Data-driven remanufacturing assembly intelligent control system for improving resource and production efficiency

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Original Article

Keywords: Data-driven, Remanufacturing, Assembly, Intelligent control, Production efficiency, Resource efficiency

Posted Date: May 23rd, 2020

DOI: https://doi.org/10.21203/rs.3.rs-30235/v1

Title page

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ORIGINAL ARTICLE

Data-driven remanufacturing assembly intelligent control system for improving resource and production efficiency

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Received June xx, 201x; revised February xx, 201x; accepted March xx, 201x

Abstract: Remanufacturing has been considered to be one of the most effective ways to deal with sustainable manufacturing. This paper proposes a data-driven intelligent control system for improving the production and resource efficiency of the remanufacturing assembly systems. First, an optimization model of the reassembly scheme is established for minimizing the quality loss and comprehensive cost. Remanufactured parts are measured, grouped, coded, and dimensional chain calculated based on the data acquisition and processing technology. Then, an intelligent control method for remanufacturing assembly process is proposed, which is a real-time monitoring and dynamic compensation response to abnormal quality to achieve intelligent control of reassembly process. The intelligent control information system that include information perception and fusion technology, real-time monitoring and dynamic compensation architecture are studied and implemented through data-driven technologies. Finally, a case study illustrates its practicability offering a technical support for sustainability of remanufacturing.
Keywords: Data-driven; Remanufacturing • Assembly; Intelligent control • Production efficiency • Resource efficiency

1 Introduction

With the rapid development of the economy and the society, the contradiction between the economic growth and the resource consumption in the world has become increasingly serious [1]. Driven by rapid urbanization and population growth, it is expected that annual global waste production will increase from 2.01 billion tons in 2016 to 3.4 billion tons in the next 30 years [2]. Garbage disposal has generated 1.6 billion tons of carbon dioxide equivalents in 2016, accounting for about 5% of global emissions. The remanufacturing technology with low carbon and energy saving is becoming more and more important. It has become one of the effective ways to solve the problem of world resource crisis and environmental pollution [3]. Remanufacturing is considered to be one of the best ways to protect the global ecological environment and solve the shortage of resources [4], and it is of great significance to the global energy crisis and ecological environment protection.

However, the remanufactured products with low carbon and environmental protection are difficult to meet customer expectations [5] and market demand [6]. The quality of remanufactured products becomes the shackle of the development of the remanufacturing industry [7]. How to assemble the uncertainty of remanufactured parts with high production and resource efficiency becomes a challenge for the remanufacturing assembly system [8]. In order to reduce the quality error caused by the uncertainty of remanufactured parts, more and more experts and scholars are research on remanufacturing process management in recent years. The relevant literatures are as follows. On the optimization model of remanufacturing assembly production, Oh and Behdad [9] studied a graph-based optimization model for simultaneous reassembly and procurement planning in assemble-to-order remanufacturing systems. Considering inventory and reassembly capability, Zahraei [10] proposed a recover-and-assemble remanufacturing system to optimize smoothing and the safety stocks. Soh [11] proposed a methodology for a systematic, concurrent consideration of design for reassembly and disassembly guidelines and constraints for product remanufacturing. Cho [12] studied a mathematical model and solution algorithms to determine the disassembly, reprocessing and reassembly lot-sizes. Jiang [13]

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presented an optimization method for remanufacturing process planning for improving reliability and reducing cost in remanufacturing systems. Yu and Lee [14] studied a scheduling algorithm for job-shop-type remanufacturing systems with parts matching requirement. These studies mainly focused on minimizing costs and maximizing benefits to construct optimization models and methods for remanufacturing assembly systems in uncertain environments.

As for the management direction of remanufacturing system, Ponte studied the value of regulating returns for enhancing the dynamic behaviour of hybrid manufacturing-remanufacturing systems [15]. Arredondo-Soto explored the impact of human resources on remanufacturing process, internal complexity, perceived quality of core, numerosity, and key process indicators [16]. Liu studied an integrated optimization control method for remanufacturing assembly system [17]. Ndhaief [18] addressed a joint production and maintenance problem under environmental constraints and reliability issues in a manufacturing/remanufacturing context. Liao has studied an environmental benefits and costs assessment model for remanufacturing process under quality uncertainty [19]. Furthermore, Lean remanufacturing is used as a tool to improve the performance of remanufacturing assembly system by Vasanthakumar [20, 21], and Lean Production is used to tackle remanufacturing process challenges and contribute to shorter lead times by Kurilova [22].

The remanufacturing assembly system with the excellent quality, high efficiency, energy conservation, material saving and environmental protection is the key to ensure that remanufactured products meet diversification, personalization and green of the customer's needs. However, compared with the original manufacturing assembly system, the remanufacturing assembly system has higher uncertainty [23], complexity and dynamics. There are many phenomena, such as low production efficiency [24], unstable product quality, frequent abnormal production accidents and high product repair rate, which make the optimization and control of remanufacturing assembly system become a challenge to be solved in remanufacturing enterprises [25].

As mentioned above, it is the challenge for the management of remanufacturing assembly system to deal with uncertain information, enhance the utilization of remanufactured parts, ensure the stability of remanufacturing assembly process, and improve the quality of remanufactured products. The above studies made an important contribution to improve the management and control ability of reassembly system, but there are also the following research gaps:

- The existing research mainly focuses on quality control, operation optimization, planning and scheduling, and has achieved a lot of meaningful results. However, these are mainly at the level of models and methods, which need to be studied and integrated into an intelligent management and control platform with data-driven to provide greater impetus for the optimal management of remanufacturing assembly system.
- The information scale of remanufacturing assembly system is huge, data individuality is strong, and heterogeneous network relationship is complex. Therefore, it is a significant scientific problem to further study data-driven technology to realize rapid, reliable, stable sharing and integration of production data of reassembly system.

To overcome above-mentioned problems, a data-driven remanufacturing assembly intelligent control system for production and resource efficiency is proposed to increase the utilization ratio of remanufactured parts and improve reassembly quality with the uncertain environment, dynamic process and complex task requirements. Both practical and academic contributions are provided.

From the point of literary theory, the paper is important theoretical significance to propose an optimization model of the reassembly scheme to minimize the quality loss and comprehensive cost, which reveals the connotation of the reassembly quality loss cost and dynamic compensation measures cost in reassembly system. It provides theoretical and methodological support for optimizing the configuration of reassembly resources and improving the production efficiency. From the view of practice, a data-driven remanufacturing assembly intelligent control system is designed, which provides practical technical support for improving the quality of remanufacturing assembly. It can clearly guide production staff how to operate in reassembly process to improve the utilization rate of remanufactured parts and the reassembly quality.

To achieve above research goals, the paper has been organized as follows: Section 2 explains the framework, model and key technologies of intelligent control information system. Section 3 verifies the validity and feasibility of the intelligent control information system in a remanufactured engine assembly workshop.

