Maintenance accessibility evaluation method based on D-H model and comfort in a virtual maintenance environment

Dong Zhou1,2,3 · Hongduo Wu1,2,3 · Ziyue Guo1,2,3 · Qidi Zhou1,2,3 · Yuning Liang1,2,3

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Abstract
Maintainability, especially for complex products, is a very important general quality characteristic. Physical accessibility is the primary element in maintainability design. Up to now, VR (virtual reality) technology-assisted maintainability evaluation, analysis and design, called virtual maintenance, has become the mainstream and achieved some results. In virtual maintenance, the most widely used accessibility evaluation method is to use virtual human accessible envelope to judge and evaluate accessibility. However, this method can only give two kinds of evaluation results: accessible and inaccessible. Moreover, the envelope lacks sufficient data and theoretical support, so the precision and accuracy of evaluation method need to be improved. In this paper, a parameterized accessibility evaluation method is proposed and the corresponding evaluation models and tool are created. Firstly, to objectively describe the movement of human body, a 6-joint and 5-link D-H (Denavit–Hartenberg) link model is established from the waist to the fingertip of the human body, and the ranges of 10 degrees of freedom and angles related to accessibility are determined according to ergonomics. Then, comfort is introduced to refine the accessibility evaluation, and a multi-level accessibility evaluation system based on comfort is constructed according to RULA (the rapid upper limb assessment). Thirdly, in order to facilitate the application of this method in virtual environment, accessibility envelope models and accessibility evaluation tool are created based on the proposed method. Finally, compared with RULA and the accessible envelope provided by DELMIA, respectively, the results from virtual and real environment of the comparative experiment show that the proposed method and tool are accurate, more precise and more efficient.

Keywords Virtual maintenance · Parameterization · Accessibility evaluation · Ergonomics · D-H model · RULA

1 Introduction
Maintainability is the inherent property of the product. For large and complex products, maintainability is very important to the performance of products, operation cost and safety of use. Physical accessibility is the most important design index in the qualitative requirements of maintainability, and the first element of maintainability design analysis [1, 2]. Accessibility refers to the degree of difficulty for maintenance personnel to reach maintenance objects. Good accessibility can make product maintenance convenient, fast, accurate and effective and greatly save manpower, physical and time costs.

The early maintainability design works mainly relied on the physical prototypes or full-scale solid models of the product [3]. However, because these models are difficult to obtain in the product design stage, some necessary analysis and verification cannot be carried out, which hinders the implementation of design for manufacturing and assembly (DFMA) [4]. Virtual reality technology provides a means to carry out maintainability design analysis and verification based on virtual prototype. It can find the existing problems in the early stage of product design and give timely feedback for optimization, make up for the defects and deficiencies such as long cycle and difficult change and provide a lot of data information for researchers to analyze. Therefore, the accessibility design and evaluation through virtual maintenance is a major trend of maintainability research. However,
at present, the accessibility evaluation based on virtual maintenance technology is still based on qualitative evaluation, mainly through static verification and dynamic simulation. However, static verification has some defects, such as strong subjectivity and lack of theoretical support; dynamic simulation not only consumes a lot of time and energy to design the simulation process, but also the results of analysis and evaluation depend on the level of simulation designers, so the results are not accurate.

In the process of maintenance, the comfort of operation seriously affects the efficiency and effect of maintenance. Even if the maintenance target is accessible, the maintenance operation forces the maintenance personnel to maintain an uncomfortable maintenance posture, which is also a design defect of accessibility. Therefore, accessibility and comfort are two inseparable maintainability evaluation factors. The main idea of this paper is to refine and optimize the accessibility evaluation through comfort.

This manuscript is organized as follows. The second section discusses related work. The third part introduces the basic principle and steps of the parametric evaluation method of product entity accessibility based on comfort in virtual scene. In addition, the modeling process of accessibility evaluation model and the usage rules of evaluation tools are given. In the fourth part, a virtual maintenance case of airborne equipment is used to verify the effectiveness and superiority of the proposed method. Finally, the conclusions of this paper are given.

## 2 Related work

### 2.1 Virtual maintenance

Virtual maintenance technology can improve the level of maintainability design and shorten the design time and cost of equipment maintainability because of its advantages of simulating physical environment and obtaining space data effectively.

In the late 1980s, some foreign research institutions have begun to study virtual simulation technology. In the design phase of F-16 fighter, in order to break through the limitation of physical prototype, LMTAS used virtual reality technology to find many maintainability problems and improve the scheme [5]. The University of Salford has established an immersive virtual platform considering constraints, which can effectively support virtual assembly [6, 7]. Kallmann et al. studied the interaction characteristics of virtual interaction objects and improved the timeliness and interactivity of virtual simulation [8]. Vujosevic et al. studied a new generation method of maintenance sequence. Through the combination of user interaction method and undirected closed graph method, the constraints are constantly updated to obtain a specific maintenance sequence [9]. Wampler et al. proposed a new idea. They decomposed maintenance tasks and obtained a four layer decomposition model with the lowest layer being the macro-motion layer. Simulation commands can be generated directly according to the macro-motion layer and realize dynamic simulation [10].

