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ORIGINAL ARTICLE

A new type haptics-based virtual environment system for assembly training of complex products

PingJun Xia · António M. Lopes · Maria Teresa Restivo · YingXue Yao

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Abstract Virtual reality (VR)-based assembly training has been an interesting topic for the last decades. Generally, there are two shortcomings for nowadays virtual assembly training systems. One is that the operators cannot move around the virtual environment in a natural way as people activity in the real world: they are constrained in a fixed position or can only move in a limited space. The other is that most of the virtual assembly training systems are based on geometry constraint modeling only, which lacks haptics feedback. A new type haptics-based virtual environment system for assembly training of complex products is described in this paper. A new low-cost motion simulator is designed and integrated with the virtual environment to realize free walking by human. An automatic data integration interface is developed to transfer geometry, topology, assembly, and physics information from a computer-aided design system to a VR application, and a hierarchical constraint-based data model is rebuilt to construct the virtual assembly environment. Physics-based modeling and haptics feedback are undertaken to simulate the realistic assembly operations. The application examples and evaluation experiments demonstrate that both motion simulator and haptics have great value for training of assembly processes.

Keywords Virtual reality · Haptics · Assembly training · Motion simulator · Physics-based modeling

1 Introduction

Virtual reality, as a synthetic 3D virtual environment and interaction technology emerging in recent years, has rapidly evolved into many kinds of applications, from automotive

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Dr. Pingjun Xia is a research fellow at UISPA, IDMEC-Polo FEUP in Portugal. His research interests include virtual reality and haptics in industrial and medical environments.

The main contribution There are two shortcomings for nowadays virtual assembly training systems. One is that the operators cannot move around the virtual environment in a natural way as people in real world, they are constrained in a fixed position or can only move in a limited space. The other is that most of the virtual assembly training systems are based on geometry constraint modeling only, which lack haptics feedback. This paper aims at solving these two problems.

The novel The novel of this paper is mainly in experimental techniques. A new type haptics-based virtual environment system for assembly training of complex products is described to overcome the previous two shortcomings. A new low-cost motion simulator is designed and integrated with the virtual environment to realize free walking by human. An automatic data integration interface is developed to transfer geometry, topology, assembly, and physics information from a computer-aided design system to virtual reality application, and a hierarchical constraint-based data model is rebuilt to construct the virtual assembly environment. Physics-based modeling and haptics feedback are undertaken to simulate the realistic assembly operations.

Industrial applications This system can be used for assembly and maintenance planning and training of complex products. The product designers and assembly engineers can use this system to plan assembly sequence and path, simulate assembly or disassembly operation, and get the realistic operation skills for actual production.

P. Xia (✉) · A. M. Lopes · M. T. Restivo
IDMEC-Polo FEUP, Faculty of Engineering, Porto University,
Porto, Portugal
e-mail: smallping@fe.up.pt

P. Xia
e-mail: smallping_hit@yahoo.com.cn

Y. Yao
School of Mechanical and Electrical Engineering,
Harbin Institute of Technology,
Harbin, China

engineering to aerospace industry, from medical to service, from education to training, from entertainment to military, etc. As a typical application in engineering, virtual reality-based assembly training has been an interesting topic for the last decades. By providing realistic representations of the physical world to supply a cheaper solution than current training based on real mock-up models, and by providing important perceptual cues and multimodal feedback to supply a more natural learning media than plain documents, blueprints, or videos, virtual reality-based assembly training has been considered as a promising approach to allow the trainees to learn and operate new processes and methods before they are actually installed, and thus effectively transfer into the real-world operational skills.

Generally, there are two important aspects for virtual reality-based industrial training: immersion and interaction. To give the trainee users a realistic experience, it should provide a multimodel immersive virtual environment to make the users have the sensation of being almost in the real world, and it should also provide a natural way for them to interact with and control the objects in 3D virtual environment. Traditional computer-based training systems are normally operated by means of ordinary human–computer interfaces such as keyboard and mouse, which are far from the real procedures and therefore not effective in industrial training. The nature of interaction with virtual environment, the difference in perception levels between task execution in real world and in virtual environment, human factors, ergonomic issues, accessibility evaluation, force and tactile feedback, and many other considerations related to the effects of human–computer interaction should be taken into account. Among these considerations, haptics feedback is particularly important for assembly task training because it can increase the users' sense of immersion and interaction, help the users to get a better understanding of virtual objects, to feel more secure and more confident in the real-world assembly process, and thus improve task efficiency times. However, most of today's virtual reality-based assembly training systems only uses a desktop computer to generate high-quality graphics or movies to the trainees, which lack immersion and haptics feedback.

In this paper, a new type haptics-based virtual environment system for assembly training of complex products is presented. According to the different classification standards of immersion and interaction, related works about virtual reality-based assembly training are reviewed in Section 2. In Section 3, the functional requirements of assembly training for large-scale complex products are discussed; and in Section 4, the framework of a new type haptics-based virtual environment system is described. The key technologies and implementations are discussed in Section 5 including the design and integration of the motion simulator, models transformation and virtual environment construction, physics modeling and haptics feedback, etc. Application examples and evaluation experiments are given in Section 6 and some conclusions are given in Section 7.

2 Related works about virtual reality-based assembly training

Since the emergence of virtual reality technology, many academic and industrial research groups have been interested in the application of this new technology in assembly training and a lot of prototype systems have been developed. In this section, a review is made of virtual reality-based assembly training according to immersion and interaction.

2.1 System classification according to immersion

Virtual reality technology involves several knowledge fields, allowing different levels of implementation which fit different user requirements: for example, VR systems can run on a stereoscopic cave environment or in a simple desktop computer. Based on its immersion and realism, virtual reality-based assembly training systems can be grouped into four categories: desktop system, head-mounted display (HMD) system, CAVE system, and Cybersphere system.

1. *Desktop system*. A desktop system employs the display screen of an ordinary computer or low-level workstation as the window to observe the virtual environment. The operator wears stereoscopic glasses to observe the 3D virtual scenes. With the help of data gloves and 3D trackers, the operator can interact with the virtual environment. Compared to other types of virtual reality systems, the desktop system provides a more convenient interface for engineering training, because it is cheap and easy to use. Many desktop training systems have been developed. A typical system was developed by Li et al. [1], a desktop virtual reality prototype system called V-REALISM for industrial maintenance and training. The geometric models of the system were constructed using feature-based modeling and assembly function by external computer-aided design system (CAD) tools, a hierarchical structure was proposed to partition and organize these imported models in virtual environment and a visibility culling approach was developed for fast rendering and user interaction. Another system was developed by Peng et al. [2].

They provided a desktop virtual reality-based integrated system for complex product maintainability design and training, including processes and tools that could be effectively used to plan, quantify, and maintenance. Practical examples implied that early and effective planning and training of a maintainability program can significantly improve the reliability and availability of product system. As an affordable and portable training media for industrial applications, the main shortcoming of the desktop system is that the immersive sense is poor because the display device is only a relatively small computer screen.

2. *HMD system*. Head-mounted display system employs head-mounted display, data glove, and other interactive devices to seal the operator's vision, hearing, and other sensations from the surrounding environment. In this system, the operator really becomes a participant within the system and can interact with the virtual environment. The immersiveness of this system is better than that of the desktop system. However, because of the restriction of the head-mounted display, the system has the deficiencies of intensive restraint sense, low-resolution ratio, and easy visual fatigue, etc. A typical HMD training system was developed by Kashiwa et al. [3]. They presented an immersive virtual reality system for industrial maintenance and training. In this system, different assembly or disassembly procedures were modeled using Petri nets and then coupled to the virtual environment. The interaction between the trainee and the system was by means of wearing a head-mounted display and data glove. Another system was developed by Ritchie et al. [4]. They were concerned with the application of HMD-based immersive virtual reality for designing and routing cable harnesses and their results showed that immersive VR can be used as an effective tool for design and manufacturing training.
3. *CAVE system*. The CAVE system evolved at the beginning of the 1990s. Its main body is a room whose walls, floor, and ceiling are composed of large screens. High-resolution images are projected on these screens by high-power projectors. Wearing stereoscopic glasses, the operator can observe 3D virtual scenes in any position of the space. The CAVE system has realized a virtual environment of large-view angle, panorama, and sharing by several people. But there are also some deficiencies for this system. Its cost is very high because larger space and more hardware equipments are required. Furthermore, the operator is still restricted in a limited narrow space and is not able to walk for a long distance in the virtual environment. A typical system was developed by Johnson and Vance at Iowa State University [5]. They presented a CAVE-based assembly application called Virtual Environment for General Assembly (VEGAS), which used dataglove from 5DT for human grab motion, VRJuggler software for virtual environment management, and Voxmap PointShell from Boeing Corporation for collision detection. A similar system was also developed at Zhejiang University by Wan et al. [6]. They created a multimodal immersive virtual assembly system called MIVAS. By viewing the virtual assembly application as a finite state machine, they incorporated tracking devices, data glove, voice commands, human sounds, fully immersive four-sided CAVE, together with optimization techniques for both complex assembly models and assembly operations to provide engineers an intuitive and natural way for assembly planning and training.
4. *Cybersphere system*. In all the systems described above, there exists one important limitation: the operator is constrained in a fixed position or can only move in a limited space, they cannot move around the virtual environment in a natural way as people in real world. In order to remove this limitation, Warwick University in England, cooperating with some companies, has developed a new type of fully immersive virtual environment system—Cybersphere [7]. A large, hollow, translucent sphere supported by means of a low-pressure air cushion is adopted as the display device in the Cybersphere system. This air cushion enables the sphere to rotate in any direction. An operator is able to enter into the large hollow sphere by means of a close entry hatch. Walking movements of the operator cause the large sphere to rotate. Images are projected upon the surface of the large sphere by means of high-power projectors. Signals provided by sensors, fed to the computer via cables, are used to update the projected images in order to provide to the operator the illusion of walking freely through the computer-generated virtual environment. Cybersphere is the first system to realize free walking of the operator in a fully immersive virtual environment and has been used as a unique teaching and training tool for technicians from the manufacturing sector. The current limitations of the system, because it is a closed sphere, are that all the interactive devices have to be wireless and most of them cannot be obtained from the market; and because the sphere has to rotate continuously to support the operator and act as display device, the material properties are demanded to be quite high and the manufacturing of this sphere is very difficult; at the same time, it does not allow the user to operate the virtual objects using haptic device.

