Digital assembly technology based on augmented reality and digital twin: a review

Chan QIU, Shien ZHOU, Zhenyu LIU*, Qi GAO, Jianrong TAN

State Key Laboratory of CAD and CG, Zhejiang University, Hangzhou, China, 310027

Abstract: Product assembly simulation is considered as one of the key technologies in the process of complex product design and manufacturing. Virtual assembly realizes the assembly process design, verification and optimization of complex products in the virtual environment, which plays an active and effective role in improving the assembly quality and efficiency of complex products. In recent years, augmented reality (AR) and digital twin(DT) technology have brought new opportunities and challenges to the digital assembly of complex products due to their characteristics of virtual reality fusion and interactive control. This paper expounds the concept and connotation of AR, enumerates a typical AR assembly system structure, analyzes the key technologies and applications of AR in digital assembly, and points out that DT technology is the development trend of intelligent assembly research in the future.

Keywords: Augmented reality; Digital twin; Digital assembly; Virtual simulation; Assembly analysis

1 Introduction

With the development of products towards the direction of complexity, miniaturization and precision, the assembly filling density and precision requirements of products are getting higher and higher, and the difficulty of assembly is getting greater and greater. Assembly design and process planning have become the weak links of product design and manufactural ng. Product assembly simulation technology is an effective means to improve the level of complex product assembly design and process planning.

Traditional assembly simulation technology builds a physical prototype to test
whether its assembly performance indicators are qualified, and feedback the results to designers to improve and adjust the assembly process. Due to the need to produce a real physical prototype, the cost of products increases and the competitiveness of products in the market is adversely affected.

With the development of computer technology, graphics technology, based on Virtual Reality (VR) digital assembly gradually into the line of sight of people, which uses digital prototype (DP) for assembly operations, instead of physical Prototype in a Virtual environment simulation of the real product assembly process, get the assembly performance, avoid production material loss caused by the physical Prototype, which significantly improved the accuracy and efficiency of complex product assembly design.

Although VR technology is becoming increasingly mature and plays an important role in the process of product design and analysis, it still has the following deficiencies in the assembly simulation of complex products: (1) The product digital prototype and environment model established in VR world cannot accurately reflect the real assembly scene; (2) Users' senses are limited in the virtual environment, and it is difficult to fully experience the real assembly process, resulting in low simulation reliability; (3) Despite the existence of GPU acceleration technology, the real-time performance of VR assembly simulation is still not ideal.

In recent years, digital assembly technology is not content to simply in the virtual environment ideal assembly modeling, simulation and analysis, more emphasis on combined with the real assembly environment, assembly condition, gradually from the development of digital assembly based on VR to AR digital assembly, from digital assembly based on the DP to the DT. AR and DT technologies bring new opportunities and challenges for complex product assembly simulation. Some scholars tried to apply digital twins to industrial production.

AR is a cutting-edge digital technology that emerged in the early 1990s. The concept was proposed by Tom Caudell of Boeing and his colleagues when they designed the auxiliary wiring system [1]. In 1997, Azuma [2] divided AR into three
important parts: virtual reality fusion, real-time interaction and 3D registration, and elaborated its application scenarios in many fields such as medical treatment, entertainment and industry. In the past two decades, many large international enterprises, such as Microsoft, IBM, HP, Sony and Google, have conducted in-depth research on AR technology and developed such AR auxiliary devices as HoloLens and Meta [3], which greatly improved the application value of AR technology in different fields and promoted the popularization of AR technology.

In the field of industry, researchers try to apply AR technology to the whole life cycle processes such as product planning, design, assembly and maintenance, and combine virtual parts objects with real environment to construct an augmented virtual fusion environment, in which product behaviors and attributes are analyzed [4]. AR based product assembly simulation technology is, to some extent, an advanced method of VR assembly. It overcomes the tedious scene construction steps in VR method through the superposition of virtual model and real objects, and plays an important role in helping users to carry out assembly design, planning and operation. Dini [5] pointed out that AR is well compatible with through-life engineering services (TES), and has such advantages as no need for paper manual to access technical documents, accurate sensing of product status by sensors, assembly maintenance and guidance, etc. However, these all require the AR system to be equipped with powerful computing capacity to process huge data. Didier [6] applied AR to train assembly and maintenance, and explained the maintenance steps to users by combining virtual model with visual prompts. Haritos [7] USES optical devices to identify marks placed on aircraft parts, so that users can receive virtual text information in an enhanced environment. De Crescenzo [8] described the detailed application scene of AR in the maintenance of aircraft fuel tank, and used 3D rectangular frame information to prompt the staff to perform operations such as opening the fuel tank cap, observing the oil level and closing the fuel tank cap. Dong [9] presented the measured data of tire pressure and other sensors in a visual form and analyzed them. Using AR technology, the virtual information of the solution was covered on the corresponding
parts of the vehicle to realize fault diagnosis.

