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Research Article

Digital Twin-Assisted Simulation of Complex Assembly Models in Descending Process and Implementation of Key Link Characterization

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In this paper, the simulation and key link characterization of the complex assembly model step-down process are studied and analysed in depth using the digital twin approach, and the method is used in the practical process. The physical model step-down method MORA algorithm and its physical interpretation in various simplified cases are given, and the MORA method is improved on this basis. The concept of local activeness based on knot structure is introduced, and the process of model transformation and downscaling and decomposition based on local activeness is explained in detail. The high-fidelity mapping of solid equipment is completed in virtual space, which can accurately reproduce and predict the health state of engineering equipment throughout its life cycle, effectively avoiding the huge property losses and safety risks caused by early failure of vulnerable structures and providing a safe and stable working environment for offshore oil and gas production. With the prototype monitoring data as reference, the response surface method is used to identify the parameters of the finite element model of the hinge node, which improves the fidelity of the virtual model of the hinge node. Considering the friction coefficient changes and load characteristics during the degradation of the hinge node, the dynamics simulation conditions are set, and the operating states of the hinge node at different stages of its whole life cycle are simulated by using the high-fidelity virtual model of the hinge node, and the prediction model of the hot spot stress of the hinge node is established to monitor its in-position state in real time, and the operation and maintenance overhaul method based on the health state of the hinge node is proposed. The system is divided into four modules: multilevel inverse modelling of the assembly twin, statistical shape characterization and analysis of batch parts, optimization of fixture positioning and flexible assembly of thin-walled parts, and optimization of low-stress assembly of bolted joint structure, which verifies the feasibility of the method and provides guidance for the actual product forming process.

1. Introduction

With the continuous development of the economy, people's demand for personalized products is increasing, requiring product production lines to have multispecies, small-lot, multifreedom, and high-reliability production capacity, and production lines should independently adapt to various changes brought about by-product personalization, which include changes from within and changes from outside [1]. The traditional rigid automated production line produces a single product, which can no longer meet the demand of diversified production, and industrial production line flexibility and intelligence have become the mainstream development trend. Industrial robotic arms are widely used in all aspects of flexible production lines, and robotic arms replace humans to complete the tasks of handling and assembly in the production process. In these operational tasks, the requirements for robotic arm cooperation and functionality are increasing, and the traditional single robotic arm based on the demonstration mode is already difficult to meet all the needs, while the multirobot collaborative operating system can well solve these problems [2]. For example, the cost

of designing a robotic arm that can handle large, heavy loads is very expensive. However, with a multirobotic arm system, where each arm only must carry a relatively small load, a handling system containing two or more small-cost arms can transfer heavy loads. In addition, a multirobotic arm synergistic system can perform different subtasks in parallel, thus facilitating the handling of decomposable tasks such as automated assembly in smart production. In short, a multirobotic arm system has higher load capacity and flexibility to perform coupled tasks.

The performance of complex products is closely related to the quality of assembly; the assembly error is one of the evaluation indicators of the quality of assembly, which is mainly determined by two steps of part feature modelling and assembly accuracy analysis and is affected by various factors such as part manufacturing errors, material properties, positioning forms, and coupling processes, which is difficult to be predicted by classical methods. Assembly error prediction requires the construction of a prototype including all parts and process information, and the traditional physical prototype construction method is prone to scrap parts that do not meet the performance requirements, resulting in a great waste of resources and rising product costs. However, digital prototype models often ignore many elements in the real environment, resulting in discrepancies with the actual part assembly, making it difficult to meet the performance requirements of products with high accuracy [3]. Flexible and intelligent industrial production lines have become the current mainstream development trend. Industrial robotic arms are widely used in all aspects of flexible production lines, and robotic arms replace humans in completing tasks such as handling and assembly in the production process. Therefore, the use of digital technology to truly reproduce the complex product forming process, to guide the actual production and assembly of parts, is a major research hotspot in the current manufacturing products. At present, the flat width processing method has been widely used in woven fabric dyeing and finishing processing and gradually become the development direction of knitted fabric printing and dyeing processing. Knitted fabric is a material with good air permeability and softness made of yarns trapped each other, the force deformation of knitted fabric presents a high degree of nonlinearity and complexity, due to the relatively large width of the product in the knitted fabric flat width processing, and tension pulling in the processing process is easy to produce from the edge to the centre of the contraction, as well as due to unfavourable winding control resulting in the uneven layer, wrinkles, uneven density, and other defects. In addition, the knitted fabric structure will be affected by the tension of the larger deformation which cannot restore the original weaving structure; knitted fabric flat width processing tension size needs to fully consider the size of the knitted fabric deformation [4]. Therefore, low tension and stable tension control are the key influencing factors of knitted fabric flat processing quality, and how to determine the tension setting model and stable, small fluctuation of low-tension control technology is the difficult point of knitted fabric flat printing and dyeing.

Digital twin technology is a technology proposed in recent years for the fusion of virtual simulation and physical reality, which is a technology that integrates physical reality data, integrates multidomain and multiscale mapping simulation models, and covers the whole process and product life cycle. The study of knitted fabric flat width dyeing and finishing process involves several disciplines, including product pretreatment, roll dyeing control, and product finishing, and other processing aspects. This paper applies digital twin technology to the study of key issues in textile processing, aiming to explore and provide a reference for the study of complex textile processing problems. Product digital assembly modelling and simulation is an advanced technology that uses computer theory to construct a digital model of a product in a virtual environment, to simulate the behaviour of a physical prototype in the whole life process, such as assembly and maintenance. It is important to analyse the assembly process and error transmission of the product digital model through simulation methods to verify whether the part assembly sequence, assembly path, force deformation, etc. meet the engineering requirements, which is important to guide the actual part manufacturing and assembly operations, improve the efficiency of product development, and reduce costs.

