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Design And Analysis Method Of Maintenance Operation Space Based On Hand Operations

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Abstract

As an important component of maintenance design work, maintenance design analysis has long faced the problem of heavily relying on equipment physical prototypes and lacking objective evaluation methods. The rise of virtual maintenance technology has gradually freed maintenance design and analysis work from the dilemma of dependence, and has also made objective and quantitative maintenance design and analysis work possible. The design level of maintenance operation space not only affects the progress of maintenance work, but also affects the safety and comfort of maintenance personnel. Therefore, it is necessary to conduct a reasonable analysis and evaluation of maintenance operation space. The previous research work still focused on qualitative evaluation and lacked innovation, which could not meet the needs of analysis work. Therefore, this article innovatively proposes the evaluation index of coverage. Based on virtual prototyping and kinematic models, the coverage of the operating space of the handheld tool and the environmental space of the target maintenance component is calculated, and the analysis and evaluation results of the maintenance operation space design focusing on hand operations are obtained. This study can provide new analytical ideas and evaluation tools for maintenance design analysis work, effectively promote the development of maintenance design work, and further improve the level of equipment maintenance.

Keywords: maintainability design, maintenance operation space, virtual maintenance, limb kinematics

1. Introduction

As an important component of general quality characteristics, maintainability is one of the inherent attributes of products. The level of maintainability design affects whether a product can recover its original function through maintenance when encountering faults during its lifespan. If the level of maintainability design is poor, it will not only increase maintenance costs, but also pose hidden dangers to the safety of maintenance personnel when carrying out maintenance tasks (Jiele Shen et al., 2022; Jie Geng et al., 2023; Luo Xu et al., 2021; Wenmin Zhu et al., 2020). Operating space design is an important aspect of maintenance design, which refers to the working space provided by the product to maintenance personnel during maintenance activities. The size of the operating space has a very important impact on the smooth completion of maintenance tasks, as well as ensuring the safety and comfort of maintenance personnel.

Early maintenance design work mainly relied on the physical prototype of the product (Ziyue Guo et al., 2020). However, due to the difficulty in obtaining the physical prototype during the product design phase, it was not possible to carry out necessary analysis and verification work, which hindered the development of manufacturing and assembly design work (Olga Battaïa et al., 2019). With the continuous progress of technology, modern equipment structures are becoming increasingly complex, and traditional maintenance related technologies are gradually unable to meet the requirements of high-tech development. Virtual reality technology has begun to be widely applied in the field of maintenance simulation (Zhenguo Xu et al., 2021; Ziyue Guo et al., 2018; Ruoxi

Liang and Qunfeng Ye, 2022; Xin Wang et al., 2020). This technology not only changes the dilemma of heavily relying on the physical prototype of equipment for maintenance work, but also provides the possibility for quantitative maintenance design and analysis work, including quantitative analysis of maintenance operation space design.

When studying the issue of maintenance operation space, human arms and maintenance tools are two important focus points. Jian Xia et al. established a scoring mechanism that comprehensively considers human arm motion simulation and collision detection of maintenance tools based on maintenance scenarios in virtual environments (Jian Xia, 2017). This study is based on subjective judgment for scoring, but still lacks the objectivity of analysis. Yuantao Zhang focuses on the specific maintenance task category of replacement maintenance, and utilizes the human factor design analysis module function of CATIA software to achieve maintenance operation space analysis (Yuantao Zhang and Zhenli Ma, 2010). This method is simple and easy to implement, but lacks innovation. Gualeni Paola et al. proposed that the available space around the machinery itself and related systems has a significant impact on the maintenance work inside the ship's engine room. The evaluation criteria for this available space include factors such as component size, interference type, and operator parameters (Gualeni Paola et al., 2022). This tool is based on data-driven models and Bayesian inference, which improves the traditional decision-making process of cabin layout design and has considerable feasibility. However, the selection of influencing factors still needs to be comprehensively considered.

