Overview of virtual assembly for array antennas and future work under industry 4.0

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ABSTRACT

With the development and application of computer technology, the design and production mode of manufacturing industry is gradually moving towards digitization and intelligence. As a key component in space exploration, navigation, and national defense, the assembly quality of array antennas is crucial. In response to the problems of invisibility and difficulty in assembly of array antennas, this paper analyzes the current research status of virtual assembly from four aspects: virtual assembly system, assembly sequence planning, collision detection, and virtual assembly interaction, by introducing virtual reality technology. Finally, future work is pointed out for Industry 4.0. This research can provide a theoretical basis for the virtual assembly of array antennas.

Keywords: Array antenna, virtual assembly, assembly sequence planning, collision detection, human-computer interaction

1. INTRODUCTION

In recent years, China's early warning detection system has been a key component of the "integrated information network of heaven and earth" system. This system includes key research projects such as a new generation of early warning aircraft, detection satellites, and aircraft carriers, all of which require the construction of high-precision integrated antennas, also known as array antennas. For instance, the array antenna of a new generation of detection satellites consists of 500 sub-arrays, over 1 million parts, and more than 100 million assembly welding points. Its size exceeds 50 meters, and the unit cost is more than 300 million. Moreover, it needs to provide continuous, trouble-free service for over 8 years in space under harsh environmental conditions without maintenance. As such, the reliability requirements for this system are extremely high.

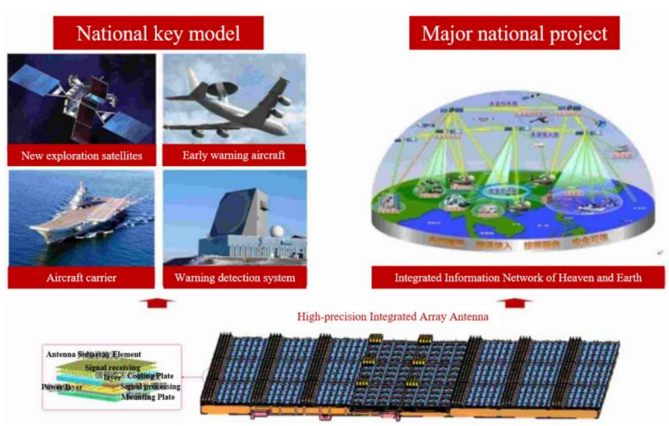

Figure 1. Array Antenna Schematic.

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Due to the complexity of the array antenna's structure, as shown in Figure 1, its assembly process is highly dependent on the experience of skilled workers. The current assembly method involves using "blind plug, blind assembly, blind adjustment", which makes it difficult to guarantee assembly quality. As a result, on average, it takes over 12 months and hundreds of repeated attempts to produce a qualified product, with a zero rate of assembly success. Given the low efficiency and quality of assembly for such a complex electromechanical product, it is essential to introduce a new assembly optimization method to achieve overall improvement in the array antenna's assembly quality.

With the increasing maturity of digital twin technology, virtual manufacturing has provided new ideas for the manufacturing industry to solve the aforementioned problems. As the key link and the last step in virtual manufacturing, virtual assembly has become the focus of research in major institutions and universities. Traditional industrial assembly research is based on the assumption that part disassembly and assembly is reversible. However, in the actual production process, there are always some irreversible mountings and dismountings, and the use of traditional assembly methods results in a lot of resource consumption. By using virtual prototypes and digital twins, the disadvantages of traditional assembly can be overcome, and the optimization of assembly processes can be achieved through iterative modification and testing in a virtual environment.

2. CURRENT STATUS OF DOMESTIC AND INTERNATIONAL RESEARCH

Under the guidance of virtual reality technology, virtual assembly technology has begun to mature and its application areas have been expanding. Most research on virtual assembly by domestic and foreign scholars has focused on product information projection, virtual system development, assembly interaction and planning, and collision experiments.

2.1 Status of virtual assembly system

Virtual assembly systems with high immersion, low design, assembly and maintenance costs, and high assembly efficiency have been a hot spot for research at home and abroad.

Mingzhe Tang[1] studied the virtual assembly and virtual repair of speed reducers, and applied Unity3D software and HTC VIVE device to realize a virtual assembly system including navigation module, learning module and training module. Anchao Hu[2] developed a virtual assembly system based on virtual reality technology, which has a free virtual assembly perspective, verifies the feasibility of assembly paths, and simulates the manufacturing process of ship segment assembly. Peng Huang[3] proposed a distributed solution to solve the problem of insufficient real-time collision detection by developing a distributed collaborative virtual assembly system.