2. Status of Research

A multidomain-coupled digital twin model of CNC machine tool is established, which contains hydraulic, electrical, mechanical equipment, and its control system. The article debugs the system operation response in the established machine tool coupling system, focuses on the response characteristics of the coupling system, and studies the impact of machining tool trajectory on the product machining profile, which is the multidomain coupling modelling technology under the research idea from the equipment electromechanical control response to the product machining level, and the virtual machining and virtual control of the workpiece is realized in the article through the virtual debugging of the CNC machine tool motion trajectory, the construction of software platform [5]. If a multimanipulator system is used, each manipulator only needs to bear a relatively small load, and a handling system containing two or more low-cost manipulators can transfer heavy objects. A digital twin model architecture for machining tools on CNC machine tools is proposed, and the model is applied to tool detection, life prediction, and tool selection decision, and the tool wear amount is quantitatively analysed by using a convolutional neural network algorithm to achieve accurate prediction of tool wear amount and remaining life [6]. The research differs from the electromechanical modelling approach from a data-driven perspective, based on deep learning from multiple sample data, to optimize the detection model of tool wear, while using tool wear data to construct a mathematical model of wear degradation and life decay under actual machining conditions [7]. The product model validation method mentioned in the article is to use the existing data of tool machining milling time and remaining machining times for the unused prediction of tool life, for machining

processes with big data conditions, provides a way to predict the usage performance of products and equipment [8]. The spatial expression for the cantilever travel path of the road header is firstly calculated, and secondly, the collision conditions between the coal seam and the road header are mathematically modelled [9]. The control buttons for controlling the cantilever of the road header are designed in the virtual model to realize the simulation of the coal mining site within the virtual environment, which provides a good solution for early warning prevention of special operations and virtual equipment monitoring in special environments.

The design of complex multidisciplinary systems requires the knowledge of a collaborative group of experts, where designers with different disciplinary backgrounds work with analytical engineers, manufacturing engineers, marketing experts, and managers [10]. To support collaborative issues in simulation and design, it is important to document models, capture their semantics, and place them in a well-organized knowledge base suitable for use on the Internet [11]. A variety of unified modelling approaches and simulation languages exist, and they can be classified according to the following criteria: graphical and language-based approaches, procedural and descriptive modelling, multidomain and single-domain modelling, continuous and discrete system modelling, and function-based and object-oriented approaches [12]. Like other modelling methods, in the bonding diagram approach, complex systems are first decomposed into subsystems, and then, the subsystems are further hierarchically decomposed top-down into components with known dynamic behaviour or elements expressing physical processes, and the decomposition is based on power exchange between subsystems, components, and elements [13].

Power is distributed, transferred, stored, or converted to other forms while flowing within a system, so the bonding diagram method is best suited for modelling continuous processes and systems, but with some augmentation of the bonding diagram, discrete-time systems and continuous-discrete hybrid systems can also be modelled. A unified description of the energy distribution, storage, transfer, and consumption of the underlying physical processes makes bonding diagrams suitable for various types of physical systems and for multidomain systems that contain different forms of energy and their interactions. And, since most of the power exchange between components or subsystems in a system occurs in physical systems with couplings such as shafts, hydraulic lines, or wires, there is a clear correspondence between bonding diagram model structures and physical system mechanisms.

3. Digital Twin-Assisted Simulation Analysis of Complex Assembly Models for Step-Down Processes

3.1. Simulation Design of Digital Twin Assembly Model. A digital twin is a simulation process based on physical models, making full use of sensor-aware data, inheriting multidisciplinary, multiphysical, multiscale, and multiprobability, completing the high-fidelity mapping of physical equipment in virtual space, adding, or extending new capabilities to physical entities, and realizing health management and maintenance of physical equipment throughout its life cycle [14]. The unique virtual model of the digital twin, as an important carrier expressing all information of the physical system, can synchronize the in situ state of physical equipment and realize adaptive update according to the change of health characteristics of a physical system and realize the performance degradation detection, damage, and life prediction of a physical system by combining with the intelligent diagnosis and prediction rule model built based on big data. A study on the application framework of digital twin technology in the health management of hinge nodes of soft rigid arm mooring systems is carried out.

The five-dimensional digital twin model, as the basic conceptual model for the application of digital twin technology on the ground, can most directly reflect the specific content of digital twin technology in the application process, organically integrating the real physical system, the sensor monitoring data in the operation process, the high-fidelity twin in the virtual space, and the integrated service system into a new health management paradigm of digitization, intelligence, and visualization. In this paper, the five-dimensional digital twin model is represented by the following equation.

$$M_{\mathrm{DT}} = \left(\mathrm{PE}, \mathrm{VE}, \mathrm{Ss}, \mathrm{CN}^2\right). \tag{1}$$

The mechanical system is mainly composed of motor-driven active rollers and friction-driven idler rollers. According to the requirements of knitted fabric processing, the fabric is expanded and unfolded by the spreading rollers on the threaded surface after the fabric is finished, and the fabric is adjusted by the gravity floating rollers. After the roller rolls the dyeing liquid, it is sent to the measuring device before the roll, in which the roller and the roll spacing of the roll before the device are small, to reduce the knitted fabric curling and wrinkling, etc., the winding axis and the A-frame are connected with the frame through the slide rail, and the slide rail is equipped with a hydraulic cylinder drive at the bottom, and the variable tension winding is realized by adjusting the distance between the winding device and the roll before the device. Due to many parts and connections of the mechanical model, it is necessary to do the Boolean merging process [15]. After the model processing is completed, the kinematic subconstraints are added between each roll shaft. Rotational subconstraints are added between the shafts and the bearing base, i.e., only one direction of rotational freedom is retained, and the base of the frame is fixed to the earth by applying fixed subconstraints to keep it fixed to the ground. The winding section consists of a movable platform and winding roller, so the movable platform and the ground slide are set as a planar moving sub. In addition, the connection end of the winding drum and the motor shaft adopts the cross shaft type universal joint connection in consideration of the vertical distance difference, so for this shaft end connection, a Hooker sub for universal joint

connection rotation will be applied, allowing the up and down movement of the universal joint while rotating, which makes the winding drum have better mobility and better meet the field implementation requirements; the mechanical model and typical motion sub are shown in Figure 1.