Based on the requirements of comprehensive maintenance design analysis and the existing research problems, this paper proposes a quantitative maintenance operation space design analysis method that focuses on hand operations and considers maintenance tools. The innovative indicator of coverage is proposed to evaluate the level of component maintenance operation space. Firstly, digital prototype data is obtained from the virtual environment, followed by static feature analysis of hand operations. Based on this, a kinematic model of hand operations is constructed. Finally, coverage calculation and analysis are conducted based on the digital prototype and kinematic model to evaluate the level of maintenance operation space. This study provides a new analysis approach for maintenance operation space design, which can provide an evaluation tool for maintenance design related work.

2. Methodology

In section 2.1, virtual prototype data was obtained through finite element analysis of digital prototypes, and the data was organized. Section 2.2 analyzed the static characteristics of hand operations and obtained a simplified model suitable for kinematic analysis. Section 2.3 is based on the content of Section 2.2 to construct a kinematic model of the hand operated limb holding the tool. Based on virtual prototype data and hand operated limb kinematic models, visual point cloud processing is performed to calculate the coverage of hand operation space and component environment space, and the design analysis result of maintenance operation space - coverage rate is calculated.

2.1. Virtual prototype data acquisition

In the current field of virtual maintenance, DELMIA is a design and analysis tool with high application frequency. This type of software has a considerable closed feature, and the file format used internally cannot directly provide reliable input for data analysis work due to the limitations of the software platform itself. The only solution is to first load the target components and their corresponding system model files directly into DELMIA, fully simulate the actual situation of maintenance work, analyze with the help of the software platform's own functional modules, and then convert the software output file into a file format that facilitates visual model modeling for maintenance accessibility calculation through data format conversion processing.

Due to the closed nature of the DELMIA software platform itself, in order to obtain data related to digital prototypes, it is preferred to use the finite element function in the analysis and simulation module used for static strength analysis to obtain target maintenance component and system feature data, and then use relevant algorithms to convert and process the data (Yangping Wang, et al., 2012). The finite element function of the analysis and simulation module in DELMIA is to decompose the target component into several interconnected polygonal mesh patches according to the given rules, where the shape, size, and number of mesh patches can be pre-set. These parameters directly affect the quality of the divided mesh patches (Yupu Pei et al., 2012). After obtaining the mesh that meets the requirements after division, the finite element function of the analysis and simulation module in DELMIA software is used to obtain the node data expressed by the mesh patches, including two types of grid node data and node coordinate data.

2.2. Analysis of static characteristics of hand operations

The human hand is a delicate and complex component of the human body structure, and its function is also an important part of human basic activity functions. Especially in maintenance activities, maintenance workers mainly rely on their hands to complete maintenance tasks. Static feature processing of the hand is to study the static features of the bones and joints from the fingers to the forearm. The human hand consists of two main parts, fingers and palms, with a total of 22 degrees of freedom. Therefore, if we analyze a specific hand operation by treating each joint as a separate individual, the workload will be very huge. When studying hand operations involved in maintenance activities, it is possible to simplify the hand structure appropriately to improve analysis efficiency. The following figure provides a visual representation of the hand structure. (see Fig.1).

Fig. 1. Hand structure diagram.

By observing some typical hand operations in maintenance scenarios, it can be seen that during maintenance activities, it is rare to involve individual movements of a specific finger. More often, the finger part as a whole works together with the palm to complete grasping and other movements, relying on the rotation of the wrist joint to adjust the small range angle. Therefore, in this section of the research work, we will no longer specifically study the individual activities of a certain finger, but instead consider the fingers and palms in a grasping state as a combined whole, working together with the wrist and forearm to complete hand operations. The real-life photos of repair scenarios represented by wrench operation and screwdriver operation are shown below. (see Fig.2).

Fig. 2. Classic repair scenarios.

The traditional static features of the hand consider the main joints of the hand as active nodes. Based on this, the study of hand activity takes into account that in most maintenance activity scenarios, the joints of the hand are considered as a whole, and the static features of the hand can be simplified, ignoring the details of the hand joints and only using the wrist joints as active nodes. The simplified diagram is shown below. (see Fig.3).

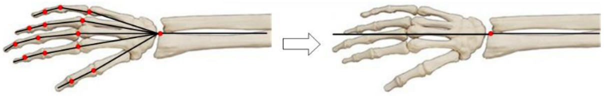


Fig. 3. Simplified diagram of hand static features.