2 Data-driven remanufacturing assembly intelligent control system

It is undeniable that the Data-driven remanufacturing assembly intelligent control system is the key to guarantee the quality of remanufactured products, which determines performance reliability and customer satisfaction [26]. Therefore, it is important to study Data-driven remanufacturing assembly intelligent control system in order to realize the high production and resource efficiency for the sustainable development of remanufacturing industry. In order to achieve the above goals, this section studies (i) Framework, (ii) Modelling and (iii) Intelligent control information system.

2.1 Framework

The data-driven remanufacturing assembly intelligent control system consists of four layers: the data perception layer, network layer, uncertainty processing layer and intelligent control layer. These four layers are integrated with existing manufacturing execution system (MES) technology and applied in remanufacturing assembly system.

- Remanufacturing assembly data perception layer

Based on the recognition, classification and identification of remanufacturing assembly resources, the data perception layer collects reassembly resources (materials, equipment, personnel, energy and environment) and their status data in the remanufacturing assembly system. For the attribute information of remanufactured parts and the different grades of reassembly operations, special identification and two-dimensional code are used. The remanufacturing assembly perception layer can online recognize and dynamic perceive the information and operation status of remanufacturing assembly resources.

- Remanufacturing assembly network layer

It is mainly composed of fieldbus, sensor network, ethernet, internet, network management system and data management system. It can transform, store, route and transfer protocol for multi-source sensing data.

- Remanufacturing assembly uncertainty processing layer

Based on accurate, real-time and dynamic perception of remanufacturing assembly system, the physical perception data of remanufacturing assembly workshop to assembly resource state and its behavior are mapped by the idea of object-oriented design in the remanufacturing assembly uncertainty optimization layer. It selects data cleaning and screening methods for feature extraction, feature recognition, feature analysis and data routing of perceptual data. Combining with the distributed state fusion estimation model, the acquired information (the basis of identification, measurement and optimization uncertainty) is synthetically processed, and the real-time perceived data (mainly including remanufactured parts, remanufactured assembly process, remanufactured assembly control, etc.) is collected, stored and processed. It integrates and fuses data to represent the operation state of remanufacturing assembly system. On this basis, the uncertainties of remanufacturing assembly are identified and quantified. With the classification selection model of remanufacturing assembly and the online quality control model, the reassembly scheme optimization model is determined.

- Remanufacturing assembly intelligent control layer

The remanufacturing assembly intelligent control layer mainly includes monitors, analyses, extracts and optimizes the perceptual fusion information, and uses human-machine interaction technology to realize the intelligent control for remanufacturing assembly system [27]. Its functions are visual monitoring, real-time tracking, optimal decision-making, on-line quality control, scheme formulation and quality information traceability of remanufacturing assembly system. The intelligent control system also provides services such as resource configuration, data security, protocol conversion and system application [28].

The intelligent control system makes the real-time information collection technology of remanufacturing assembly workshop as the hardware basis. This is an integrated software support with online quality control experts. According to the based database knowledge and workshop information in the reassembly process, the dynamic analysis on quality attribute values of key quality control point in reassembly process is put. It deduces the reassemble scheme optimization model and rationally allocates the resources in the reassembly workshop. It makes the real-time monitor [29] and quality dynamic compensation in the assembly process and realizes remanufacturing intelligent assembly to ensure the reassembly quality and the service security of remanufactured products.

The intelligent control method realizes the online instruction and quality control of reassembly process (Fig 1). It generates system log and updates the history database, which is used to correct the reassembly scheme optimization model and improve the reliability and validity of the models.

The data-driven remanufacturing assembly intelligent control system is a hardware and software integration system, so how to integrate these technologies in a platform is a difficult problem to design and implement. Our solution is as follows:

The integrated development environment is JAVA. Based on intelligent control method, the heterogeneity of reassembly resources are configured and developed by SIMATIC STEP and WINCC. Oracle is used as the Web server database to realize the development of the system and function modules. Industrial middleware (such as KepserverEX) is applied to map the physical address of hardware resources in the configuration system to the address of resource middleware. The remanufacturing assembly process is used as a carrier to configure production processes, reassembly stations (such as intelligent management and control resources, data addresses and production events) and production rules (such as coding rules, dimensional chain and quality standards). The optimization model of the reassembly scheme, real-time monitoring and dynamic compensation are encapsulated in jar file format, which is convenient for system call and transplantation.

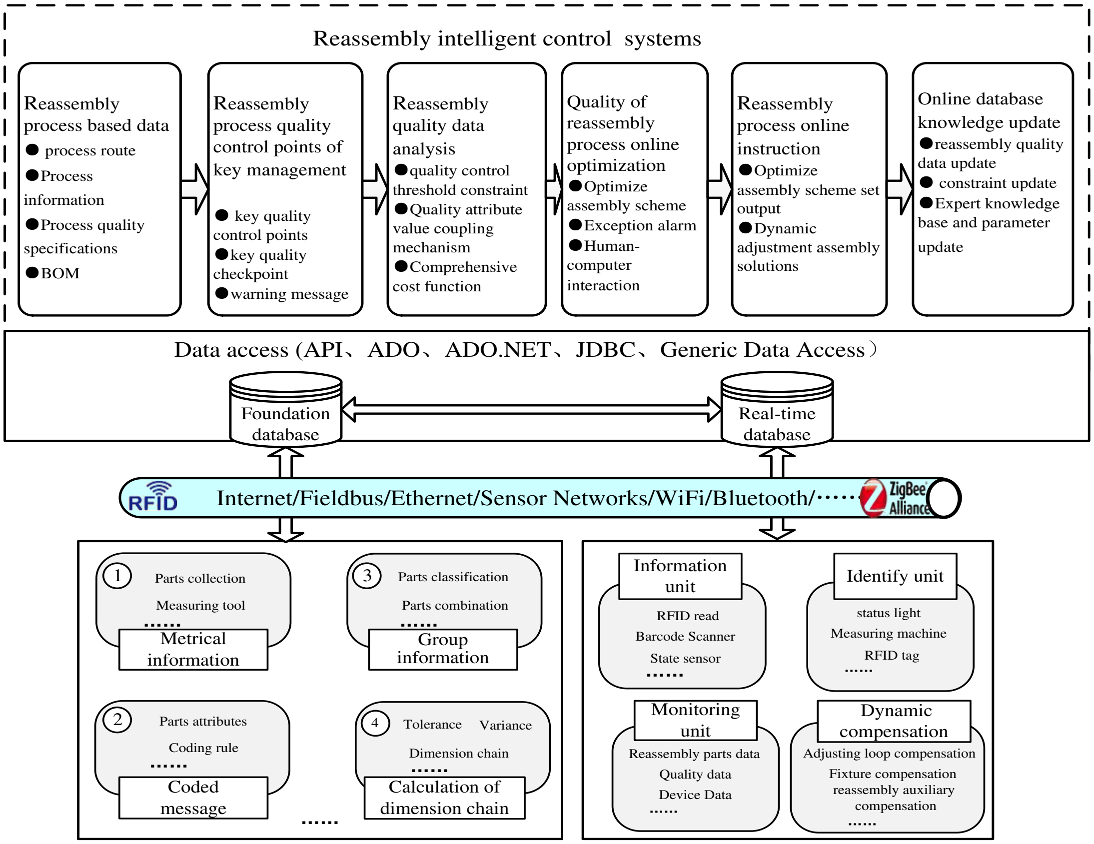

Figure 1 The framework of data-driven remanufacturing assembly intelligent control system

2.2 Modelling

- ***Reassemble scheme optimization model***

In order to accurately describe the reassembly scheme optimization model in reassembly process, this paper makes the following definitions:

Definition 1: The reassembly scheme optimization model is mainly the remanufactured parts, reuse parts and original parts needed in the reassembly workshop, operational and technological standards of reassembly workstations, quality attributes of remanufactured products, materials, information, and methods related to reassembly processes.