The data of the digital twin is characterized by multitime scale, multidimensional, multisource, and heterogeneous. This has caused a great waste of resources and increased product costs; the adoption of digital technology has reduced the probability of assembly failure and improved product economic benefits. However, digital prototype models often ignore many elements in the real environment, causing them to be inconsistent with the actual assembly of parts. Meet the performance requirements of products with higher precision. The data are mainly derived from real physical systems, virtual twin models, service systems, and algorithmic fusion data. The data obtained from the real physical system includes static data and dynamic data; static data is mainly extracted from the existing database, such as material mechanics parameters, processing process, and assembly sequence of equipment, while dynamic data is the data of the operation state of the real physical system monitored by sensors in real time; the virtual model can generate auxiliary data through simulation, and these data reflect the operation of the real physical system in different connections which represent the association rules between systems, including the connection between physical system and database, the connection between the physical system and virtual model, the connection between the physical system and service system, connections between virtual models and databases, connections between virtual models and service systems, and connections between service systems and databases [16]. The virtual model relies on operational state data from the real physical system, and the virtual model is made more representative of the real physical system by tuning and optimizing the model (e.g., parameters, boundary conditions, and dynamic characteristics), driving the virtual model for state updates in real time, and establishing a real-time interactive mapping between the real physical system and the virtual model.

Data is the foundation and direct driver of the entire twinning process, and the mirror replication of the virtual system to the physical system relies on the real-time acquisition and rapid transmission of high-precision sensor data. The soft rigid arm mooring system has a complex structure and diverse features and relies on sensors with stable and durable working performance to obtain information on structural response, load change, operation, and service environment during its service. At the same time, it is also necessary to consider the information transmission efficiency between sensors and build a fast and efficient sensing network to ensure low delay and less missing data signal transmission, which is also a key factor to realizing the synchronous mapping of the virtual system to the physical system. The sensing data acquired in real time can be used not only to monitor the current state of the system but also to predict the future state of the system with the help of big data and dynamic data-driven analysis and decision-making technologies.

$$\max F = (x - x_i)^2 - (y - y_i)^2 - (z - z_i)^2, \tag{2}$$

$$\|f(x) + Q\|_2 = \sqrt{\sum_{i=1}^{n} [f(x_i) - z_i]^2}. \tag{3}$$

Starting from the physical system of the soft rigid arm mooring system, the integrated sensor data acquisition system acquires the operational state data of the physical system and establishes a multisystem-level virtual model in the virtual space with the same geometric, physical, behavioural, and rule attributes as the real physical system, then uses the historical and real-time data collected by the sensors to update the virtual model and guarantee the fidelity and reliability of the model; through the real-time data, AI intelligent algorithms are driven to diagnose the current state of the equipment and predict the degradation trend of the equipment; finally, an integrated service system is used to assist in operation and maintenance to achieve monitoring, simulation, diagnosis, prediction, and control of the equipment. The tension of open-width processing of knitted fabrics needs to fully consider the deformation of knitted fabrics. Therefore, low tension and stable tension control are the key factors influencing the quality of knitted fabric open-width processing.

$$p_k = [I\,0]\prod_{i=1}^{k}{}^{i} A_i(\theta_j)[0 \quad 0 \quad 1 \quad 1]^T. \tag{4}$$

Complex products are composed of a series of parts connected, and the assembly process not only has information on the types and quantities of parts, but also has many other types of assembly information, such as the structure, function, fit constraints, degrees of freedom, surface accuracy, dimensional tolerances, hierarchical relationships, and other basic information of parts, assembly sequence information containing the division of assembly tasks and hierarchical decomposition, and assembly scene information containing assembly tools, fixtures, and other assembly resources and the assembly environment, assembly resources such as jigs and fixtures and assembly scenario information of the assembly environment [17]. The diversity of assembly information leads to various ways of description, such as part shape information described in vector form, assembly task information described in the semantic form, and assembly process information described in diagram form. The part assembly path planning is closely associated with this assembly multisource information, and the assembly path not only depends on the starting and ending points of the assembly, but to some extent, it is also related to the coupling of the assembly multisource information, as shown in Figure 2, and how to describe the multisource information reasonably is of great significance for the reuse planning of the assembly path.

Complex products are characterized by many parts and components, so if the assembly path planning is carried out according to "assembly-parts," it will increase the complexity of the assembly path planning and the difficulty of solving the calculation. To complete the assembly

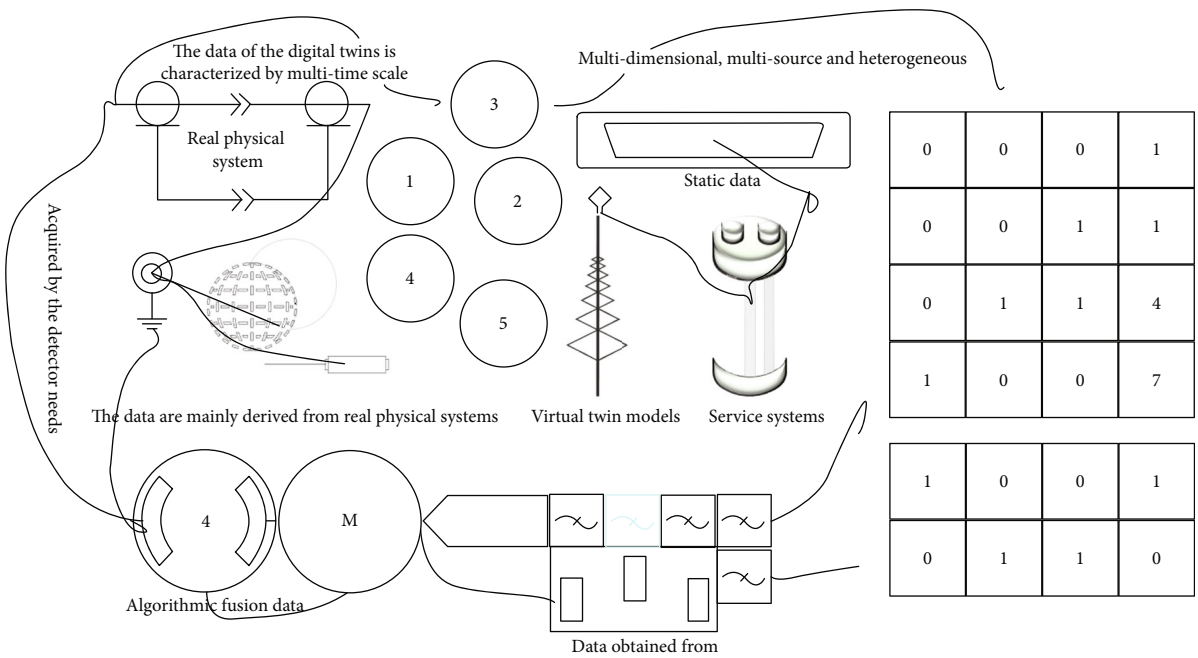

Figure 1: Simulation framework of digital twin assembly model.

