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Research and Implementation of CPS for Transmission Front Middle Case Assembly Line

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Abstract: As an indispensable part of the automobile factory transmission system, the transmission assembly line has a high level of automation and can play as a pioneer in the digital transformation of production. However, for the transmission production process, especially the front and middle case, there are many problems, such as a low degree of informatization, low efficiency of information transmission, and lack of a platform for rapid information release and sharing. This leads to the difficulty of timely discovery and feedback of exceptional events, resulting in low assembly efficiency. Therefore, this paper constructs its cyber–physical system (CPS) with the help of the Internet of Things (IoT) technologies, such as physical identification, information collection, and transmission. It contributes to improving the intelligent level of transmission of front and middle case assembly, strengthening the close integration, interaction, and collaboration between a large amount of assembly data and the physical entity of the assembly process, realizing the real-time monitoring of the transmission front and middle case assembly process, timely discovering, provide feedback, and dealing with exceptional events. In addition, scientific and effective adjustment strategies based on the data can be provided. Ultimately, the assembly efficiency of the transmission front and middle case is improved, ensuring the stability of the assembly line.

Keywords: transmission front and middle case; assembly; cyber-physical system (CPS); internet of things (IoT); control system; intelligent production

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1. Introduction

With the take-off of China's macro economy, the resulting rapid development of infrastructure construction, the real estate industry, and highway logistics and transportation industry, coupled with the continuous release of domestic regulations and policies, China's heavy automobile industry achieved tremendous growth between 2010 and 2020. Although in the past two years, due to the short-term economic slowdown combined with the epidemic containment, early consumption overdraft, and other factors, the market suffered a cyclical decline. However, as the epidemic gradually alleviates, logistics demand will improve, infrastructure projects will gradually recover, and demand for heavy automobiles will increase. Therefore, in the long run, heavy automobile manufacturing enterprises need to continue to pay attention to increasing internal industry competition. Under such a background, how to improve the efficiency of the production line and improve its competitiveness is an important subject faced by these enterprises.

Transmission is an indispensable part of heavy automobile transmission systems. The accurate assembly of the transmission case, especially the accurate assembly of front and middle cases, is an important way to ensure engineering safety and economy. At present, the assembly efficiency of transmission front and middle cases has been one of the bottlenecks restricting the overall assembly efficiency of transmission.

The assembly of transmission front and middle cases adopts the classic assembly line mode. At present, most of the research on production optimization of assembly lines under a changing environment focuses on the solution mode of "mathematical modeling-intelligent algorithm designing" [1,2]. The authors of this paper have been committed to the research in this aspect in the early stage. To solve the original operation plan failure caused by process changes and spatial-temporal coupling constraints, the corresponding mathematical models were constructed, and the improved versions of the NSGA-II and Imperial competition algorithms were designed. The algorithms can obtain the optimal solutions for internationally recognized standard cases [3,4]. However, the construction of mathematical models was based on specific assumptions, with the data given in advance. The intelligent algorithms designed on this basis are difficult to be applied to actual production, not to mention real-time dynamic control [5].

In recent years, the extensive application of information technology and the Internet of Things technology in the manufacturing field under the environment of Industry 4.0 has provided a new way for solving such problems—the digital transformation of production and manufacturing. Considering that the automation of transmission assembly lines has reached a certain level, accelerating the digital transformation of transmission front and middle case assembly lines is an important method to solve the current problems [6].

The key technology to realize digital transformation is to establish a correlation network among physical entities to obtain all data during the production process and conduct data analysis. Producing process monitor and control, as well as the development of strategic decisions for the production, can be realized when meeting unexpected events based on this collected data, reducing downtime and maintenance costs [7,8]. However, as the basis of the digital transformation of the production line, the process data has the characteristics of being massive, multi-source, and heterogeneous; the assembly process information is incomplete and unstructured; and correlation of process data is poor, which makes the information difficult to timely transfer to on-site assembly to effectively guide the assembly progress, and leads to the poor assembly balance rate and low one-time pass rate.

Cyber–physical systems (CPS) are an important method to implement intelligent manufacturing, utilizing advanced information communication, computer, and network technologies to realize the deep and close integration of the digital cyber world and physical world and to monitor, coordinate and control actual physical processes in real time [9]. That is, all the massive, multi-source, and heterogeneous assembly process information data are integrated into a unified, structured representation and dynamically correlated with each other. It also supports real-time monitoring and optimization exploration of the assembly line. This point has been fully demonstrated by our previous work, in which the CPS technology is applied in a fixed assembly system used by a turbine [10].

Therefore, the construction and application of CPS in transmission front and middle case assembly lines is reasonable and worth studying. With the help of IoT technologies, this paper systematically and structurally sorts out data of the assembly system, perceives, collects, and transmits assembly data in real time, monitors the assembly process of transmission front and middle cases and provides a reasonable assembly schedule based on data analysis and processing in order to carry out the intelligent control of the assembly progress and enhance the assembly efficiency. To the best of our knowledge, there is no published study on CPS for transmission front and middle case assembly lines in the literature. This work is helpful for filling this gap.

The rest part of this paper is organized as follows. Section 2 shows the literature review of research on CPS and its implementation in manufacturing systems. In Section 3, the characteristics and main problems of the data of transmission front middle case assembly are analyzed. In Section 4, the CPS framework of the transmission front middle case assembly line based on IoT was designed, focusing on the physical assembly systems, process monitoring systems, and cyber control systems. Based on the B/S framework, programming tools were used to develop the process control system for transmission front middle case assembly. Then the system was applied, and the effectiveness of the system was verified by an engineering instance, which is described in Section 5. In Section 6, conclusions are given.