Definition 2: Assuming the assemble parts set Θ includes the remanufactured parts, reused parts and original parts. Θ_i is the i -th kind of parts set ($i=1,2,\cdots,n$). Θ_{ij} is the j -th key quality control point of Θ_i ($j=1,2,\cdots,m$).

Definition 3: $P(\Theta_{ij})$ is the actual quality attribute value of Θ_{ij}, including tolerance, torque, bending, roundness and so on. It gets by the online real-time information collection technology.

Definition 4: The reassembly quality transfer function is as follows:

$$P(\Theta_{(i-1)j}) \otimes x_{ij\gamma} = P(\Theta_{ij}) \tag{1}$$

Where, $\otimes$ is the coupling effects of quality attribute value which assembly procedures set on the next one. Where, $x_{ij\gamma}$ is the parts set. When Θ_i selects the γ quality level, $\sum_{\gamma=1}^{\varphi} x_{ij\gamma} = 1$, $x_{ij\gamma}=\{0,1\}$, and $\gamma=1,2,\cdots,\varphi$. Θ_{0j} is a null set, which is the starting point of reassembly.

Dynamic compensation cost constraint: $R(\Theta_{ij})$ is the standard quality control threshold of Θ_{ij} (that is the allowed range of quality attribute value such as tolerance, torque, bending and roundness).

$P(\Theta_{ij})$ must be within the range of $R(\Theta_{ij})$, that is

$$P(\Theta_{ij}) \subseteq R(\Theta_{ij}) \tag{2}$$

If $P(\Theta_{ij})$ without the range of $R(\Theta_{ij})$:

$$P(\Theta_{(i-1)j}) \otimes x_{ij\gamma} \not\subset R(\Theta_{ij}) \tag{3}$$

Then increase the assembly quality dynamic compensation measure $M(\Theta_{ij})$, such as adjusting loop compensation to ensure as follow:

$$P(\Theta_{(i-1)j}) \otimes x_{ij\gamma} \otimes M(\Theta_{ij}) \subseteq R(\Theta_{ij}) \tag{4}$$

Thus, the dynamic compensation cost constraint is

$$Mc(\Theta_{ij}) = h[M(\Theta_{ij})] \tag{5}$$

Reassembly quality loss cost constraint :

The expression of quality loss cost is

$$L_{ij} = k(P(\Theta_{ij}) - R(\Theta_{ij})_{\gamma})^2 / C_{pmi} \tag{6}$$

Where, C_{ij} is the comprehensive cost of the *i*-th key quality control point of *j*-th assemble procedure, including the quality loss cost L_{ij}, assemble cost G_{ij} (including the cost of equipment, manpower, energy consumption and management) and cost of parts' value V_{ij} caused by $P(\Theta_{ij})$ deviating from $R(\Theta_{ij})_{\gamma}$.

k is a quality loss cost constant:

$$k = R(\Theta_{ij})_{\gamma} / [\Delta(r_{ij\gamma})]^2 \tag{7}$$

Where, $\Delta(r_{ij\gamma})$ is the range value of $r_{ij\gamma}$. C_{pmi} is the process capability indices of the *i*-th procedure based on the taguchi.

G_{ij} and V_{ij} come from the actual production data of enterprise:

$$C_{ij} = \sum_{\gamma=1}^{\varphi} (\omega_l L_{ij} + \omega_g G_{ij} + \omega_v V_{ij}) x_{ij\gamma} \tag{8}$$

Where, ω_l, ω_g and ω_v respectively are the adjustment coefficient corresponding to its value, $\omega_l + \omega_g + \omega_v = 1$, $\omega_l \geq 0$, $\omega_g \geq 0$, $\omega_v \geq 0$.

Different levels of parts have different values, and the degree deviating from the target value of key quality control point is also diversity, which causes different quality loss cost. At the same time, it has different cost of dynamic compensation measure. Therefore, the selection has an important influence on the quality and cost. With the target of minimizing the comprehensive cost, the optimization model of reassemble scheme in this paper is as follows:

$$\min F = \sum_{i=1}^{n} \sum_{j=1}^{m} \sum_{\gamma=1}^{\varphi} [(\omega_l L_{ij} + \omega_g G_{ij} + \omega_v V_{ij}) x_{ij\gamma} + Mc(\Theta_{ij})]$$

$$\begin{cases} P(\Theta_{(i-1)j}) \otimes x_{ij\gamma} = P(\Theta_{ij}) \\ P(\Theta_{ij}) \subseteq R(\Theta_{ij}) \\ P(\Theta_{(i-1)j}) \otimes x_{ij\gamma} \otimes M(\Theta_{ij}) \subseteq R(\Theta_{ij}) \\ Mc(\Theta_{ij}) = h[M(\Theta_{ij})] \\ \sum_{\gamma=1}^{\varphi} x_{ij\gamma} = 1 \\ x_{ij\gamma} = \{0,1\} \\ \omega_l + \omega_g + \omega_v = 1 \\ \omega_l \geq 0, \omega_g \geq 0, \omega_v \geq 0 \\ \gamma = 1,2,\cdots,\varphi \\ i = 1,3,\cdots,n \\ j = 1,2,\ldots,m \end{cases} \tag{9}$$

2.3 Intelligent control information system

Based on the framework of the data-driven remanufacturing assembly intelligent control system, reassemble scheme optimization model and its solution, an intelligent control information system is needed to implement this function. Therefore, the following key technologies are necessary for designing and developing the information system.

2.3.1 Information perception and fusion technology

The paper implements the measurement, grouping, coding and calculation of dimension chain by information perception and fusion technology, whose main contents are as follows (Fig 2):

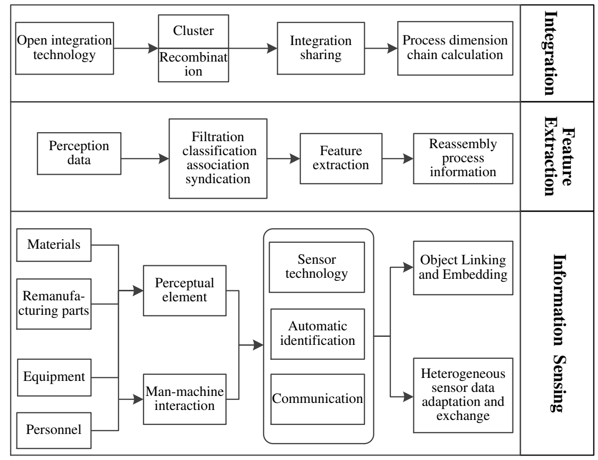

Figure 2 Information perception and fusion technology

Information sensing: with equipping the sensor in personnel, machine, material and other reassembly resource, it uses the internet, communications, computers, automatic identification and sensing technology to solve the adaptation and exchange of heterogeneous data perception problem. It can realize the mapping state and behavior of physical sensing data and reassembly resource, and the active perception of reassembly resources and its process state data.