In recent years, researchers have developed DT by integrating DP and AR. It first appeared in a course of professor Grieves in Michigan University in 2003, and was defined as a digital system including physical products, virtual products and the connection between them in subsequent articles [10]. DT was not paid much attention at the beginning, and it was not until 2011 when AFRL, the US Air Force Research Laboratory, and NASA, the US National Aeronautics and Space Administration, proposed to construct the digital twinned body of future aircraft that this technology received widespread attention [11]. The DT defined by NASA is a digital model integrating multiple physical fields, multiple scales, and multiple probabilities. It uses physical model, sensor data, historical data and other data to interact with the simulation model in real time, so as to realize the function of real-time evolution of product state and trend [12]. Revetria[13] integrated applications of AR and DT, are dedicated to applications that improve the safety of work environments.

DT is a process and method to describe and model the characteristics, behavior, formation process and performance of physical entity objects by means of digital technology. It is a virtual model completely corresponding to and consistent with physical entities in the real world, which can simulate its behavior and performance in the real environment in real time. DT can not only use the existing theories and knowledge of human beings to establish virtual models, but also use the simulation technology of virtual models to explore and predict the unknown world, so as to discover and find better methods and approaches and constantly pursue optimization.

At present, there are many researches on AR, but few scholars summarize the complete cutting-edge technologies based on AR and DT assembly, and the representative is the review literature of Nee research team [14-16]. Therefore, this paper sorts out the development status of AR technology in recent years and the assembly simulation method based on AR, aiming to provide ideas for r & d personnel to build AR assembly system, and analyzes the research hotspot and development trend of digital assembly based on DT.
2 Structure of typical AR assembly system

Different from the complete immersion effect achieved by traditional VR technology, AR is more inclined to substitute the virtual model or information in the computer into the real world. Compared with VR, it combines the model constructed in the virtual environment with the real environment around the user, so as to realize the interaction between the real world and the virtual world, and reduce the tedious scene modeling and rendering work.

In order to realize real-time integration and interaction between product and assembly environment in AR environment, it is necessary to establish a digital assembly system platform based on AR. Research members domestic and abroad designed and developed a series of prototype systems based on AR for different application objects. For example, ARMAR system proposed by US Air Force research laboratory and Columbia University in 2007 [17], ACARS system developed by national university of Singapore in 2012 [18], and ARPPSM system developed by Algeria Advanced Technology Development Center in 2013 [19] have effectively solved the problems in the assembly design.

Typical AR Assembly systems are divided into six functional modules: Video Capture, Image Analysis and Processing, Tracking Process, Interaction Handling, Assembly Information Management and Rendering [15], as shown in figure 1.
(1) Video Capture

Video acquisition is the first step to build AR assembly system, which is mainly realized by various cameras. Radkowski [20] and Petersen [21] used CMOS/CCD camera to capture real assembly scenes of products. Wang [22][23] et al. used Stereo camera to build 3D assembly scenes, and Khuong [24] used Depth sensor camera to capture real-time Depth information. All of them can provide support for the follow-up vision-based tracking of parts to be assembled.

(2) Image Analysis and Processing

Graphic algorithms are used to process assembly operations images, mainly through computer vision. As a common function library, OpenCV is widely used [25]. For example, Continuously the Adaptive scheme - shift algorithm is often used to detect the user’s hand operations, it can accurately identify the position of the palm and fingertips and their binding relationship between the assembly parts.

(3) Tracking Process

Tracking processing uses real-time response of sensor or visual detection system to reflect the position and state of assembly parts in enhanced space. The sensors have the advantages of high accuracy, low delay, low jitter, etc., which can adapt to the
tracking of parts in various assembly scenes, mainly including electromagnetic sensor [26] and optical sensor [27]. The visual detection system is divided into two types: labeled tracking and unlabeled tracking. The former has good robustness and accuracy, but has optical occlusion problems [28]. The latter gets rid of the restriction of markers, but has weak adaptive ability [29].