2.2 System classification according to interaction

The training of assembly and maintenance tasks in virtual environment heavily relies on the environment awareness gained by users through intuitive and natural interaction. The execution of virtual assembly operation through specific 3D interaction devices significantly affects the performance of the users. Force and tactile feedback can enhance the user presence in the virtual environment and consequently his performance during the task execution. According to the interaction, virtual reality-based assembly training systems can be grouped into two categories: constraint-based interactive training system (no haptics) and haptics-based interactive training system.

1. *Constraint-based interactive training system*. Early virtual assembly training systems are mainly based on geometry constraints, which lack physics and haptics. The user can interact with the virtual worlds via joysticks, space mouse, or data gloves; and the impression of actually being in the virtual world can be created and enhanced by special optical and audio devices such as head-mounted displays and 3D sound. Due to the absence of haptics, when the trainee operates the virtual objects there is no force or tactile feedback, which leads to a big difference from the real world. Because of no physics, geometry constraints are the main approach to realize realistic behavior and dynamics simulation. When the related parts come in close proximity to each other, the potential geometry constraint can be captured, the precise position and the reduced degrees-of-freedom (DOF) of the object can be calculated by the constraint solver and then constraint-based motion simulation can be visualized. Several typical geometry constraint-based virtual assembly training systems have been developed. VADE [8], a virtual assembly design environment developed by Washington State University, was a well-known application of virtual reality in assembly design and training. VADE captured the designer's intent by using constrained motion simulation. The constraints (axial, planar, etc.) were extracted from the assembly models designed in CAD systems and were simulated during virtual assembly processes to more accurately reflect real-world assembly operations. One- or two-handed assembly operations were supported using position tracking and data glove; stereo vision was provided by an HMD or stereo glasses. UVAVU [9], an unbelievable vehicle for assembling virtual unit developed by Heriot–Watt University, was another system to assemble the product from CAD models to train the operators by working in virtual environment. The operators' actions can be monitored and assembly sequence plans were automatically generated. A virtual assembly work cell [10], which was developed by University of Patras in Greece, was an immersive and interactive virtual environment created for the verification of performance factors related to manual assembly processes. The interaction devices included a Virtual Research helmet, a Virtual Technologies 18-sensor data glove, a Division 3D Mouse, and a Polhemus Fastrack tracking system. Zhang et al. [11] studied movement navigation based on geometry constraint recognition. The uniform representations of assembly constraint, equivalent relation between constraint and degree of freedom, and movable DOF reduction were defined. With constraint-based DOF analysis, the accurate locating of parts can be realized, and the realistic assembly operation process can be simulated. Marcelino et al. [12] developed a geometric constraint manager to support interactive assembly and maintenance tasks training in virtual environment, which included features like multiplatform operation, scene graph independence, multiple constraint recognition, and automatic constraint management. The constraint manager was capable of validating existing constraints, determining broken constraints, enforcing existing constraints, solving constrained motion, and recognizing new constraints. Although geometry constraint-based interactive method has been proved to be successful for assembly training application, the main shortcoming of this method is that it cannot support intuitive and natural human–computer interaction and behavior simulation in virtual environment, and there is no force or tactile feedback.
2. *Haptics-based interactive training system*. Haptics refers to operating and sensing virtual objects by using special interaction devices to get the tactile and force feedback. Haptics feedback allows users to get the feeling of touching an object, perceiving the nature of its surfaces and the resistance because of mass properties. Haptics is particularly important for assembly and maintenance training application as, in reality, operators usually employ tools and parts to be maintained that have well-known mass and stiffness properties, and the VR system is expected to transmit the same sensation. If these factors are neglected during virtual training, such training could possibly be useless or could even affect negatively the experience. In recent years, several haptics-based virtual reality systems have also been developed for assembly training. Abate et al. [13] presented a haptics-based approach to virtual training for aerospace industry. They implemented an interactive environment in which each of the main assembly and maintenance activities

could be simulated by the trainee exploiting a hand-based haptics device and could be operated by means of specific haptic-rendering techniques to provide realistic feedbacks. The interaction of the system was accomplished by means of commercially available VR interface devices such as head/hand trackers, digital gloves (CyberGloves), and the Immersion CyberForces force feedback system. The open dynamics engine, an open-source physics library had been integrated into the system for adding rigid body physics calculation and simulation. Their results which aimed at testing and evaluating the effectiveness of the haptics feedback for assembly and maintenance tasks showed that the combination of virtual reality techniques and haptics interaction is a better solution to enhance technical training of assembly and maintenance tasks by enabling users to perceive the physical characteristics of the simulated environment in a realistic way, thus improving their overall knowledge of the procedures as well as their efficiency. HIIVR [14] was another haptically enabled interactive and immersive virtual reality system developed by Deakin University of Australia. Unlike the existing VR training systems, the presented idea tried to imitate real physical training scenarios by providing comprehensive user interaction, constrained within the physical limitations of the real world imposed by the haptic devices within the virtual environment. The proposed system helped in procedural learning and procedural skill development as well, due to its high physically interactive nature. SHARP [15], a system for haptic assembly and realistic prototyping, was also developed by the virtual reality applications center of Iowa State University. This system was built based on VEGAS and used haptics device PHANTOM to realize physically based modeling for simulating realistic part-to-part and hand-to-part interactions during virtual training. Vo et al. [16] investigated the benefits of haptics-based interaction for performing assembly related tasks in virtual environment. Comparing to traditional visual-only interaction methods, quantitative results showed that haptics-based interaction was beneficial in improving performance by reducing completion time for weight discrimination, permitted higher placement accuracy when positioning virtual objects, and enabled steadier hand motions along 3D trajectories.

Although these studies have made evident progress in this area, the development of a haptics-based virtual reality training system is still a challenging project because of the complexity of the physical processes and the limitation of the currently available VR interface devices. Realistic and natural interaction between part–part and hand–part, dynamic simulation of part physical behavior, real-time collision detection with high-precision parts, guarantee of haptic feedback at a high update rate (1,000 Hz), all these problems are attracting more and more researchers, and there is still a long way to go before haptics-based virtual assembly training gets a wide application in industrial products.

3 Functional requirements of assembly training for large-scale complex products

Large-scale complex products can be defined as the products that have complex mechanical structure, complex manufacturing and assembly process, and complex engineering management. Generally, there are two types of assembly organization modes, one is the assembly streamline mode finished by automatic robot and the other is the manual assembly mode. In this paper, we mainly study the manual assembly for complex products, such as aircrafts, rockets, satellites, and ships etc. Comparing to the general mechanical products, assembly of large-scale complex products requires a long period and high cost, quality and precision, various fixtures and jigs, and special skills and experiences. New workers must spend a long time to master these operation skills and experiences, and now they mainly depend on 2D drawings and process documents to understand assembly process, which makes it very difficult to imagine the 3D shape and structure of products, and usually leads to quality and safety problems. As an efficient training tool, virtual reality-based assembly training is urgently needed to guide assembly operations and industrial production.

1. Fully immersive virtual environment is best. Generally, large-scale complex products have fixed frame-based structure with big size. During assembly production, the workers must enter into the product to operate: for example, the inner structure of ship cabins and aircraft compartments are very complicated, and most of the parts need to be installed inside the product. Because of the narrow space and limited vision, assembling of these parts requires dexterous operation skills. For the desktop virtual environment system, the virtual scene can be only displayed on the flat screen and this is difficult for the operator to understand the inner structure of complex product. But for a fully immersive virtual environment such as Cybersphere system, the inner structure of complex product can be displayed on the sphere screen surface around the operator so he can feel that he has entered into the product; for example, he can get a strong sense that he is inside

the ship cabins or aircraft compartment, and all the inner structure and parts are displayed around him just as he is inside the product as in real life, which can improve the reality and reliability of assembly training.