Feature extraction: the sensory data forms in real-time, dynamic reassembly process information by the complex event processing engine, which is filtering, grouping, association and aggregation for the sensory data of reassembly process to realize the feature extraction.

Information integration: it adopts open object-oriented technology and uses unified standards, rules and codes for all the information in the intelligent control information system of reassembly process. According to the reassembly demand of information, it clusters and regroups the information and its functional structure and correlation, and produces information in the form of unified data, to realize the integration and sharing of reassembly system information.

2.3.2 Distributed state fusion estimation model

To solve the problem of high uncertainty in remanufacturing assembly process, with the support of multi-source information sensing technology, the intelligent control information system collects all kinds of data in the process of remanufacturing and assembly by using Internet technology, communication technology, automatic identification and sensing technology. However, these independent data cannot accurately represent the state of remanufacturing assembly process.

How to fully integrate these multi-source perceptual data, accurately describe the status of the remanufacturing assembly process for evaluation, prediction and optimization the remanufacturing assembly process is a key problem must be solved by the remanufacturing assembly control system. Therefore, the distributed state fusion estimation model is proposed to realize multi-source perceptual data fusion in remanufacturing assembly process. The distributed state fusion estimation model of remanufacturing assembly process is as follows:

Assuming a state vector is:

$$x(i)=\sum_{j=1}^{J}\varsigma_{ij}\hat{x}_{ij} \tag{10}$$

Where, $\hat{x}_{ij}$ is the observation value of inductor for j-th state vector of i-th reassembly station. ς_{ij} is fusion weighted matrix.

Assuming an input vector is:

$$y(i)=\sum_{l=1}^{L}\sigma_{il}\hat{y}_{il} \tag{11}$$

Where, $\hat{y}_{il}$ is the observation value of inductor for j-th input vector of i-th reassembly station. σ_{il} is fusion weighted matrix.

So the state equation of remanufacturing assembly process is:

$$x(i+1)=\Phi x(i)+\Psi y(i) \tag{12}$$

Where, i is the i-th reassembly station, $x(i)\in R^{n\times 1}$ is state vector of the i-th reassembly station. $y(i)\in R^{m\times 1}$ is input vector of the i-th reassembly station, includes the attributes of i-th parts and the operation of i-th reassembly station. Φ and Ψ are the state fusion matrix. They are mainly obtained from actual production data of remanufacturing assembly workshop.

The distributed state fusion estimation model collects and processes all kinds of information of remanufacturing assembly process by multi-source perception technology, and then forms enough accurate information to characterize the state of remanufacturing assembly process, eliminates the uncertainty of remanufacturing assembly process, and predicts the shape and performance of remanufacturing assembly. It provides support for quality control of remanufacturing assembly.

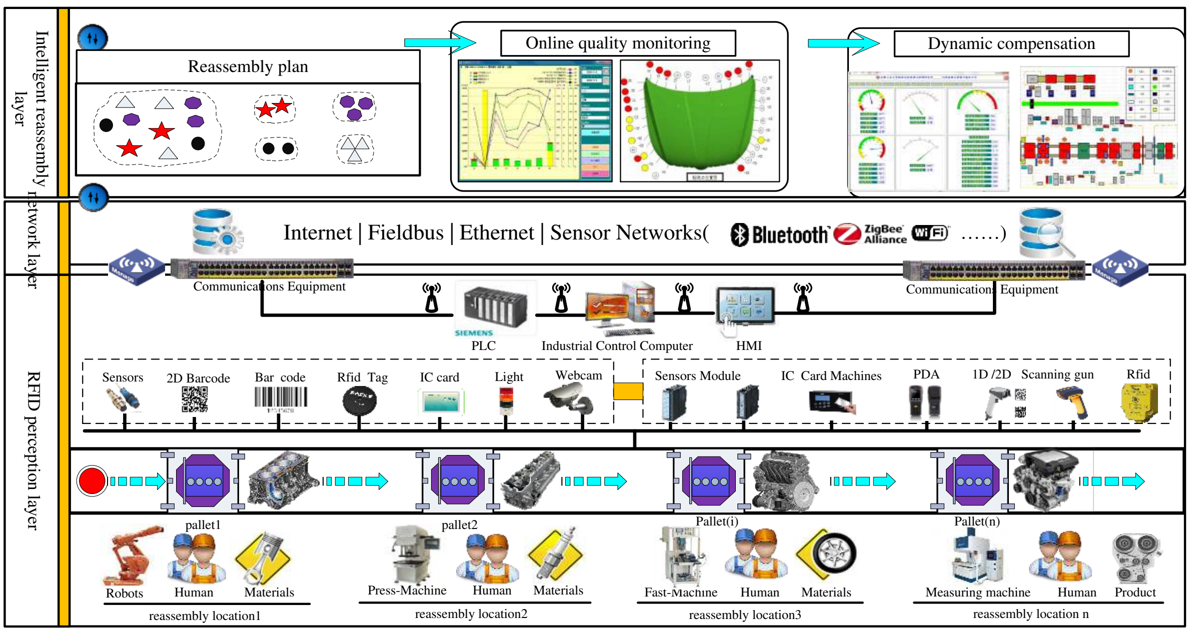

Figure 3 Real-time monitoring and dynamic compensation of reassembly quality

2.3.3 Real-time monitoring and dynamic compensation of reassembly quality

Due to the high uncertainty of remanufacturing production process, abnormal events in reassembly process occurred frequently. The quality control of reassembly must be combined with real-time situation of production site, so that all kinds of unexpected problems can be solved timely and accurately. Accurate and reliable information and real-time quality data of remanufactured parts are the premise of successful running for intelligent control information system in reassembly process. Firstly, it identifies the quality data of products, and then collects the quality attribute value of key quality control point. On the basis of the real-time reassembly information collection and disposition in remanufacturing workshop, the real-time monitoring and dynamic compensation of reassembly quality can be realized. Its main function framework is as shown in Fig 3.

RFID perception layer implementation: It comprehensively uses the Internet, communications, computer, automatic recognition and sensing technology, and realizes the active perception the state data of remanufactured parts and reassembly process. By defining the open and interoperable standards, linking and embedding technology of use object, the real-time and dynamic mapping of part information and reassembly resource's state and behavior is realized, and the information of reassembly system is adopted unified standards, rules and codes, to realize the information identification, grouping, coding, computation of dimension chain of remanufactured parts.