2. Literature Review

Since the concept of CPS was first proposed by American scientist Helen Gill in 2006 [11], it has been rapidly accepted by many scholars and has been extensively researched in major industrial fields such as aerospace, national defense, health/medical equipment, traffic control, and infrastructure construction [12,13]. Some scholars focused on the construction of CPS systems. Chen et al. [14] developed a conceptual framework for a new paradigm of CPS-based smart factories by applying virtual reality mapping and convergence, virtualization, and cloud services technologies to producing systems. Zhang et al. [15] proposed a CPS architecture based on data and studied it from CPS node configuration, heterogeneous node interconnection technology, and data-driven adaptive configuration method, realizing intelligent management and control of the production process. Iarovyi et al. [16] studied and developed the CPS of a production execution system based on a knowledge-driven method, which was applied and verified in a production system based on pallet.

In addition, different scholars have carried out a variety of research focuses according to different needs. Some scholars focused on studies of data models that support data collection and analysis in the cyber system.

Zhang et al. [17] emphasized the importance of data in CPS and put forward an information model construction method with the guidance of process to conduct data modeling for design information, material information, processing information, and sustainability information of products. Hu et al. [10] constructed a CPS for the assembly system of steam turbines based on IoT. To guide data collection, the task information model of steam turbine assembly welding based on UML was proposed. Then, the data flow that followed the business flow was described, and the decisions were made based on the collected data. Wan et al. [18] constructed the ontology model of intelligent manufacturing equipment with the aim of optimizing its utilization and studied the modeling and data association technology, with a discussion of the knowledge base updated in the manufacturing cyber–physical systems (MCPS) in order to achieve the reconfiguring of manufacturing resources. Zhao et al. [19] focused on the sustainable producing capability of industrial robots and constructed a dynamic and unified data model based on ontology to analyze and evaluate their capability correctly.

Some scholars focused on the identification and collection of manufacturing process data based on RFID, QR codes, and other IoT technologies. Rahul et al. [20] used RFID tags to read and store the process information of each part in the automobile manufacturing workshop, improving the efficiency and performance of the automated automobile manufacturing system. Zhuang et al. [21] studied a process-based dynamic tracking and management of producing material. QR codes were used to label materials to improve the tracking efficiency of multiple sources and multiple materials and realize the breakthrough of logistics information tracking from zero during discrete assembly processes of the complex products. Zhen et al. [22] also studied a logistics-control technology based on QR codes for complex product assembly lines and realized the traceability of workshop logistics.

Some scholars have focused on data analysis and applied research based on CPS systems. Kleanthis et al. [23] introduced the concept of networked physical micro-services in the manufacturing field, combined with IoT technology, under the support of model-driven engineering development and manufacturing the semi-automated CPuS-IoT system, captured domain knowledge, predicted, and updated the life cycle of the manufacturing system. Schulze et al. [24] took the industrial cooling tower system of an automobile factory in Germany as the research object and built a CPS. Through the comprehensive analysis method combining the data collection, process monitoring, white box, and black box models of the system, they provided the enterprise with the strategy, tactics, and operational three-layer management decision scheme. The water demand and energy demand of cooling tower systems are optimized by dynamically adjusting operation strategies. Ying et al. [25] addressed a meta-heuristic algorithm on the basis of an information physical assembly system (CPAS) to solve the automatic assembly sequence planning problem, in which the physical characteristics of the manipulator were taken into consideration. Huang et al. [26] constructed a CPS scheme based on three pull control strategies: path bottleneck, constant work-in-process, and capacity relaxing CONWIP, aiming at the manufacturing system of a single customized product with limited resources. The optimal balance between CPS scale and production system performance during CPS deployment was also explored. Son et al. [27] built an automobile body production line CPS with the support of a digital twin. The aim was to solve failure problems of execution according to plan caused by unexpected issues, such as equipment failures in the automobile-producing process. This paper designed a product information model, process information model, plan information model, plant information model, and resource information model, collected relevant data in real time, and predicted the production process.

Most of the above studies are based on the design and research process of the research object and different focuses according to their own needs. In addition, less consideration is given to data combing and support, which cannot be applied to the front and middle case assembly line of transmission directly.

3. Transmission Front and Middle Case Assembly Line

The assembly line is an important production mode of large-scale production in the automobile manufacturing industry. Since it was first designed by Ford Motor Production Company in 1913, the assembly line has been rapidly adopted by automobile manufacturing enterprises because of its advantages, such as shortening the product production cycle, optimizing transportation routes, and improving production efficiency. The transmission front and middle case assembly line is a mixed assembly line that can be operated by multiple workers at some stations. The stations are fixed on an assembly line in accordance with the assembly operation sequence, and the workpiece passes through each station in turn, and a complete product is formed after the workers complete the corresponding assembly tasks at each station [3,4].

In our study, an actual transmission front middle case assembly line of a Chinese heavy automobile manufacturing corporation is considered, as shown in Figure 1. Figure 2 shows its main assembly process. In this line, a total of 12 stations are included, among which 1, 2, 3, 6, 8, 9, and 12 are automatic stations, and 4, 5, 7, 10, and 11 are manual stations. Moreover, stations 7 and 10 are single-person working stations; stations 4, 5, and 11 can be operated by multiple people; and the maximum number of workers is two, two, and four, respectively. Workers can be deployed according to demand.

Figure 1. Transmission front middle case assembly line.

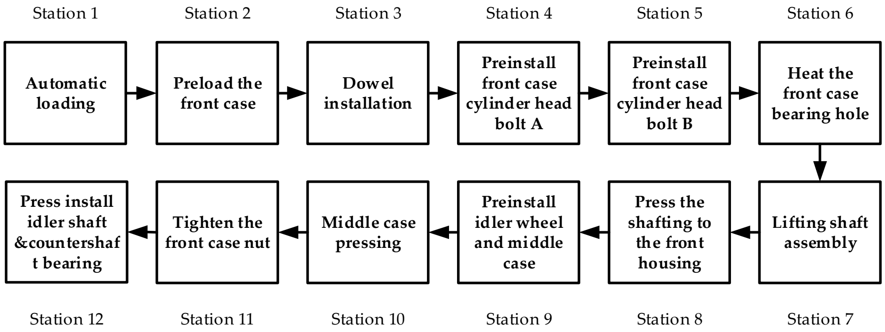


Figure 2. Process flow on stations of Transmission front middle case assembly line.

