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Digital twin-driven 3D visualization monitoring and traceability system for general parts in continuous casting machine

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Abstract
There are lots of general parts with frequent maintenance and high interchangeability for continuous casting machine during its operation and maintenance. To acquire the service information of each general part under the environment of high temperature and serious oil pollution for predicting remaining life and preventative maintenance, a digital twin-driven monitoring and traceability system for general parts in continuous casting machine is proposed. First, the systematic architecture of proposed approach is given in detail, where a typical five-layer model for digital twin-driven monitoring and traceability is established. Second, the Web-based 3D visualization monitoring for continuous casting machine is achieved by using lightweight 3D twin model. After that, an assembly model based on polychromatic sets is built for expressing and describing the assembly relationships and assembly process of general parts. Meanwhile, an encoding rule for part and position is put forward by considering assembly position information. On the basis of that, the general parts with total process information are traced in the service life cycle. Finally, digital twin-based 3D visualization monitoring and traceability prototype system is developed and implemented, where the experiment cases verify the effectiveness and feasibility of the proposed approach.

Keywords: Digital twin, 3D twin model, 3D visualization monitoring, Traceability, Polychromatic sets

1. Introduction

Digital twins as precise, virtual copies of machines or systems, are revolutionizing industry. Driven by data collected from sensors in real-time, these sophisticated computer models mirror almost every facet of a product, process or service (Tao and Qi, 2019). For instance, NASA uses digital copies to monitor the state of its spacecraft. Energy companies General Electric and Chevron use them to track the operations of wind turbines. Digital twin is the interaction and deep integration of information space and physical space, taking full advantage of physical model, sensor, operational history data and so on, integrating simulation process of multi-disciplinary, multi-physical, multi-scale and multi-probability, by means of virtual and real interaction feedback, data fusion analysis, decision iteration optimization for enhancing or extending the ability of physical entity (Grieves and Vickers, 2016). As a mirror of physical world, digital twin can be employed to simulating, predicting, and optimizing by simulating physical manufacturing systems and processes. Using digital twin together with intelligent algorithms, organizations can achieve data-driven operation monitoring and optimization (Tao et al., 2018), develop innovative products and services (Söderberg et al., 2017), and diversify value creation (Kaewunruen and Lian, 2019) and business applications.

Digital twin is essentially a system of sustainable process optimization with physical entity and twin model, which is one of the core technologies in the Cyber-Physical System (CPS) (Feng et al., 2018). Digital twin has been attached extensively by researchers. Tao et al. (2019) proposed first Five-dimension digital twin model and gave some application fields of digital twin in the future. DebRoy et al. (2017) constructed a digital twin of additively manufactured (AM) systems to reduce the total number of experiments needed for part qualification, minimize defects and provide structurally sound, reliable parts. Lu et al. (2019a) proposed a slicing-based object fitting method for generating the geometric digital twin of an existing reinforced concrete bridge from four types of labelled point cluster. Sun et al. (2019) presented a digital twin model for cutting tools in machining process ,where digital twin-driven cutting tool wear condition monitoring, remaining useful life prediction, cutting tool selection decision-making and cutting service were addressed

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deeply. Currently, the research about digital twin mainly focuses on product design (Debroy et al., 2017; Lu and Brilakis 2019b), intelligent manufacturing (Schleich et al., 2017; H. Li et al., 2019; Sun et al., 2019), user-defined workshop (Tao, Qi, et al., 2018; Lu et al., 2020; Leng et al., 2019), product operation and maintenance services(Tao and Zhang, 2017; Tuegel et al., 2011; Samir et al., 2019). Visualization, real-time monitoring, fault prediction and health management of equipment in complex environments are considered as typical application fields of digital twin. It together with big data, data mining and intelligent algorithms, can provide a novel solution for preventive maintenance, fault prediction, remaining life prediction of complex mechanical equipment (Qi and Tao, 2018). Therefore, it can provide a novel solution for fault diagnosis and life prediction of general parts in continuous casting machine in the service life cycle.

Continuous casting machine is considered as key steel-making equipment in steel-making enterprise, its second cooling device (segment device) consists of bending segment, bow segment, straightening segment and horizontal segment (Boehmer et al., 1993). Each segment is composed of several roller-groups according to assembly constraints, where the roller-group is combined with mandrel, roller, bearing chock and bearing. The structure scheme of continuous casting machine is shown in Figure 1 and the structure diagram of the segment and roller-group is shown in Figure 2 (Wondrak et al., 2010).