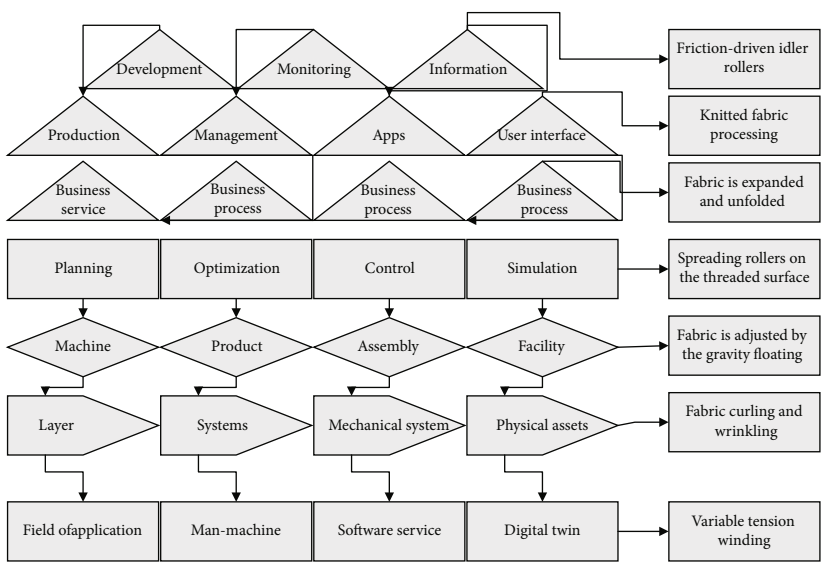

Figure 2: Schematic diagram of assembling multiple sources of information.

path planning of complex products better and more efficiently, the assembly is usually assembled according to the hierarchy of "complex assembly - subassembly - component - assembly - part."

$$\mu = \frac{1}{3n}\sum_{i=1}^{n}\left(p^i - q^i + r^i\right), \tag{5}$$

$$\mathrm{Cov}_{j,k} = \frac{1}{3n}\sum_{i=1}^{n}\left(p^i q^i - q^i r^i + r^i\right) j. \tag{6}$$

The attitude information of a component can be represented by giving a reference attitude and performing a certain attitude transformation on the reference attitude. The attitude transformation process in 3D coordinates can be represented in the form of a 3D attitude transformation matrix, which can be characterized by multiplication operations of the attitude matrix and the rotation matrix.

The fit feature information is an important parameter used to describe and constrain the fit relationship of parts in an assembly. For complex products, the fit relationship between parts is an important part of the assembly path planning for building assemblies, and the assembly paths of parts with similar fit feature constraints are reusable to a

certain extent, so the part fit features need to be analysed and reasonably represented.

$$\begin{bmatrix} a \\ b \\ c \end{bmatrix} = \begin{bmatrix} r_{11} & r_{12} & r_{13} \\ r_{21} & r_{22} & r_{23} \\ r_{31} & r_{32} & r_{33} \end{bmatrix} \cdot \begin{bmatrix} a' \\ b' \\ c' \end{bmatrix}. \tag{7}$$

Parts generally have multiple geometric features; however, generally, only individual features will interact with other parts to form the fit relationship between features; this feature fit relationship is determined by feature matching elements, so how to accurately extract these feature matching elements and match is the premise of the construction of part fit feature information. The tension of open-width processing of knitted fabrics needs to fully consider the deformation of knitted fabrics. Therefore, low tension and stable tension control are the key factors influencing the quality of knitted fabric open-width processing. Part features are divided into matching features and other features according to whether they have matching relationships with other parts, and the matching features are mainly plane features, surface features, shaft features, hole features, slot features, table features, cavity features, etc., and these features can be decomposed into three types of feature elements: point, line, and surface. By combining feature elements and contact matching, motion constraints that limit degrees of freedom are generated between mating parts.

3.2. Simulation and Characterization of the Descending Process with Key Links. When the bonding diagram causality is labelled according to the principle of preferential integral causality, sometimes, some of the energy storage elements of the system bonding diagram have differential causality. In this case, the number of state variables of the system is equal to the number of energy storage elements with integral causality. The energy variables corresponding to the energy storage elements with differential causality depend on the state variables of the system and are nonindependent variables. When writing the state equations of the system from this type of bonding diagram, one will also encounter algebraic loop problems, sometimes quite complex, especially in the nonlinear case. Since bond graph modelling emerged before object-oriented modelling, the concepts of knowledge encapsulation and inheritance are not common in bond graph modelling; however, according to the above account, these modern modelling principles are also well known in bond graph-based modelling of physical systems [18]. Early in the modelling process, bond graph models are qualitative descriptions of physical processes, and only the relevant physical mechanisms are captured, implying that models at the physical process abstraction level can have different implementations at the mathematical model abstraction level as the modelling process progresses. Organically integrate real physical systems, sensor monitoring data during operation, high-fidelity twins in virtual spaces, and integrated service systems to become a digital, intelligent, and visualized new health management paradigm. In the subsequent modelling stages, the form of the intrinsic equations remains noncausal. In contrast to the object-oriented approach to submodel connectivity, the bonding diagram submodels can be assembled into a full cause-free model that corresponds exactly to the physical structure, and the causal relationships are automatically determined in the final full bonding diagram.