As for the research on assembly information model, Zhiyu Chen et al[4] based on the basic characteristics of assemblies and assembly relationships, for the assemblability of parts reflected by the errors of assembly boundaries, and analyzed the degree of assembly between parts by calculating the values of overfitting boundaries. bronsvoort H et al[5] oriented integrated product model, built wood for the assemblies and parts in them separately, and analyzed the assembly relationship from the connection information perspective focused on the assembly relationships and applied the model to a variety of planning and assembly simulation studies.

Qiao Hu et al[6] focused on the retrieval method of three assembly models, proposed an evaluation method for the retrieval of assembly parts oriented to the similarity of assembly information and geometric information, and solved the models separately by retrieval algorithms to achieve the repeated and reliable use of assembly part models. Zhao Xiaofei[7] focused on information management and system implementation in the study of virtual assembly, and based on the analysis of the key data structures in the assembly, the assembly information was collected using SolidWorks software, and the hierarchical connection diagram of the assembly process and the assembly information database were established, and the virtual assembly of diesel engine oil delivery pump was used as the research object, and the developed virtual assembly information management system was functionally tested The virtual assembly information management system was tested and validated.

2.2 Status of assembly sequence planning research

Assembly Sequence Planning (ASP) technology is a key factor influencing assembly quality and efficiency, and is also a key issue that needs to be focused on in order to achieve virtual assembly. In recent decades, scholars have focused on the quantitative research of mathematical methods in the field of assembly sequence planning, including priority constraint method, cut-set method, geometric reasoning method, and graph theory-based methods.

Bourjault A et al[8] obtained the optimal assembly relationship between parts in the form of expert question and answer, and derived a feasible assembly sequence by analyzing the priority as a constraint. Homen D[9] took an alternative approach for the study of assembly sequences by using the idea of inverse reasoning and analyzed the disassembly sequence of the assembly parts from the finished product and then deduced its feasible assembly sequence in reverse.Kumar Gulivindala Anil et al[10] processed the assembly process with cut set generation algorithm when dealing with the assembly association diagram and deduced the assembly sequence. Minghui Zhao et al[11] proposed a bidirectional assembly sequence planning method based on course learning and migration learning to solve the assembly sequence planning problem for complex assembly models, which can complete the assembly task with arbitrary initial states by fewer steps, and validated this method on the simulation platform of ROS-Gazebo and TensorFlow. Kaijun Zhou et al[12] proposed a method to express the assembly sequence using the edges of the assembly relationship graph by analyzing the geometric feasibility of the edge sequence and recovering the edge sequence.

In recent years, scholars have started to use heuristic search algorithms for the solution of the assembly sequence planning problem, which has greatly improved the solution efficiency, and the commonly used algorithms include particle swarm algorithm, simulated annealing algorithm, genetic algorithm, bee colony algorithm, etc.

Bonnevil F et al[13] used chromosomes to represent the assembly sequence and used genetic algorithm to solve the ASP solution problem, simulating the iterative process of chromosomes to produce the optimal offspring as the optimal assembly sequence.Wang J F et al[14] guided the construction of the assembly sequence in the implicit solution space based on the derived disassemblable candidate list, and combined the ant colony algorithm and the principle of disassembly method to ensure the geometric feasibility of the assembly sequence.

In order to improve the solution rate, researchers have proposed to apply hybrid algorithms to fuse different algorithms as a way to improve the efficiency of solving ASP problems. Deepak Kumar Kolur et al[15] combined particle swarm algorithm and immune algorithm and proposed to combine the geometric feasibility of the product with the product processing attributes and construct the objective function on this technique to plan the product assembly sequence. Wang Dou et al[16] used genetic algorithm to optimize the hybrid ant colony genetic algorithm, and after obtaining the initial population quickly by the ant colony algorithm, analyzed the "pheromone" of the path obtained by the ant colony planning to speed up the iteration of the algorithm in the form of information accumulation to achieve the global optimal solution of the assembly sequence model quickly. Qianwen Qu et al[17] also used a hybrid algorithm for the assembly sequence, proposing the imperial competition algorithm to obtain the initial population, and then combined with the genetic algorithm to obtain the optimal assembly sequence using the iterative solution process of the genetic algorithm.

2.3 Status of collision detection research

Collision detection technology is a key technology in virtual assembly systems. By designing collision detection for the assembly process, it can prevent the occurrence of interpenetration between components in the virtual assembly scene and avoid completing the assembly without contact, ensuring an immersive experience for users.