China’s research on virtual maintenance mainly focuses on static and dynamic simulation control for maintenance process and secondary development of DELMIA and Jack software to realize the required functions [11]. Wang et al. used DELMIA to carry out dynamic simulation of maintenance process, and analyze the maintainability of aircraft based on Simulation [12]. Wang et al. have studied the modeling and simulation of virtual digital prototype and human interaction behavior, established the relationship with product CAD system and realized the development of related functions in JAC [13]. Li et al. decompose the maintenance task to the maintenance dynamic element level and get the maintenance task decomposition model. The use of maintenance kinesiology can better describe people's sports behavior [14]. Lv and other scholars from Beijing University of Aeronautics and Astronautics used the hybrid control method to control the action of virtual human, combined the peripheral control method with the algorithm control method and made full use of their advantages to provide a new means for realizing the accurate control of virtual human action [15]. Zhou et al. have established a new maintenance activity simulation management model MTN (Maintenance Task Net), which combines the abstract description of maintenance activities with the underlying activities of dynamic simulation, and can drive the virtual environment and virtual human to simulate maintenance tasks [16]. In order to get rid of the constraints that virtual maintenance simulation on digital mockups (DMUs) requires a lot of time and professional maintenance knowledge, Guo et al. proposed an immersive maintenance simulation method in virtual environment based on virtual reality and comprehensively evaluated the product maintainability state by using fuzzy comprehensive evaluation (FCE) [17]. Yang et al. divided the virtual maintenance dynamic simulation process into two parts: simulation preparation stage and simulation generation stage, and defined the main work of each stage to better carry out maintenance simulation [18].

To sum up, the research on virtual maintenance technology mainly focuses on the development of virtual maintenance platform, virtual digital prototype modeling, virtual human modeling, simulation command generation and human motion synthesis [18]. However, there are three main problems: 1) for the modeling of complex virtual digital prototype, especially flexible cable, the current technology is still very limited and needs further research. 2) In dynamic simulation, the authenticity of virtual human action has been questioned, and the maintainability analysis and evaluation
results are not very accurate. Therefore, it is necessary to study the virtual human action control method to improve the action credibility. 3) Designing virtual dynamic simulation has always been a cumbersome and complex thing, which greatly affects the work efficiency of designers. How to realize the rapid synthesis of virtual human actions, how to realize the automatic generation of simulation process and even how to improve the static virtual maintainability evaluation effect without generating maintenance actions are aspects that need technical breakthrough.

2.2 Accessibility analysis and evaluation

Around 1950, the concept of maintenance accessibility was proposed by some American scholars. Maintenance accessibility refers to the difficulty of approaching the parts to be repaired when repairing the product [19].

In terms of application, many reliability and maintainability engineering software have been developed. DEPTH and CREW CHIEF developed by the US air force can analyze the maintainability of products by using virtual mannequins to help researchers analyze the relationship and interaction between maintenance personnel and systems [20]. American RC has developed a software BlockSim that can analyze and calculate reliability and maintainability, which can describe the system through reliability block diagram [21]. The IVAS system designed by the State Key Laboratory of Zhejiang University can establish a very real virtual environment and has powerful interactive means to support virtual people to carry out virtual process simulation in it, which plays a good auxiliary role in the whole life cycle of product equipment development and the realization of concurrent engineering [22]. It is not difficult to find that virtual maintenance has become the main and effective means of accessibility analysis and evaluation.

In terms of maintenance accessibility design, analysis and evaluation of complex equipment, the main research ideas are to build a strong correlation maintenance accessibility index system and to give play to the effectiveness of virtual maintenance. Huang et al. studied the construction method of maintenance accessibility evaluation index based on evaluation purpose. It is considered that in the product scheme design stage, the rationality of line replaceable unit (LRU) layout, maintenance channel settlement and inspection hole distribution should be used to evaluate the maintenance accessibility [23]. The design of China’s first aircraft electronic digital prototype was completed in 2003. The prototype has established a complete product digital standard system, which can check and analyze the maintenance accessibility, interference and personnel analysis in the maintainability analysis [24]. Xu et al. established the evaluation index system of equipment maintenance accessibility. Based on virtual simulation, the evaluation incidence matrix is constructed by using index correlation degree and directed graph, and a comprehensive evaluation model of maintenance accessibility is proposed at last. They also pointed out that carrying out maintainability verification in the process of equipment digital prototype design is of great significance to improve equipment maintainability [25]. In recent years, Guo et al. proposed an immersive maintainability verification and evaluation system (IMVES) based on virtual reality, which enables users to interact with maintenance objects and conduct immersive simulation, so as to solve the problem that accessibility evaluation through non-immersive virtual maintenance simulation is very cumbersome and time-consuming [26].