Although the automation level of this assembly line has reached a certain degree, providing the foundation for the digital transformation, there are still the following problems:

(1) There are various sources of process data in the product assembly process from manual stations and automatic stations, respectively; however, they lack a unified identification and processing platform, and the utilization rate of information is low.

(2) Most of the assembly process information depends on workers to record, read, and transmit even in automatic stations, and there may be problems such as missed reading, misreading, or transmission errors. Moreover, the process information cannot be timely associated with the physical entity, resulting in poor information transmission efficiency.

(3) The production plan of the assembly line mainly relies on the traditional simple analysis method and personal experience. The generality and expansibility of the developed schemes are usually poor, and it is difficult to adapt to the complex and changeable manufacturing environment.

4. IoT-Based CPS Framework

4.1. The Overall CPS Framework

The overall CPS framework of the transmission front and middle case assembly line is shown in Figure 3. The main elements of this system include the actual physical assembly layer, the assembly process monitoring layer based on the IoT, and the cyber control layer.

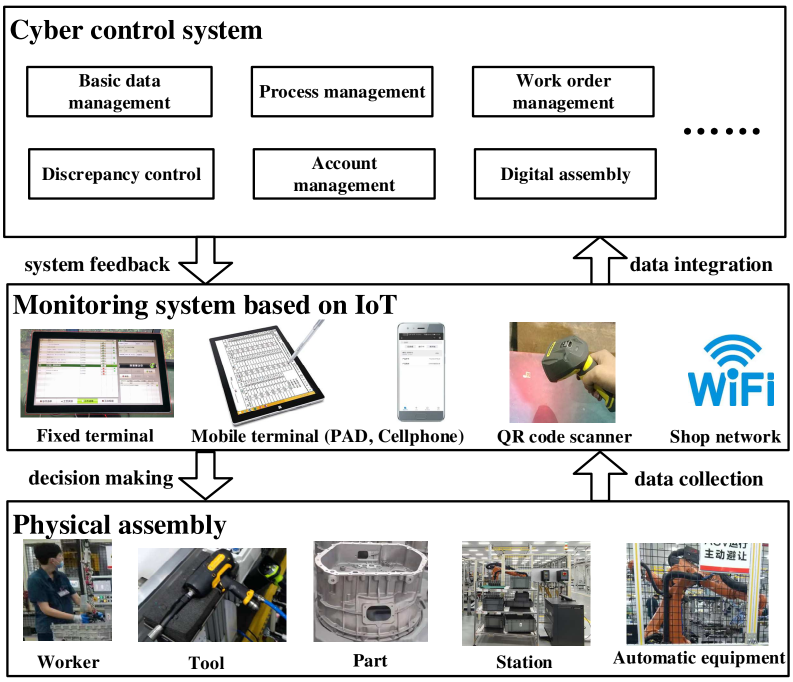


Figure 3. Overall CPS framework for Transmission front middle case assembly line.

The physical assembly layer includes all production factors of the assembly workshop, such as assembly workers, equipment, parts, and materials. This layer executes the commands of the system and feedback on the execution status to the cyber control layer of the system through the Internet of Things to ensure the management and control of the production status of the workshop by managers in real time.

The monitoring system layer connects the physical assembly layer and the cyber control layer, and its main function is to collect and transmit process data based on Quick Response (QR) code, Integrated Circuit (IC) card, and other IoT technologies to realize the data connectivity from the physical world to the information world. It collects production status data of workers, equipment, parts, and logistics based on the assembly data model, then transmits these data to the cyber control layer to provide a data basis for informed decision-making.

The cyber control layer includes all functional modules of the management and control system. Based on the assembly data model, it analyzes the process data collected by the IoT and makes decisions to realize the feedback and guidance of the information world to the physical world, such as the monitoring of the physical manufacturing process, discrepancy control, work order management, and so on. Through the cyber control layer, we can realize the effective control of the assembly process of transmission front and middle cases and improve the efficiency of the assembly line, as well as reduce the assembly cost.

4.2. Monitoring System of the Assembly Process Based on IoT

The monitoring system of the assembly process based on IoT is mainly composed of a fixed terminal, portable android device (PAD) mobile terminal, mobile phone terminal, QR code scanning gun, and wireless fidelity (WIFI) network.

The specific implementation means in the assembly line are as follows:

(1) Workers' information is bound with an IC card. When a worker is engaged in production, they will swipe the card to work at the corresponding station. The system will record the information of the worker on duty and associate it with the current work order.

(2) The QR code is used to identify the welding equipment, parts, and site stations, by printing it on the surface of parts and equipment tooling to achieve better management of production resources. At the same time, the corresponding metal QR code is allocated to different stations to distinguish them to better distribute the production work order. Workers can scan QR codes with handheld PADs to quickly and easily obtain information on parts and materials, equipment tooling, and site without looking up the serial number and other tedious operations, greatly improving efficiency.

(3) The assembly site is equipped with a monitoring terminal, through which workers can feed back the site production status data to the system to realize remote control of the production status by the management terminal. Meanwhile, based on the process data collected on site, the system can respond to unexpected production conditions in time to avoid production suspension, delays, and other consequences and improve production efficiency.

4.3. The Management and Control System

4.3.1. Structured Process Data Model

The transmission front middle case assembly process data model is shown in Figure 4. It extends the assembly process from six aspects, including task order, workers, equipment, parts, stations, and process specifications. In addition to process specifications, attribute information of the other five process elements is composed of basic information, planning information, and execution information. Among them, the task order relates to the other five process elements: In the planning stage, the workers, equipment, parts, execution stations, and process specifications required by the task order are specified based on the task order, and the respective planning information is generated. In the actual execution stage, the production operation is carried out in accordance with the task order in the assembly site, and the process information in the actual execution process is collected and summarized into the process execution information. On this basis, the control of the transmission front and middle case assembly process is realized.