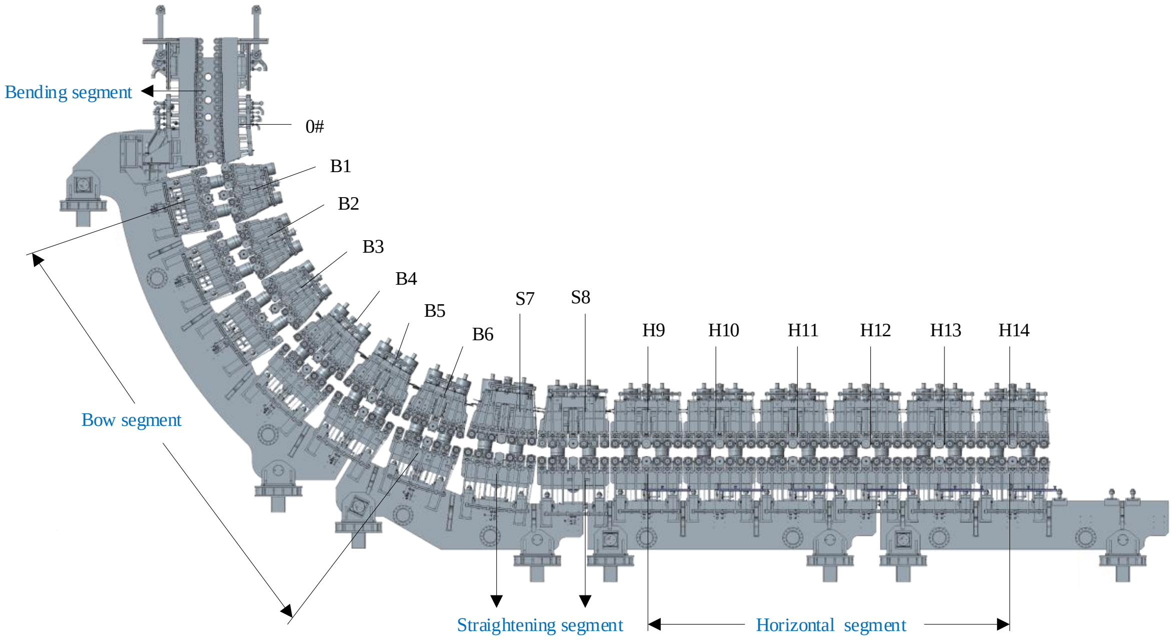

Fig. 1 Structure scheme of continuous casting machine

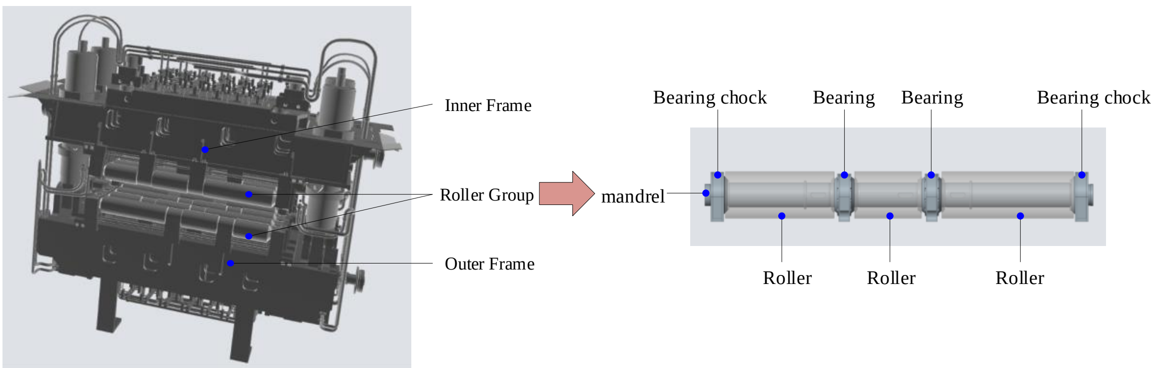

Fig. 2 Structure diagram of segment and roller-group

There are a number of general parts with frequent maintenance and high interchangeability in the assembly process of segment, such as mandrel, roller, bearing chock, bearing, frame and so on. Especially, roller-group assembled by mandrel, roller, bearing chock and bearing involves in the steel slab production directly, where the whole performance of roller-group determines the quality of steel slab production. Due to the uncertainty and randomness of assembly position of rollers in the segment and the position of segment installed in the continuous casting machine, the performance degradation and remaining life of the general parts are different between any two roller-groups. With the change of segment installation position, the external environment, such as temperature, load, and resistance, is different during the steel slab production accordingly. It causes various states of wear, fatigue and bending for casting rollers. Thus, the performance of casting roller has great impact on the quality of steel slab production.

Furthermore, the inventory of steel-making enterprise or maintenance enterprise will store a certain number of segments and casting rollers as spare parts for ensuring the normal operation of continuous casting machine. Thus, those spare parts can be conveniently and quickly installed into the casting machine when faults or maintenance for shortening the time of continuous casting machine shutdown and improving the production capacity of continuous casting machine. Especially, the casting roller as important part in segment has some faults frequently such as wear, crack or bending. Therefore, the continuous casting machine need checked and repaired regularly. There exist lots of rollers, which are equipped with the same size and high interchangeability. However, the casting roller and segment are not marked physically and properly, which can be not monitored and traced in the process of assembly, disassembly, maintenance and overhaul. It has an important influence on its service life and preventive maintenance. In practice, it is difficult for tracking the working position and working condition of general parts under the environment of high temperature and serious oil pollution.

Product's traceability is the basis of the digital twin of casting machine equipment, which provides data source support for twin data. Currently, there exist plenty of works dedicated to traceability, which mainly focus on product quality (Zhang et al., 2011), food safety (George et al., 2019), drug, part in production workshop (Liewald et al., 2018) using Bar or QR code, RFID. Based on that, Alonso-Rorís et al. (2016) proposed a cost-effective and reusable traceability system based on semantic technology for tracing and controlling processes and products. Byun et al. (2018) presented a graph-oriented persistence approach for the visibility data to achieve efficient and privacy-enhanced object traceability based on unified and linked EPCIS events. To solve the data information transmission and sharing problem, Li et al. (2019) constructed a three-layer model of real-time data based on RFID for tracking and monitoring the workshop production process. The mentioned previously methods can solve the issue of product traceability in the general environment. Nevertheless, the RFID tag and bar code label will not work under the environment of high temperature and serious oil pollution.

Currently, there are few studies on the traceability for general parts in continuous casting machine. It is also very necessary to obtain the complex working condition information of each general part by means of monitoring together with digital twin. Based on digital twin, monitoring and traceability for the general parts in continuous casting machine can not only help the operator manage online running information of general parts in the form of 3D visualization, but also record and track their service information. The relationships mapping between general parts and working position can provide data source for performance degradation analysis and residual life prediction of general parts. In addition, it also can offer support for preventive maintenance, assembly optimization and intelligent decision in the aspect of big data service. Therefore, the paper aims to design and implement of 3D visualization monitoring and traceability system of general parts in continuous casting machine based on digital twin. Firstly, systematic architecture of the proposed approach is constructed, where a typical five-layer model for digital twin-driven monitoring and traceability is established. The 3D visualization monitoring for continuous casting machine is achieved based on lightweight 3D twin model using the Internet of Things (IoTs), information technology, network technology and so on. After that, an assembly model based on polychromatic sets is built for expressing and describing the assembly relationships and assembly process of general parts. Meanwhile, an encoding rule for part and position is put forward by considering assembly position information. Based on that, the general parts equipped with total process information can be traced in the service life cycle.

This paper is organized as follows. Section 2 gives a systematic architecture of monitoring and traceability system for general parts in continuous casting machine based on digital twin. In Section 3, Web-based 3D visualization monitoring for continuous casting machine is given in detail. Traceability for general parts considering assembly position information is put forward based on polychromatic sets in Section 4. Subsequently, the prototype system and experiments are designed and implemented in Section 5. Finally, the paper is concluded and further work directions are given in Section 6.

2. Systematic architecture of proposed approach

The systematic architecture of monitoring and traceability system for general parts in continuous casting machine based on digital twin is shown in Figure 3. It consists of the five layers: physical layer, transport layer, data layer, model layer and application layer. Here, the 3D twin model for continuous casting machine is a mirror 3D model of the physical continuous casting machine equipment, which includes the total elements information. The 3D model can be displayed in any Web browser through the lightweight processing technology. The twin data is obtained by making use of IoTs technology for collecting data from the physical layer. The exchange and synchronization of data between physical equipment and 3D twin model are accomplished by the data center on the server. Thus, the digital twin of continuous casting machine is accomplished through integrating the twin data and 3D twin model. Based on that, the continuous casting machine is monitored in the form of 3D visualization. Furthermore, traceability for general parts is achieved by synthetically considering assembly/working position based on polychromatic sets in the application layer.