Network layer: it is mainly made up of reassembly workshop fieldbus, sensor network, Ethernet fieldbus, the internet, network management system, and data management system. It can exchange, store, route and transfer the data of reassembly workshop.

Intelligent reassembly layer: on the basis of monitoring, analyzing and extracting the above information, intelligent reassembly control system considers the loss cost of assembly quality and dynamic compensation measure cost of remanufacturing assembly quality, and construct the reassembly scheme optimization model, with the target of minimizing the comprehensive cost. By the intelligent optimization algorithm, the optimal reassembly scheme is put. Under the support of real-time information of reassembly workshop, online real-time monitoring of quality is realized. When the reassembly quality is abnormal, it will make dynamic compensation and realize intelligent control in reassembly process.

3 Case study

This case illustrates the data-driven remanufacturing assembly intelligent control system in a remanufacturing enterprise, also analyzes the significance and value. The case study has four aspects: (1) background, (2) system analysis, (3) application effect, and (4) discussion and management enlightenment.

3.1 Background

A remanufactured engine company dismantled the recycled waste engine, cleaned and tested the worn parts and reused parts, and remanufactured the worn parts by the remanufacturing technical transformation. Then, the reused parts, remanufacturing parts and original parts are assembly in the reassembly workshop. After field investigation, the project team found the following problems in the company's remanufactured engine assembly workshop.

However, there are many uncertain factors in the reassembly process, the tolerance zone of the quality attribute value of remanufacturing parts and reused parts is large, the range of reassembly quality error fluctuates greatly, the control standard of reassembly quality refers to the original manufacturing standard, and the utilization rate of remanufactured parts is low.

- Low efficiency of manual data acquisition

The data of assembly process is expressed in the form of work order. After hot test and offline, the work order is collected and entered into the system database. Hand-based data processing method makes the flow of all kinds of information in the remanufacturing process unobstructed, unable to achieve real-time feedback and control of information.

- Poor quality management model

Operators of each reassembly station complete the operation according to the process specifications, and the reassembly quality standards copy the original assembly standards. The repairing rate of the reassembly workshop is as high as 15%, the after-sales service cost is high, and large batch claims occur one after another.

- Insufficient monitoring and control of reassembly line

The number of remanufacturing assembly lines is small, but more than 100 models are produced. There are many factors affecting reassembly quality, but the control methods and technical effects are limited, and the quality of remanufactured products is difficult to guarantee.

In view of these difficulties and challenges, the prototype of intelligent control information system for remanufactured engine assembly process is designed and developed.

3.2 System analysis

Based on J2EE framework, Oracle is used as Web server database. The data-driven remanufacturing assembly intelligent control system for remanufactured engine assembly process has been developed with the associated enabling technology.

In view of the actual situation of the reassembly workshop of engine remanufacturing, the information collection and fusion system adopts RFID, IC reader, PDA and scanning gun to integrate in human-machine interface. It provides real-time and dynamic data support for intelligent control information system of reassembly process (Fig 4).

With the help of the information collection and fusion system, information collection interface (Fig 4-i) can collect information of remanufactured crankshaft (Key Quality Control Points: First Axis Diameter Width; Quality attribute: 45.90; Reassembly cost: 1.80; and so on), reassembly workstations (OP104) and operator (ZXL1001231). According to the BOM database of the remanufactured engine (STKWD) (Fig 4-ii), the intelligent control information system can be querying and displaying the order details (STK20140511) and reassembly process of the remanufactured engine (STKWD) (Fig 4-iii). Then, the reassembly quality loss cost and dynamic compensation measures cost are calculated, the optimization model of reassembles scheme is established for the minimum quality loss and comprehensive cost. It is executed by the program in the background of the system (Fig 4-iv). Based on the multi-source information perception and fusion technology, the intelligent control information system can monitor the key quality (OP104: axial clearance is too small) information of remanufacturing crankshaft assembly station in real time (Fig 4-v), and provide support for the reassembly quality optimization control through the dynamic monitoring of the quality control chart (Adjustment ring compensation). It also makes dynamic compensation response to the abnormal quality situation to realize intelligent control in reassembly process (Fig 4-vi). All the remanufacturing parts assembly information is input, and then optimal feasible assembly solution is deduced in accordance with the optimization model of reassemble scheme. The system marks the solution, and outputs the optimized remanufacturing assembly scheme (Fig 4-vii).

The data-driven remanufacturing assembly intelligent control system builds a system log to facilitate the storage and query of information related to reassembly process and provides support for reassembly traceability (Fig 4-viii).

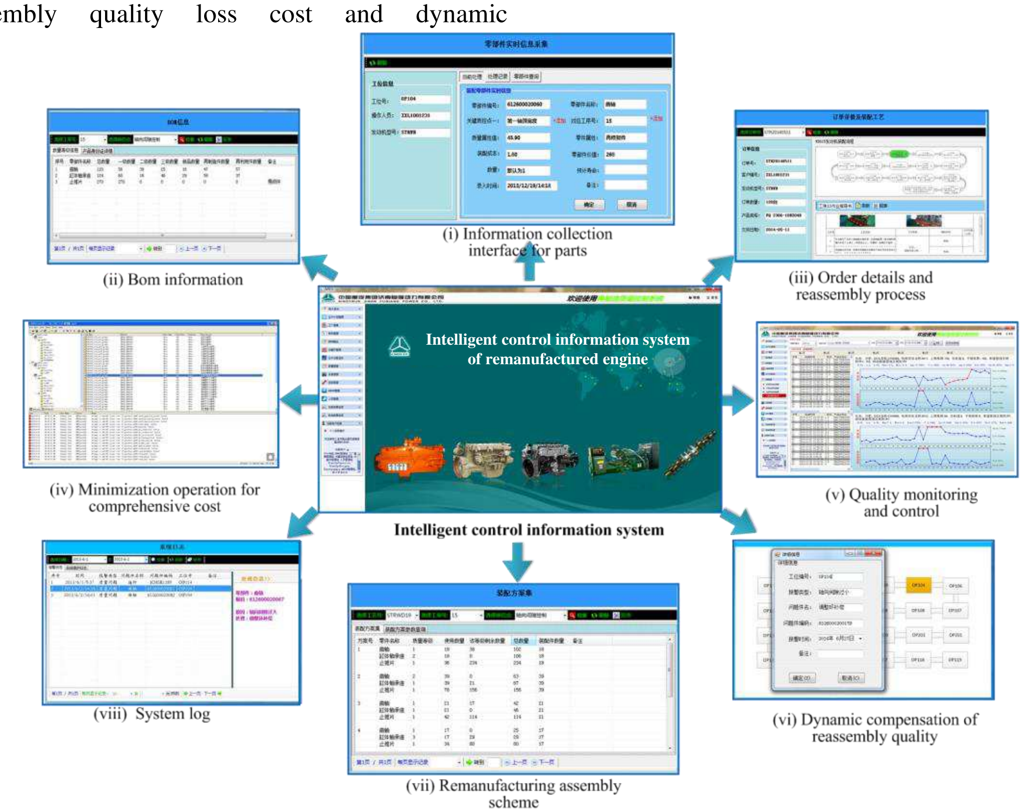

Figure 4 The intelligent control prototype system

3.3 Discussion

Since the data-driven remanufacturing assembly intelligent control system was implemented since 2018 in the remanufacturing engine reassembly workshop, its benefits are as follows.