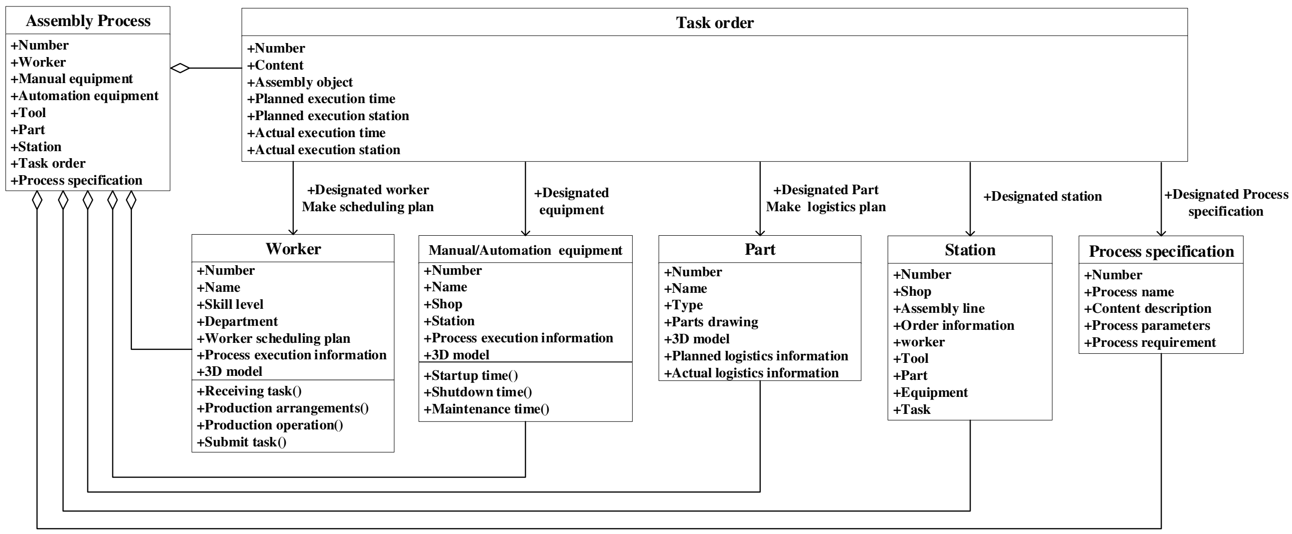


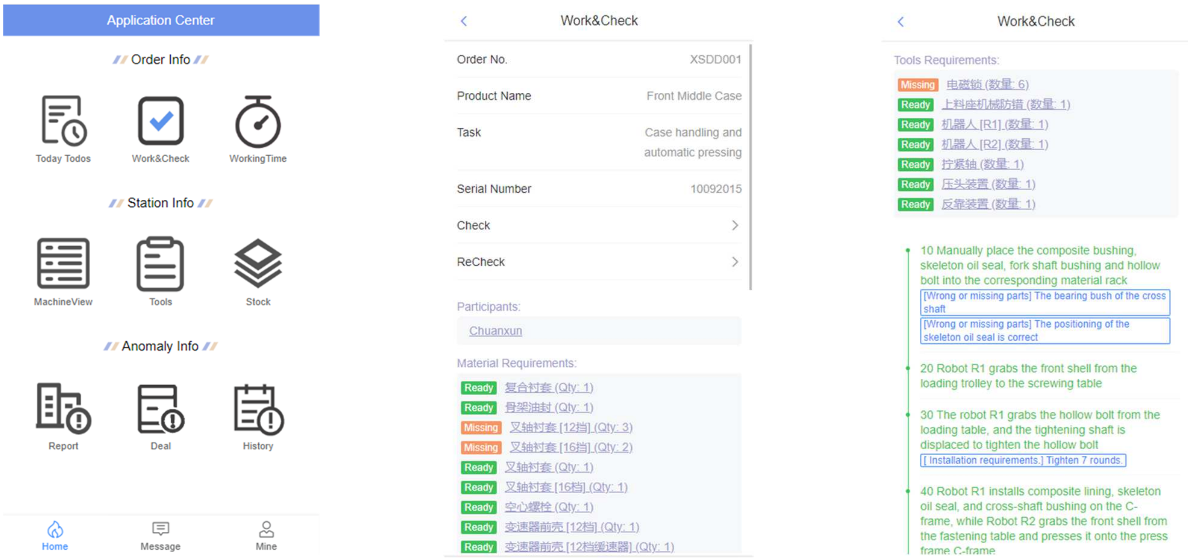
Figure 4. Transmission front middle case assembly process data model.

4.3.2. System Function Design and Implementation

Based on the above CPS framework, the transmission front middle case assembly control system is developed based on a B/S framework using Java and Python coding. The database is PostgreSQL, and the system terminal is developed in Edge/Chrome. According to the different preliminary analyses and functional requirements, the transmission front middle case assembly control system is divided into the executive terminal and the management and control terminal. The executive terminal is deployed at the station, which can guide the assembly operation, record and view the assembly process, provide feedback on assembly anomalies, and record quality inspection results, etc. The management and control terminal is mainly responsible for the maintenance of the assembly process, the management of orders, assembly simulation, scheduling, and the management of assembly resources, etc.