The three layers are the technical component layer, the physical process layer, and the mathematical description layer. The modelling of the system starts with the identification of the technical components and the connections between them, which are usually expressed in a graphical or nonstandard notation independent of the specific implementation; in the physical process layer, the relevant physical processes occurring in the components and the interactions between them are defined, which can be expressed qualitatively by graphical methods such as key sum diagrams, generalized networks, and line diagrams; finally, in the mathematical description layer, the mathematical model is built. It is usually generated automatically from the graphical description, and the mathematical model is expressed using an object-oriented noncausal modelling language or a block diagram, etc., as shown in Figure 3.

The physical model contains information on the material parameters and constraint boundaries of the structure, and the system-level physical model is modelled using ADAMS, which has a certain current research base. The physical model of the hinge node is created using the DM module in ANSYS Workbench, and the geometric model is imported into the transient dynamic's analysis module associated with it, which can realize the simulation of the dynamical behaviour and response extraction of the related structure. The behavioural model can not only map the motion behaviour of the real structure but also stimulate its degradation behaviour. The multibody dynamics equations of the soft rigid arm mooring system can be used to build the behavioural model at the subsystem level, and this part already has a certain research foundation, and the finite element models based on the fatigue damage process can all realize the behavioural model mapping at the member level.

The first task in implementing hinge node health management for soft rigid arm mooring systems is to create high-fidelity virtual models [19]. The virtual model of the hinge node is highly consistent with the physical system in terms of the structural shape, dimensions, and relative motion relationships, but there are model simplifications in detail. Meanwhile, the environmental loads on the hinge nodes are characterized by a high degree of nonlinearity and a wide range of action, and there is a problem of simplification of the boundary conditions in the finite element virtual model simulation, which leads to deviations between the simulation results and the monitored structural response. In addition, the structure will show performance degradation, damage, and other behaviours during long-term service, and the virtual model with constant parameters cannot accurately restore the process. For this reason, a set of well-adapted and fault-tolerant virtual model parameter identification schemes is needed to address the problem of parameter changes during the service of hinged structures and to track the parameter state of the physical system in

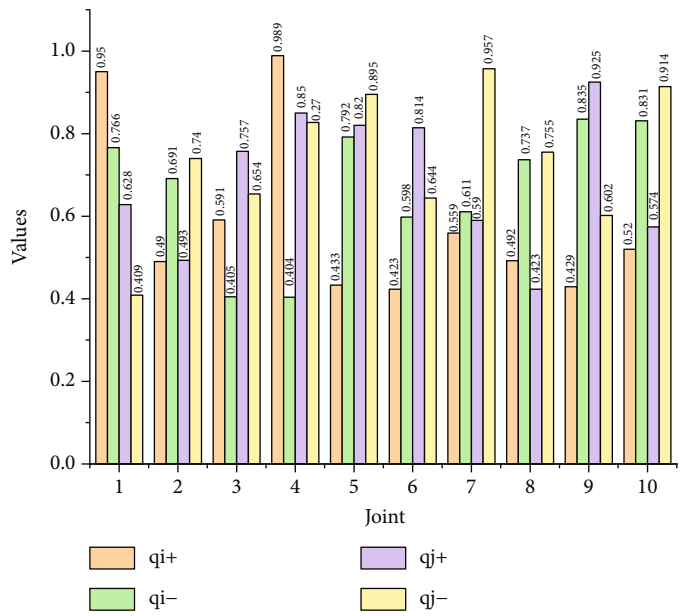

Figure 3: Physical limitations of the joints of the robotic arm.

real-time, to improve the fidelity of the virtual model. Parameter identification is to optimize the model according to the structural response and find the optimal combination of parameters that can characterize the model state within a reasonable range, involving parameters such as structural dimensions, material properties, constraints, cell types, and meshes.

After removing or transforming the relatively low active bonds, the transformed bonding diagram is obtained and some dynamic interactions of the original bonding diagram are changed or removed. The transformed bond graph can then be simulated with the same inputs, and the results obtained are compared with the original bond graph simulation results, and the small error indicates that the deleted and transformed low active bonds as well as components contribute little to the system dynamics and can indeed be deleted and transformed.

After obtaining a transformed bonding diagram with similar dynamic properties to the original bonding diagram, the driving and passive subdiagrams can be divided on the transformed bonding diagram, and if subdiagrams can be found, the dynamic properties of the obtained driving and passive submodels have been proved to be approximate to the original model by the comparison of the simulation results mentioned above and are therefore appropriate. The similarity of the simulation results is a sufficient condition for the decomposed model to approximate the original bonding graph model. The presence of subgraphs allows for further simplification of the model, rather than just removing the energy components. If the dynamic output of our interest lies in the driven subgraph, the entire passive subgraph can be removed: if the dynamic output of interest lies in the passive subgraph, the driven subgraph must be retained. In the second case, if the parameters of the passive subsystem are kept constant, or if only small changes are made in the design so that the boundaries of the subgraph remain inactive, the simulation can be done in the following two ways, including the connection between the physical system and the database, the connection between the physical system and the virtual model, the connection between the physical system and the service system, the connection between the virtual model and the database, the connection between the virtual model and the service system, and the connection between the service system and the database. First, the driven subgraph is simulated to get the input of the passive subgraph and generate a data file, and then, this data file is used to replace the driven subgraph and simulate the passive subgraph, i.e., a sequential simulation is used, and the driven and passive subgraphs are simulated in parallel (as shown in Figure 4).

A reusable conformal space construction method based on the reuse degree of the assembly path is proposed. The features of the conformal space for assembly path reuse are analyzed, the expression of the conformal space considering a priori path information is given, and the concept of a priori degree of a priori path positional point is proposed in combination with ant colony pheromone, which is introduced into the expression of a priori path information and the construction of a priori space [20]. For the problem of low reusability of conformation space of batch parts of complex products, the construction of reusable conformation space of batch parts is realized by path reusability calculation and reusability multigranularity cohesive hierarchical clustering with fused assembly multisource information. Finally, the feasibility and practicality of the method are verified by using a CNC milling machine as an example. The traditional path planning algorithm is a complete planning process for a given starting and target poses, and each planning is a complete exploration in the conformal space, ignoring the a priori path reusability existing in the conformal space, and the repeated search generates redundant consumption. The assembly path planning of batch parts of complex products,