When carrying out maintenance activities, maintenance tools are essential for maintenance personnel. Choosing appropriate maintenance tools can improve maintenance efficiency and reduce fatigue among maintenance personnel. This section focuses on the three most commonly used maintenance tools in maintenance activities, namely screwdrivers, pliers, and wrenches, to study the static feature processing of human handheld maintenance tools.

During the maintenance process, maintenance personnel hold maintenance tools and their hands come into contact with them. In sufficiently small action units, such as a small rotation, the contact surface between the hands and the maintenance tool usually does not change. Therefore, in a short period of continuous maintenance activities, The connection between fingers and palms and the contact point with the repair tool can be regarded as a moving node to describe the relative position relationship between the hand and the repair tool, without considering the contact situation between the end of the finger and the repair tool. Under this premise, the action model of a person holding a maintenance tool approaching the target maintenance component and performing maintenance tasks can be simplified into a motion mechanism composed of three connecting rods. The motion nodes include the contact points between the tool and the target maintenance component, the contact points between the human palm and the maintenance tool, and the human wrist joint. The specific description of the static characteristics of handheld maintenance tools can be found in the following figure. (see Fig.4).

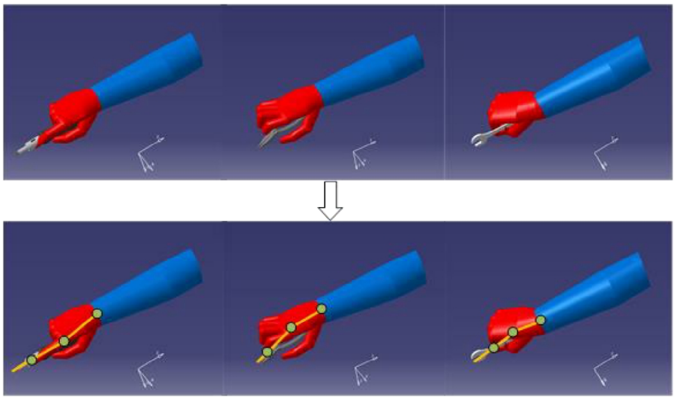


Fig. 4. Static characteristic diagram of handheld maintenance tool status.

2.3. Construction of hand operation kinematic model

For a complete maintenance operation, hand operation is a dynamic process. For such a motion mechanism, the motion model can be simplified into a motion mechanism composed of three connecting rods to accurately describe its motion state. Specifically, in the hand kinematic model established in this section, not every joint has degrees of freedom. For the contact point between the human palm and the maintenance tool, this joint can be regarded as a zero degree of freedom joint, meaning that the two connecting rods of this joint do not undergo relative motion, but cannot be connected into a complete connecting rod, and there is an angle between the two connecting rods. The established hand kinematic linkage mechanism is shown below. (see Fig.5).

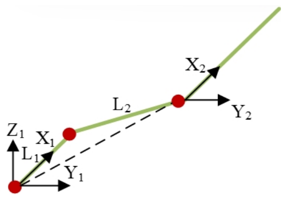


Fig. 5. Hand kinematic model.

When describing the motion state of hand operations, the formula for connecting rod transformation can be used for calculation. The formula is as follows.

$$ {}^{i-1}_{i}T = \begin{bmatrix} cos\theta_i & -sin\theta_i & 0 & a_{i-1} \\ sin\theta_i cos\alpha_{i-1} & cos\theta_i sin\alpha_{i-1} & -sin\alpha_{i-1} & -sin\alpha_{i-1} d_i \\ sin\theta_i sin\alpha_{i-1} & cos\theta_i sin\alpha_{i-1} & cos\alpha_{i-1} & cos\alpha_{i-1} d_i \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (1) $$

Among them, a_{i-1} is the length of the common perpendicular line connecting the joint axes at both ends of connecting rod i-1, and d_i is the distance along the common axis direction of two adjacent connecting rods on the joint axis i, α_{i-1} is the angle between the two axes when connecting rod i-1 turns around axis i of a_{i-1} according to the right-hand rule, θ_i is the angle formed by the extension of a_{i-1} and the rotation of a_i around the joint axis i.