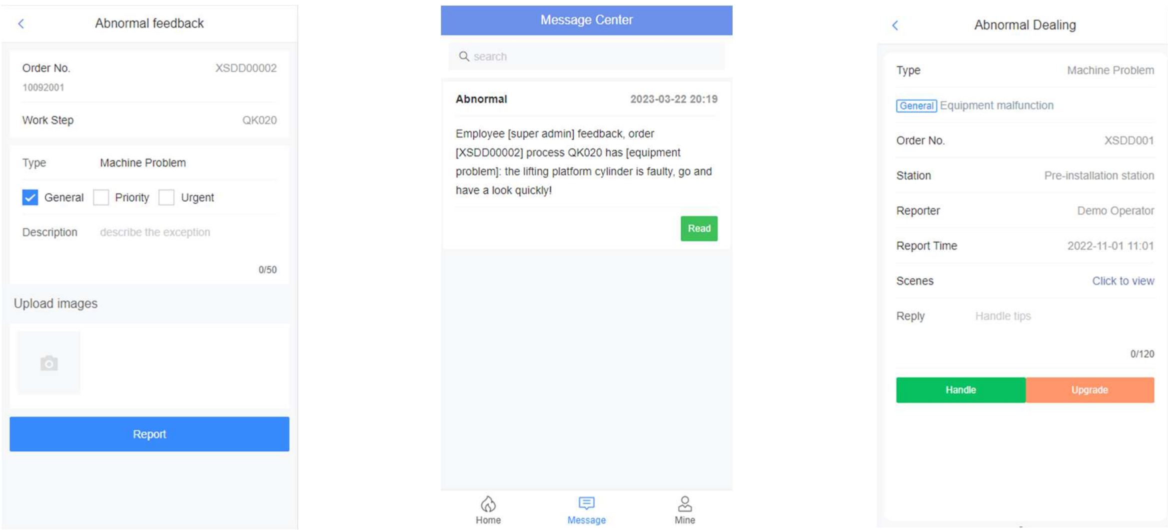
(1) Implementation of the executive terminal function

Workshop managers and assembly workers can view information such as assembly orders, work inspection contents, working time, and line storage through the mobile phone executive terminal, as well as view, report, and handle anomalies. Figure 5a shows the main functions that can be viewed and operated at the execution terminal. Figure 5b shows the information on orders, workpieces, personnel, and parts for tasks at a station. The parts demand is compared with the line storage of the station to display the parts lacking materials. Figure 5c shows the required resources for the assembly task. The resource requirements are compared with the standing list to show the missing resources. The sequence of work steps and the technical requirements of work steps are shown below. If part and resource requirements are defined separately in each work step, they are also displayed. In addition, if an abnormality occurs on the workstation, the corresponding assembly worker can directly report the abnormality on the mobile execution terminal, as shown in Figure 6a. Then, the mobile execution terminal of the workshop manager will receive a message reminder, and the workshop manager can open the "Message" interface to view the abnormal event (Figure 6b) and handle or upgrade it on its execution terminal (Figure 6c). And the handle information is reported back to the assembly workers or to the higher level of management.



(**a**) (**b**) (**c**)

Figure 5. The executive terminal function for the assembly tasks of a station. (**a**) main functions; (**b**) Station task information; (**c**) required resources.



(**a**) (**b**) (**c**)

Figure 6. The executive terminal function for abnormality. (**a**) abnormality report; (**b**) "Message" interface; (**c**) abnormality handle.

(2) Implementation of the management and control terminal function

Figure 7 shows the basic interface of the management and control terminal. The IP address and information of the current station are displayed in the upper right corner. The station information can be configured on the "terminal" page of the management and control terminal. On the right side, the current task information, logged-in personnel, and unprocessed exceptions at the current station are displayed, respectively. The left side shows the process flow. The process specification shows the requirements of parts and resources and marks the missing parts and resources in red. Meanwhile, the process steps are also shown to facilitate the guidance of workers. File viewing allows the manager or worker to view files related to tasks. Virtual assembly displays the assembly process through animation.

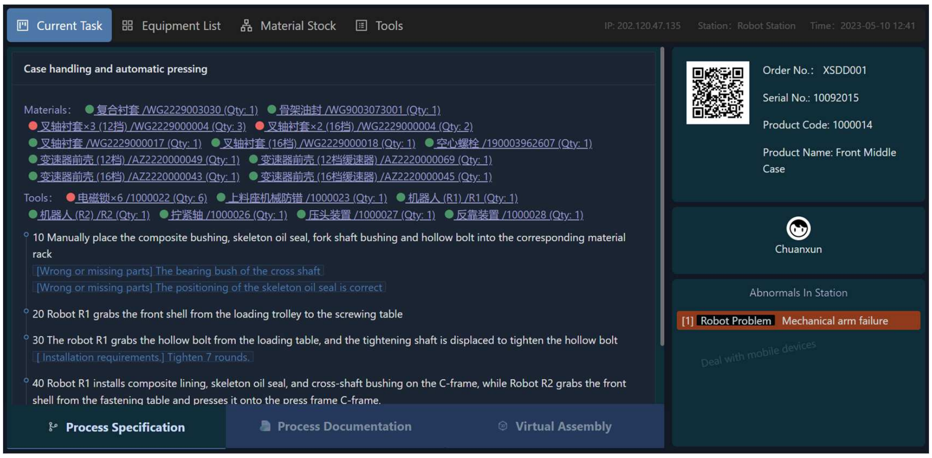


Figure 7. A basic interface of the management and control terminal.

In addition, after the assembly exception is feedback by the execution terminal, the plan administrator can see the corresponding unexpected event at the management and control terminal. The system can display its emergency degree, number, type, work order, station, reporter, specific description, processing time, and processing status, etc. The unexpected events occurring in a period of time (this month, one week, one month, three months, half a year, and one year) can be viewed based on exception type, time, order, or station.

5. Application Results and Discussions

5.1. Implementation of the Proposed System

In this paper, a front and middle case assembly in the transmission assembly workshop of an automobile manufacturing enterprise is considered, and the control system is applied on-site. The management and control terminal of this system is developed by Java and installed on the application server in the form of the Windows platform. The executive terminal of this system is developed by Python and Java and installed on the fixed PAD terminal and mobile phones of workers in the form of an application (APP).

Since the transmission is a mass-production product on the assembly line, experiments were performed over a six-month period. Real-time control of the assembly process in the engineering instance was realized through the following operations.