The five-dimension digital twin model is employed as reference (Tao et al., 2018), where some supplement and improvement is given for satisfying the demand of 3D visualization monitoring and traceability for general parts in continuous casting machine. The proposed digital twin model be expressed as in the following,

$$\boldsymbol{M}_{dt}=(PE,CN,DD,VE,Ss) \quad (1)$$

Where, *PE* represents the physical equipment entity, *CN* represents Connection among *PE*, *VE*, *DD* and *Ss*. *DD* represents twin data, *VE* represents the virtual equipment, and *Ss* represents service for *PE*. In this paper, the *PE* refers to the physical layer, *CN* refers to transport layer, *DD* refers to data layer, *VE* refers to model layer and *Ss* refers to application layer.

Additionally, the process of Web-based 3D visualization monitoring using lightweight 3D twin model is offered in detail, and the encoding rule considering assembly position is given for encoding physically general part. Furthermore, the assembly model based on polychromatic sets is built for describing the assembly relationships of roller-group and segment in continuous casting machine, which can provide support for traceability of general parts together with encoding rule.

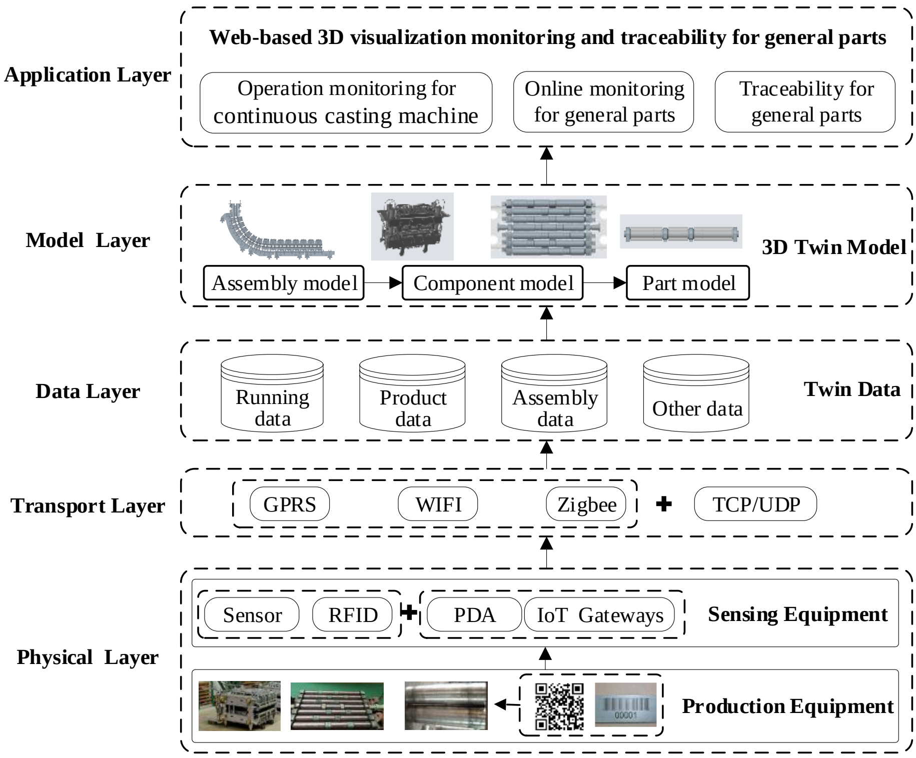

Fig. 3 Systematic architecture of monitoring and traceability for general parts based on digital twin

2.1 Physical layer

Physical equipment mainly consists of production equipment and sensing equipment, where the interconnection and intercommunication among different physical equipments is realized through IoTs technology. The production equipment

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includes continuous casting machine, segment, roller-group, general part, and their attached bar/QR code, etc. The sensing equipment includes sensor, RFID and some device such as IoTs gateways, PDA terminals that connect them to network. The sensors are used to collect the operating parameters of continuous casting machine and external environment information, and transmit those data to the IoTs gateway. The basic information from RFID and bar/QR code can be read and obtained by using PDA terminals. The collected data can be pre-processed, forwarded, and controlled by means of IoTs gateways and PDA for linking to the network communication. To meet the requirement of traceability for general parts, the production equipment is encoded and their surface is marked with bar/QR code or serial code by using DPM (Direct part marking), such as laser marking.

2.2 Transport layer

The IoTs gateway and PDA terminal can transmit collected data over the network by using communication modes such as WiFi, GPRS, Zigbee, where TCP/UDP can be chosen as the communication protocol. The data center on the server receives the data from IoTs gateway and PDA terminal through the communication network. Meanwhile, a parse application is developed and deployed on the server, where the uploading data is received and parsed into standard data format for being stored conveniently in the database.

2.3 Data layer

Twin data includes these data related to equipment in the physical layer, algorithms, encoding rules, and other data transmitted from transport layer, which can be grouped into operation data, product data, assembly data, and other data according to the data source. Operation data mainly includes operation parameters of continuous casting machine, such as casting speed, slab thickness, slab temperature, power, current, etc. Product data mainly includes BoM of continuous casting machine, part size, two-dimensional drawing, maintenance process, etc. Assembly data includes data related to continuous casting machine assembly, segment assembly, roller-group assembly and so on. Other data mainly includes traceability algorithms for general parts, parts encoding, position encoding, encoding rule and auxiliary data. All the above data are stored in the server database, where the database can be MySQL, SQL Server, DB2 and other relational database software.

2.4 Model layer

3D twin models are produced from the physical solid of continuous casting machine according to product data in the data layer, which are mainly divided into continuous casting machine model, assembly model, component model and general part model in terms of the assembly process of general parts. The 3D twin model parameters (size, shape, layout, assembly relation, etc.) are consistent with the physical entity equipment, where lightweight 3D model file formats such as Json, Obj, can be obtained through Blender software.

2.5 Application layer

The lightweight 3D model can be displayed in any Web browser through WebGL technology. Together with twin data, Web-based monitoring and traceability system for general parts in continuous casting machine is developed and implemented using MVC, Signal, C#, WebGL, Threejs, and Html5, etc. The application system is mainly composed of three main modules, i.e., operation monitoring for continuous casting machine, online monitoring and traceability for general part.

The above system architecture can be considered as overview of proposed approach, where the key technologies and main solution for digital twin-based monitoring and tracking general part in continuous casting machine equipment are put forward in detail. The subsequent sections will focus on the 3D visualization monitoring and traceability for general part.

3. 3D visualization monitoring for continuous casting machine

3D visualization monitoring can help the engineer acquire conveniently assembly topology, geometric shape, and online running information of continuous casting machine equipment. Meanwhile, the MBD (Model Based Definition) technology can be used to effectively solve the problem semantic gap between the 3D model and semantic label. The 3D model lightweight technology can be used for realizing Web-based display and interaction of 3D model. The engineer can flexibly obtain the 3D model information of product by using mobile devices without the limitation of the 3D modeling software platform, time and place. It means that users do not need to install software and just need a Browser.

