errors in the matching parts and the delivered tools to be



(a)Assembly turbines list (b) Assembly Tasks (c) Parts list (d) Tools list

FIGURE 6. Workstation explore on a smart phone.

TABLE 2. Improved production efficiency of the turbine assembly.

Performance	Not CPS	CPS	Decreased percentage
Average production span (h)	285.7	275.3	3.6%
Average suspension time (h)	27.2	12.9	52.6%
Average overtime work (h)	9.0	4.2	53.3%
Number of delayed turbines	2	0	100%

immediately discovered and corrected before the assembly task starts which significant decreases quality issues in the turbine assembly. Table 1 provides statistics on the number of errors and quality issues during assembly of the ten turbines.

The IoT monitoring system collects the turbine assembly progress data and the real-time status of the moving workers, specified fixtures and tools, parts and sub-assemblies in the assembly workstations. When a disturbance or assembly deviation from the existing schedule is detected, the collaborative manager component can re-sequence the assembly tasks, re-assign the workers, re-plan and control the logistics of the required parts, sub-assemblies and tools, to ensure that the turbine assembly can be completed before the given due date. This approach realizes a full closed-loop assembly system incorporating the assembly task scheduling, worker assignment, logistics planning, real-time assembly status monitoring and dynamic collaborative control between the assembly tasks, workers and logistics, which greatly enhances the assembly efficiency due to a significant decrease in suspension time and worker overtime due to unexpected events. The IoT-based CPS can ensure that the final assembly of the customized turbines will be completed before the given due date. Table 2 shows the improved production efficiency of the turbine assembly.

VI. CONCLUSION

Turbines for the power generation industry are typical ETO products, which are highly customized. Since each turbine costs hundreds of millions RMBs, the financial penalties for delivery delays are significant, making it crucial to deliver an ordered turbine by the given due date. However, unexpected disturbances can occur, such as worker absences, quality issues requiring disassembly and re-assembly or delayed part delivery, which disrupt the existing assembly schedule. Thus, the turbine assembly process should be controlled at all levels, including the dynamically moving workers and the required parts and tools. Effective control relies on accurate, detailed and real-time assembly process information.

The paper proposes an IoT-based cyber-physical framework and approach for collaborative control of the turbine assembly process under uncertainty. The main characteristics of the turbine assembly process have been analyzed. The turbine being assembled is placed at a fixed workstation, while the workers, tools and parts involved in the assembly task are dynamically moved to this workstation. The information model of the assembly task has been defined using UML to describe the relationship between the assembly task and the workers, tools, parts, start and completion time. An IoT-based monitoring system has been designed to collect real-time information on the workers, tools and parts related to the task by adopting the RFID and 2D data matrix code in order to identify unexpected events. Using the captured real-time information in the turbine assembly process, collaborative control of the task sequence, worker assignment, logistics planning and control can be undertaken when disturbances occur. Finally, an IoT-based CPS has been developed and tested for a real turbine assembly. The experimental results have shown that the quality and efficiency of the turbine assembly are obviously enhanced due to a decreasing in part and tool delivery errors, quality issues and suspension time.

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