Up to now, there are two main methods to evaluate the accessibility based on virtual maintenance. One is to evaluate the accessibility by designing and analyzing the simulation process. The process of maintenance simulation not only costs a lot of energy, but also is not necessarily true. In addition, the evaluation process depends on expert experience, which is subjective. Another accessibility evaluation method is to use the virtual human accessibility envelope to judge whether the target is accessible. For example, the accessibility analysis tool provided by DELMIA software developed by Dassault Company of France is shown in Fig. 1. Engineers can get the evaluation result of maintenance accessibility by observing the relative position relationship between maintenance target and arm envelope. However, this method can only give two evaluation results: accessible and inaccessible. The accessible envelope, in addition, lacks sufficient data and theoretical support, such as the ranges of motion of the joints on the arm and the support of ergonomics theory. The range within the envelope is only the range of motion

![Fig. 1 Virtual human hands accessible space envelope in DELMIA](image)
formed by shoulder to hand sweeping. It doesn't take into account the impact of lumbar activity on accessibility either.

### 2.3 Evaluation method of human comfort

At present, the methods of human comfort evaluation are mainly obtained through the experimental statistics. There are three widely used methods: OWAS (Ovako Working Posture Assessment System) [27], RULA (Rapid Upper Limb Assessment) [28] and LUBA (Loading on the Upper Body Assessment) [29].

OWAS mainly analyzes and evaluates people's body posture at work and carries out grading evaluation according to the possible degree of injury caused by working posture. OWAS method mainly encodes the weight of four parts of human body: head and neck, trunk, arm, leg and human load. Through a large number of experimental observation and verification, the researchers obtained the comfort parameters of each body posture and divided it into four levels according to the harm of posture to the body, so as to evaluate the staff's posture. The RULA ergonomic assessment tool considers biomechanical and postural load requirements of job tasks/demands on the neck, trunk and upper extremities. The different place between RULA and OWAS is to grade the posture of the limbs by scoring. Compared with the coding classification, the method can score according to the angle of different joints, so as to get the final posture score. LUBA establishes a relationship between each upper limb posture and its maximum working duration, which is more suitable for the scene of maintaining a posture for a long time.

### 3 Proposed method

In this paper, accessibility and comfort are regarded as two interrelated maintainability evaluation factors. Therefore, this paper introduces comfort, refines and optimizes the accessibility evaluation based on objective data and mathematical model, proposes a rapid maintainability grading evaluation method in virtual environment and develops an accessibility evaluation tool based on this method, which can be applied in DELMIA and CATIA. The implementation process of the accessibility parametric evaluation method proposed in this paper is shown in Fig. 2.

![Fig. 2 The method structure diagram of this paper](image)

- **1. Collection and analysis of entity accessibility evaluation information in virtual maintenance**
  - Virtual human
  - Physical activity restriction
  - Digital prototype
  - Position

- **2. Kinematic modeling of human body**
  - Simplification of human body
  - D-H parameter modeling

- **3. Construction of multi-level accessibility evaluation system based on comfort**
  - Joint selection based on comfort
  - Activity scope division and scoring based on RULA
  - Accessibility score based on trunk comfort and limb comfort

- **4. Construction of accessibility evaluation model in virtual environment**
  - Searching accessible boundary by Monte Carlo simulation
  - Accessible boundary extraction and modeling

- **5. Case verification**
  - Virtual environment
  - Real environment
method are used to build human kinematics model; third, the accessibility is graded and the multi-level accessibility evaluation system is built from the perspective of comfort based on RULA; fourth, for the convenience of use, a multi-level accessibility evaluation model tool based on the proposed method is developed; finally, the accuracy, precision and efficiency of the method and tool are verified in a case.

Before discussing the methods proposed in this paper, the assumptions in the construction and use of the whole method need to be specified first.

- There are no obstacles between the person and the maintenance object;
- The influence of human skin and muscle thickness is ignored when establishing human kinematics model;
- It is considered that there are enough accessible points randomly generated when generating the accessible envelope model by Monte Carlo simulation;
- If the maintenance operation interface can be completely covered by the accessible envelope model of a certain score, the maintenance component is judged to be accessible at the score.

### 3.1 Data analysis of virtual maintenance accessibility evaluation

Compared with the real environment, the important advantage of virtual environment is that there are a lot of data in virtual environment for researchers to use, so it is necessary to determine the data needed for accessibility analysis in virtual environment.

In the virtual environment of maintenance operation, the accessibility analysis needs to be judged according to the accessible range of limbs and the spatial position of the maintenance object. Therefore, it is necessary to understand the virtual human modeling technology and obtain the motion constraints of each limb structure of the virtual human body, including the lengths of the limb and the ranges of motion of the included joint degrees of freedom, so as to construct the accessible envelope model of the limb and obtain the accessibility of the limb range. In the evaluation stage, accessibility is the maintainability evaluation factor generated by the relative distance between human and maintenance object. Therefore, it is necessary to obtain not only the spatial location information of virtual human and maintenance object, but also the virtual human model and digital prototype of maintenance object, that is, the data of size and shape.