The wraparound box algorithm is the most frequently used algorithmic model in collision detection techniques. Klosowski J T et al[18] proposed a collision detection algorithm based on discrete direction polyhedra using a wraparound box tree, aiming to identify objects moving at high speed in complex scenes. This algorithm effectively solves the problem of detecting high-speed collisions by using the K-DOPs bracketing box principle.Rong Zhang et al[19] proposed a method for collision detection by transforming the OBB bracketing box formulation into a rotation group with unconstrained optimization. Using this method, the accuracy and working speed of collision detection can be improved by genetic algorithm. qu X et al[20] proposed a new collision detection algorithm in order to detect collisions in complex virtual environments, which can handle complex virtual environments containing multiple objects at the same time and is a good reference for cases where both coarse and exact collisions exist. Chunan Hu et al[21] proposed an algorithm for collision detection by studying the compactness of the bounding box and the multi-layer modeling structure, which can significantly reduce the cutting test time and improve the efficiency of collision detection. This method is particularly effective in studying the selection and updating of objects in complex environments. Jing-Rong Sun et al[22] proposed an algorithm for collision detection that mixes AABB enclosing boxes and OBB enclosing boxes to improve the structure of the problem tree and speed up the traversal method. The geometric triangles in space are downscaled to a two-dimensional plane by projection, and the coordinate transformation method is added to the collision detection algorithm. This can improve the detection speed while ensuring the accuracy of the model solution. The schematic diagram of the wraparound box is shown in Figure 2.

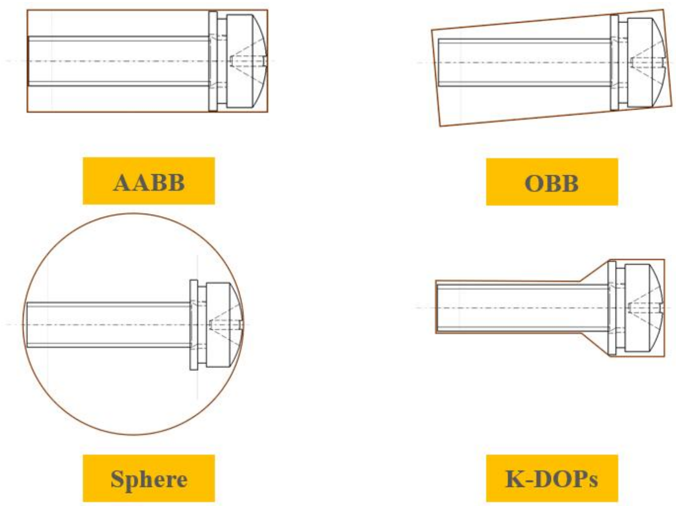

Figure 2. Schematic diagram of the wraparound box.

2.4 Status of virtual assembly interaction research

Domestic and foreign scholars have researched and upgraded human-computer interaction devices such as mouse, touch screen, Leap Motion, and Kinect optical devices to improve users' virtual assembly experience, as shown in Figure 3.

The data glove is a virtual reality hardware device that contains various sensors that can be used for model manipulation in virtual applications. By using the data glove, vibration and mechanical feedback can be generated when grasping objects to enhance the immersion of the virtual assembly system. Li Jing et al[23] designed a virtual assembly system with a four-cylinder engine as the research object, using data gloves as the main interaction tool, and capturing the relative position changes of the human hand and the object to be grasped through an orientation tracker to achieve the detection of the specific step in which the assembly is located in a virtual environment. With the help of EON Studio engine, Cui S.L.[24] developed the data glove interaction in a secondary way, focusing on coordinate conversion and collision detection in the assembly operation to realize a virtual assembly model based on data glove interaction. Boonbrahm P[25] used the visual recognition technology of camera to detect the user's finger after wearing the data glove, and the collected finger The information action is projected to the 3D simulated finger in the virtual environment to operate the product assembly, and a natural manual interactive assembly system is developed.