2. Human activity should be considered. For mechanical products, there are two types of organization form for assembly production, one is the streamline mode and the other is fixed-place mode. The streamline mode means to set up the assembly line according to the assembly procedure of the mechanical product and different parts are assembled in different steps. This mode mainly adapts to large-batch production and automatic assembly such as automobile, etc. The fixed-place mode means to fix the main product frame in an assembly region: the workers are demanded to move around the working positions to assemble each part onto the product frame step-by-step and then form the whole product. This mode is especially suitable for large-scale complex products because of their small batches and manual assembly. Compared with the streamline mode, during the assembly process of large-scale complex products, the workers need to move a long distance in the workshop and to carry out assembly and disassembly operations at different workplaces, so more human activities are involved. Especially for products such as airplanes and satellites, the workers need to move into the product to perform assembly operations, the human activity and ergonomics factors such as fatigue and safety should be taken into account.
3. Haptics is needed for intuitive and natural interaction. Haptics feedback is a vital part of human perception and it is also fundamental for physical user interfaces. For virtual reality-based training system, haptics is the most crucial part because it helps to imitate the real physical training environment and it also provides physical movement constraints during the virtual simulation so as to imitate the real physical movements while performing the real assembly process. The development of a haptics-based interaction paradigm is helpful for the improvement of assembly task execution. For large-scale complex products, the manipulation of virtual objects requires a high level of perception. Because the execution of assembly tasks is not just simple assembly or disassembly operations of virtual parts, accessibility, reachability, ergonomics, sequence, and path are also important issues which should be investigated during the interaction with the virtual models, and the introduction of haptic feedback can contribute to get a comprehensive understanding and accurate evaluation of the assembly process.

4 A new type haptics-based virtual environment system

Currently, the existing VR training systems (such as Desktop, HMD, and CAVE system) have two important limitations: one is restricting the operator's activity during the assembly process the other is lacking haptics feedback. Especially for large-scale complex products, these limitations are particularly obvious. To overcome these shortcomings, a new type haptics-based virtual reality training system is designed as shown in Fig. 1. In a big room, a new type motion simulator is fixed on the ground, which is designed to implement the operator's free walking. A spherical cap, whose diameter is 5.5 m, is established as the display screen. The high-power projectors are fixed on the wall and ceiling to project the virtual scenes generated by the graphic workstation on the spherical screen to produce the virtual environment. A haptics device such as PHANTOM is fixed on the motion simulator as the interaction tool and the trackers are connected with the user's feet to capture his position and orientation. The trainee can wear stereoscopic glasses to observe the 3D virtual scenes; at the same time, he can also operate the haptics device to interact with the virtual environment to get force or tactile feedback. During assembly or disassembly processes, the trainee can walk straight on the motion simulator, he can also turn left or turn right, just as in his real activities in real assembly workshop. According to the user's position and orientation, the system can generate the corresponding virtual scenes and then project on the spherical cap screen by the high-power projectors. Inside the spherical space, the trainee can be surrounded by the 3D stereo graphics and get a strong sense of immersion and then operate the haptics device to execute assembly or disassembly tasks. This new type virtual environment system can overcome the restriction of human activity and realize the free walking of the operator as in real assembly production, and it can also provide haptics feedback for the

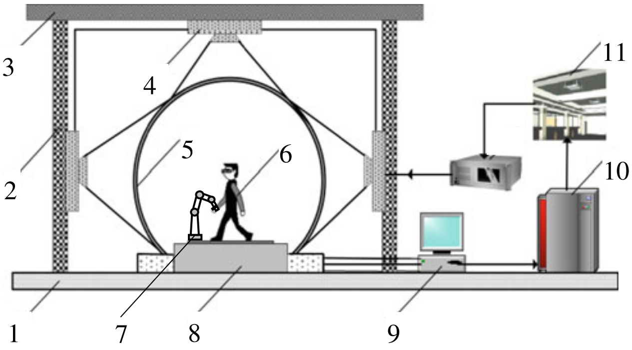


Fig. 1 A new type haptic-based virtual environment system. (1-ground; 2-wall; 3-ceiling; 4-projector; 5-sphere screen; 6-operator; 7-PHANTOM device; 8-motion simulator; 9-control computer; 10-graphic workstation; 11-virtual scene)

operator to feel and manipulate the virtual objects as in real world, which is very suitable for assembly training for large-scale complex products in the manufacturing industry.

5 Key technologies and implementations

5.1 Design and integration of motion simulator

In virtual reality systems, motion simulation mainly relies on how to make the operators realize and apperceive their activities in the virtual environment, like free walking in the real world. Some researchers also call this technology as VR locomotion, the movement and navigation of the participant within the virtual environment, which is one of the most important methods for VR interaction. However, most of the existing VR systems lack motion simulation. Although several typical motion simulators have been developed, such as Virtual Perambulator [17], ATLAS [18], and Torus Treadmill [19]; most of them are uncommon in the practical applications for VR systems because of the complexity and high cost, the safety issues in simulating high speeds, and the difficulty to handle rotations or uneven terrain. In this paper, a new low-cost motion simulator is designed for virtual assembly training. The appearance of the motion simulator is shown in Fig. 2. On the platform of the motion simulator, the operator is able to walk straight and turn from side-to-side while his physical position is not changed. Two sets of footplates driven by servomotors are adopted to follow the operator's feet. The footplates can move back and forth and rotate along a fixed axis. Each foot of the operator is connected with a tracker to get its position and orientation. The walking activities of the operator are implemented through the interaction between the footplates and his steps. Figure 3 illustrates the principle of the motion simulator: each footplate can slide in its slideway perpendicular to the paper and each footplate can rotate along the same fixed axis, the rotation being driven by the corresponding servomotor.

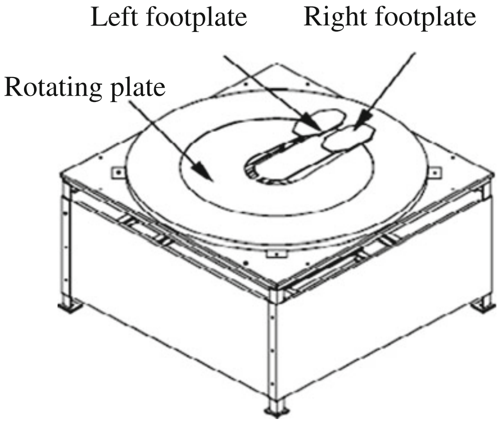


Fig. 2 View of the motion simulator

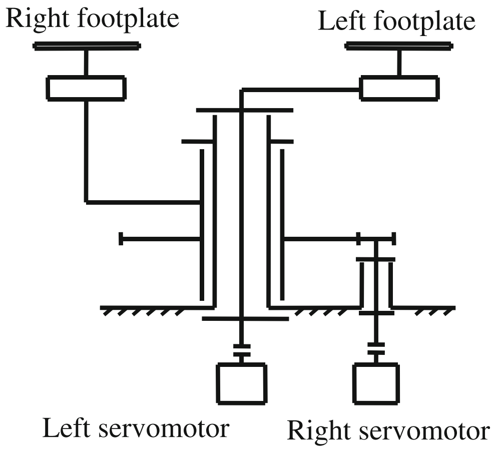
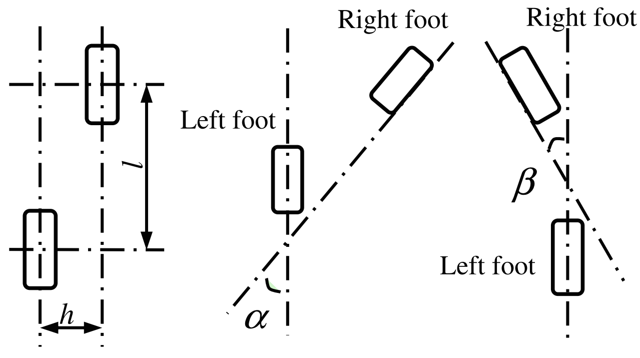


Fig. 3 Principle of the motion simulator



a) Walking straight b) Turning right c) Turning across

Fig. 4 Human walking data

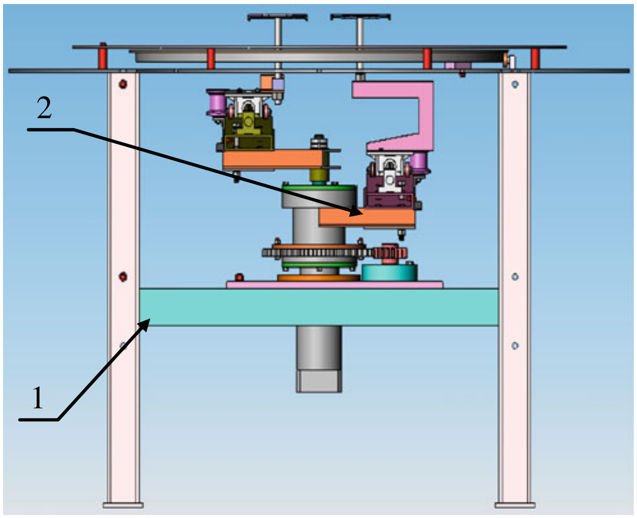
Investigation of people's walking activities in the real world [20], including walking straight, turning left, and turning right, has led to the walking data in Fig. 4 and Table 1. According to these data, the structure of the motion simulator can be designed as shown in Fig. 5, comprising two main parts: main transmission part and supporting frame. Through the main transmission part, the servomotors are able to drive the footplates to rotate along a fixed axis. The servomotors are driven by the control computer according to the signals from the trackers attached to the operator's feet. Linked to the ground, the supporting frame sustains the main transmission part and also protects the operator. As shown in Fig. 6, the key innovations of the motion simulator include: (1) each footplate is able to slide back and forth along the guide pole and it is connected with the slideway board by return springs, which implement the return stroke of the footplate and create the obstruction sense of walking. There is an angle α between the guide pole and the horizontal direction, which can help the operator move with the help of his weight. The guide pole is asymmetrically assigned to the rotation center and the extension length of the front is far greater than that of the

Table 1 Data measurement for human walking

Height (cm)	Distance h (cm)	Distance l (cm)	Angle α (°)	Angle β (°)
160	10	58	40	35
165	12	60	50	45
168	13	68	45	40
172	15	65	48	30
175	15	70	50	35
178	16	70	48	38
180	15	75	55	40
182	18	75	45	35
185	20	80	50	35

back end, which is meant to satisfy the movement of the footplates and the rotating plate. (2) Each of the two footplates is able to rotate along the same fixed axis and the rotation is driven by the corresponding servomotor through the transmission system. The left footplate is directly driven by the servomotor through the joint and the right footplate is driven by the other servomotor through gear drive transmission system. (3) There are grooves in the rotating plate and the footplate stanchion can slide in the groove. By the stanchion, the footplate can drive the rotating plate to rotate freely.