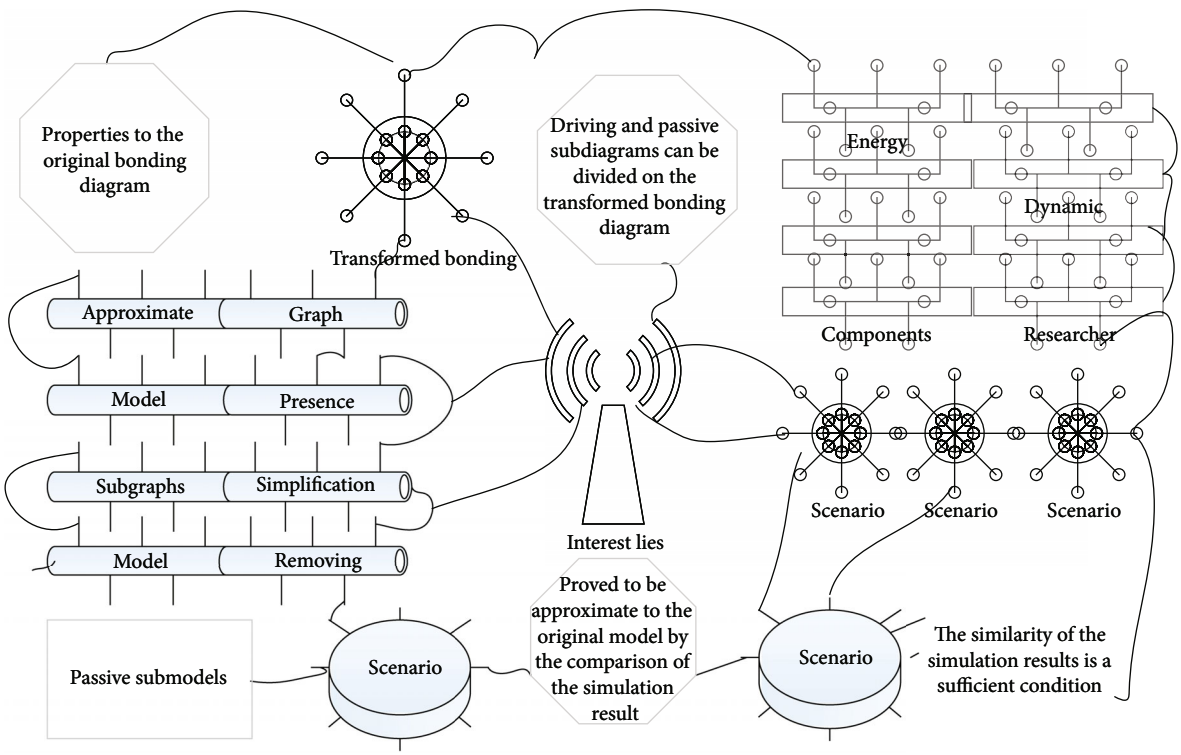

Figure 4: Flow of updating the physical parameters of the virtual model of the hinge node.

if replanned for each part, leads to a long product assembly cycle and low planning efficiency, so the constructed reusable conformal space based on the need for a method can achieve fast assembly path planning by reusing a priori paths for the characteristics of the reusable conformal space; this chapter proposes based on algorithms for path reuse in homogeneous and heterogeneous spaces. Two improved strategies are proposed to achieve reuse planning of assembly paths.

4. Results and Analysis

4.1. Simulation Results of Digital Twin Assembly Model. The cold roll pile dyeing machine control system studied in this paper has five active motors that are jointly controlled to achieve stable operation of the knitted fabric flat width process. These include the upper fabric roll drive motor, the spreading roll drive motor, the roll motor, the winding motor for winding up the dyed fabric, and the preroll motor for preroll tension control. The knitted fabric flat width processing process mainly relies on the contact between the fabric and the roll body, which is driven forward by friction. As the knitted material itself tension sensitive and easy to deformation characteristics, which requires the active motor can achieve accurate control of the front and rear tension, multimotor joint control of the difficulty is the multistage speed chain in the speed response synchronization; the current practical application of multimotor joint control strategy mainly masters order control, master-slave control, and other common ways. The tension value is less than 20 N, and the speed is within the range of 30~60 m/min, and the tension has a certain anti-interference ability before and after the flat width operation. The cold roll pile dyeing machine equipment studied in this paper uses variable frequency speed control of five motors; all motor types are three-phase asynchronous motors, using the motor reducer integrated model, using the stator current of the motor as shown in Figure 5.

The results show that the motor speed climbs rapidly with high torque and current at the instant of starting, and the output torque and current tend to stabilize when the speed is stabilized. When the target speed is adjusted from 30 r/min to 50 r/min, the output torque increases rapidly to accelerate the motor speed response, and the motor speed tends to stabilize around 0.1 s, indicating that the vector control speed regulation model has good robustness, and the frequency conversion speed regulation method under asynchronous motor vector control can meet the requirements of stable tension control for knitted fabric flat width processing operation. The target speed of all motors in the master order reference control strategy is the same, which has certain defects, that is, the target speed of each motor is from the same fixed value; when the speed of one motor in the multimotor fluctuates, the speed of the remaining motors is difficult to make timely dynamic speed adjustment according to the fluctuating motor, which cannot meet the requirements of this paper that the front and rear motors of the cold roll stack dyeing machine have associated control.