For continuous linkage transformations, the values of each linkage parameter can be calculated based on the transformation matrix of a coordinate system {N} relative to coordinate system {0}.

$$ {}^{0}_{N}T = {}^{0}_{1}T\,{}^{1}_{2}T\,{}^{2}_{3}T \cdots {}^{N-1}_{N}T \quad (2) $$

Among them, the transformation matrix ${}^{0}_{N}T$ is a function of n joint variables.

The parameters used in the hand operated limb kinematic model studied in this section are as follows. (see Table 1).

Table 1. Parameter table of hand operated linkage model.

i	a	α	d	θ
1	0	$\pi/2$	0	θ_1
2	0	$\pi/2$	0	θ_2
3	0	$\pi/2$	L_1	θ_3
4	0	$\pi/2$	0	θ_4
5	L_2	0	0	θ_5

θ_1: The upward angle of holding the tool with fingers, ranging from -15 ° to 0 °

θ_2: The angle of holding the tool with fingers to the right, ranging from -45 ° to 135 °

θ_3: The angle of rotation for holding the tool with fingers, ranging from -90 ° to 90 °

θ_4: At the wrist, the angle at which the palm bends laterally, ranging from -30 ° to 50 °

θ_5: At the wrist, the angle of the palm facing upwards, ranging from -90 ° to 80 °

The relative position change constraint relationship between adjacent degrees of freedom is determined based on the activity angle of each degree of freedom and the length of each connecting rod. The relative position change constraint relationship between adjacent degrees of freedom in the hand operated limb kinematic model is as follows:

$$ {}_1^0T = \begin{bmatrix} cos\theta_1 & 0 & sin\theta_1 & 0 \\ sin\theta_1 & 0 & -cos\theta_1 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{3} $$

$$ {}_2^1T = \begin{bmatrix} cos\theta_2 & 0 & sin\theta_2 & 0 \\ sin\theta_2 & 0 & -cos\theta_2 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{4} $$

$$ {}_3^2T = \begin{bmatrix} cos\theta_3 & 0 & sin\theta_3 & 0 \\ sin\theta_3 & 0 & -cos\theta_3 & 0 \\ 0 & 1 & 0 & L_1 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{5} $$

$$ {}_4^3T = \begin{bmatrix} cos\theta_4 & 0 & sin\theta_4 & 0 \\ sin\theta_4 & 0 & -cos\theta_4 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{6} $$

$$ {}_5^4T = \begin{bmatrix} cos\theta_5 & -sin\theta_5 & 0 & L_2cos\theta_5 \\ sin\theta_5 & cos\theta_5 & 0 & L_2sin\theta_5 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{7} $$

2.4. Design analysis of maintenance operation space

This section mainly includes two parts: hand operation dynamic fitting and coverage calculation. By decomposing a specific maintenance action and using Monte Carlo simulation methods, the dynamic fitting point cloud of hand operations is obtained, and the degree of coverage of the maintenance operation space by the surrounding environment is calculated.

After determining the size parameters, human body parameters, and motion parameters of the maintenance tool, Monte Carlo simulation is conducted based on the limb kinematic model to determine all the position points that the tool and hand can reach, and to fit a complete operating space for the maintenance action.

The Monte Carlo simulation method can mainly solve two types of problems: deterministic problems and stochastic problems. The deterministic problem is a problem where the statistical characteristics of the desired probability model are known, and the known statistical characteristics are the solution to the problem. Under this premise, a large number of random sampling experiments are conducted using Monte Carlo simulation methods to obtain the required approximate estimates. Another type of problem is the randomness problem, which is the hand operation space problem required to be solved in this section. It is a randomness problem, that is, based on the given hand limb kinematic model and its motion constraints, the position reached by the human handheld maintenance tool is randomly generated, forming a fitting area for the operation space of the human handheld maintenance tool. This study used uniformly distributed random number sampling, which assumes that the probability of each link reaching a given angle in the constructed limb kinematic model is equal. Uniform distribution refers to the fact that the probability (density) corresponding to each sample point in the entire sample space is equal, which can be considered as the simplest probability distribution. The results obtained by Monte Carlo simulation method are presented in the form of a visual point cloud, as shown in the following figure. (see Fig.6).