The 3D CAD product model includes assembly topology and geometric shape information, which has the characteristic of big file, slow rendering and display. Lightweight representation of 3D model reduces the size of product or part files for quickly browsing 3D product model through the internet. Product structure relationships and part position are recorded in the lightweight assembly model, which can be viewed in the Browser by using WebGL. The process of 3D visualization monitoring for continuous casting machine is shown in Figure 4.

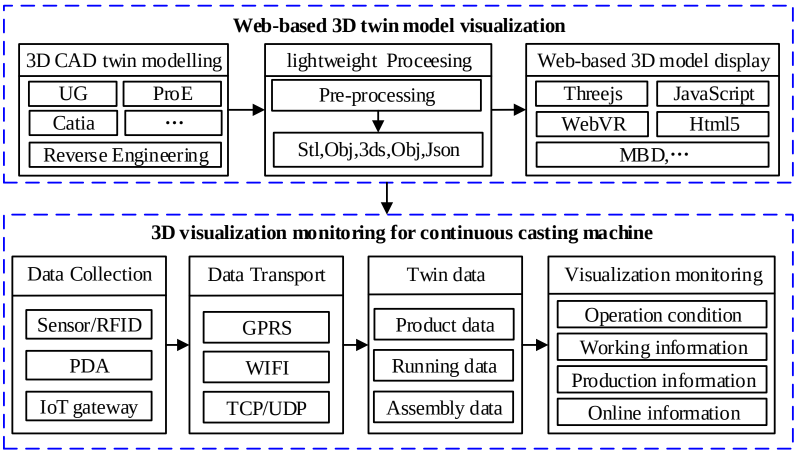

Fig. 4 Process of 3D visualization monitoring for continuous casting machine

3.1 Web-based 3D twin model visualization

In the paper, the virtual equipment is an important part of digital twin for continuous casting machine, which is considered as the 3D twin model. The 3D twin model can be generated rapidly by means of reverse engineering, 3D CAD modeling software such as UG, ProE, Catia and so on. The CAD model is not suitable for Web-based 3D visualization. It needs to be processed for satisfying requirement of the local rendering in the browser. Here, a solution for Web-based 3D visualization is given in detail in the following.

Step1: Lightweight processing for 3D CAD model.

Step1.1: 3D CAD model is pre-processed. All geometric objects are obtained and duplicate objects are removed. The corresponding material objects according to their material information are generated. Meanwhile, the corresponding scene tree is obtained in terms of the model tree.

Step1.2: Discrete triangle and discrete line data are acquired by pre-processing all geometric objects. Discrete triangle data includes vertex data, UV data, vector data and index data. Discrete line data includes vertex data and index data.

Step1.3: Index data of the discrete triangle is sorted and reduced for improving the compression rate of compression algorithm. The vectors of the discrete triangle are grouped according to the quadrants, and processed into integer for reducing the number of bytes of vector data storage.

Step1.4: Index data of discrete line is reduced and all geometric objects are processed into blocks.

Step1.5: The blocks of all geometric objects are compressed by using lzma (Lempel-Ziv-Markov chain-Algorithm) and generated several files with suffix bin. The attribute data, scene tree and animation tree of all geometric objects are processed into Json and generated the main file with suffix js, which records the data of geometric objects, material objects, scene tree structure, animation tree structure and user defined data.

Step2: Web-based 3D twin model display.

The main file with suffix js and corresponding files with suffix bin are loaded in the Web page. After that, the data of discrete triangle and discrete line are restored. The scene objects and animation objects are built according to the scene tree structure and animation tree structure, and then rendered by using WebGL technologies (Threejs, JavaScript, Html5, etc.) (Gesquière and Manin, 2012; Lavoué et al., 2013).

Through the given method, the lightweight 3D twin model can be displayed in any Web browser, which is integrated into the Web-based information system. The SignalR technology instead of the traditional polling method is employed to automatically push data from the server to the client in real-time for twin data combined with the 3D twin model.

3.2 3D visualization monitoring for continuous casting machine

The 3D twin model of continuous casting machine is used as the information carrier. Together with twin data, the 3D visualization monitoring for operation information, working condition, production information and online information of continuous casting machine can be achieved.

- Operation information: the operating information about continuous casting machine, such as continuous working time and health of general part, equipment exception, running state and so on.
- Working condition: the external working environment, such as power, current, voltage, temperature, etc.
- Production information: the information about steel slab production, such as width and length of steel slab, production capacity, quality, etc.
- Online information: the working or service information about the general parts, such as assembly position, length of running time, total amount of making steel and so on.

Through the 3D visualization monitoring, it not only can reduce the operator's time cost but also improve the level and efficiency of continuous casting machine equipment management.

4. Traceability for general parts in continuous casting machine

Traceability for general parts in continuous casting machine refers to the general parts with frequent maintenance and high interchangeability, such as frame, roller, mandrel, roller, bearing and chock bearing. With change of assembly position of segment, the corresponding external environment of general parts will change, such as temperature, load, resistance, etc. Thus, the wear, crack or bending of general parts will be various among assembled parts. Therefore, traceability for general part is not only a simple record of usage information but also records the working position and working condition of each part and association mapping relationships between parts and working positions. Based on that, the working environment information of each general part can be obtained for its remaining life prediction and assembly scheduling. The digital twin-based process of traceability for general parts in continuous casting machine is shown in Figure 5. To trace the general parts and their total process information in the service life cycle, the general parts are encoded and marked physically by using the DPM, and the assembly or working position should be also encoded and associated with general parts. The assembly model is built based on polychromatic set for expressing and describing the assembly process and assembly relationships during the process of general parts installed into casting equipment. On the basis of that, the assembly/working position, check/repair, external working environment related to general parts can be traced and obtained under the environment of digital twin for continuous casting machine.

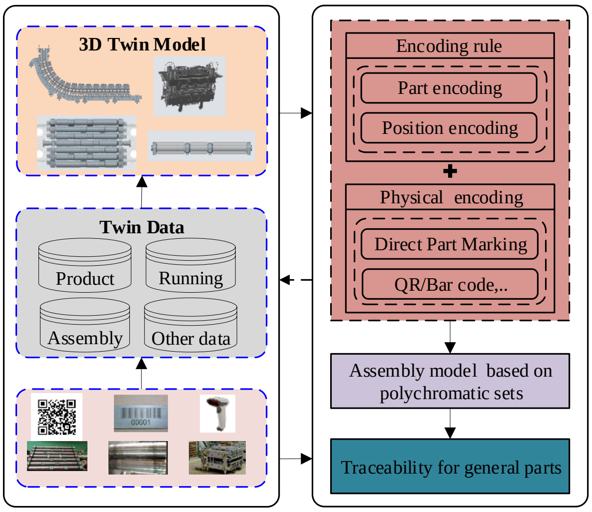

Fig. 5 Digital twin-based process of traceability for general parts in continuous casting machine

4.1 Encoding rule considering assembly position

To trace the assembly/working position of general parts in continuous casting machine, these general parts should be encoded. Moreover, it is necessary to encode the assembly position during the process of general parts and segments assembly. Here, an encoding rule considering assembly position is constructed. It is very useful for tracking the total factor information of general parts during the process of assembly and operation online.