Therefore, the speed output feedback of adjacent motors is used to realize the multimotor joint control strategy. The idea of this strategy is to use the speed output value of the previous motor as the target speed input value of the next

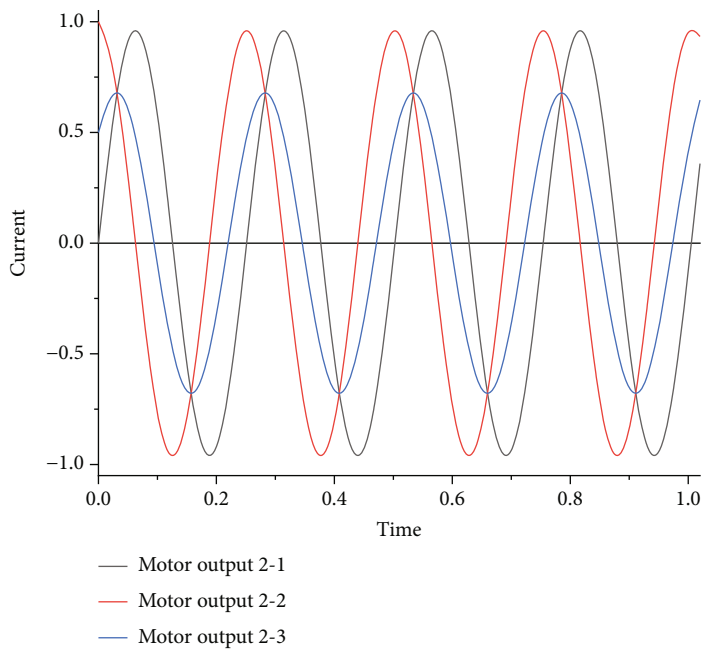

Figure 5: Stator current.

motor after the input is adjusted by PID parameters to realize the tension adjustment and complete the speed control requirement of the next motor. This strategy realizes the joint control of tension by using the input and output of multimotor speed as the correlation factor.

Subarray is the basic component unit of phased array antenna; each subarray includes base, truss, wall plate, support frame, reflecting surface and transmitting end, and other basic parts, and its assembly structure is shown in Figure 6, which is assembled from a mixture of rigid and flexible body parts. In this section, a comprehensive analysis will be carried out for the rigid error of the support parts and the flexible error of the reflecting surface of the splicing layer in the antenna subarray, and the error statistics on the target features after the subarray assembly is completed will be calculated, and the installation error of the array element layer and the positioning error during the assembly process will not be considered in this process.

For batch part assembly, it is difficult to construct a digital twin of each part to predict the overall assembly error, and it is necessary to construct a statistical feature representation of this batch of parts for error analysis. This chapter constructs an assembly twin for batch parts by hierarchically extracting part real-data statistics based on the previous work, calculating the discrete point probability distribution of batch part features based on contour similarity and proposing a hybrid vector ring method to analyse the error statistics of rigid-flexible assembly products.

4.2. Simulation and Characterization Results of the Step-Down Process with Key Links. This chapter proposes a method for predicting the positioning-assembly accuracy of complex products based on twin data, simulating the whole assembly process of real thin-walled parts from fixture positioning to welding completion, and improving on the existing method to predict the product twin assembly accuracy. Firstly, the basic process of thin-walled part assembly is described, and reasonable assumptions are made to introduce the application scenario and construction process of product twin in the positioning-assembly process. The advantages of the flexible tooling system for positioning thin-walled parts with free-form surfaces are introduced, and the adjustment method of the fixture positioning ball head based on isometric offset surfaces is proposed to analyse the influence of geometric errors and physical characteristics of the thin-walled twin on its force deformation. To minimize the mean value of deformation of the discrete point set on the thin-walled part, a hybrid particle swarm-based multiclamp positioning optimization method is proposed to ensure a strong deformation resistance of the thin-walled part at the positioning stage. The discrete error of the positioned thin-walled part is taken as the input condition, and the real assembly error of the thin-walled twin is calculated by improving on the traditional influence coefficient method and considering the flexible assembly under the action of various attributes such as feature alignment and physical interference. Finally, the feasibility of the method is verified in the flexible assembly process of the phased array antenna array (as shown in Figure 7).

The synchronization of multistage tension control can be improved by increasing the gain coefficient, and a reasonable gain coefficient can effectively enhance the followability of tension control; as shown in the figure, when the gain coefficient is 2, the change of tension of 2~4 levels with tension 1 is better. However, by adjusting the gain coefficient method will increase the peak of the follower tension; comprehensive result considered for knitted fabric low tension control applications in the gain coefficient in the range of 1~2 control effect is best. The traditional bolt joint analysis has not considered the interaction between the bolt and the

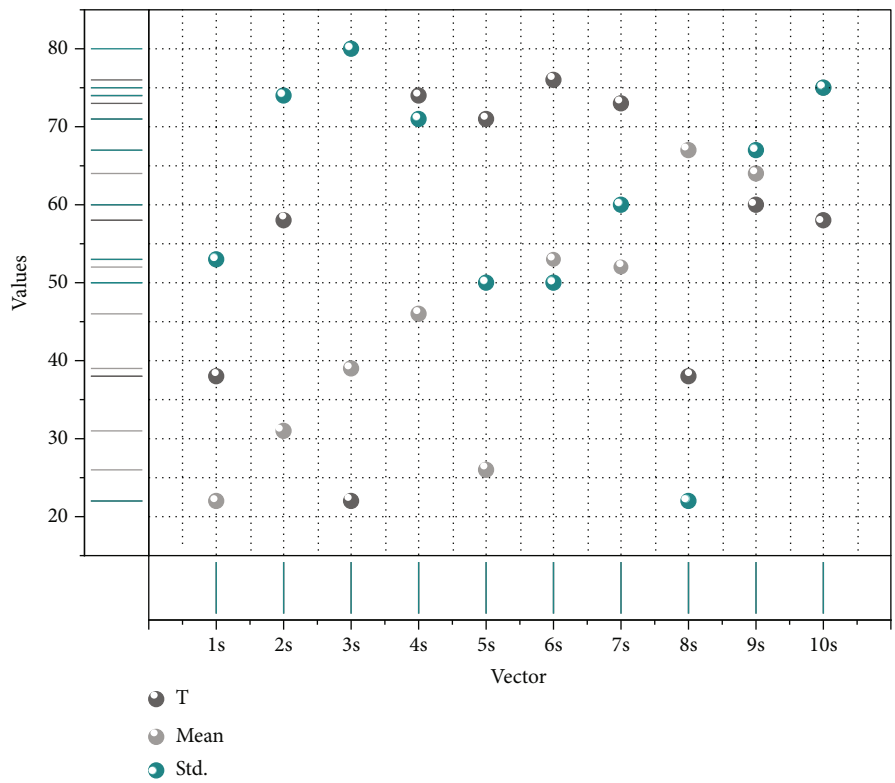

Figure 6: Discrete point statistics of the reflective surface and the lateral line of the wall plate assembly edge.