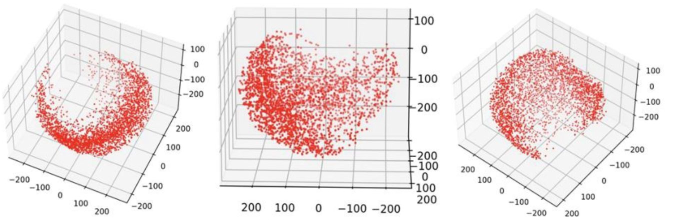


Fig. 6. Schematic diagram of hand operation space.

When calculating coverage, it is necessary to first determine the type of maintenance tool to be selected and the maintenance operation to be carried out. The maintenance operation needs to be specific to the rotation angle and movement distance. After determining the parameters, the relative position of the maintenance personnel and the target maintenance component should be clearly defined to ensure that the operating space model is consistent with the surrounding environment model in the coordinate system and has no positional deviation. In the same coordinate system, by calculating the number of feature points of the operating space model located within the range of the surrounding environment model, the interference between the human operating space and the surrounding environment can be obtained when carrying out maintenance tasks with a handheld maintenance tool in the actual state. Based on this, it is judged whether the operating space is good.

The specific steps for analyzing the coverage of maintenance operation space for target maintenance components are as follows:

- Find the analysis range of the operating space on the reference coordinate axis. Select the reference coordinate axis, search for the surrounding environment model area that may be covered by the operating space model, and obtain the coordinate range of the feature points of the operating space model within this range;
- Slice coverage analysis of surrounding environment models. Traverse each surrounding environment model slice within the coverage analysis range, as well as the operating space model slice under that condition. If the coordinate range of the point in the slice of the operating space model is within the range of the surrounding environment model slice, it can be determined that the point has interference and does not meet the requirements of the operating space;
- Coverage calculation. If the operating space model has a total of M feature points, and the number of feature points that are determined to be outside the range of the surrounding environment model is K, the coverage can be calculated as (M-K)/M.

The analysis approach for operating space coverage and the coverage analysis represented in point cloud form are shown below. (see Fig.7 and Fig.8).

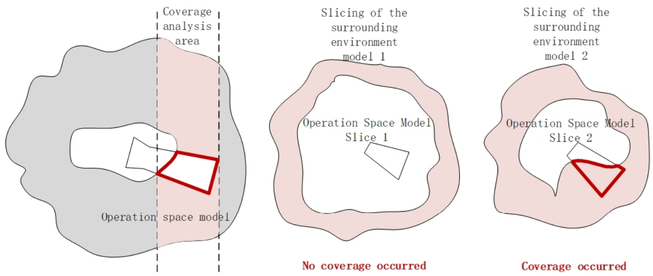


Fig. 7. Schematic diagram of operation space coverage analysis process.

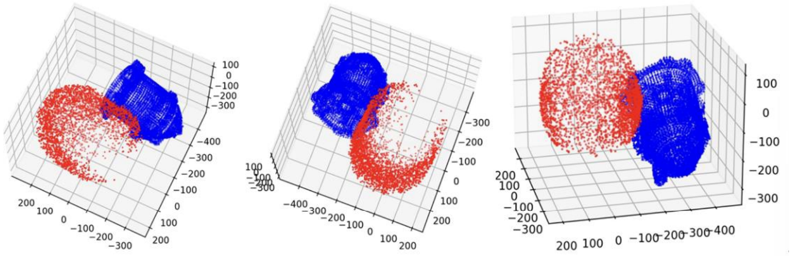


Fig. 8. Surrounding Environment - Operating Space Coverage Diagram.

The design analysis of maintenance operation space based on hand operation is based on a series of calculations, and the results are based on the degree of interference between the operation space range and the surrounding environment fitted by human hands and maintenance tools - coverage rate. The higher the coverage, the lower the level of maintenance operation space. At the same time, for a certain target part, the model can also determine whether its operation space can meet basic maintenance needs, that is, whether maintenance operations can be carried out.

3. Case Analysis

This chapter uses the starter in the auxiliary power unit (APU) of C919 as a case study to conduct analysis and evaluation of maintenance operation space design based on manual operation. Study the interference between the hand operating space and the surrounding environment during a specific maintenance operation, calculate the coverage of the surrounding environment model and the operating space model, and obtain a numerical value that can evaluate the level of maintenance operating space for the component.