4.1.1 Position encoding

A continuous casting machine composed of multiple flows is called so more cast, where each flow has same segments structure. So it is necessary to consider the factors such as the number of continuous casting machines, the number of flows, the number of segments, the number of roller-groups, and the structure of the roller-group. Comprehensively considering the above factors, the assembly position encoding for a continuous casting machine can be given. The specific encoding rule is shown in Figure 6.

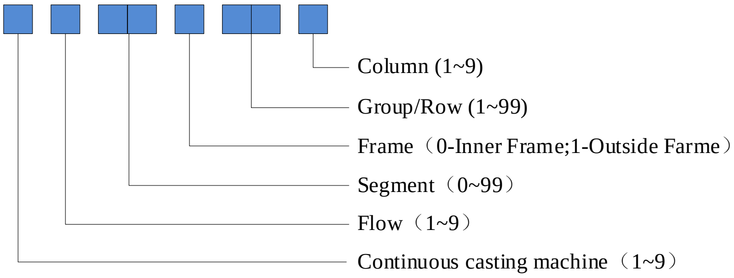

Fig. 6 Position encoding rule

According to the position encoding rule, the different level position encoding can be expressed as follows:

Position encoding= continuous casting machine encoding +flow encoding + segment encoding +frame encoding +group encoding +column encoding.

Here, two examples are given for illustrating the proposed position encoding rule.

① The position encoding 1101 represents segment B1#, flow 1# continuous casting machine 1#.

② The position encoding 11010011 represents column 1#, group 1#, segment B1#, flow 1# continuous casting machine 1#.

4.1.2 Part encoding

The general parts should be encoded for unique identification. Meanwhile, an appropriate surface position of the general part is marked physically with the corresponding QR code or bar code by taking advantage of DPM. It is useful for preventing the loss of identification code under the environment of high temperature, serious oil and maintenance.

4.2 Assembly model based on polychromatic sets

The continuous casting machine maintenance mainly involves segment maintenance or repair. The segment is disassembled from continuous casting machine, and taken apart when segment need repaired. The segment is assembled by repaired or new general parts (especially casting roller), which as spare component will be installed into the continuous casting machine when the coming maintenance. The assembly process of general parts installed into casting equipment mainly consists of roller-group assembly, frame assembly, segment assembly, and segment installed. There are multiple assembly positions chosen in the process of roller-group assembly, frame assembly, segment assembly and segment installed. The position that is chosen as an assembly position during different assembly process will determine finally the working position of general parts installed into continuous casting machine. The assembly position where general parts or components are installed is random and uncertain. Furthermore, there is a hierarchical relationships between them. How to express and describe the physical assembly position during assembly process and build the correlation mapping relationships between general parts/components and assembly position is very important. It is the basis and premise of traceability for the general parts in continuous casting machine.

To trace the general parts in continuous casting machine, it is necessary to build an assembly model for expressing and describing the assembly relationships and assembly process information of general parts. It is obvious that there are hierarchical relationships for continuous casting machine assembly model. Here, the polychromatic sets is employed to describe the assembly process information in continuous casting machine.

Polychromatic sets theory is a relatively new mathematics theory and information processing tool, which has been widely used in many fields, such as product conceptual design (Han et al., 2019), assembly sequence planning (Xu et al., 2012), etc. It can not only describe characteristics of sets and elements, but also describe relationships of elements and entirety. The classical mathematical expression of polychromatic sets is given as follows:

$$PS=\left(A,F(a),F(A),\left[A\times F(a),A\times F(A),A\times A(F)\right]\right) \tag{2}$$

Where, A is a set of elements. $F(a)$ and $F(A)$ are respectively individual color set of elements and the unified color set of A. $A\times F(a)$ is a Boolean matrix representing the relationships between element set A and the individual color of all elements. $A\times F(A)$ is a Boolean matrix representing relationships between the element set A and the unified color $F(A)$. And $A\times A(F)$ is a Boolean matrix representing relationships between individual color $F(a)$ and unified color $F(A)$.

The assembly process of general parts installed into casting equipment mainly consists of roller-group assembly, frame assembly, segment assembly, and segment installed. According to the assembly process of general parts installed in continuous casting machine, the components/subassemblies can be regarded as element set A, assembled parts information corresponding to the components or subassemblies are considered as the individual color $F(a)$, and assembly position information of components/subassemblies is the unified color $F(A)$.

The assembly hierarchical model for continuous casting machine can be described in detail based on polychromatic sets as follows:

$$A=\{a_1, a_2, a_3,\dots a_n\} \tag{3}$$

Where, a_i represents component/subassembly i in continuous casting machine, n is the total number of components/subassemblies.

$$F(a)=\{f_1, f_2, f_3,\dots f_m\} \tag{4}$$

Where, f_j represents assembled part j and its coding information, m is the total number of assembled parts.

$$F(A)=\{F_1, F_2, F_3,\dots F_r\} \tag{5}$$

Where, F_k represents assembly position k, r is the total number of assembly positions.

The relationships between components/subassemblies, assembled parts and assembly positions can be represented by the Boolean matrices $A\times F(a)$ and $A\times F(A)$ as follows:

$$A\times F(a)=\begin{array}{c} \begin{array}{cccc} f_1 & f_2 & \cdots & f_m \end{array} \\ \begin{bmatrix} c_{11} & c_{12} & \cdots & c_{1m} \\ c_{21} & c_{22} & \cdots & c_{2m} \\ \cdots & \cdots & \cdots & \cdots \\ c_{n1} & c_{n2} & \cdots & c_{nm} \end{bmatrix} \end{array} \begin{array}{c} \\ a_1 \\ a_2 \\ \cdots \\ a_n \end{array} \tag{6}$$

$$A\times F(A)=\begin{array}{c} \begin{array}{cccc} F_1 & F_2 & \cdots & F_r \end{array} \\ \begin{bmatrix} d_{11} & d_{12} & \cdots & d_{1r} \\ d_{21} & d_{22} & \cdots & d_{2r} \\ \cdots & \cdots & \cdots & \cdots \\ d_{n1} & d_{n2} & \cdots & d_{nr} \end{bmatrix} \end{array} \begin{array}{c} \\ a_1 \\ a_2 \\ \cdots \\ a_n \end{array} \tag{7}$$

In the formula (6), if c_{ij}=1, it means that the element a_i consists of assembled part f_j. In the formula (7), if d_{ij}=1, it means that the element a_i is installed into the assembly position F_j.