In remanufacturing production inventory management and optimization, the intelligent control system can deduce the optimized remanufacturing assembly scheme, according to the information of remanufactured parts, reused parts and original parts in database. It has extended the dimensional accuracy of remanufactured parts, with tolerance reduced by 20% and variance reduced by 40%.

In remanufacturing production process control and quality management, the intelligent control system also can track the position of the remanufactured parts on the reassembly line, monitor the operation process, feedback the results of the reassembly station operation in real time, and accurately guide the operation of the workers in the reassembly process. For example, in the reassembly station of remanufacturing crankshaft, it improves the axial clearance qualification rate of 14.4%. The intelligent control system increases the passing rate of torque by 3.67%, makes the engine crankshaft run more smoothly, and reduces piston deflection and connecting rod bending.

In remanufacturing workshop stability management, the intelligent control system can realize the monitoring of material flow, information flow and reassembly process in the reassembly workshop, and alarm the abnormal situation for the managers. The average abnormal accident rate in the workshop decreased by 48.7%, and large accidents were eliminated.

In remanufacturing production management and service, the intelligent control system can trace the quality of remanufactured assembly, and trace the quality reasons of remanufactured engine by date, order number, abnormal quality, and fault type. The average percent of pass enhances by 2.462% (Fig 5), and the cost of after-sales service has been reduced by 2.30 million CNY/year. For the remanufacturing enterprise, the intelligent control system can efficiently utilize the production data of enterprises and realize data-driven production optimization, so as to improve the production and resource efficiency of remanufacturing enterprises.

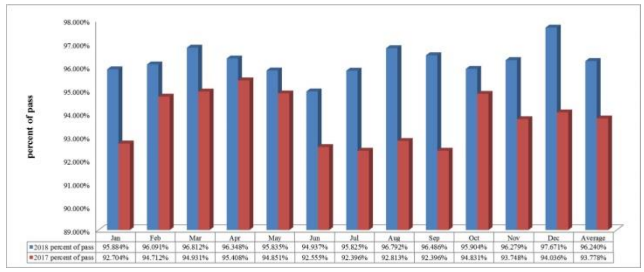

Figure 5 The percent of pass in 2017 and 2018

The data-driven remanufacturing assembly intelligent control system takes remanufacturing product quality, cost, delivery time, energy consumption and waste discharge as control objects, and builds remanufacturing intelligent space on the basis of interconnection and status monitoring of remanufacturing production resources. The remanufacturing intelligent space will connect their independent information systems into a complete, reliable and effective whole, and achieves system and system integration, system and equipment integration, equipment and equipment integration. Intelligent assembly unit is constructed to monitor and calculate the reassembly process in real time. Real-time data of reassembly process are analyzed and mined efficiently. Autonomous optimization control of equipment is realized, and intelligent control of remanufacturing assembly is achieved. For remanufacturing enterprises, the intelligent control system can efficiently utilize the production data of enterprises and realize data-driven production optimization, so as to improve the production and resource efficiency of remanufacturing enterprises.

Compared with the similar direction of literatures, in addition to quality control [17] and uncertain optimization [18, 30], this paper also has system integration. The data-driven remanufacturing assembly intelligent control system is a preliminary exploration of intelligent manufacturing methods and technologies. It is an effective method to deal with the uncertainty of remanufacturing production. Multi-variety, small-batch and individualized for remanufacturing customer requirements [31], uncertain, complex and dynamic remanufacturing assembly process, as well as multi-objective requirements of excellent quality, high efficiency, energy conservation, material saving and environmental protection, urgently need the organic combination of intelligent manufacturing technology and remanufacturing assembly system [32]. Therefore, it is important to study data-driven remanufacturing assembly intelligent control system for production and resource efficiency of remanufacturing industry.

4 Conclusions

Improving the performance and service safety of remanufactured products to meet customer expectations is necessary for the sustainable development of remanufacturing industry, but the uncertainty and complexity of reassembly process has become a constraint to the quality of remanufactured products. In order to deal with this challenge, the data-driven remanufacturing assembly intelligent control system is studied with combination of remanufacturing technology and intelligent technology. Its main innovations are as follows: (i) Base on data acquisition and processing technology, the intelligent control method is proposed to realize measurement, grouping, coding, calculation of dimensional chain and real-time dynamic monitoring, and the reassemble scheme optimization model is built; (ii) information perception and fusion technology and distributed state fusion estimation model are researched for the key technologies of the intelligent control information system; and (iii) the solution of multi-technology integration is studied for the intelligent control system development and implementation. Moreover, the intelligent control information system is developed in reassembly workshop of remanufacturing engine, the results show that the intelligent control system can the results show that the intelligent control system can enhance pass average percent by 2.462%, and reduce the cost of after-sales service by 2.30 million CNY/year.

Of course, this paper is limited to intelligent management of remanufacturing engine assembly workshop, which needs further integration of intelligent space and digital twin technology for remanufacturing system in the future. This paper proposes a train of thought and research direction for the data-driven intelligent management of remanufacturing production, and provides theoretical and technical support for further large-scale and sustainable production in remanufacturing industry.

5 Declaration

Funding

Supported by Key project of the National Natural Science Foundation of China (No. 71632007), Hong Kong Scholars Program (XJ2019059), Chinese Postdoctoral Science Foundation (No. 2017M611574), Humanities and social science research of Ministry of Education (No. 17YJC630082).

Availability of data and materials

The datasets supporting the conclusions of this article are included within the article.

Authors' contributions

The author' contributions are as follows: Wei Cai was in charge of the whole trial; Conghu Liu wrote the manuscript; Guang Zhu and Mengdi Gao assisted with sampling and laboratory analyses.

Competing interests

The authors declare no competing financial interests.

Consent for publication

Not applicable

Ethics approval and consent to participate

Not applicable

Acknowledgements

The authors acknowledge the technical support from Shanghai Jiao Tong University and Hefei University of technology. The project is supported by Key project of the National Natural Science Foundation of China (No. 71632007), Hong Kong Scholars Program (XJ2019059), Chinese Postdoctoral Science Foundation (No. 2017M611574), Humanities and social science research of Ministry of Education (No. 17YJC630082).