3.1. Construction of maintenance scenarios

This case study used the starter of the Auxiliary Power Unit (APU) in C919 for analysis. APU is a small gas turbine engine that can provide electricity and bleed air for the aircraft. The style of its digital prototype is shown in the following figure, where the starter circled in red oval is the target maintenance component in this case. (see Fig.9 and Fig.10).

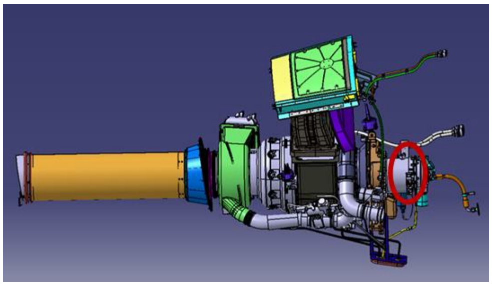


Fig. 9. Digital prototype of auxiliary power unit (APU).

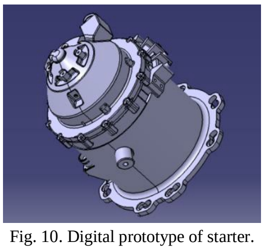


Fig. 10. Digital prototype of starter.

3.2. Digital prototype data acquisition

In the APU digital prototype, separate the individual starter digital prototype model and import it into DELMIA software. In DELMIA, select the Analysis Simulation-Advanced Mesh Tools module and use the finite element function to perform mesh patch decomposition on the digital prototype model of the starter. The specific decomposition status is shown in the following figure. (see Fig.11).

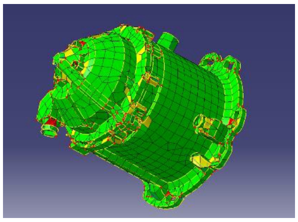
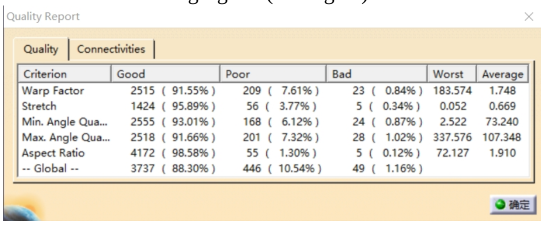


Fig. 11. Exploded view of starter grid surface.

The finite element function of the analysis and simulation module in DELMIA is to decompose the target component into several interconnected polygonal mesh patches according to the given rules. The shape, size, and number of mesh patches directly affect the quality of the partitioned mesh patches, and indirectly affect the efficiency of related maintenance design analysis work and the accuracy of the analysis results obtained. Therefore, it is necessary to conduct quality checks on the grid patches, and the more patches rated as "good" under each criterion, the better. In this case, 88.30% of the total grid patches were rated as "good", which is acceptable. The specific exported data is shown in the following figure. (see Fig.12).



Quality Report

Quality | Connectivities

Criterion	Good	Poor	Bad	Worst	Average
Warp Factor	2515 (91.55%)	209 (7.61%)	23 (0.84%)	183.574	1.748
Stretch	1424 (95.89%)	56 (3.77%)	5 (0.34%)	0.052	0.669
Min. Angle Qua...	2555 (93.01%)	168 (6.12%)	24 (0.87%)	2.522	73.240
Max. Angle Qua...	2518 (91.66%)	201 (7.32%)	28 (1.02%)	337.576	107.348
Aspect Ratio	4172 (98.58%)	55 (1.30%)	5 (0.12%)	72.127	1.910
-- Global --	3737 (88.30%)	446 (10.54%)	49 (1.16%)		

确定

Fig. 12. Grid surface quality analysis chart.

3.3. Design analysis of maintenance operation space

The design and analysis of maintenance operation space based on hand operation also require standard data such as joint movement angles and joint length parameters of the human body, as well as maintenance tool data. Joint angle data is shown in Table 2, and joint length data for Chinese males aged 18-60 in the 95th percentile are used, as shown in Table 3. (see Table 2 and Table 3). The maintenance tool is a PH2 * 100 Phillips screwdriver with a stem length of 100mm.