Leap Motion is a virtual reality hardware device based on hand position tracking commonly used in the field of virtual assembly, which can present a wide variety of interactive functions by defining gestures.Boudjelthia A[26] et al. designed and implemented an interactive virtual grasping system using a Leap Motion device augmented by the Unity3D engine in virtual environment to interact with the real world, allowing real-time product grasping. In addition, the most significant advantage of this virtual grasping system is the use of Unity3D's mature physics engine, which improves the human-computer interaction response speed and also avoids the product through-mold phenomenon in the virtual environment after adding a collision volume to the product. Hu Hong et al[27] developed an astronaut virtual assembly simulation system based on Leap Motion finger tracking with the aim of meeting the needs of virtual training of astronauts in Chinese manned space missions. The analyzed interaction requirements were applied to the virtual training of astronauts, and the trainers generally recognized the system highly and gave feedback that the system was highly immersive and helped a lot to improve the training efficiency.

Kinect, as a supporting sensor designed by Microsoft for somatosensory games adapted to PC-based somatosensory control software, can realize the recognition and tracking of human skeleton and interact with the PC side through custom gesture operations. Based on this sensor, Qing Zhang et al[28] carried out secondary development on the basis of Kinect sensor to improve the immersive experience of users in the virtual reality environment, modified the original model, and designed the collision part, when the sensor captures the human gesture information and the model triggers the preset changes when the collision area is determined. Fan Chenxiao[29] used the Kinect and Unity development platform to enhance the basic interaction between the user and the virtual model, and embedded neural network algorithms to optimize the action recognition accuracy of the Kinect sensor.Liao H et al[30] established a virtual assembly digital model in a laboratory environment, built a running assembly scene into the virtual platform, and used gesture recognition to interact with the The user can change the assembly scene by body movement in the virtual reality. Zhenqing Xie[31] developed a virtual assembly system based on gesture recognition using Unity3D platform and Kinect device, combined with AR technology.

HTC VIVE series devices, as the VR development devices launched by HTC, have quickly occupied half of the VR display through its high level of sedation and excellent performance. Minli Dai[32] implemented an industrial assembly training system through the Unity3D engine and HTC VIVE hardware devices, which is more convenient in terms of interaction by dividing it into two scenes in two dimensions and three dimensions. Xia Xiaoqing[33] provided design principles and specifications for virtual assembly system interaction design by constructing a hierarchical model of user requirements for virtual assembly system. Wu, Qinghua[34] designed and developed a hydraulic turbine virtual assembly prototype system by studying the assembly sequence planning method for the assembly process and the assembly sequence evaluation method in the overhaul assembly environment. Bin Chen[35] designed and implemented a virtual assembly prototype system, and validated and developed the designed virtual assembly prototype system by taking the A model traveling wave tube as an example.

(a) Data glove

(b) Leap Motion

(c) Kinect

(d)HTC Vive

Figure 3. Human-computer interaction devices.

2.5 Summary

In summary, research on virtual assembly at home and abroad mainly focuses on the development of virtual assembly systems in different scenarios, with the aim of improving the quality and efficiency of assembly. In the solution of assembly sequence, graphical methods are commonly used to construct the assembly environment, while random algorithms can achieve higher efficiency only in spacious workspaces. Therefore, intelligent optimization algorithms are often used to solve the problem of assembly sequence, and the algorithm needs to be optimized according to the actual engineering background to improve its solving efficiency. In terms of virtual assembly interaction methods, it is difficult to simultaneously achieve the optimal accuracy of product assembly and the interactive experience of manual operation, as different types of interaction methods have their own suitable application scenarios. This paper uses virtual reality headsets as a visual interaction medium for virtual assembly systems, and uses controllers to control the assembly process, thereby enhancing the immersive experience of the virtual assembly system.

3. FUTURE WORK

To address the problems of invisible assembly and difficult assembly in the assembly process of array antennas, based on the analysis of the current research status of virtual assembly for array antennas, this paper proposes to introduce virtual reality technology to achieve smart and virtual assembly of array antennas in a three-dimensional virtual space, which can serve array antenna assembly teaching. The future implementation work involves the following:

Firstly, based on the characteristics of array antenna assembly, analyze the key technologies involved in realizing the array antenna virtual assembly system, and establish the array antenna assembly information model.

Then, in order to plan the assembly sequence, divide the assembly units of the array antenna, construct an adaptive function, and use an intelligent algorithm to solve the assembly sequence planning problem of the array antenna.

Next, regarding collision detection, use a mixed hierarchical bounding box as the collision detection method in the virtual assembly of the array antenna. Through the construction of collision mathematical models, geometric constraint recognition, and feedback force calculation, achieve tactile rendering in collision detection.

Finally, in terms of system development, design virtual assembly scenes, model preprocessing methods, and human-computer interaction methods, and develop and implement the functions of the virtual assembly system for array antennas through a 3D engine.

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