It should be noted that the component/subassembly considered as one assembled part, will be assembled into the parent new component/ subassembly in the process of general parts installed into the casting machine equipment.

The above given polychromatic sets model can be used to express explicitly and formally the assembly process and assembly relationships information of general parts installed into the casting continuous equipment during its operation and maintenance.

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4.3 Traceability for general parts in continuous casting machine

According to the assembly model based on polychromatic sets, the Boolean matrices $A\times F(a)$ and $A\times F(A)$ can be also used to reason the assembly/working position information of assembled parts in component/subassembly. It is easy to describe the assembly relations in the assembling process and facilitate programming. Furthermore, the other service information about general parts will be obtained and traced by the above encoding rule and assembly model to provide data support for real-time monitoring and predicting remaining life of general parts.

5. Implementation

5.1 Prototype system

The proposed approach has been implemented in a prototype system, which is developed on the platform Microsoft Visual Studio C# 2013, while SQL SEVER 2012 is used as the backend database system. The system is composed of three main modules, i.e., basic information management, 3D visualization monitoring and traceability for general part. The basic information management includes mainly part/component encoding, position encoding, and operation parameters about continuous casting machine, etc. 3D visualization monitoring includes mainly lightweight 3D model, online parameters, online working time length, and total amount of steel. Traceability for general part includes mainly general part assembly process, online working position, and history-working position. Based on that, the association relationships between general part and working environment can be obtained, which can provide data sources for studying on performance degradation and residual life prediction of the general part. Moreover, the prototype system has been deployed in steel-making enterprises for 3D visual monitoring and tracking general parts in so more cast. A typical main interface of the prototype system is shown in Figure 7, where the statistics for fault warning, repair information about segment and general part is presented in the form of pie/carve chart**.** Here, the 2150# casting machine equipment produced by Siemens VAI is employed as an example to verify the effectiveness and feasibility of the proposed approach.

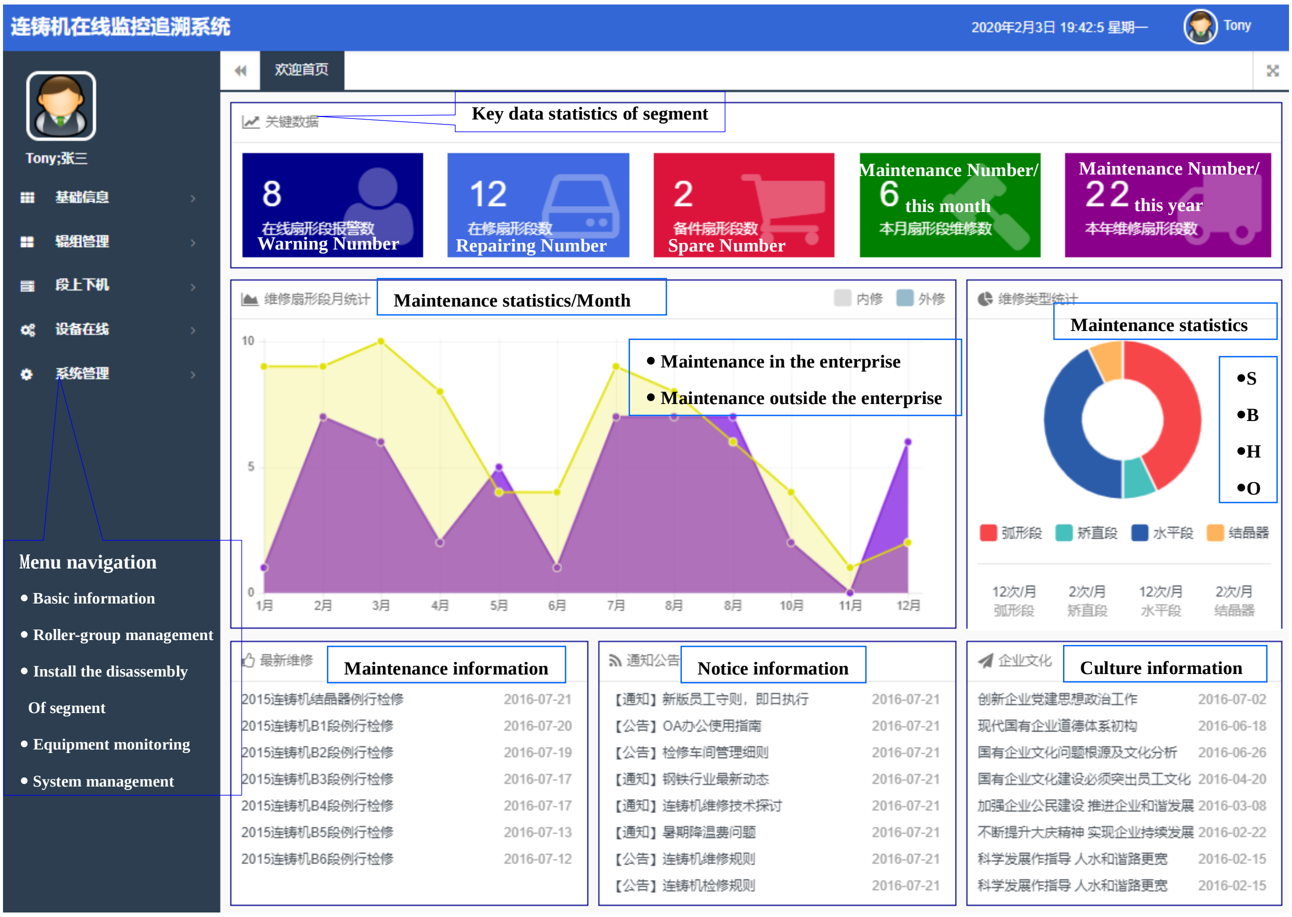
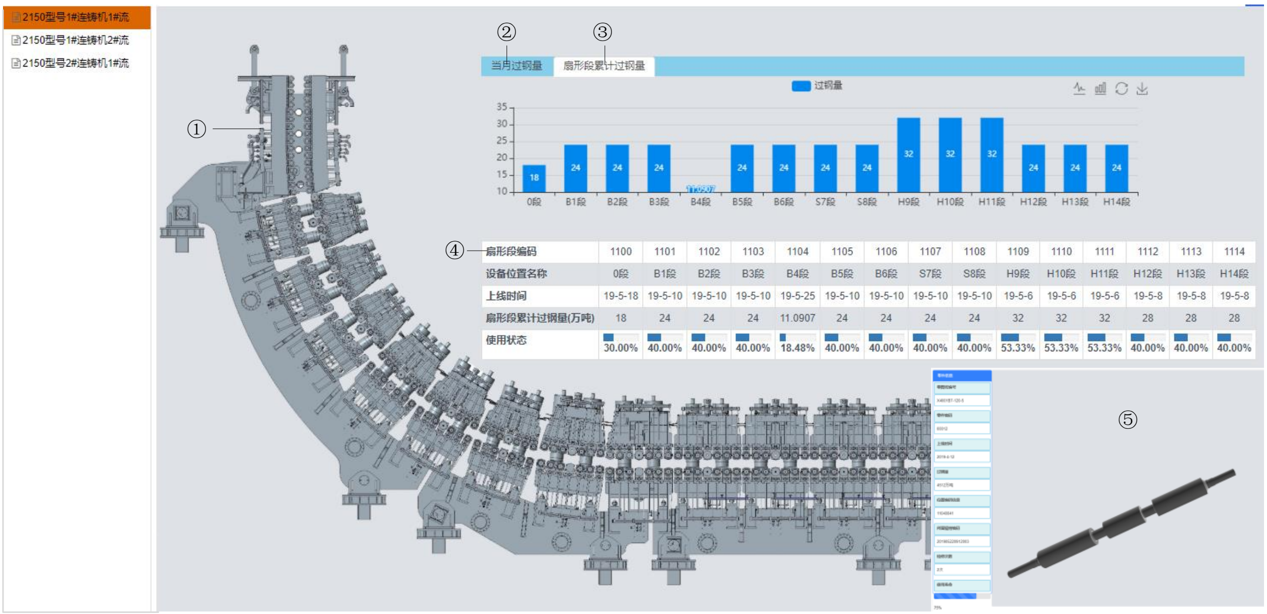