The integration of the motion simulator into the virtual environment is shown in Fig. 7. During the working course of the machine, the operator stands on the footplates and his feet are connected with motion trackers. A data interface reads the position and orientation data from the motion tracking system in real time. When the operator walks straight, the servomotors do not act and the footplates only slide back and forth to follow the operator's feet. The position data is obtained by the data interface and sent to the graphic workstation to set the viewpoint of the virtual environment, and the virtual scene can be changed to fall back, which makes the operator feel that he is walking in the real workshop to assemble the product. When the operator turns left or right, the orientation data obtained by the data interface is sent to the control computer to be converted into rotation angle information about the fixed axis and then used by the servomotor to drive the corresponding footplate to rotate by an angle to exactly follow the operator's foot, while the other servomotor makes the slide poles of the two footplates parallel again and the subsequent actions continue. An independent servomotor is adopted for each footplate to avoid the influence between the two footplates.



1-Supporting frame 2-Main transmission part

Fig. 5 Front view of the motion simulator

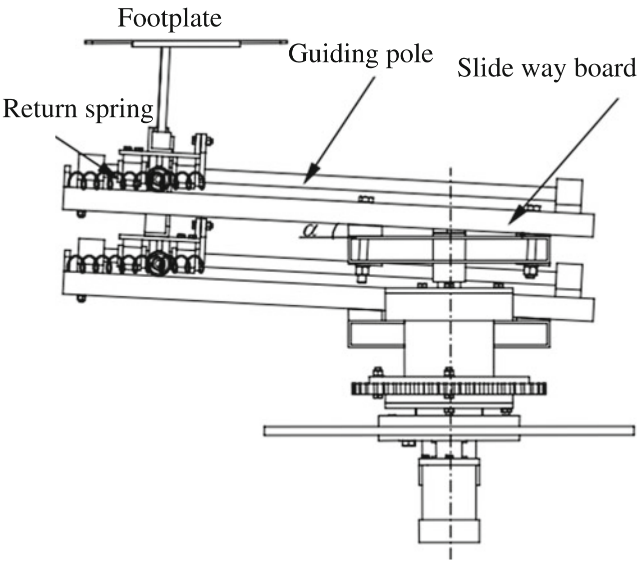
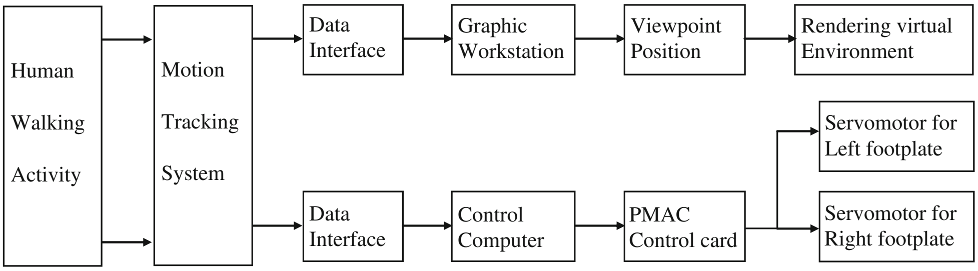


Fig. 6 Side view of the main transmission part

5.2 Models transformation and virtual environment construction

The product models, tools and fixtures models are designed in a commercial CAD system (e.g., Pro/Engineer, SolidWorks, CATIA, I-DEAS, Unigraphics). While in a CAD system, a part can be expressed by a precise mathematical method using CSG or B-Rep; in a VR environment, the models are usually expressed only by polygons, which cannot be used for virtual assembly operation, planning, and evaluation. Because of this difference in data format between CAD and VR systems, an automatic data integration interface is required to perform data transformation from CAD to VR as shown in Fig. 8. By using a CAD API development toolkit, the related information and data can be extracted from CAD neutral files (OBJ or SLP) and CAD inner database. Four types of data are mainly taken into account, namely geometry data, topology data, assembly data, and physics data. The geometry data is used

Fig. 7 Integration of the motion simulator into virtual environment



for model display and collision detection, and the topology data is used to rebuild the hierarchical mapping relation of product, part, feature, surface, and polygon. A part is composed of assembly features, a feature is the aggregation of geometry surfaces, and a geometry surface is the aggregation of polygons. The polygons are the mesh unit to visualize in virtual environment. Each part object, feature object, surface object, and polygon object has a unique identity number for recognition in virtual environment. The assembly data mainly includes assembly constraint relationships, assembly position matrix, and assembly tolerance, which are used for constraint recognition and precise positioning. The physical data contains all the physical conditional information such as mass, material, inertia, surface friction, etc.; they can be extracted from object's mass property and material property. These four types of data can be extracted from the CAD system respectively by different approaches using API toolkits, and then input into the virtual reality environment.

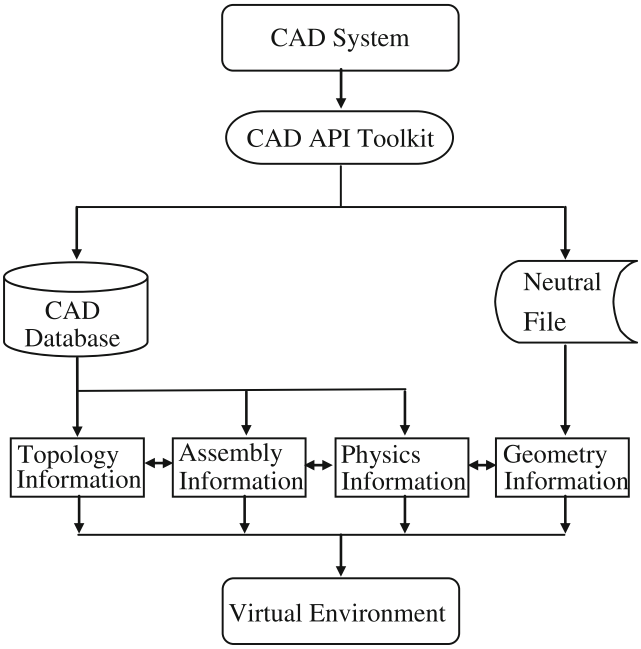
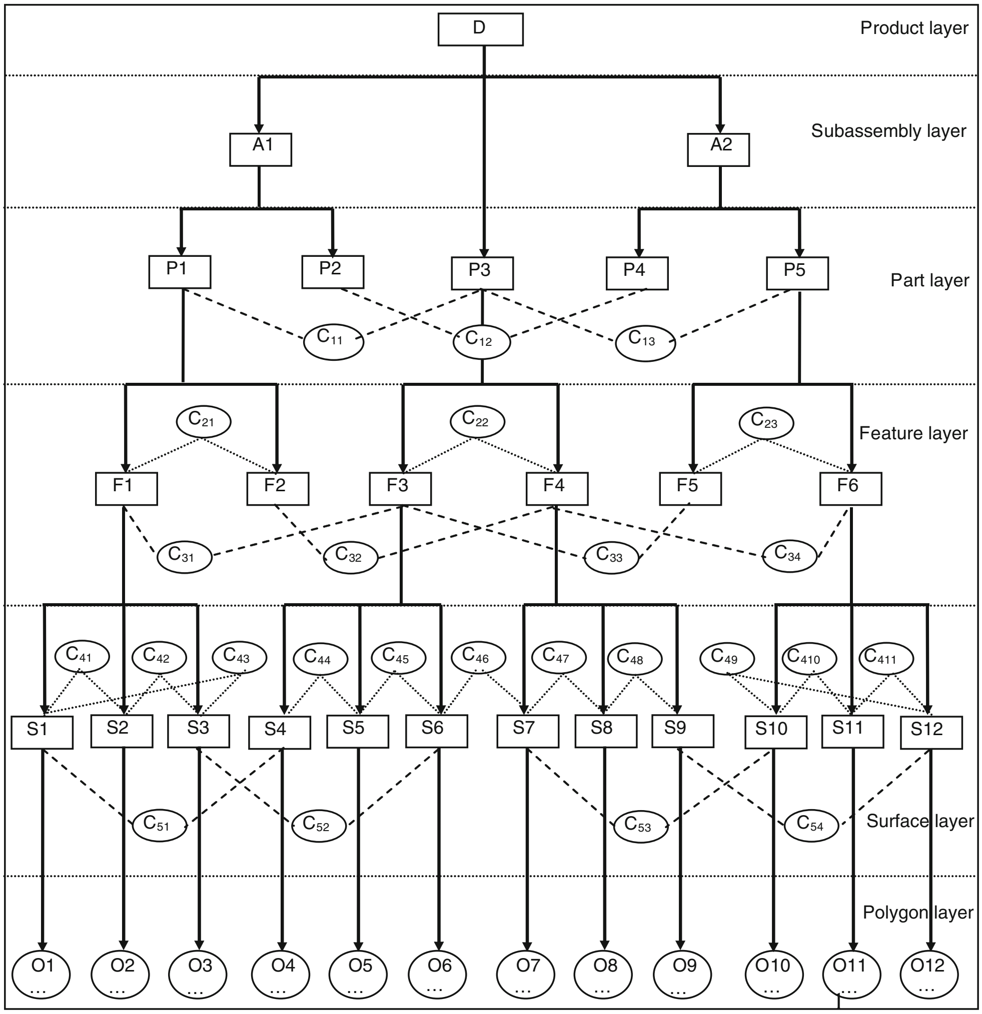