(4) Interaction Handling

Interactive processing refers to using interactive AR systems such as glove interactive devices and desktop interactive devices to combine real assembly environment with virtual assembly parts [30]. Glove interactive devices represented by Hand Exoskeleton Device can capture hand movements and assembly gestures in real time [31], desktop interactive devices like Phantom track the user's hand position and assembly force, Sukan[32] built an interactive assembly system named ParaFrustum, which can support users to view target assembly objects from appropriate viewpoints, thus avoiding the problem of viewpoints occlusion.

(5) Assembly Information Management

Assembly information management is used to store all assembly information extracted from CAD model, and it enables users to access and modify the implementation information during AR assembly operation without relying on CAD system [33]. Raghavan [34] constructed Liaison Graph to manage assembly information, which make it convenient for designers to plan various assembly sequence schemes. Henderson [35] used intelligent intention-based illustration system to dynamically generate assembly process charts.

(6) Rendering

Rendering is a process of adding parameters to the assembly model in the AR environment and outputting them in the form of video to reduce the problems of insufficient information and accuracy in the reconstruction of the assembly model, which is divided into two categories: visual rendering and haptic rendering. The former obtains the visual representation of assembly data through OpenGL and Open Scene Graph [36], while the latter obtains the force feedback of users' contact through
tactile devices [37].

AR assembly system collects video through the camera to provide support for follow-up visually based tracking of parts to be assembled. The image of assembly operation is processed by graphics algorithm. Real-time response of sensors or visual detection system is used to enhance the position and status of assembled parts in space. The real assembly environment is combined with the virtual assembly parts with interactive equipment, and the parameters of the assembly model are supplemented by rendering in the AR environment.

3 Key technologies of AR based digital assembly

Digital assembly is to analyze the assembly process and error transfer of the product digital model through simulation method, and verify whether the assembly sequence, assembly path and stress deformation of parts meet engineering requirements. It is of great significance to guide the actual parts manufacturing and assembly operation, improve the efficiency of product research and development and reduce the cost. The existing researches on digital assembly of products based on AR technology are mainly divided into several aspects, such as virtual and real fusion modeling, assembly scene perception, assembly operation navigation and assembly process collaborative design.

3.1 Virtual reality fusion modeling technology

Virtual and real parts fusion modeling is a key technology to obtain the position of virtual objects in the real world through camera, calculate their motion state in real time by using tracking method, and ensure the consistency of information of parts in two environments, so as to perfectly integrate virtual objects with real environment. It is mainly realized by 3D registration technology.

All the existing 3D registration methods of AR technology use plane marks as the positioning reference, and the system structure is complex, the image processing requires a large amount of calculation, and the error amount is easy to introduce in the process. Zhou[38] proposed a visual-based 3D registration method using stereoscopic markers. This method only needs a color CCD camera to complete the 3D
environment registration, which can effectively simplify the registration system and algorithm, and eliminate the matching error of multiple sensors. Li [39] proposed a non-iterative solution based on the efficient lookup table (LUT) to solve the problem that only four corners of the square AR tag were available, the main idea is to extract the key parameter $\beta$ from the camera pose and create the LUT of $\beta$ by considering the symmetrical structure of the square mark. Thus, the 3D registration scheme with high stability can be realized in the presence of noise, as shown in figure 2.

![Fig.2 AR 3D registration based on visual effective lookup table [38]](image)

Leu[40] developed a simulation system that acquired data from 3D object surface to build CAD model and conducted data exchange with AR system. This system also provides motion capture, mechanical modeling, multimodal rendering and other operations, and integrates the design, planning, evaluation and testing functions of the assembly system. Zhang[41] proposed a method to realize 3D AR registration by using the natural circle features of images. This method makes use of predefined plane coordinate system and a circle feature in the target plane to estimate position and pose, and realizes 3D AR registration according to rotation matrix and translation vector. Hořejš [42] according to confirm the assembly on the marked points in the software environment in the real world space position, so as to define the plane and data, using software solution processing network camera image data, add virtual 3D
model instruction to the real image and display, the method to shorten the time of assembly tasks. Kim [43] proposed a use AR technology will ship CAD model associated with the image, the method of using digital camera to obtain the hull of a 2D image and extract the features, set up in the image block and the corresponding relationship between a CAD model, calculation block of the initial position, and lie algebra method is used to reduce the registration error, and achieve more precise parts 3D registration process. Wang [44] proposed a 3D registration tracking method based on the fusion of model and natural feature points, the linear parallel multimodal template matching method is adopted to quickly identify the target object, obtain the reference view close to the current perspective and complete the rough estimation of camera posture, RPNP algorithm is introduced to improve the accuracy and speed of registration and tracking, so as to overcomes the defect of lack of texture features and reduces the search space.