Fig. 7 A typical interface of the prototype system

5.2 3D visualization monitoring

Through the previously proposed method, 3D twin model for the continuous casting machine is constructed, which can be displayed and accessed in any Browser by making use of the WebGL lightweight technology. To meet the operator's practical demand, online operation state of continuous casting machine can be queried at different levels along with the corresponding 3D twin model. For example, continuous casting machine→flow→segment→frame→ roller-group→casting roller. The typical interface of 3D visualization online monitoring is shown in Figure **8,** where the 3D twin model for continuous casting machine is viewed with operation condition, assembly information about segment and general part, and some key information including total amount of making steel of each segment (every day and month), assembly position, assembling time, assembled parts is also given in the form of chart/diagram**.**



① 3D twin model for continuous casting machine
② The statistics for total amount of making steel every day
③ The statistics for total amount of making steel of each segment
④The assembly position, segment code, assembling time and usage rate of each segment
⑤The information of casting roller assembled in the position selected

Fig. 8 3D visualization online monitoring for continuous casting machine

5.3 Traceability for general part

The general parts and assembly/working position are encoded in terms of the encoding rule in Section 4.1, where the surface of general parts is marked with corresponding code by using the DPM. Moreover, the polychromatic sets-based assembly model for describing and expressing assembling process information from roller-group assembly to segment installed in Section 4.2. Here, the assembly process of roller-groups installed into frames of segment B1# is taken as an example to verify the effectiveness of the previously proposed method in Section 4. The casting roller-groups layout of segment B1# is shown in Table 1, where each segment consists of the inner framework and outside frame composed of three rollers as shown in Figure 2. The 4th, 5th and 6th column represents the assembly position in segment.

The number of assembly positions, casting rollers and roller-groups in segment B1# can be obtained by using the Table 1. It is obvious that the number of casting rollers is 38, the number of roller-groups and corresponding assembly positons is 14. The relationships among assembled parts, components/subassemblies and assembly positions can be expressed by using the assembly model mentioned in Section 5. Figure 9 shows assembly model based on polychromatic sets for assembly process of roller-group installed into the frames of segment B1#, where the element a represents roller-group (I1~I7, O1~O7), the individual color F(a) represents the corresponding assembled casting roller (Ø220×515, Ø220×495, Ø220×910, Ø220×1525), and the unified color $F(A)$ represents the assembly position of roller-group installed into the inner/outside frame of segment B1#. Additionally, the solid dot '●' denotes 1 and blank denotes 0. It is easy to obtain the assembly position of casting roller by using the Boolean matrixes $[A\times F(a)]$ and $[A\times F(A)]$. For example, the assembly position $F_2(A)$ is installed by the roller-group a_3, which consists of the casting rollers f_4, f_{10} *and* f_{11}. Based on that, the current and history assembly/working position of each casting roller can be acquired by the encoding rule and assembly model. The traceability interface for general parts is shown in Figure 10, where the history information about each segment and its corresponding assembled general parts at the any position of continuous casting machine equipment can be monitored and traced. For example, the segment history information installed in the segment B4#, and the roller online and history information assembled in the corresponding segment B4# position is queried through the interface.

Table 1. Casting roller-groups layout of segment B1#

<table>
<tr><th>Segment</th><th>Frame Type</th><th>Roller-group</th><th>1</th><th colspan="2">2</th><th colspan="2">3</th></tr>
<tr><td rowspan="14">B1#</td><td rowspan="7">Inner Frame</td><td>I1</td><td>Ø220×515</td><td colspan="2">Ø220×495</td><td colspan="2">Ø220×910</td></tr>
<tr><td>I2</td><td colspan="2">Ø220×910</td><td colspan="2">Ø220×495</td><td>Ø220×515</td></tr>
<tr><td>I3</td><td>Ø220×515</td><td colspan="2">Ø220×495</td><td colspan="2">Ø220×910</td></tr>
<tr><td>I4</td><td colspan="5">Ø220×1525</td></tr>
<tr><td>I5</td><td colspan="2">Ø220×910</td><td colspan="2">Ø220×495</td><td>Ø220×515</td></tr>
<tr><td>I6</td><td>Ø220×515</td><td colspan="2">Ø220×495</td><td colspan="2">Ø220×910</td></tr>
<tr><td>I7</td><td colspan="2">Ø220×910</td><td colspan="2">Ø220×495</td><td>Ø220×515</td></tr>
<tr><td rowspan="7">Outside Frame</td><td>O1</td><td>Ø220×515</td><td colspan="2">Ø220×495</td><td colspan="2">Ø220×910</td></tr>
<tr><td>O2</td><td colspan="2">Ø220×910</td><td colspan="2">Ø220×495</td><td>Ø220×515</td></tr>
<tr><td>O3</td><td>Ø220×515</td><td colspan="2">Ø220×495</td><td colspan="2">Ø220×910</td></tr>
<tr><td>O4</td><td colspan="5">Ø220×1525</td></tr>
<tr><td>O5</td><td colspan="2">Ø220×910</td><td colspan="2">Ø220×495</td><td>Ø220×515</td></tr>
<tr><td>O6</td><td>Ø220×515</td><td colspan="2">Ø220×495</td><td colspan="2">Ø220×910</td></tr>
<tr><td>O7</td><td colspan="2">Ø220×910</td><td colspan="2">Ø220×495</td><td>Ø220×515</td></tr>
</table>