Fig. 8 Data transformation from CAD to VR

A hierarchical constraint-based data model is designed to represent and reorganize all these models and data, and then an efficient scene graph structure can be generated to construct the virtual assembly environment. As shown in Fig. 9, the data model is composed of product layer, subassembly layer, part layer, feature layer, surface layer, and polygon layer. For the elements in different layers, there exist the hierarchical mapping relationships; and for the elements in the same layer, there exist the constraint relationships. The product layer can be described by $Z=(D)$, where D is the product object, including product name, product ID, and the other design and management information. The subassembly layer can be described by $B=(A, H^A, H^Z)$, where A is the subassembly object, H^A is the hierarchical mapping relationships between subassembly objects, because a subassembly object may be composed of other subassembly objects. H^Z is the hierarchical mapping relations between product objects and subassembly objects. The part layer can be described by $L=(P, H^B, H^Z, C^P)$, where P is the part object, H^B is the hierarchical mapping relationships between the subassembly objects and part objects, and H^Z is the hierarchical mapping relationships between product objects and part objects because a part may belong to a subassembly or belong to the product directly. C^P is the constraint relationships between part objects, such as C_{11}, C_{12}, C_{13}, etc., and they can be understood as the assembly constraints which reflect the spatial relations between individual parts, i.e., axis–hole assembly constraint and face-mating assembly constraint, etc. The feature layer can be described by $T=(F, H^L, C_1^F, C_2^F, HC^{F\text{-}P})$, where F is the feature object and H^L is the hierarchical mapping relationships between part objects and feature objects. C_1^F is the inner constraint relationships between the features of the same part, such as C_{21}, C_{22}, C_{23}, etc., which are used to define the part shape and structure. C_2^F is the external constraint relationships between the features of different parts, such as C_{31}, C_{32}, C_{33}, C_{34}, etc., which are mainly pointed to assembly constraint relationships. $\mathrm{HC}^{\mathrm{F\text{-}P}}$ is the hierarchical mapping relationships between the constraints of feature objects and the constraints of part objects. Because the part object is composed of features, the constraint relationships between

Fig. 9 The hierarchical constraint-based data model



parts (C_{11}, C_{12}, C_{13}, etc.) can be hierarchically decomposed as the external constraint relationships between features (C_{31}, C_{32}, C_{33}, C_{34}, etc.). The surface layer can be described by J=(S, H^T, $C_1{}^S$, $C_2{}^S$, $\mathrm{HC}^{\mathrm{S\text{-}F}}$), where S is the surface object, and H^T is the hierarchical mapping relationships between feature objects and surface objects. $C_1{}^S$ is the inner constraint relationships between the surfaces of the same part, such as C_{41}, C_{42}, C_{43}, etc., which are used to define the feature shape and structure. $C_2{}^S$ is the external constraint relationships between the surfaces of different parts, such as C_{51}, C_{52}, C_{53}, C_{54}, etc., which are mainly related to assembly constraint relationships between surfaces, such as parallelism, coincidence, perpendicularity, alignment, and coedge, etc. $\mathrm{HC}^{\mathrm{S\text{-}F}}$ is the hierarchical mapping relationships between the constraints of surface objects and the constraints of feature objects; according to the data model, the feature object is composed of geometry surfaces, so the external constraint relationships between features can be also decomposed as the external constraint relationships between surfaces. The polygon layer can be described by M=(O, H^J), where O is the polygon object and H^J is the hierarchical mapping relationships between surface objects and polygon objects. For each surface object, it is composed of many polygons, which are used for real-time graphic display and precise collision detection in virtual environment. Generally, for the hierarchical constraint-based data model, the inner constraints are only used to maintain object inner structure and shape, and the external constraints are used to define the relative position and assembly relation between different objects, and they are the main geometry constraints which should be taken into account for constraint recognition and assembly operations.

The hierarchical scene graph is shown in Fig. 10. The root node of the scene graph includes light node, virtual factory node, product node, and tool node; and the product node is organized hierarchically according to subassembly node, part node, and surface node. Each separate node has its transform node and geometry node, the transform node is used to control the position and direction of the object, and the geometry node is used to display the object in virtual environment. The scene graph has several advantages. Firstly, it can be integrated with the data model directly; in

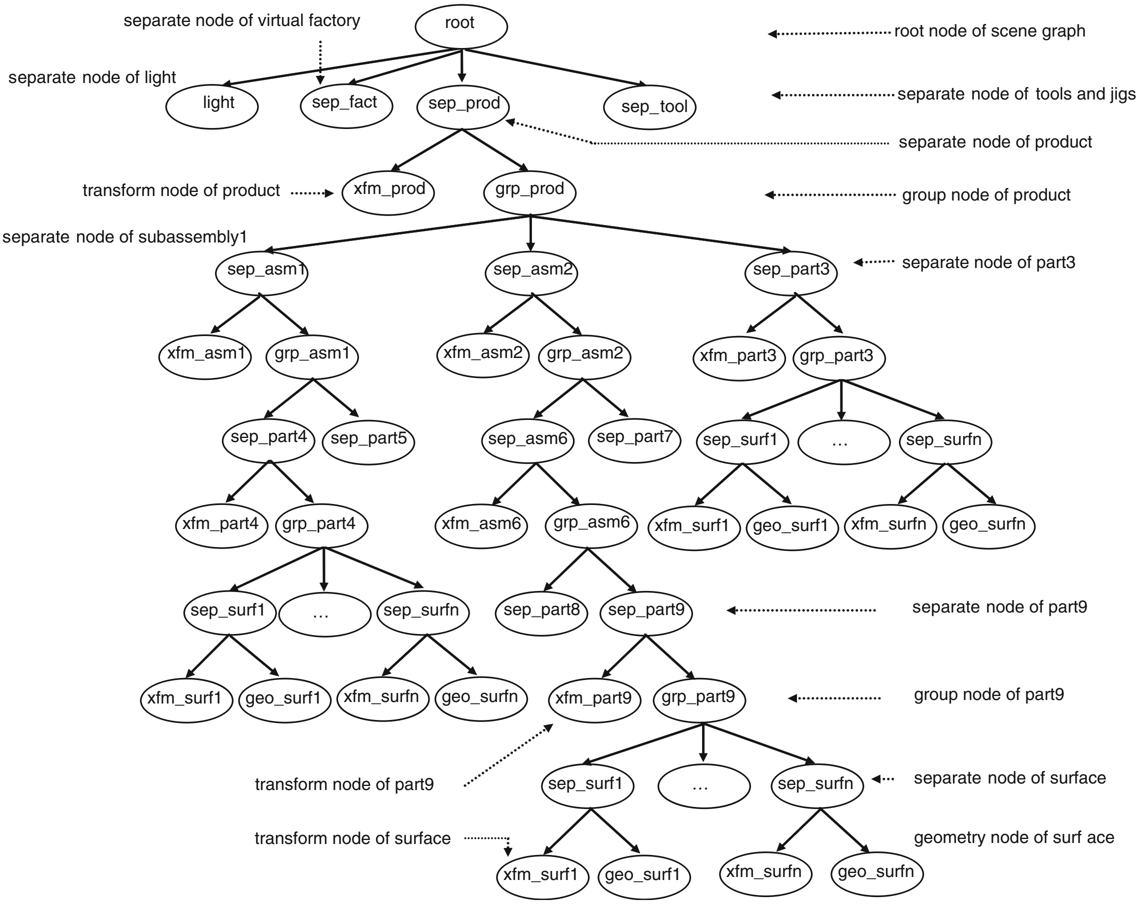


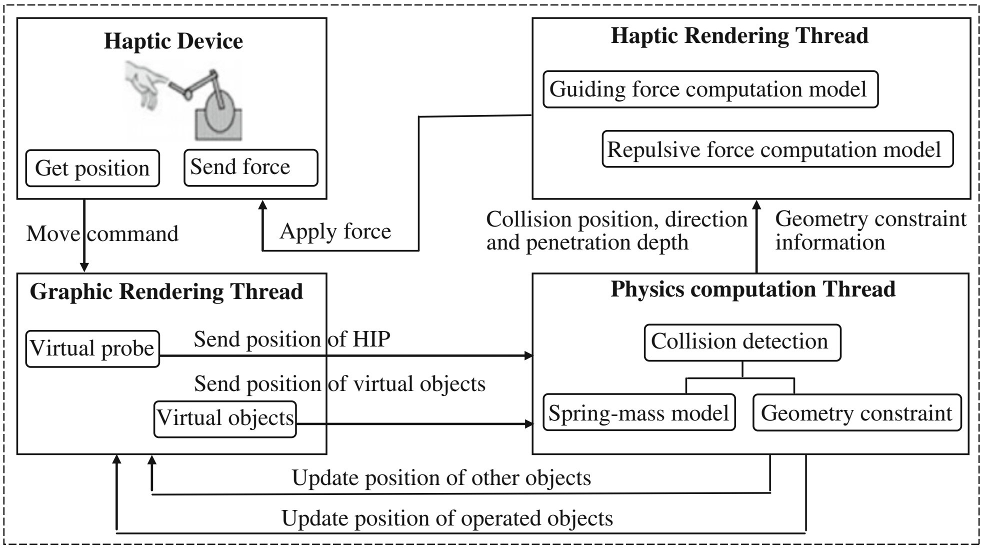
Fig. 10 The structure of scene graph

virtual environment when the product models are loaded, the scene graph structure can be generated automatically according to the hierarchical constraint-based data model. Secondly, the user can select different layer objects to operate, for example, the user can operate a part object, he can also select a subassembly object as a whole for assembly or disassembly, and each layer object has its own position, orientation, and physical condition information. Finally, geometry surface is separated from the model as an intermediate layer object, which provides convenience for collision detection and geometry constraint recognition because geometry surfaces are the foundation to define geometry constraints such as against, collinear, concentric, etc.