(1) Data integrated management

In the engineering instance, work-order information was generated by systems applications and products in data processing (SAP) system and sent to the workshop and the assembly. The corresponding assembly tasks were planned by the workshop group leader and sent to the corresponding workers. Tools, materials, and other resource information were provided by a manufacturing execution system (MES), and information on automation equipment was obtained from the programmable logic controller (PLC). Interfaces between the constructed system in this paper and these systems were developed, and all of the data from these systems were unified, defined, and managed under the support of the data model in the proposed system.

(2) Monitor of assembly worker

According to the radio frequency identification (RFID) data acquisition scheme of assembly workers, both the workers involved in the assembly tasks and their working time can be obtained from this system. When the assembly workers are within the RFID sensing range, the corresponding workers' information can be queried through the RFID signal. If a task is in process, the working time of the participating workers is increased correspondingly. When the assembly task is completed, the total working time of the participating workers can be obtained.

(3) Monitor of logistics

Logistics distribution of assembly resources (tools, parts, and materials) is accompanied by the work order. The large assembly resources are placed in trays with RFID tags and distributed by automated guided vehicles (AGVs). Each of them is labeled by a two-dimensional code. The workers receive them through scanning, and the corresponding received information (receiver, receiving time, receiving station, etc.) is recorded in the system. Administrators and workers can access relevant information at any time. The small assembly resources are distributed directly to the line inventory before production.

(4) Monitor of assembly progress

The assembly progress, i.e., the execution state of the process, is fed back by workers in the fixed terminal or the mobile terminal. It usually contains five state points: start, suspension, continuation, completion, and end. As shown in Figure 8, by comparing the recorded start and end times and the initial planned ones, we can determine whether the assembly progress lags behind. And the abnormal assembly quality can also be detected timely according to the quality inspection results before the end of the assembly. The worker should report the abnormality, and the abnormality handle module will be triggered when the assembly schedule lags behind, or the quality is abnormal.

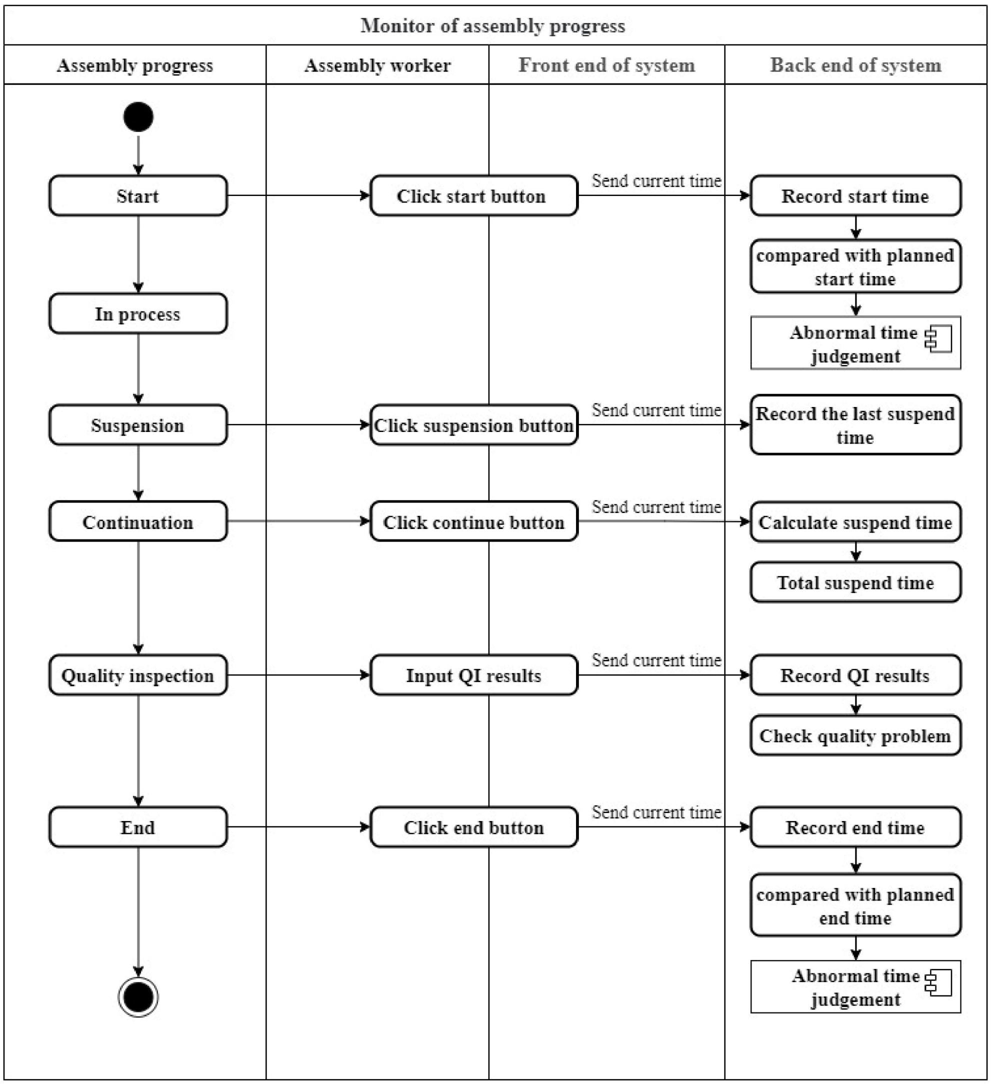


Figure 8. Assembly progress monitoring.

Through the application of the proposed system in a Chinese automobile manufacturing enterprise for a period of time, conclusions can be drawn that all of the above operations are conducive to the timely discovery and handle abnormalities of the worker shortage, untimely resource distribution, and abnormal quality, as well as the adjustment and optimization of assembly schedule in case of progress deviation. The result is the improvement of assembly efficiency and line balance, etc.

5.2. Performance Analysis of the Proposed System

To gain a more comprehensive and digitized analysis of the proposed system, system performance is verified and described from four different aspects of the completion rate of the process data, the production factor coverage rate, the physical control rate, and the line balance rate.