	a_1	a_2	a_3	a_4	a_5	a_6	a_7	a_8	a_9	a_{10}	a_{11}	a_{12}	a_{13}	a_{14}
$F_1(a)$	•													
$F_2(a)$	•													
$F_3(a)$				•										
$F_4(a)$			•											
$F_5(a)$					•									
$F_6(a)$		•												
$F_7(a)$					•									
$F_8(a)$		•												
$F_9(a)$							•							
$F_{10}(a)$			•											
$F_{11}(a)$			•											
$F_{12}(a)$							•							
$F_{13}(a)$							•							
$F_{14}(a)$						•								
$F_{15}(a)$	•													
$F_{16}(a)$						•								
$F_{17}(a)$						•								
$F_{18}(a)$					•									
$F_{19}(a)$		•												
$F_{20}(a)$								•						
$F_{21}(a)$									•					
$F_{22}(a)$								•						
$F_{23}(a)$											•			
$F_{24}(a)$								•						
$F_{25}(a)$									•					
$F_{26}(a)$										•				
$F_{27}(a)$										•				
$F_{28}(a)$									•					
$F_{29}(a)$										•				
$F_{30}(a)$												•		
$F_{31}(a)$													•	
$F_{32}(a)$												•		
$F_{33}(a)$														•
$F_{34}(a)$													•	
$F_{35}(a)$												•		
$F_{36}(a)$														•
$F_{37}(a)$														•
$F_{38}(a)$													•	

(a) Boolean matrix $[A \times F(a)]^{T}$

	a_1	a_2	a_3	a_4	a_5	a_6	a_7	a_8	a_9	a_{10}	a_{11}	a_{12}	a_{13}	a_{14}
$F_1(A)$	•													
$F_2(A)$			•											
$F_3(A)$				•										
$F_4(A)$						•								
$F_5(A)$							•							
$F_6(A)$		•												
$F_7(A)$					•									
$F_8(A)$								•						
$F_9(A)$									•					
$F_{10}(A)$											•			
$F_{11}(A)$										•				
$F_{12}(A)$												•		
$F_{13}(A)$														•
$F_{14}(A)$													•	

(b) Boolean matrix $[A \times F(A)]^{\mathrm{T}}$

Fig. 9 Assembly model based on polychromatic sets for assembly process of roller-group installed segment B1#

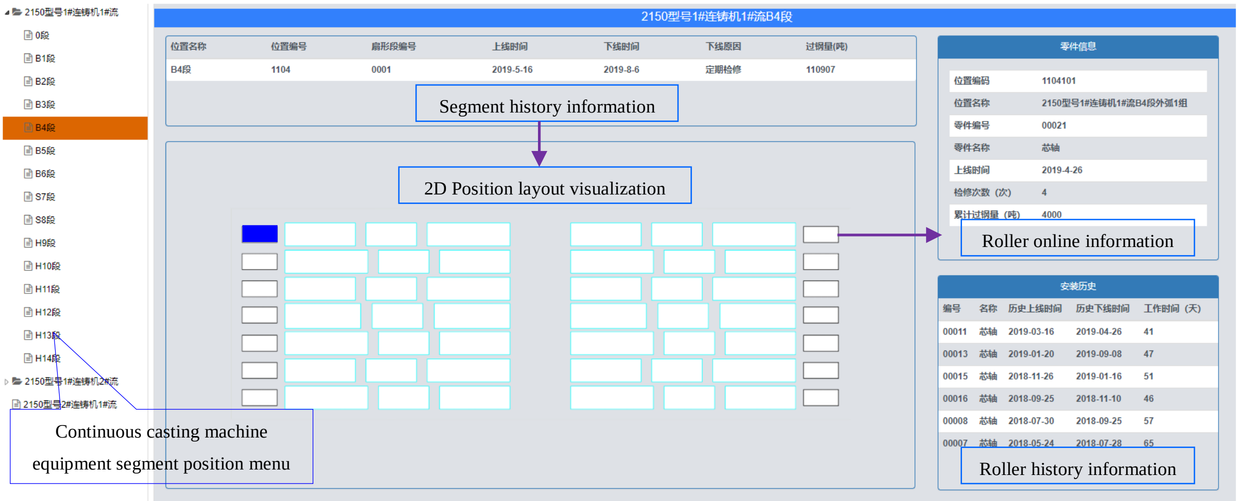


Fig. 10 Traceability interface for general parts

5.4 Discussion

The proposed 3D visualization monitoring and traceability system has been implemented in some steel-making enterprises, which can help users find more accurately and conveniently the casting roller that need to be repaired by using the 3D twin model, improving maintenance efficiency by 6%. Through the twin data, the maintenance period and lifespan of casting roller is increased by about 10%~15%, its maintenance times decreases by about 15%, and the maintenance cost is reduced by about 18%. The general part can be monitored and traced in its service life cycle. However, the existing methods about continuous casting machine only monitor the equipment working wholly, not monitoring and tracking more concretely each general part due to complex working condition.

In addition, the five-dimension digital twin model is employed as a reference framework, which has more advantage than other methods. For example, the twin model and twin data can provide support for performance degradation analysis, simulating and remaining useful life prediction of casting roller in the future work.

6. Conclusion and future work

The casting roller as key part of general parts with high interchangeability and maintenance frequency has an impact on the quality of steel slabs in the process of steel-making. To obtain the service information of each casting roller for predicting remaining life and preventative maintenance in the service life cycle, digital twin-based monitoring and traceability system for general parts in continuous casting machine is presented. The systematic architecture of 3D monitoring and traceability for general part in continuous casting machine based on digital twin is constructed. The process of Web-based lightweight 3D twin model for continuous casting machine is given in detail, and real-time data-driven 3D visualization monitoring is achieved synthetically by using the IoTs technology. After that, an encoding rule for general part/component and assembly position is offered by considering assembly position information. Meanwhile, polychromatic sets-based assembly hierarchy model is constructed for describing the assembly relationships and assembly process in continuous casting machine. It is easy to programing and implement.

Through the proposed system, the real-time running state and history working condition information related to general parts can be acquired and traced. It can not only help operator monitor and manage the general parts in their service life cycle, but also reduce the operation and maintenance cost. In addition, it can also be the basis and premise of assembly scheduling optimization and inventory optimization of casting roller, thereby realizing the total process and factor information management, and intelligent services for continuous casting machine in the service life cycle. On the basis of the research results, our subsequent studies will aim at big data-driven fatigue prediction, wear prediction and residual life prediction of casting roller.

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