5.3 Physics modeling and haptics feedback

In virtual environment, the user cannot only visualize the product to understand its inner structure and spatial relationships but can also use the haptic device to plan assembly sequence and path, simulate assembly or disassembly operations, evaluate human ergonomics and safety, etc. Physics modeling and haptics feedback are very important to accurately evaluate product assembly performance and increase training task efficiency. A multithread method must be designed to support physics modeling and haptics feedback. There are three separate threads in the system: haptic rendering thread, physical calculation thread, and graphical rendering thread. The haptic rendering thread is responsible for calculation of force and torque and then rendering by the PHANTOM device, launching at a high priority and high frequency (about 1,000 Hz). The physical calculation thread performs all the work including collision detection, physics computation, dynamic simulation of realistic part behavior, and geometry constraint recognition and solution, which is running at a second priority and frequency (about 100 Hz). The graphic rendering thread is mainly responsible for visualizing the entire scene graph the graphic rendering thread and virtual objects and it runs at a low frequency of about 30 Hz. Because there are several threads in the system, and each of them runs at a different rate, an efficient communication mechanism must be provided. As shown in Fig. 11, when the user operates the haptic device to move an object, the graphic rendering thread gets the new move command from the device and then it sends the new position of haptic interface point for the operated virtual object to the physics calculation thread.

Fig. 11 Framework of multithread communication



At the same time, the position of the other virtual objects can be also obtained from. In the physics computation thread, a real-time collision algorithm is provided to detect if the virtual objects contact each other. If they are in contact state, a spring-mass model is used to calculate the new position of the virtual objects to simulate the dynamic behavior. If they are in assembly state, a geometry constraint recognition and resolution algorithm is used to calculate the new position of the virtual object for assembly operation. After calculation, the validated new position can be sent back to the graphic rendering thread to update the virtual objects. At the same time, the collision position, direction, penetration depth, and geometry constraint information can be sent to the haptic rendering thread to calculate the force feedback.

The overview of the haptics-based assembly training process is shown in Fig.12. Contact state is mainly referred to simulate the collision reaction and dynamic behavior of the virtual part, and assembly state is mainly referred to simulate the mating or insertion phase of the virtual part. In virtual environment, when two parts are close enough to each other and the distance and orientation of their assembly features reach a specified range, the assembly simulation state can be activated. Otherwise, the contact simulation state is executed.

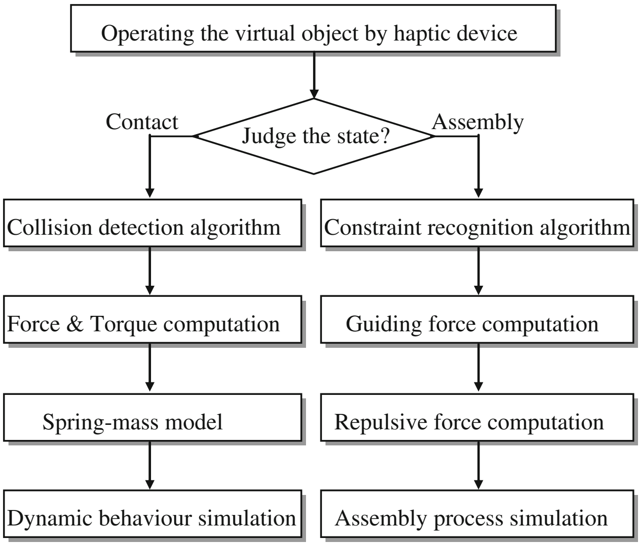


Fig. 12 Overview of haptic-based assembly training

5.3.1 Physics-based dynamic interaction

During the contact simulation stage, the user can manipulate the haptic device, the position and orientation data can be obtained and mapped from haptic workspace to virtual environment workspace, and then used to operate the virtual object. When the operated virtual object collides with the other virtual objects, real-time collision detection is used to calculate collision position, normal and penetration depth, and the feedback force or torque can be generated to the user. The collision detection algorithm is developed based on a multithread method and hierarchical data model, the bounding box collision detection is carried out in the graphic thread, which runs at the lowest rate. Then the precise collision detection is carried out in the physics thread, and the computation and rendering of force and torque is carried out in the haptic thread. A spring-mass model is used to simulate the dynamic behavior of virtual parts [21]. The virtual coupling method is applied to supply a dual representation for the operated part: the tracked model and the displayed model. The tracked model of the part is invisible to the user and controlled by the PHANTOM device to calculate its position and orientation, and then use this data for collision detection and penetration depth calculation. The displayed model is visible to the user and used for graphic display. A linear spring and a torsional spring are used to couple the tracked and the displayed model. The realistic manipulation of the part is obtained by the displayed model to visually prevent 3D models passing through each other and the collision force is computed using the penetration depth of the tracked model of the operated part into the other parts. As shown in Fig. 13, the linear spring/dashpot is used to apply a translational force F to the displayed model in order to follow the tracked model by performing translational movement. The torsional spring/dashpot is used to apply a torque T to the displayed model in order to keep the orientation of the displayed model relative to the tracked model. By applying force F and torque T to the displayed model, it keeps following the tracked model moved by the operator without interpenetration of parts, and the displayed part can achieve dynamic behavior that mimics the real world interaction of parts.

The force F and torque T are given by

$$F = k_T(p_t - p_d) - b_T(v_t - v_d) \qquad (1)$$

$$T = k_R \times \theta_{t-d} - b_R \times \omega_{t-d} \qquad (2)$$

where, k_T is the linear stiffness constant, b_T is the linear damping constant. p_t and p_d are the positions of center of mass for tracked model and displayed model in the world coordinate frame. v_t and v_d are the linear velocities of the tracked model and displayed model.k_R is the torsional stiffness constant, b_R is the torsional damping constant. θ_{t-d} is the rotation angle of displayed model relative to tracked model in world coordinate frame and ω_{t-d} is the angular velocity of displayed model relative to tracked model.

5.3.2 Haptics-based assembly operation

During the assembly simulation stage, when two parts are close enough to each other, a real-time computation is carried out of the distance and angle of related assembly features, and if they come into a certain range, a geometry constraint can be automatically captured, the precise assembly position can be calculated, and an attractive force or repulsive force can be also generated to realize the mating or inserting process as naturally and realistically as in real world. In order to avoid unnecessary computation and improve system efficiency, the collision detection algorithm is closed in this stage. The virtual part is adjusted to the precise position by geometry constraint and haptics feedback, not by collision detection. This is very useful for low-clearance parts and complex products because positioning a part only by high-accuracy collision detection is a time-consuming and low-efficiency process. As shown in Fig. 14, a peg hole mating is used as an example to discuss the realization of geometry constraint and haptics feedback. By using the haptic device, the user operates the axis part, which is composed of five surfaces, to mate it into the hole of the base part, which is composed of four surfaces. According to the hierarchical constraint-based data model, the surface is designed as an independent object, and in the scene graph it is constructed as a separate node. In virtual environment, each surface can be represented by specific elements that define its parametric equation. For example, a point on the plane and its normal vector defines a planar surface while a point on the cylinder axis, its direction and the radius value defines a cylinder surface. In the scene graph structure, for each separate surface node, there is a transform node (beginning with xfm_) to control its position and orientation, and also a geometry node (beginning with geo_) for graphic display and collision detection.