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Figures

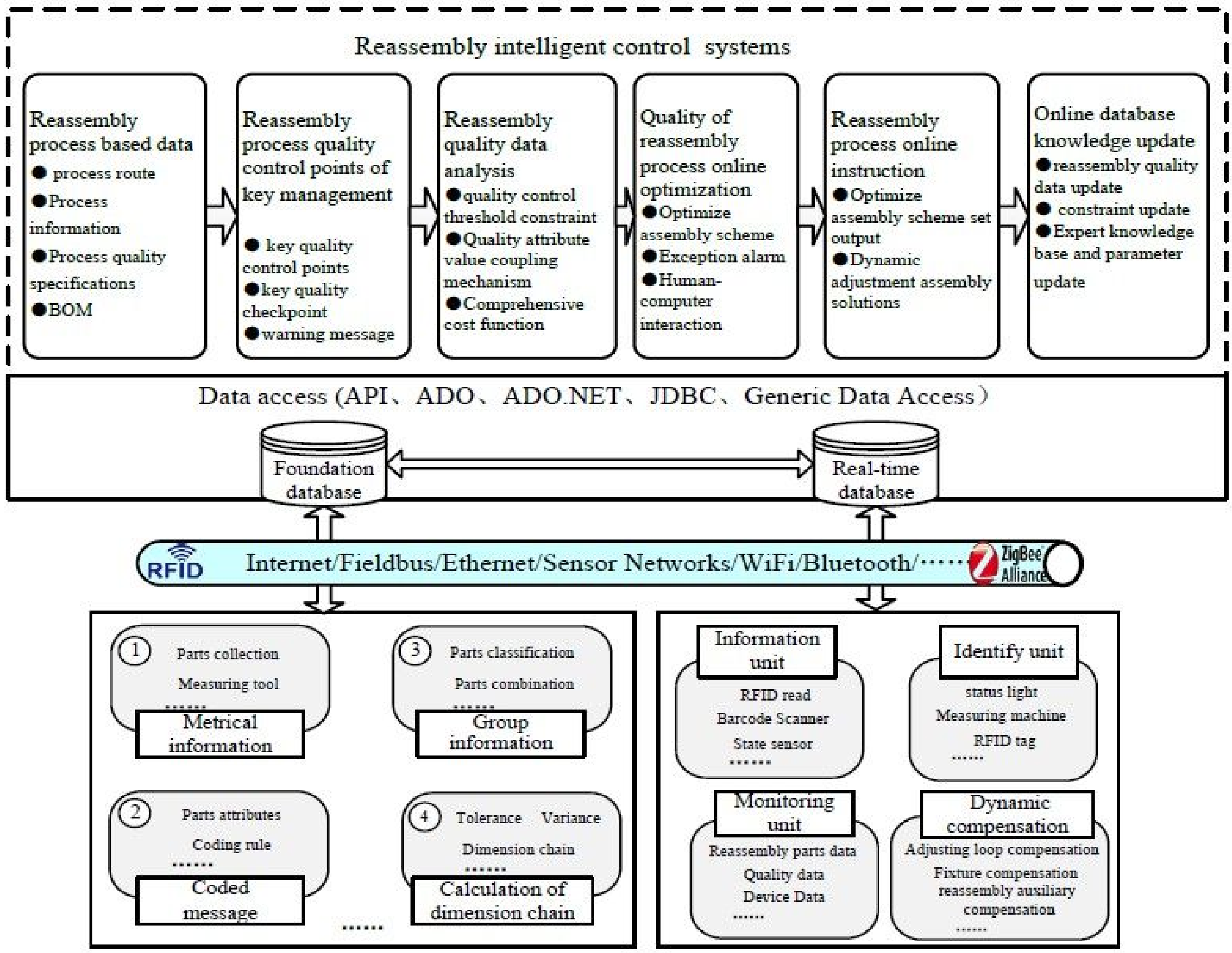

Figure 1

The framework of data-driven remanufacturing assembly intelligent control system

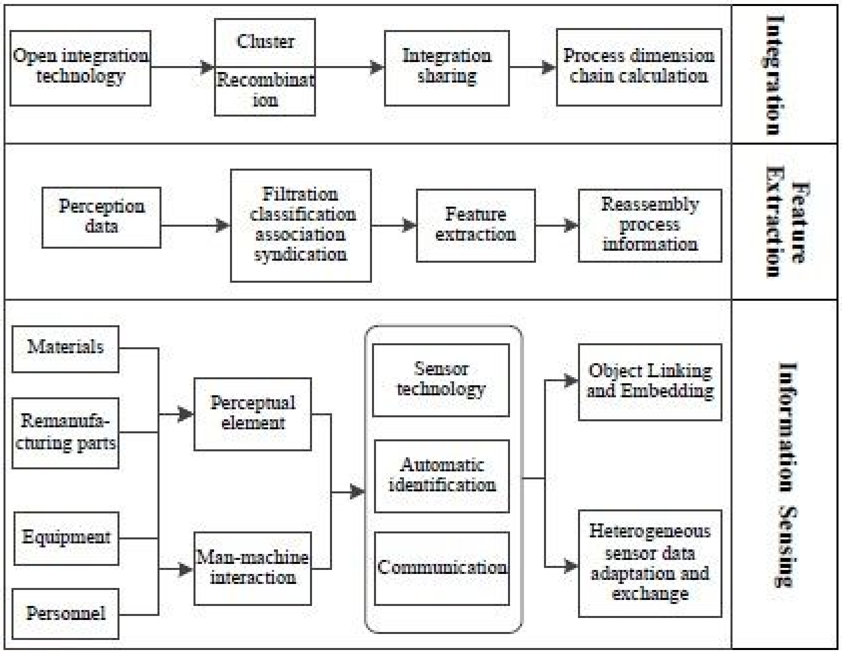

Figure 2

Information perception and fusion technology