### 3.2 Kinematic modeling of human body

The human body is a very complex structure, in order to facilitate the study of human motion, we need to build a human model. Different human models have different ways of movement, among which H-Anim human model is widely accepted and applied in various fields [30]. According to the characteristics of human body, H-Anim model obtains the data of each joint node of human body model and establishes the node database, including various types of information such as attitude parameters and degree of freedom parameters. There are 77 joints and 47 bone segments in H-Anim model, and each bone is connected by joint [31]. However, for the common maintenance activities, the H-Anim model contains too many joints and bone segments, and there is a lot of redundancy, so it needs to be simplified to get the manikin suitable for maintenance activities in virtual environment.

#### 3.2.1 Simplification of human body

The accessibility discussed in this paper is on the premise that the maintenance personnel have been standing in the best maintenance position, so the impact of the accessibility caused by the joints below the waist is not discussed.

The joints and limbs above the waist were simplified and the linkage model was reconstructed. Firstly, a standard link model is established from waist to fingertip, and the nodes are waist–chest–neck–shoulder–elbow–wrist–fingertip. Among them, waist can rotate and tilt, chest and neck movement cannot affect the range of hand movement, but from shoulder to fingertip a series of nodes can affect accessibility. In addition, because this paper only considers the maximum envelope range that the arm can reach, and does not consider the specific motion of the hand, the hand can be regarded as a bone structure, that is, a rigid link. The simplified human model of the upper part of the body is shown in Fig. 3, and the red nodes are reserved nodes.

#### 3.2.2 D-H parameter modeling

In order to study the relationship between the joints and degrees of freedom of the arm in motion, this paper uses the Denavit–Hartenberg parameter method for limb kinematics modeling [32]. The D-H parameter method can express the motion relationship between the connecting rods, so as to deduce the motion relationship of the end of the limb relative to the starting end. The construction of human D-H model can be divided into two steps.

1. Analysis of Degree of Freedom

   The degree of freedom of joints determines the way and direction of limb movement. The degrees of freedom of five joints from waist to wrist are discussed as follows.
Waist (three degrees of freedom): trunk forward and backward, trunk left and right, rotation; 
Neck (no degree of freedom): no degree of freedom affecting accessibility; 
Shoulder (three degrees of freedom): arm up and down, arm forward and backward, rotation; 
Elbow (two degrees of freedom): bend, rotate; 
Wrist (two degrees of freedom): bend to both sides, bend back and forth.

The model has ten degrees of freedom in five joints, and the schematic diagram is shown in Fig. 4, where \( Z_i \) \( (i = 0, 2, \ldots, 9) \) represents the degrees of freedom, \( L_j \) \( (j = 1, 2, \ldots, 5) \) represents the length of trunk or limb.

2. Establishment of Limb Kinematics Model based on D-H Parameter Method

The D-H parameter method establishes a coordinate system for each degree of freedom, describes the relative motion relationship between joints by the change matrix between coordinate systems and controls the angle and range of motion. The change matrix of coordinate system \( i \) relative to coordinate system \( i-1 \) is shown in Eq. (1).

\[
i^{-1}_i T = \begin{bmatrix}
    c\theta_i & -c_\alpha_i s\theta_i & s_\alpha_i s\theta_i & a_i c\theta_i \\
    s\theta_i & c_\alpha_i c\theta_i & -s_\alpha_i c\theta_i & a_i s\theta_i \\
    0 & s_\alpha_i & c_\alpha_i & d_i \\
    0 & 0 & 0 & 1
\end{bmatrix}
\]

(1)

where \( s\theta_i \) represents \( \sin \theta_i \); \( s_\alpha_i \) represents \( \sin \alpha_i \); \( c\theta_i \) represents \( \cos \theta_i \); \( c_\alpha_i \) represents \( \cos \alpha_i \); \( a_i \) is the length of the rod, which represents the distance between the two connected joint axes; \( \alpha_i \) is the angle, which means the angle of \( x_i \) axis on degree of freedom \( i \) rotating from \( z_{i-1} \) axis to \( z_i \) axis according to the right-hand law; \( d_i \) is the translation, representing the distance difference between adjacent connecting rods on the joint axis, and the positive direction of \( z_{i-1} \) axis is its positive direction; \( \theta_i \) is the amount of rotation, which indicates the angle of \( z \) axis rotation from \( x_{i-1} \) axis to \( x_i \) axis according to the right-hand rule.

Then, the parameters of D-H linkage model are determined according to ergonomics, Chinese National Institute of Standards GB10000-1988 [33] (human parameters of different countries and regions can be referred to other data) and experiments, including the motion angle of each degree of freedom, the length between each joint (rod length), as shown in Tables 1 and 2.