For axis and hole mating, the assembly process can be divided into two phases. The first phase is to adjust the operated part to make their mating axes align as shown in

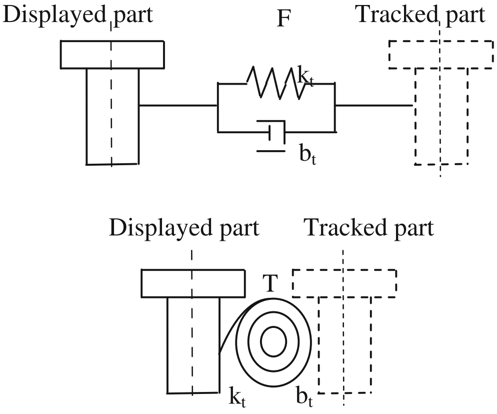


Fig. 13 Spring-mass model between tracked and displayed part

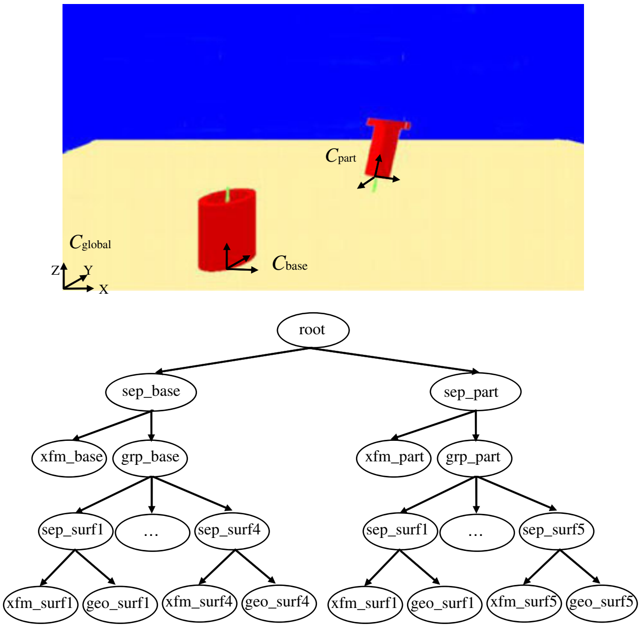


Fig. 14 Axis-hole mating and scene graph

Fig. 15a. The second phase is to insert the operated part into the hole to get it to its final position as shown in Fig. 15b. Then the precise position of the operated part can be calculated by geometry constraint. The angle of the two parts α can be computed from the direction vectors of the mating cylinder axes and the distance d can be also computed from the center point of the cylinder axis of the operated part to the direction vector of the base part cylinder axis by means of

$$\alpha = \mathrm{arc}\,cos\left(V_{\mathrm{base}} \cdot V_{\mathrm{part}}\right) \tag{3}$$

$$d = \frac{\left|V_{\mathrm{base}} \times P_{\mathrm{base}}P_{\mathrm{part}}\right|}{\left|V_{\mathrm{base}}\right|} \tag{4}$$

where, P_{base} and P_{part} are the points on the hole cylinder axis of the base object and the operated object, V_{base} and V_{part} are the vectors of the hole cylinder axis of the base object and the operated object. This data can be extracted from the CAD system during data transformation and then mapped into the global world frame of reference in the virtual environment. For the first phase in Fig. 15a, in order to adjust the operated part to the correct position, a rotation matrix $\mathbf{M_R}$ which rotates the operated part around vector $\boldsymbol{n}=(V_{\mathrm{base}}\times V_{\mathrm{part}})$ via point P_{part} must be calculated and applied first to make the axes parallel, and then a translation matrix $\mathbf{M_T}$ can be calculated and applied to translate the operated part along distance d to make the axes align. The detailed description of the rotation matrix $\mathbf{M_R}$ and translation matrix $\mathbf{M_T}$ can be found in reference [22]. After axis alignment, the user can operate the haptic device to simulate the inserting process, and haptic feedback is an important cue to assist the operator in finding appropriate position and orientation. According to the geometry constraint, two types of force feedback can be generated: the attractive force and the repulsive force. Similarly, a dual-model representation mechanism can be also used during this mating phase: the tracked model and the displayed model. Firstly after axis alignment, the tracked model and the displayed model are put at the same position. But when the user operates the haptic device, the tracked model is controlled by the haptic device, and the displayed model is controlled by the geometry constraint. As shown in Fig. 15b, c, the tracked model may be deviated from the mating cylinder axis, but because of the geometry constraint, the DOF of the displayed model is restrained and it can only be moved along the mating cylinder axis. In each simulation loop, we can use the haptic data to update the tracked model and use the geometry constraint to calculate and update the corresponding displayed model.

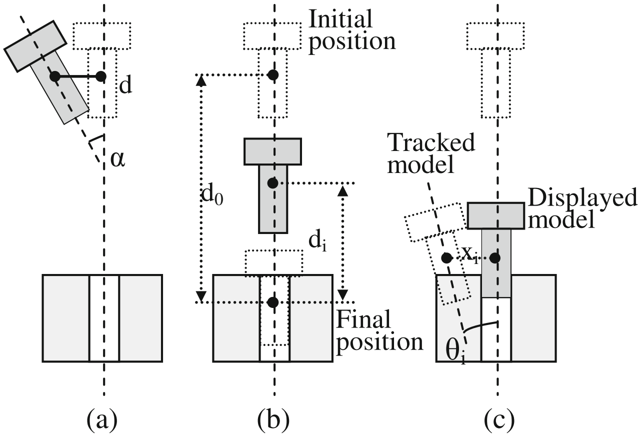


Fig. 15 Haptic-based assembly process for axis-hole mating

For peg hole mating, an attractive force can be generated to guide the user to move the operated part along the constrained direction. This force is given by

$$F^i_{\mathrm{att}} = K_1 \times \frac{d_i}{|d_0|} \times F_{\max} \tag{5}$$

where, K_1 is a stiffness constant, $F_{\max}$ is the maximum force value defined for the haptic device, d_0 is the distance vector from the initial to the final position of the displayed model after axis alignment, d_i is the distance vector at time t_i from the current to the final position of the displayed model. These distance vectors are given by

$$d_0 = P^0_d - P^f_d \tag{6}$$

$$d_i = P^i_d - P^f_d \tag{7}$$

where P^0_d and P^f_d are the initial position and final position of the center point of the cylinder axis on the display model of the operated part,P^i_d is the current position of the center point of the cylinder axis on the display model at time t_i.

When the tracked model is deviated from the mating axis, a repulsive force or torque can also be generated to oppose the user action. This makes the user feel the geometry constraint and makes the mating process as natural and realistic as in real world. The repulsive force can be calculated by:

$$F^i_{\mathrm{rep}} = K_2 \times x_i \tag{8}$$

where $K_2$is a stiffness constant, and $x_i$is the distance from the mating cylinder axis on the tracked model to the mating cylinder axis on the displayed model given by

$$x_i = P^i_t - P^i_d \tag{9}$$

P^i_t and P^i_d are the center points of the mating cylinder axis on the tracked model and the displayed model respectively at time t_i. The repulsive torque can be also calculated by:

$$T^i_{\mathrm{rep}} = K_3 \times \frac{\theta_i}{\pi} \times T_{\max} \tag{10}$$

with K_3 a stiffness constant, $T_{\max}$ the maximum torque value defined for the haptic device, and θ_i the angle between the mating cylinder axis on the tracked model and the displayed model.

$$\theta_i = \operatorname{arc} cos(V_t^i \cdot V_d^i) \tag{11}$$

V_t^i and $V_d^i$are the direction vectors of the mating cylinder axis on the tracked model and the displayed model at time t_i.

6 Application and evaluation

A new haptics-based virtual environment system has been developed by our group. The hardware and software for system realization are listed in Table 2. The virtual reality software WorldToolKit is used as the graphic engine for the creation of virtual environment. AGEIA PhysX, a famous physics engine is used to calculate and simulate the parts dynamic behavior. OpenHaptics, the SDK toolkit from SensAble Company, is used to control and apply haptic rendering. The multichannel scene management, immersive visualization and rendering, overlap and edge-blending, geometry and color correction etc., are done by TechViz, a famous virtual reality visualization and management software which has been applied in many areas in engineering.

This novel virtual environment system with motion simulator and haptics has been applied in virtual assembly planning and training for complex products. Figure 16 is the spherical cap screen for stereo display and inside the sphere is the motion simulator for free walking. Figure 17 is the multichannel projection for image correction and edge-blending etc. After data transformation from CAD to VR, the geometry, topology, assembly, and physics information are inputted into the virtual environment. The creation of the initial virtual scene is shown in Fig. 18. In the fully immersive virtual environment, the trainee can use the haptic device to operate the virtual object getting force and torque feedback, just as he would when operating the part in real world. For example, when the user moves the part in free space, he should feel gravity. When he rotates the part around an axis, he should feel torque feedback. When he moves the part along a face or along an axis, he should feel friction. As shown in Fig. 19, if two virtual objects collide into each other, he should feel collision force and torque, and the spring-mass model is used to prevent part penetration and to simulate dynamic behavior.

In order to study the performance and usability of the proposed assembly method, an experiment is performed to verify the stability of haptic rendering. As shown in Fig. 20, when two objects are close enough to each other (the green

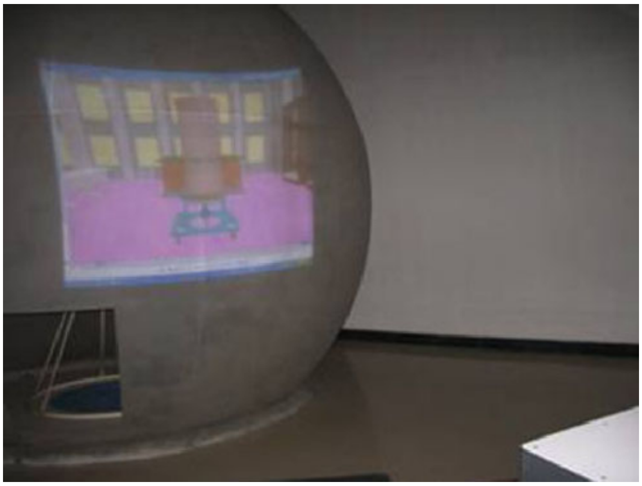


Fig. 16 Sphere screen and motion simulator

Table 2 Hardware and software for system realization

Hardware	Computer	HP XW8400 and Dell T5400
	Projector	DepthQ HD 3D stereo projector
	Tracking	Flock of birds
	Glasses	Stereoscopic 3D
	Haptics	PHANTOM Premium
	Data glove	CyberGlove
	Motion simulator	Fabricated by our group
	Sphere screen	Fabricated by our group
Software	Graphic engine	World Toolkit (WTK)
	Haptics engine	OpenHaptics SDK
	Physics engine	PhysX SDK
	Scene management	TechViz
	Data management	Oracle
	Integration tool	Microsoft Visual C++