Table 2. Angle of motion of various joints in the human body.

Number	Range	Degree of Freedom Activity Angle
1	-10°~37°	The angle of the upper body of the human body from the waist forward or backward
2	-8°~8°	The angle of the upper body of the human body from the waist to the left or right
3	-10°~10°	The rotation angle of the upper body from the waist
4	-45°~180°	The angle at which the upper arm is lifted or lowered
5	-40°~90°	The angle of forearm abduction or adduction
6	-45°~90°	Arm as axis, shoulder joint rotation angle
7	0°~140°	The angle between the upper and lower arms at the elbow
8	-70°~80°	The angle of rotation of the elbow joint with the forearm as the axis
9	-30°~50°	At the wrist joint, the angle at which the palm is bent to the side (thumb or pinky side)
10	-90°~80°	The angle at which the wrist joint and palm are bent towards the front and back (palm side or back side)

Table 3. Length parameters of each joint.

Measurement target	Chinese male (aged 18-60)						Unit: mm
	Percentile						
	1%	5%	10%	50%	90%	95%	99%
Height	1543	1583	1604	1678	1754	1775	1814
Body length	436	445	450	468	485	490	499
Shoulder width	330	344	351	375	397	403	415
Upper arm length	279	289	294	313	333	338	349
Lower arm length	206	216	220	237	253	258	268
Palm length	165	170	173	183	193	196	202

Taking the example of a person holding a cross screwdriver to remove a screw on the starter motor, this study investigates the interference between the hand operating space and the surrounding environment. The schematic diagram for executing the maintenance task in a virtual environment is shown below. (see Fig.13).

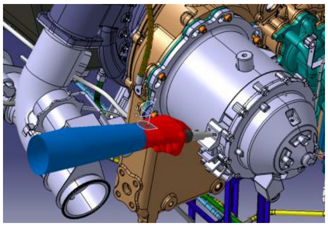


Fig. 13. Maintenance Task Diagram.

Due to the inability to obtain feature point data of the surrounding environment model in the DELMIA environment, it is necessary to simplify the surrounding environment and replace it with regular geometric bodies to study the interference between the hand operation space and the surrounding environment. The point cloud diagram is shown below. (see Fig.14 and Fig.15).

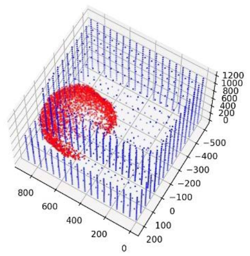


Fig. 14. Point cloud map of surrounding environment and hand operation space.

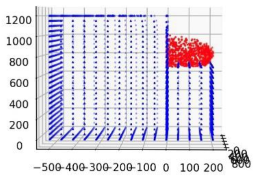


Fig. 15. The part of the hand operating space that is not in the surrounding environment.

Through calculation, it was found that the hand operation space model has a total of 3000 feature points, of which 2247 are located in the surrounding environment model, and only 753 are outside the range of the surrounding environment model. The coverage rate is 74.90%, indicating poor operation space conditions.

4. Conclusion

In the current maintenance accessibility design and analysis work, there are problems of low efficiency and strong subjectivity. The maintenance operation space design and analysis method based on hand operation proposed in this paper considers the working state of handheld maintenance tools for maintenance tasks. It no longer only considers pure manual operation, but also incorporates maintenance tools as a component of the linkage mechanism into the analysis process. By performing static feature processing on hand operations, a hand operation linkage model suitable for maintenance is obtained. Then, a hand operation kinematic model is constructed to fit the hand operation space, calculate the degree of interference between the hand operation space and the surrounding environment, and use coverage as a quantitative indicator to analyze the design of maintenance operation space. This method provides a quantitative research method for maintenance accessibility design analysis. By inputting corresponding parameters, the maintenance operation space level of components can be calculated. This type of analysis and evaluation breaks through the limitations of qualitative evaluation in the past, and adopts quantitative analysis and evaluation with a higher level of objectivity, avoiding the subjectivity of design analysis to the greatest extent, providing new research ideas and methods for maintenance accessibility design analysis.

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