The relative position change relationship (one-step change matrix) between adjacent degrees of freedom is determined by the above parameters, and the relative position change

![Fig. 3 Simplified manikin (the upper part of the body)](image)

![Fig. 4 Degree of freedom division of each joint of human body model](image)

\begin{table} 
\begin{tabular}{cccccc}
\hline 
\( i \) & \( Z_{i-1} \) & \( a_i \) & \( \alpha_i \) & \( d_i \) & \( \theta_i \) \\
\hline 
1 & \( Z_0 \) & 0 & \( \pi/2 \) & 0 & \( \theta_1 \) \\
2 & \( Z_1 \) & 0 & \( \pi/2 \) & 0 & \( \theta_2 \) \\
3 & \( Z_2 \) & \( L_2 \) & \( -\pi/2 \) & \( L_1 \) & \( \theta_3 \) \\
4 & \( Z_3 \) & 0 & \( \pi/2 \) & 0 & \( \theta_4 \) \\
5 & \( Z_4 \) & 0 & \( \pi/2 \) & 0 & \( \theta_5 \) \\
6 & \( Z_5 \) & 0 & \( \pi/2 \) & \( L_3 \) & \( \theta_6 \) \\
7 & \( Z_6 \) & 0 & \( \pi/2 \) & 0 & \( \theta_7 \) \\
8 & \( Z_7 \) & 0 & \( \pi/2 \) & \( L_4 \) & \( \theta_8 \) \\
9 & \( Z_8 \) & 0 & \( \pi/2 \) & 0 & \( \theta_9 \) \\
10 & \( Z_9 \) & \( L_5 \) & 0 & 0 & \( \theta_{10} \) \\
\hline 
\end{tabular} 
\end{table}
3.3.1 Joint freedom degrees selection based on comfort

In order to improve the practicability of the accessibility evaluation method and reduce the workload of modeling, it is necessary to select the degrees of freedom that affect the human comfort from the ten degrees of freedom included in the above D-H model.

In this paper, the degrees of freedom involved in some limb movements, this consideration is not detailed enough for the actual maintenance work; LUBA method considers the duration of working posture more, and the classification of posture is only three levels, this consideration is not in agreement with the actual maintenance work. RULA divides the motion ranges of the degrees of freedom and gives detailed scores for them, respectively. Therefore, this paper divides the ranges of the selected six degrees of freedom based on RULA (before dividing the ranges of motion angle, intersect the ranges specified in RULA with the ranges specified in Table 2) and defines the corresponding comfort scores. In this paper, the comfort is divided into "arm comfort" and "trunk comfort". The arm comfort score is the sum of the three degrees of freedom comfort scores of shoulder and elbow, and the trunk comfort score is the sum of the three degrees of freedom comfort scores of waist. The motion range and corresponding score of each degree of freedom are shown in Table 3.

### 3.3.2 Activity scope division and score based on RULA

Although OWAS, RULA and LUBA the three comfort evaluation methods all adopt the idea of dividing posture, OWAS method divides posture roughly and does not divide the angle of limb movements, this consideration is not detailed enough for the actual maintenance work; LUBA method considers the duration of working posture more, and the classification of posture is only three levels, this consideration is not in agreement with the actual maintenance work. RULA divides the motion ranges of the degrees of freedom and gives detailed scores for them, respectively. Therefore, this paper divides the ranges of the selected six degrees of freedom based on RULA (before dividing the ranges of motion angle, intersect the ranges specified in RULA with the ranges specified in Table 2) and defines the corresponding comfort scores. In this paper, the comfort is divided into "arm comfort" and "trunk comfort". The arm comfort score is the sum of the three degrees of freedom comfort scores of shoulder and elbow, and the trunk comfort score is the sum of the three degrees of freedom comfort scores of waist. The motion range and corresponding score of each degree of freedom are shown in Table 3.

### 3.3.3 Accessibility score based on trunk comfort and limb comfort

The multi-level accessibility evaluation system is constructed by the arm comfort score and trunk comfort score, and is

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### Table 2 Movement angle of each degree of freedom