(1) Completion rate of process data

As a highly-automated assembly line, the workshop had already collected and mastered some data related to the transmission front and middle case assembly line and its operation. However, due to the existence of manual stations and the inability of the workshop MES system to directly and real-time manage the entire operation process of the assembly line, the current data control of the enterprise was still insufficient.

The completion rate of the process data is a measure of the degree to which the system can master the process data related to assembly-line operation, such as production resources, logistics, and so on. It is the basis of whether the workshop can control the assembly schedule in real time and accurately. As shown in Equation (1).

$$PDCR = \frac{\text{KPN}}{\text{KPNA}} \cdot 100\%, \tag{1}$$

KPN represents the sum of process elements in a system, while KPNA represents the sum of process elements in an assembly line that needs to be managed systematically.

KPNA is divided according to the principle of "person–machine–material–method–quality inspection". The specific contents are listed in Table 1. Then the calculations of KPN and KPNA by Equations (2) and (3).

Table 1. Content of process elements.

Process	Element Point
Person (P)	Each process requires designated person (type of work and quantity), each record counts as a "point".
Machine (Mac)	Each process binding equipment at the station, each equipment counts as a "point"; each process requires a variety of cutting tools, measuring tools, fixtures, etc., and one record counts as a "point".
Material (Mat)	Each process requires a variety of materials, and one record counts as a "point".
Method (Met)	Process drawings, Operating procedures, work steps, appendix, etc., each work step counts as a "point", and appendix count as a "point".
Quality inspection (QI)	Quality inspection records for each process, each record counts as a "point".

$$\text{KPN} = \left(\sum_{i=1}^{n} P_i + Mac_i + Mat_i + Met_i + QI_i \right), \tag{2}$$

$$\text{KPNA} = \sum_{\text{J}} KPN_j, \tag{3}$$

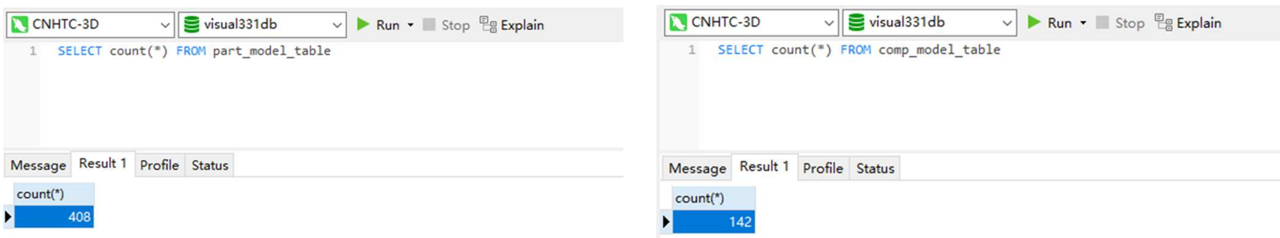
n is the total number of work steps included in the line, that is, $i = \{1, 2, 3 \ldots n\}$. J is the total number of processes included in the line, i.e., $j = \{1, 2, 3, \ldots, J\}$.

(2) Production factor coverage rate

Production factor coverage rate mainly measures the degree to which the system can master a 3D visualization model of the factors of production, i.e., equipment and parts. It is an important index to measure the digitization level of the system and can be calculated by Equation (4).

$$PFCR = \frac{\text{TNPFs}}{\text{TNPFl}} \cdot 100\%, \quad (4)$$

TNPFs represents the total number of 3D visualization models of equipment and parts contained in the proposed system, and TNPFl represents the total number of equipment and parts contained in the transmission front and middle case assembly line. TNPFs can be counted from the project files of material inventories and resource libraries of the system, as shown in Figure 9.



(**a**) The number of material inventories (**b**) The number of resource libraries

Figure 9. The number of material inventories and resource libraries contained in the project file.

(3) Physical control ratio

Physical control is basically similar to process but with slight differences. For example, what is described in the process is the configuration of workers, but the actual number of workers in the physical control, as shown in Table 2. physical control ratio can be calculated by Equation (5).

$$PCR = \frac{\text{TNPEs}}{\text{TNPEl}} \cdot 100\%, \quad (5)$$

Table 2. Content and quantity of physical control.

Category	Physical Entities Should Be Controlled	Actual Physical Entities Be Controlled
assembly worker	The total number of workers of worker team for the assembly line.	There are five manual stations in the line, each of which should record one worker at least.
tooling and equipment	The number of tooling and equipment recorded in the Line Planning Map.	The total number of tooling and equipment actually used in the line.
Product and parts	The total number of products and parts according to MES of the workshop.	Product order number and part order number from BoM.

TNPEs represents the total number of physical entities controlled by the system, and TNPEl represents the total number of physical entities involved in the transmission front and middle case assembly line.

(4) Line balance rate

Assembly line balance is to average all the processes of assembly and adjust the working load so that the operation time of each station is as close as possible. Assembly line balance is the key to ensuring the long-term stable operation of the line. Line balance rate is a direct measure index of the level of assembly line balance, as shown in Equation (6).

$$BR = \left(\sum_{j \in J} \frac{ST_j}{ST_{max}} \cdot N \right) \cdot 100\%, \quad (6)$$

Although the assembly line has been well planned in the design stage, there will be a large deviation in the actual operation. As shown in Table 3, the assembly line of the transmission front and middle case contains 12 stations, and the maximum load of all stations is 178 s.

Table 3. Operation contents of each station on transmission front and middle case assembly line.