3.2 Assembly scene perception technology

Assembly scene perception is to automatically identify human errors in AR assembly system by tracking user status in real time and displaying instructions in corresponding states so as to complete each assembly work step and improve assembly efficiency and accuracy. Rentzos[45] proposed a scene perception system integrating existing information and knowledge in CAD/PDM system. Based on the semantics of products and processes, it supports complex tasks related to assembly and can be used to assist workshop operators to complete the final assembly of products, as shown in figure 3.

Zhu[46] proposed a wearable AR auxiliary system that integrates Virtual Personal Assistant (VPA) to provide natural language-based interaction, user status recognition, location-aware feedback and other services, so as to complete assembly and maintenance tasks in the industry.
Fig.3 Template instruction of specific assembly steps based on semantics [45]

Through the real-time feedback of ergonomics, researchers at home and abroad studied the change of operator's work efficiency based on AR system scene perception to reduce the impact of human fatigue during product assembly tasks. Chen [47] proposed an adaptive guidance scene display method, so as to display the synthetic guidance scene from the best point of view in the appropriate area. Damen [26] proposed a real-time AR guidance system to sense some activities near the space where the user is currently. Vignais [48] proposed a system combining sensor network and AR technology to evaluate manual assembly tasks in real time, and feedback ergonomics in real time during this period.

3.3 Assembly operation guidance technology

AR technology integrates virtual model and real world data to estimate the position and pose relationship between parts to be assembled in real time, and generates guidance information of assembly mode in mixed environment, so that operators can complete assembly operation through interactive navigation and improve assembly efficiency.

Wang [49] [50] put forward a practical virtual component interaction system based on AR, as shown in figure 4, users can use natural gestures during assembly simulation for interface operation, the virtual component to the actual process of
component composition, and through the analysis of the constraints, the contact force between the model and the user force $f$, determine the real movement, virtual component in automobile clutch case study to verify the effectiveness of the system and intuitive.

![Virtual assembly of clutch based on natural gesture](image)

Liu [51] estimated the pose of the assembly matrix and parts, obtained the relative position relationship between the assembly matrix and parts in real time for position detection to realized the registration of AR assembly navigation information in real scenes, and applied it to the assembly examples of car door plate connector and car window drive motor. Wang[52] gained a powerful industrial training technology through AR, which can directly link instructions on how to perform service tasks to machine parts to be processed, improve the training program and reuse valuable existing training materials to help technicians acquire new maintenance skills. Weble[53] developed an assembly skills training platform based on multi-mode AR to display detailed information such as text in an interactive AR environment, and introduced a novel concept for displaying location-related information in an AR environment to compensate for the uncertainty of tracking. Damiani [54] considered using augmented and virtual reality technologies for workforce training to enable manufacturing information to interact with human resources in an effective way. Zhu [18] thinks AR rendered content should not be "read only", but is able to provide technical personnel with AR content interaction method, so he proposed an authorized
situational awareness AR system (ACARS) to assist maintenance technicians. It enables the ACARS to be context-aware and creative, and make AR developers create context-related information through the desktop 2D user interface together with maintenance technicians. Hu [55] took G25-1 Marine single-screw pump as the research object, matched 3D CAD model with actual parts based on image recognition, developed AR learning auxiliary software by using Unity3D engine and EasyAR software development kit, and realized the virtual disassembly training and dynamic operation demonstration of single-screw pump and other functions.

3.4 Assembly process collaborative design technology

Assembly process collaborative design is an effective means, in the research on AR technology in the process of product manufacturing and assembly, which associated product design, factory layout planning, parts processing and product assembly behavior of designers, planners, operators and other personnel, so as to facilitate their communication and complete the whole product life cycle together. Liverani [56] proposed the concept of a Personal Active Assistant (PAA), which can be wirelessly connected to a designer workstation to enhance information about workers and the Head Mounted Display (HMD). Ong[57] proposed a remote collaboration system so that distributed users can view the product model from different perspectives, as shown in figure 5. Collaborative AR brings great advantages to assembly tasks, including flexible collaboration time, complete knowledge retention, in-depth understanding of problems, etc., which can be perfectly integrated with existing workflow.
Fig. 5 Architecture of remote collaboration system based on constraints [57]

Most collaborative AR studies focus only on the interaction of different users with enhanced scenarios, while few focus on the interaction and collaboration between users.