| Number | Scale       | Illustration                                                                 |
|--------|-------------|-------------------------------------------------------------------------------|
| $\theta_1$ | $-10^\circ - 37^\circ$ | The inclination of the upper body forward or backward from the waist |
| $\theta_2$ | $-8^\circ - 8^\circ$ | The inclination of the upper body from the waist to the left or right |
| $\theta_3$ | $-10^\circ - 10^\circ$ | Rotation angle of human upper body from waist |
| $\theta_4$ | $-45^\circ - 180^\circ$ | The angle at which the upper arm is raised or lowered |
| $\theta_5$ | $-40^\circ - 90^\circ$ | The angle at which the upper arm is moved outward or inward |
| $\theta_6$ | $-45^\circ - 90^\circ$ | The rotation angle of shoulder joint with the upper arm as the axis |
| $\theta_7$ | $0^\circ - 140^\circ$ | The angle between upper and lower arms at elbow |
| $\theta_8$ | $-70^\circ - 80^\circ$ | The rotation angle of the elbow joint with the forearm as the axis |
| $\theta_9$ | $-30^\circ - 50^\circ$ | At the wrist joint, the angle at which the palm bends to the side (thumb side or little thumb side) |
| $\theta_{10}$ | $-90^\circ - 80^\circ$ | At the wrist joint, the angle at which the palm bend to the front and back (palm side or back side of the hand) |
represented by the matrix two parameter comfort evaluation table. The accessibility score of each case is determined by fuzzy comprehensive evaluation method, among which the evaluation factor theory field is “arm comfort” and “trunk comfort”, with the same weight, each of which is 0.5; the evaluation grade theory field is composed of 1 to 7 points, including 7 grades; the fuzzy evaluation vector synthesis operator is matrix multiplication; the determination of the score adopts the principle of maximum membership. The comfort evaluation table is shown in Table 4, with a score of 1–7, 1 point for the maintenance target location in the most comfortable accessible area, and 7 points for the maintenance target location in the least comfortable accessible area, 8 points for not accessible.

Up to now, this method can support accessibility evaluation in virtual maintenance. However, considering that every evaluation needs to readjust the virtual human’s posture and obtain the required data, and it is found that the accessibility range corresponding to each accessibility score in Table 4 is fixed, so it is more convenient to establish the accessibility envelope model of the accessibility range corresponding to each accessibility score in simulation software such as DELMIA or CATIA.

### Table 3  Comfort score table

| Limbs | Description of movement | Angle | Score |
|-------|-------------------------|-------|-------|
| Upper Arm | Stretch out or close inward ($\theta_5$) | $0\leq \theta_5 < 90^\circ$ | 0 |
| Raise or lower ($\theta_4$) | $-20^\circ \leq \theta_4 \leq 20^\circ$ | 1 |
| | $-40^\circ \leq \theta_4 < -20^\circ$ | 2 |
| | $20^\circ \leq \theta_4 < 45^\circ$ | 3 |
| Lower arm | The angle between the upper arm and the lower ($\theta_7$) | $60^\circ \leq \theta_7 \leq 100^\circ$ | 0 |
| | $0^\circ \leq \theta_7 < 60^\circ$ | 1 |
| | $100^\circ < \theta_7 \leq 120^\circ$ | 4 |

### Table 4  Comprehensive evaluation table of accessibility based on comfort

| Trunk | Arm | 1 | 2 | 3 | 4 | 5 |
|-------|-----|---|---|---|---|---|
| Waist | 1   | 1 | 2 | 3 | 4 | 5 |
| Lean forward or backward ($\theta_1$) | $0^\circ \leq \theta_1 < 20^\circ$ | 2 |
| | $-10^\circ \leq \theta_1 < 0^\circ$ | 3 |
| | $20^\circ \leq \theta_1 < 37^\circ$ | 4 |
| Lean left or right ($\theta_2$) | $\theta_2 = 0^\circ$ | 0 |
| | $-8^\circ \leq \theta_2 < 0^\circ$ | 1 |
| | $0^\circ < \theta_2 \leq 8^\circ$ | 2 |
| Rotation ($\theta_3$) | $\theta_3 = 0^\circ$ | 0 |
| | $-10^\circ \leq \theta_3 < 0^\circ$ | 1 |
| | $0^\circ < \theta_3 \leq 10^\circ$ | 2 |

### 3.4 Construction of accessibility evaluation model in virtual environment

The accessibility envelope model of virtual human is the main means of accessibility evaluation in virtual maintenance. In view of the multi-level accessibility evaluation system established in this paper, the D-H model established above can be used to search the accessible range corresponding to each score by simulation, so as to establish the accessibility envelope surface model. This paper also gives the use criteria of the accessibility evaluation model in virtual environment.

#### 3.4.1 Searching accessible boundary

Equation (3) describes the motion constraint relationship of fingers relative to the waist. After setting the limb length and the angle of movement, the position of the fingers relative to the waist can be calculated. Therefore, for the D-H model established above, input the length of limbs and trunk and other parameters (the data comes from the Chinese national standard GB10000-1988), adjust the range of motion of six degrees of freedom related to comfort in the model according to the accessibility score of each level in Table 4 and simulate the activity process from waist to fingertip through Monte Carlo simulation, so as to generate the accessibility range. In the process of Monte Carlo simulation, the other four degrees of freedom which have little relationship with comfort are set as the maximum range (Table 2). The search process for the accessible boundary from waist to fingertip is as follows.