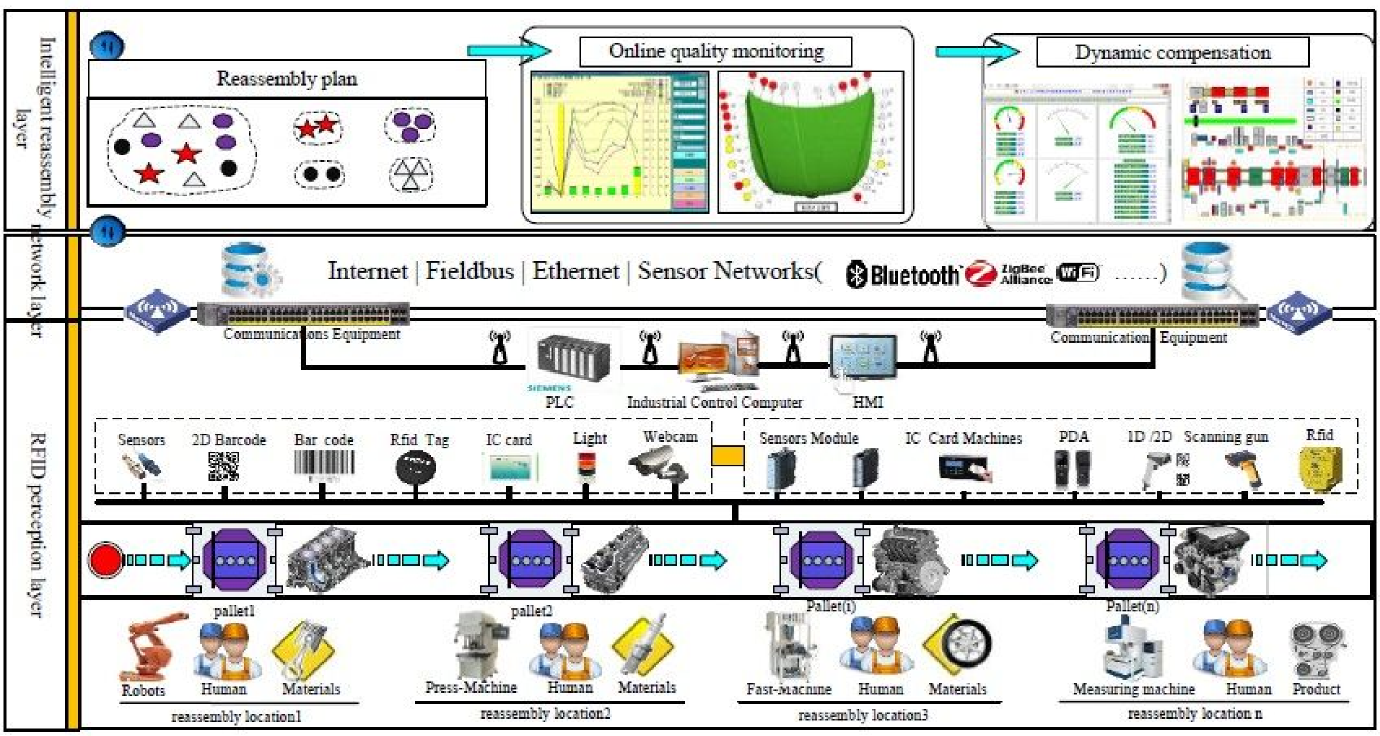

Figure 3

Real-time monitoring and dynamic compensation of reassembly quality

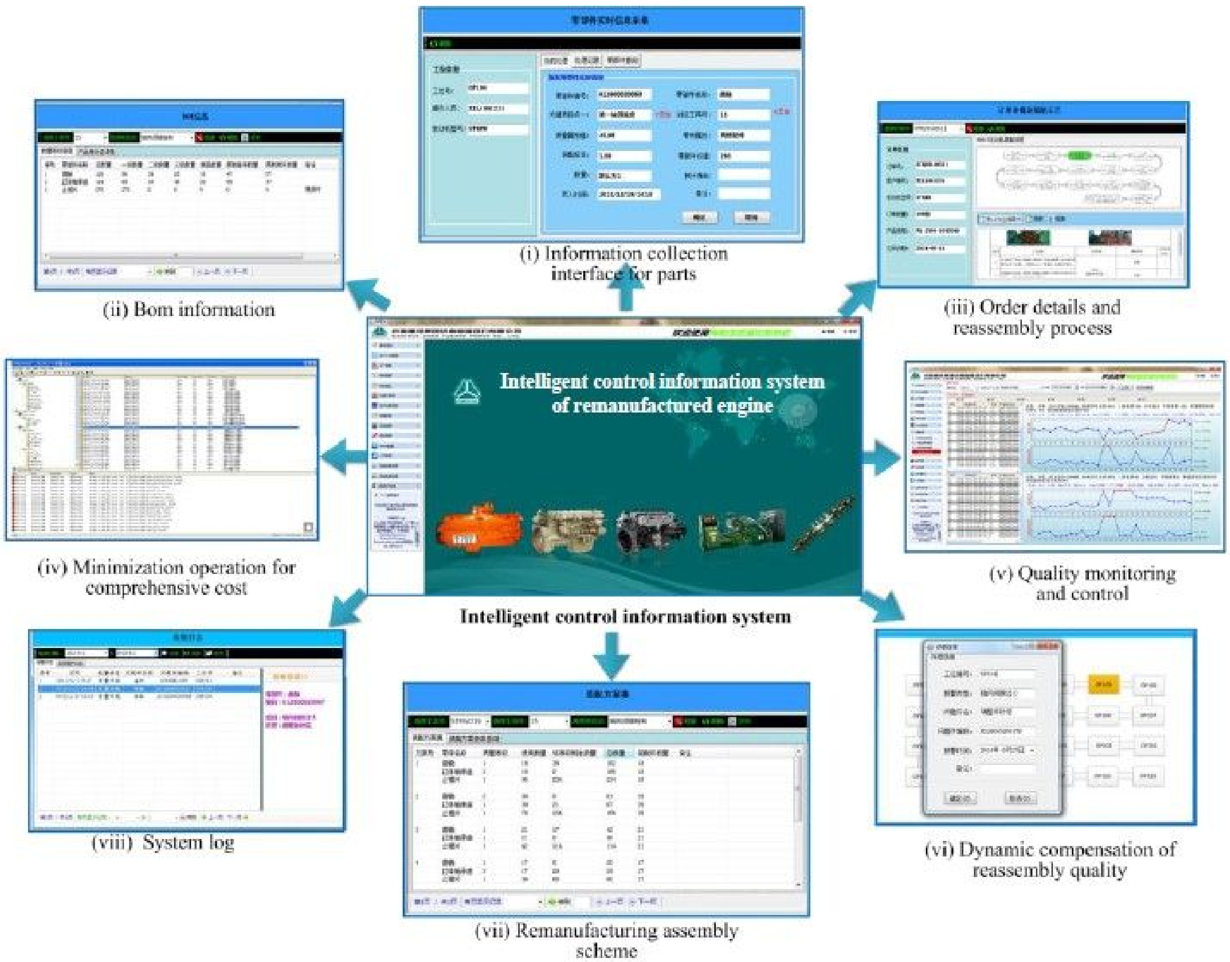

Figure 4

The intelligent control prototype system

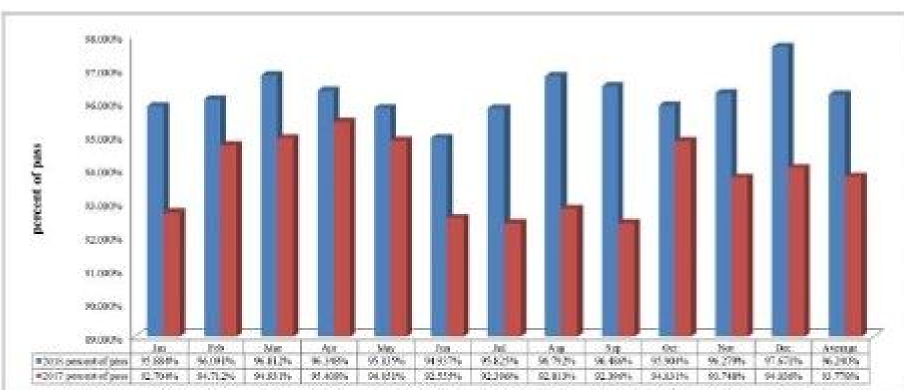

Figure 5

The percent of pass in 2017 and 2018