Oda [58] designed Gesturing in an Augmented Reality deep-mapped Environment (GARDEN), which can use sphere projection to enhance information transfer between users. Ranatunga [59] allows experts to use multi-touch gestures to translate, rotate, and annotate objects in video for remote guidance in collaboration with other users.

4 Current hotspot and development trend: AR based assembly combined with DT

At present, most of the AR based assembly systems consider the assembly navigation based on static model and data in an ideal situation first. During the assembly process, real-time adjustment and optimization cannot be carried out according to the performance state of the assembly, which may cause unstable assembly quality.
In recent years, DT has attracted great attention from famous foreign universities, research institutes and enterprises because of its whole life cycle, from real to virtual, and controlling real with virtual. Gartner, the world's most authoritative IT research and consulting firm, listed DT as one of the top ten strategic technology development trends of the year for three consecutive years (from 2017 to 2019) [60]. Through virtual and real interactive feedback, data fusion analysis, decision-making iterative optimization and other means, DT simulates the operation behavior of physical entities in the real environment with virtual model, so as to play the role of bridging the physical world with the information world in the whole life cycle of products [61]. Along with the synchronous evolution of real products in the life cycle, DT adds support or extended functions to physical entities [62], providing new ideas and means for solving assembly problems.

There have been some reports on the application of DT technology in product twinning modeling and assembly precision analysis. Damiani[63] tends to solve the processing problem of massive data accessed at the same time, which had many internal semantic dependencies. Söderberg[64] and Wärnlefjord [65] summarized the real-time data extraction and performance simulation optimization technologies needed to build the DT model to ensure the geometric accuracy of products in the manufacturing process, including positioning scheme optimization, statistical analysis, virtual edge cutting, assembly sequence optimization and other methods. Based on the concept of surface model shape, Schleich[66] constructed a complete agent model that comprehensively considered flexibility, expansibility, operability and fidelity, aiming to design digital twins of actual physical products for assembly analysis. Wang [67] proposed a DT-based assembly docking technology for low-pressure turbine units of aero engines, using multiple sensors to map and connect data between digital models and physical objects, and with the aid of physical terminal control to realize the low pressure turbine unit cell installation process real-time posture adjustment, realize the aero engine docking process of low pressure turbine unit cell docking with the 3D virtual assembly simulation process of physical fusion, model fusion and data fusion .
Zhang [68] constructed the DT of spacecraft to express its in-orbit assembly process, status and behavior, analyzed the data composition, implementation mode and function of the DT according to the structural composition and functional requirements of spacecraft, and proposed the implementation approach of the DT in the whole life cycle of spacecraft.

In a word, it is of great significance to use twin data to construct parts and assembly twins with real characteristics, and design assembly analysis methods suitable for twin models, so as to accurately predict the assembly accuracy of products and guide the assembly behavior of real products. Through real data-driven assembly model, it can synchronize the assembly state of the physical model in real time, predict the assembly performance and provide optimal assembly operation. Therefore, it further indicates that the integration of AR and DT will be the development direction of high-precision intelligent assembly technology in the future.

5 Conclusion

(1) AR and DT technology are research hotspots in the complex products digital assembly filed. This paper reviews the concept and key technologies of AR, introduces the structure of typical AR assembly system, analyzes the connotation of DT and its application in digital assembly.

(2) AR based digital assembly technology is applied to realize virtual reality fusion modeling, assembly scene perception, assembly operation navigation and assembly process collaborative design, etc. Through the interaction between virtual assembly objects and real assembly environment, the quality and efficiency of assembly design are effectively improved.

(3) DT-driven digital assembly model simulates the assembly behavior of physical entities in the real environment. With the synchronous evolution and evolution of real products in the life cycle, it greatly improves the accuracy of product assembly performance prediction.

(4) DT system synchronizes the assembly state of the physical model and predicts the assembly performance. Real-time update of assembly guidance through AR,
prediction and guarantee of assembly performance. The integration of AR and DT technology is bound to become an important development trend of intelligent assembly technology of complex products.

Acknowledgements

Support from the National Natural Science Foundation of China (grant Nos. 51875517, 51490663, 51821093) and Key Research and Development Program of Zhejiang Province (grant No. 2017C01045) is gratefully acknowledged.

Reference:


[20] Radkowski R, Oliver JH. Natural Feature Tracking Augmented Reality for


[31] Charoenseang S, Panjan S. 5-finger exoskeleton for assembly training in


[41] Zhang Y, Li M, Zeng B. The 3D registration based on the single circle of image and application in augmented assembly[J]. Mechanical science and technology for


[52] Wang X, Dunston PS. Design, strategies, and issues towards an augmented