1. Input: The value or range of parameters needed in D-H model;
2. Step1: Determine the location of root node(anywhere);
3. Step2: For each accessibility score in Table 4, find out each possible range of motion of six degrees of freedom.
related to comfort (for example, for 1 point of accessibility, corresponding to 1 point of arm comfort and 1 point of trunk comfort, where the parameter range set corresponding to 1 point of arm comfort is \( \{ \theta_1 = 0^\circ, -20^\circ \leq \theta_2 \leq 20^\circ, 60^\circ \leq \theta_3 \leq 100^\circ \} \), the range set of parameters corresponding to 1 point of trunk comfort is \( \{ \theta_4 = 0^\circ, \theta_5 = 0^\circ, \theta_7 = 0^\circ \} \));

Step3: For each parameter with a certain range of values, enough random numbers are generated in the range of values;

Step4: According to Eq. (3), enough accessible points are generated by Monte Carlo simulation;

Step5: Repeat step 2 to step 4 to search the accessible point set with 2 to 8 points;

Output: The coordinates of each point in the accessible point set of 1 to 7 points.

3.4.2 Accessible boundary extraction and modeling

The boundary points of the accessible point set, at first, need to be extracted by extracting convex package to get the accessible range. The process of boundary extraction is shown in Fig. 5.

Based on the extracted accessible boundary, the accessible envelope model can be built in CATIA, UG, 3DMax, etc. In order to ensure the authenticity and beauty of the model, the accessible envelope model needs to be smoothed. So far, the accessible envelope model from waist to one hand has been established, and the model of the other hand can be generated according to the axial symmetry. The accessible envelope model of two hands with 1 to 7 points of accessibility is shown in Fig. 6.

Based on the above model, a parameterized accessibility evaluation tool which can run under DELMIA is developed. The method of using the evaluation tool is as follows: import virtual human and the human accessibility envelope models from large to small into the virtual maintenance scene through the interactive interface; adjust the virtual human to the best maintenance position according to the location of the maintenance target; if the accessibility envelope of a certain score \( K \) completely covers the target point and the accessibility envelope of the score \( K-1 \) cannot completely cover the target point, then the score of the accessibility evaluation is \( K \). The accessibility evaluation results of this evaluation can be recorded and exported in the tool.

4 Case verification

The case verification consists of a maintenance task in three maintenance scenarios carried out in the real and virtual environment. The whole process is to disassemble the main
liquid inlet pipe of the thermal control unit of fluid physics experiment rack for the space station placed on the three-tier shelf, respectively. The accessibility evaluation results of the proposed method are compared with the RULA performed by experts to verify the excellent accuracy of this method. The accessibility evaluation models and tool established according to this method are compared with accessibility evaluation tool of DELMIA to verify the advantages of this model in precision and efficiency.

4.1 Experiment description

The disassembly of the main liquid inlet pipe of the thermal control unit of fluid physics experiment rack for the space station placed on the bottom, middle and top floor of the shelf was carried out in the real and virtual environment, respectively. The specific maintenance process is that the maintenance personnel need to screw down the main liquid inlet pipe from the thermal control unit with both hands. The height of the maintenance personnel is 175 cm (the body size is similar to the body size of the 50th percentile). The three floors of the shelf are 67.5 cm, 139 cm and 197 cm away from the ground, respectively, with good visibility at the maintenance interface, spacious operation space and sufficient light. The real and virtual maintenance environments are shown in Figs. 7 and 8.

4.2 Accuracy Verification on Comfort

In the virtual maintenance environment, the accessibility evaluation tool proposed in this paper is used to evaluate the accessibility of the maintenance operation of dismantling the main inlet pipe. The accessibility scores of the maintenance operations of dismantling the main liquid inlet pipe on the bottom, middle and high floor of the shelf are 6, 2 and 7, respectively. The evaluation processes and results are shown in Figs. 9, 10 and 11.

In the real maintenance environment, six maintainability and ergonomics experts were invited to use the RULA assessment tool to score the comfort of the maintenance operation. Experts scored the comfort according to the specific range of motion angles of upper arm, lower arm, wrist, neck and trunk specified by RULA. This process involves three evaluation tables. Table A is used to input the scores of arms and wrists (risk factor variables), table B is used to input the scores of neck and trunk (risk factor variables), and table C is used to compile the risk factor variables of table A and table B to generate a single score representing the risk level of MSD (musculoskeletal disorder), which is used to evaluate comfort. The scoring results of the six experts on the maintenance task of dismantling the main inlet pipe in the three maintenance scenarios are shown in Table 5. The average score of the maintenance operation at the bottom floor of the shelf is 5.5, that at the middle of the shelf is 3,
and that at the top of the shelf is 7. In the three maintenance scenarios, the RMSE (root mean square error) between the accessibility score and the average score of RULA is 0.6455. In the second scenario, the score deviation is the largest (but the deviation is only 1). The possible reason is that RULA has too strict attitude requirements for 1 and 2 points, so it is difficult to have a maintenance attitude to meet it in reality. Briefly, it is not difficult to find that the score given by this accessibility evaluation tool is consistent with the score of RULA in each maintenance scenario.