Fig. 17 Multichannel projection system

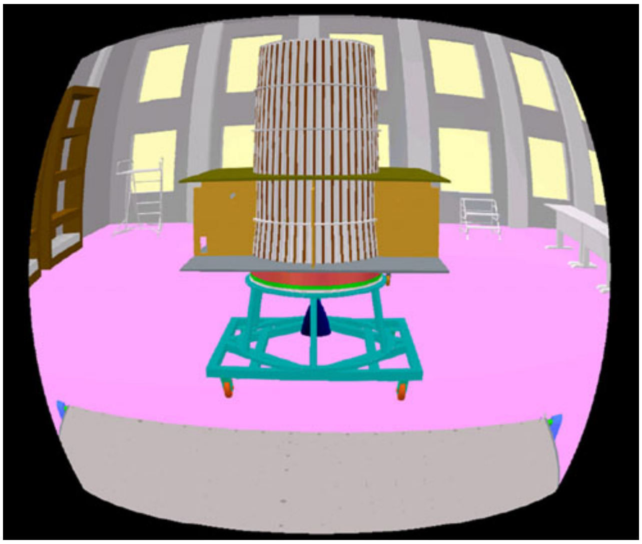


Fig. 18 Virtual scene after data transformation

bolt and the blue cover), an axis-mating geometry constraint can be captured, the bolt is adjusted to the precise mating position by geometry constraint, and then a guiding force and repulsive force can be generated to help the user to assemble the bolt to the final position. The force and torque information can be recorded during the assembly task. Figure 21 reflects the forces arisen by handling the axis part to insert into the hole part after axis align constraint. When the middle axis of axis part deviates from the middle axis of hole part, F_x, F_y, T_x, T_y are produced and Fz is attracting force to guide the user to assemble the part to the final position. From the results, we can know that the computation algorithm is reasonable and the haptic rendering is stable.

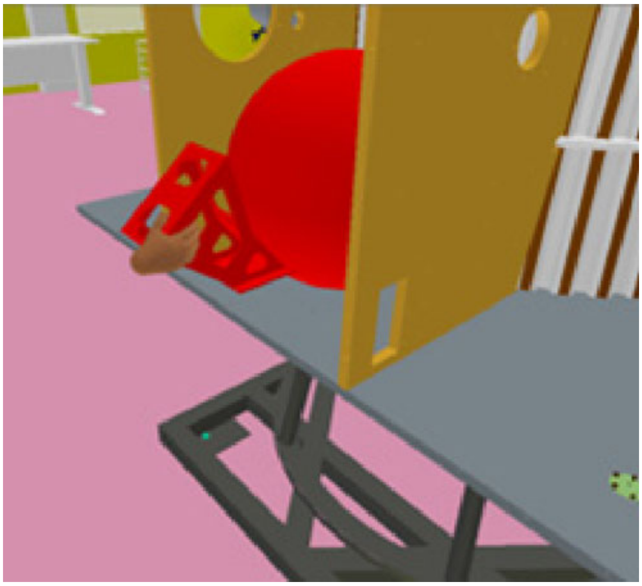


Fig. 19 Collision detection and dynamic behavior simulation

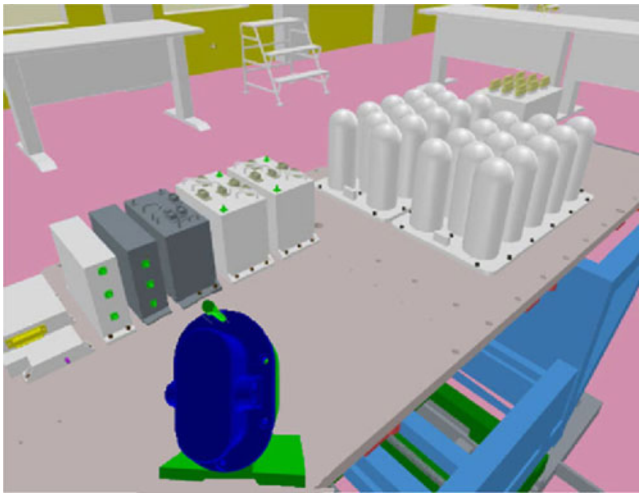


Fig. 20 Assembling part by geometry constraint and haptics feedback

In order to test the validity of the virtual environment system for assembly training, a heuristic evaluation method is applied to the training experiment concerning the following eight items. (1) Immersion with spherical system: measure how the user can get the feeling of presence in the virtual environment as in the real world when training in the spherical virtual space. (2) Motion simulator for human activity: measure if the motion simulator works well to realize free walking and the importance of human activity during assembly process for large-scale complex products. (3) Interaction with haptics and data glove. Because PHANTOM is a single-point device, it cannot support the human fingers to grab an object. The data glove can realize this, but it does not have haptics feedback. A compromise solution is to connect the PHANTOM device with the data glove and tests its effectiveness. (4) Physics-based dynamic behavior simulation measure if the spring-mass model can simulate the dynamic behavior of virtual objects as realistically as in real life. (5) Haptics for feeling collision detection measure the feedback of force and

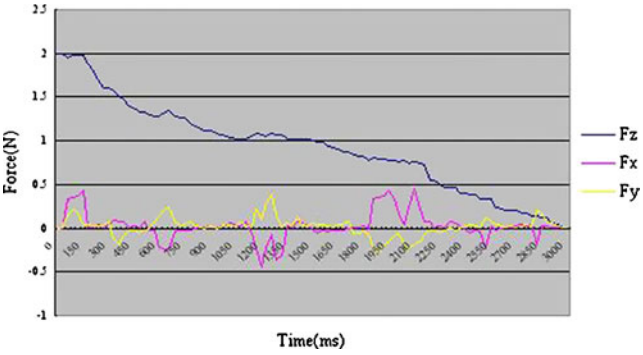


Fig. 21 Forces and torques during the assembly task

torque when two objects collide with each other. (6) Haptics for guiding assembly operation and positioning measure haptics feedback to improve assembly operation efficiency and accurate positioning. (7) Motion simulator sickness and haptics fatigue measure the fatigue and sickness of walking on the motion simulator for a long time and the use of PHANTOM with stereo glasses for a long time. (8) Simulation efficiency for complex products measure the velocity and efficiency of the system for simulation of large-scale complex products. One set of results of the heuristic evaluation are shown in Table 3.

Ten postgraduate students from our group were chosen as trainees to do the experiment. All the students do research work in virtual reality or similar CAD/CAM simulation area, so they have basic understanding about the application and the interaction devices. At first all of the students received a brief presentation about the system principle, motion simulator and haptics, and then each of them spent about 0.5–1 h to practice virtual assembly or disassembly operations until becoming familiar with the system. Finally, all the students carried out the same assembly task and gave a score in the range 1–10 (the higher the better) to the eight subjective items mentioned above. The maximum, the minimum, and the average values are shown in Table 3. From the results, we can see that: (1) most of the students consider that fully immersive spherical virtual environment and motion simulator are valuable for assembly training of large-scale complex products; (2) haptics is helpful to improve assembly operation efficiency. During the assembly process, the user can feel gravity, friction, and collision detection, he can also use haptics feedback to guide assembly operation and accurate positioning. Haptics can increase the user confidence and presence in virtual environment. The main limitations are that: (1) connecting PHANTOM with CyberGlove is not a good way for virtual assembly training, since it affects the interaction with virtual environment. The best device is a data glove with force feedback such as CyberForce, but it is very expensive. (2) For large-scale complex products, simulation efficiency will be affected. Because there are thousands of parts in a complex product, after data transformation from CAD to VR the models and data are very large, and as there are also several threads in the system, the guarantee of simulation in real time is a challenging problem.

7 Conclusion and future work

There are two shortcomings for nowadays virtual assembly training systems. One is that the operators cannot move around the virtual environment in a natural way as people in real world, they are constrained in a fixed position, or can only move in a limited space. The other is that most of the virtual assembly training systems are based on geometry constraint modeling only, which lack haptics feedback. This paper has described a novel haptics-based virtual environment system for assembly training of complex products to overcome the previous two shortcomings. A new low-cost motion simulator is designed and integrated with the virtual environment to realize free walking by human. An automatic data integration interface is developed to transfer geometry, topology, assembly, and physics information from CAD to VR, and a hierarchical constraint-based data model is rebuilt to construct the virtual assembly environment. Physics-based modeling and haptics feedback are undertaken to simulate the realistic assembly operations. The application examples and evaluation experiments demonstrate that both motion simulator and haptics have great potential for training of assembly process. The future work is to develop more efficient collision detection and physics modeling algorithms in order to realize more natural and intuitive human–computer interaction, and integrate intelligent assembly sequence or path planning algorithms to give operation guidance during the training process.

Table 3 Heuristic evaluation

Item	Feature	Min	Max	Average
1	Immersion with spherical system	6	9	8.1
2	Motion simulator for human activity	7	9	8.5
3	Interaction with haptics and data glove	5	7	6.6
4	Physics-based dynamic behavior simulation	6	9	7.9
5	Haptics for feeling collision detection	7	9	8.7
6	Haptics for guiding assembly operation and	7	9	8.8
7	Motion simulator sickness and haptics fatigue	5	8	7.2
8	Simulation efficiency for complex products	6	8	6.9

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