Station No.	Operation Contents	Operation Time (s)
1	Automatic loading	142
2	Preload the front case	156
3	Dowel installation	167
4	Preinstall front case cylinder head bolts A	178
5	Preinstall front case cylinder head bolts B	115
6	Heat front case bearing hole	85
7	Lifting shaft assembly	100
8	Press the shafting to the front housing	46
9	Preinstall idler wheel and middle case	159
10	middle case pressing	40
11	Tighten the front case nut	177
12	Press and install idler shaft and countershaft bearing	115

By observing the operation of a period of time, it can be found that the worker allocation, the division of working procedure, and the division of workstations are unreasonable in the current assembly line, as well as the optimized strategies proposed. For example, stations 4, 5, and 11 can be operated by multiple people, and their operation time can be reduced by configuring multiple people to work at the same time. The operation tasks of stations 6, 7, and 8 all belong to the shafting installation, which could be combined into a station, and some of their operations can be combined or performed in parallel. The work tasks of stations 9 and 10 are to complete the middle case on-line, which could be combined into a station, and the operation of pre-installation of the idler component is closely related to the idler assembly in part assembly line; therefore, it can be moved to the part assembly line to ensure it can be pre-installed in advance. The nuts on the side are not easy to operate, and the time fluctuates greatly. Its operation time is effectively reduced by improving the design of the tooling, eventually. In addition, logistics optimization can also be carried out to ensure the timely replenishment of case materials.

After the above optimization, the operation contents of each station and their operation time are optimized, as shown in Table 4. Then the line balance rate is increased to 89.37%.

Table 4. Optimization version of operation contents of each station.

Station No.	Operation Contents	Operation Time (s)
1	Automatic loading	120
2	Preload the front case	120
3	Dowel installation	120
4	Preinstall front case cylinder head bolts	136
5	shafting installation	110
6	middle case on-line	129
7	Tighten the front case nut	122
8	Press and install idler shaft and countershaft bearing	115

(5) Downtime ratio

For a highly automated assembly line, the downtime ratio of equipment is one of the indicators that cannot be ignored to restrict the stable operation of the assembly line. Downtime ratio is calculated by Equation (7).

$$SR = \frac{\mathrm{Dn}}{\mathrm{PC}} \times 100\%, \quad (7)$$

Dn means the number of downtimes, PC represents production capacity, and Dn and PC are both statistics of the line running for a period of time. According to exception statistics, only critical exceptions can cause downtime, as shown in Table 5.

Table 5. Types of exceptions that cause downtime.

Types of Exceptions	Notes
Robot failure	This occurs on robotic arm R1 or R2.
Turret fault	This occurs on station 1.
Servo motor alarm	This occurs on pressing devices.

Eventually, the value of the completion rate of the process data, production factor coverage rate, physical control ratio, and line balance rate before and after CPS (i.e., the use of this system) is shown in Table 6.

Table 6. Comparison of results.

Performance	Not CPS	CPS
completeness rate of process data	56%	85%
production factor coverage rate	41%	92%
physical control ratio	60%	92%
line balance rate	69.27%	87.43%
downtime ratio	1‰	0.3‰

It can be concluded from Table 6 that the system developed in this paper is successful because most of the key process data, operation data, and physical entities are mastered. This also explains from a scientific point of view why the proposed system can achieve good results on-site; that is, guiding actual production, significant and timely control of the process data and physical entities, as well as extensive coverage of the key factors. Furthermore, it is verified that our system is very valuable in improving the line balance rate and downtime ratio, which are the results of the actual operation of the system on the production site following the actual production line for a period of time. The result shows the effectiveness of the research method in this paper; on one side, the operation process of the assembly line can be further controlled, and the actual production can be guided by the mastery of real-time data and physical entities of the proposed system. On the other side, the actual production process can be optimized effectively through the system's timely feedback and processing when meeting exceptions. Secondly, it also demonstrates that the cyber–physical fusion technology as a new method to solve the production process' optimization control under the environment of Industry 4.0 has great advantages and development prospects. In addition, another conclusion can be inferred that the cost optimization will be considerable with the long-term use of this system. Finally, a conclusion can be drawn that it is feasible for manufacturing enterprises to improve manufacturing efficiency through the digital transformation of production lines.

6. Conclusions and Perspectives

To solve the low level of informatization and poor efficiency of information transmission in the current transmission assembly workshop, this paper carried out a CPS study on the front and middle case assembly line of transmissions as a pilot. At first, the characteristics and problems of the transmission front and middle case assembly line were analyzed. Secondly, a three-layer CPS framework system was proposed based on the technology of information identification, collection, and transmission of IoT, the physical assembly system, assembly progress monitoring system, and assembly control system were constructed, respectively. Then the control system for the assembly line of the transmission front and middle case was developed through programming language and database system. Finally, the developed system was successfully applied in a transmission assembly workshop of a heavy automobile factory. The results showed that the system greatly improved the workshop information level and information transmission efficiency, realized the real-time supervision and control of the transmission front and middle case assembly process, and timely detection and treatment of unexpected events. It is helpful for the improvement of assembly efficiency and control of costs. In addition, to the best of our knowledge, this article is the first attempt and exploration to optimize control of transmission front middle case assembly line with digital method and technology, which fills the gap in this research.

Although the current work achieved positive results, future research can be carried out from the following two directions to effectively guide the actual operation and optimization of the assembly line.

(1) Implementation level: systematic promotion and popularization. At present, this system is only applied to one assembly line of transmission front and middle case. In the future, it is expected to be applied and promoted to the whole transmission assembly line and even to the whole workshop and factory. At this point, many practical issues need to be considered, such as a better allocation of workers. Due to the application of the system, all the operations of the workers are strictly controlled and recorded, and they require additional relevant training. The non-cooperation and changeable proficiency of the workers should be considered. In addition, logistics distribution is also a major factor in ensuring the efficiency of assembly. The integrated optimization control of the product assembly process, worker allocation, and logistics plan should be considered.

(2) Technical level: intelligent formulation of optimization strategies. Although after the application of this system for a period of time, some unreasonable problems with worker allocation, the division of working procedure, and the division of workstations were found, and optimized strategies were proposed. However, these strategies were based on worker experience and historical knowledge and did not change the assignment sequence of tasks. In the future, intelligent optimization algorithms can be designed and nested into the system to guide actual production and truly realize efficient real-time control of the product assembly process.

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