### 4.3 Precision and efficiency verification on accessibility evaluation

The accessibility evaluation tool of DELMIA was used to evaluate the disassembly of the main inlet pipe in three maintenance scenarios. The maintenance interfaces are all accessible. In terms of whether the maintenance interface is accessible or not, the evaluation results of the accessibility evaluation tool of the paper are consistent with those of DELMIA. However, the accessibility evaluation tool proposed in this paper uses comfort to grade accessibility, and describes the impact of maintenance attitude comfort on accessibility in detail. Therefore, the evaluation results of the methods and tools proposed in this paper are more precise.

In terms of efficiency, DELMIA has been redeveloped, the accessibility evaluation model is embedded in DELMIA, and the GUI of this accessibility evaluation tool is also developed in DELMIA, as shown in Fig. 12. Through this GUI, users can quickly import, select, use and position the model and output the evaluation results.
The root node of the accessibility envelope displayed by accessibility evaluation tool of DELMIA is the shoulder. If the maintenance operation needs to bend over, the virtual human also needs to bend over manually during the accessibility evaluation, as shown in Fig. 13. This step is time-consuming. The root node of the accessibility evaluation envelope established in this paper is at the waist, considering the bending, side bending and rotation of the waist, so there is no need to adjust the attitude in the evaluation. In addition, the tool realizes the rapid positioning of the model and can quickly move the model around the evaluation object. In the evaluation process, it only needs to adjust slightly the position relationship between the model and the evaluation object.

The lengths of time of using this accessibility evaluation tool and that of DELMIA to evaluate the accessibility of

| Rater   | Score of table A | Score of table B | Score of table C |
|---------|------------------|------------------|------------------|
| Expert1 | 5                | 4                | 5                |
| Expert2 | 5                | 5                | 6                |
| Expert3 | 4                | 5                | 5                |
| Expert4 | 5                | 5                | 6                |
| Expert5 | 5                | 5                | 6                |
| Expert6 | 5                | 4                | 5                |

Average score of table C: 5.5

| Rater   | Score of table A | Score of table B | Score of table C |
|---------|------------------|------------------|------------------|
| Expert1 | 3                | 2                | 3                |
| Expert2 | 4                | 2                | 3                |
| Expert3 | 3                | 3                | 3                |
| Expert4 | 3                | 2                | 3                |
| Expert5 | 4                | 2                | 3                |
| Expert6 | 3                | 2                | 3                |

Average score of table C: 3

| Rater   | Score of table A | Score of table B | Score of table C |
|---------|------------------|------------------|------------------|
| Expert1 | 7                | 5                | 7                |
| Expert2 | 8                | 5                | 7                |
| Expert3 | 8                | 5                | 7                |
| Expert4 | 7                | 5                | 7                |
| Expert5 | 8                | 5                | 7                |
| Expert6 | 8                | 5                | 7                |

Average score of table C: 7

| Table 5 RULA scoring table of the maintenance operations in three maintenance scenarios |
|-----------------------------------------------|------------------|------------------|------------------|

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Fig. 12 GUI of the accessibility evaluation tool

Fig. 13 When using the tool of DELMIA, it may be necessary to manually adjust the virtual human’s waist posture
maintenance operations in three maintenance scenarios were recorded and compared. As shown in Fig. 14, when using the tool of DELMIA to evaluate the maintenance operation on the bottom floor of the shelf, it is necessary to manually bend the virtual human, which consumes a lot of time. In other scenarios, the lengths of time to complete the evaluation using the two tools are relatively close.

Although the accessibility evaluation method and tool have great advantages in accuracy, precision and efficiency, they also have some limitations. First, this method does not consider the influence of obstacles between personnel and maintenance parts. For this problem, it is necessary to place the hand around the obstacles next to the maintenance interface through virtual maintenance simulation, and obtain the angles of freedom of each joint in this posture to analyze whether it can be reached or at what level. Second, this method does not consider the impact of lower limb comfort on upper limb comfort, which may not affect the maximum reach range of human upper limb, but different lower limb postures, such as squatting and kneeling, will affect the comfort of the whole body, so as to change the accessible range under a certain comfort level. Third, the method proposed in this paper does not consider the limb load. However, the evaluation results are consistent with those of RULA.

5 Conclusion

In fact, the method of evaluating the accessibility in virtual maintenance is to establish a connection between comfort and accessibility, and quantify and refine the evaluation of accessibility through comfort. Specifically, a scientific and quantitative accessibility evaluation method is constructed by constructing the D-H parametric kinematics model of human body and dividing and scoring the joint angles through RULA, which solves the problems of high cost, strong subjectivity and low granularity in virtual maintenance accessibility evaluation. In order to improve the evaluation efficiency and facilitate the use of maintenance personnel, the corresponding accessible envelope surface model is built for each accessibility score, and an accessibility evaluation tool which can be integrated into DELMIA and CATIA is developed. At present, the tool has been used in research units such as AVIC First Aircraft Design and Research Institute and AECC Human Aviation Powerplant Research Institute, and the feedback is good. The future research direction of this method may consider the influence of obstacles and human body loads on accessibility.

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Declarations

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