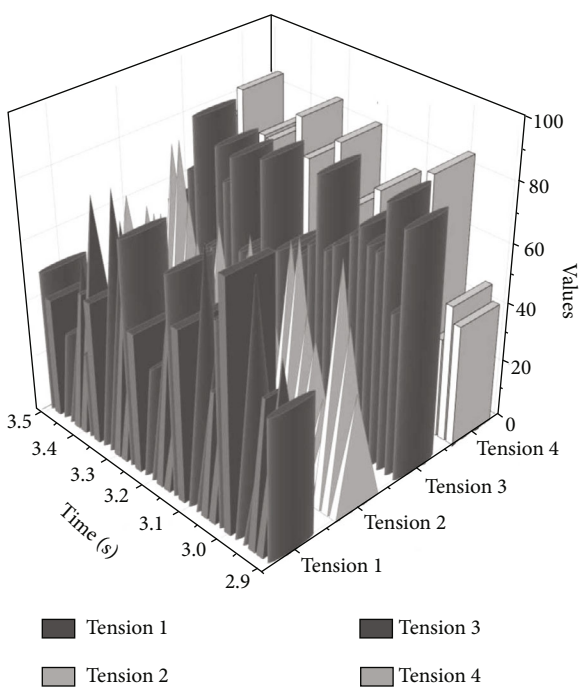

Figure 7: Gain coefficient.

transmission error in the assembly process, which makes it difficult to accurately simulate the bolt assembly stress. To a certain extent, it is also related to the coupling of assembly multisource information. In this chapter, we study the bolt assembly of the connecting plate twin based on the spring-stiffness model and construct a bolt stress model driven by multiple parameters such as part geometry and physical properties, assembly process, and service environment and achieve low-stress assembly effect by optimizing the bolting process, to guarantee the accuracy and performance stability of the product in service.

Figure 8 shows the motion response of the bracket, chassis, and cab, respectively. Based on the simulation results, the crane-related parameters in the design can be adjusted and restimulated to achieve the desired product performance. This shortens the cycle time for both product design, experimentation, change redesign, and reexperimentation and solves possible problems in the design phase, significantly reducing the design cost. This shows that it is very correct to consider systems, especially multidomain coupled systems, using bonding diagrams. Such a bonding diagram model is also very useful for detecting instabilities in vehicles and can be used for dynamic characterization of similar mechanical products, such as excavators and cranes.

CNC machine tools as typical complex customized products, widely used in ships, high-speed rail, aviation, aerospace, vehicles, and other manufacturing fields, is a basic product of China's manufacturing development. In recent years, with the rapid development of batch customization technology for complex products, the reusable design method based on product configuration design and variant design can meet the functional parameter requirements of customized products by reconfiguring some modules, leading to the serialization and modularization of CNC machine

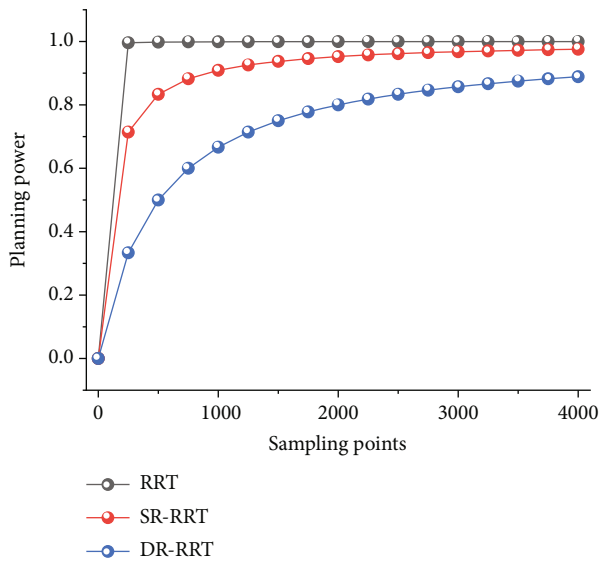

Figure 8: Path planning success rate of each algorithm with different maximum sampling points.

tools. Assembly path planning as a key link in the product life cycle of CNC machine tools, the efficiency of the assembly path planning has a great impact on the product assembly cycle, domestic machine tool enterprises due to the lack of effective support for a series of complex products digital assembly software system, and in the new model of the product assembly planning often need to replan the assembly of all the component modules, resulting in low planning efficiency. Therefore, how to improve the quality and efficiency of assembly path planning by digital means is an urgent problem for machine tool manufacturers.

5. Conclusion

Firstly, the reuse-oriented conformation space expression is analysed, and it is pointed out that the reuse-oriented conformation space should contain a priori path information, and the concept of a priori degree is defined in combination with ant colony pheromone concentration, and it is introduced into the information expression of a priori path positional points and the construction of a priori path space. The method of calculating the point distance of assembly multisource information nonlinear mapping space is proposed, and the calculation of assembly path reuse degree is realized by the many-to-many matching algorithm that fuses the assembly multisource information, and on this basis, the multigrained clustering of parts path reuse degree is realized by cohesive hierarchical clustering based on the multigrained judging criteria of assembly task coupling degree and dimensional information aggregation degree, and the uniform enclosing box dimensional information between clusters is obtained according to the clustering results. The assembly conformation space that can be reused by parts in the same cluster is constructed. Since the bond graph model describes the power flow within the system, it is suitable for power- and energy-based approach to downscaling the system, preserving the components or subsystems that make the main contribution to the dynamic behaviour of the system and the physical meaning of the parameters; comparison of the local activity of the junction structure can reveal the strength of the power or energy coupling within the system and thus can be used for decomposition and decoupling of the system, and this decomposition and decoupling have obvious physical significance. The special role of the multiport modulation converter MTF in bond diagram modelling is explored, and the bond diagram model of the mechanism is built through the motion transition relationship represented by the multiport converter MTF, while its dynamical structural characteristics are directly represented by it, which not only makes it easier to establish the equation of state of the system but also very helpful to make an intuitive force and velocity relationship between the interacting parts in the system, physical interpretation of the force and velocity relationships between the interacting components of the system. A typical mechanical-hydraulic coupled system loader is modelled in its entirety and reduced in order using a component-based bonding diagram modelling approach.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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