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A method for integrating ergonomics analysis into maintainability design in a virtual environment

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A R T I C L E I N F O

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A B S T R A C T

Designers must consider human factors/ergonomics when making decisions from the perspective of maintainability. As an important aspect of maintainability, maintenance space should be made adequate at the design stage to achieve a convenient maintenance process. A maintenance space evaluation method that considers ergonomics is proposed in this study. By comparing free swept volumes and constrained swept volumes in a virtual environment, maintenance space could be evaluated quantitatively and objectively. The results of the evaluation are obtained by combining the principles of ergonomics and maintainability. These results can help designers improve product design such that it fits ergonomics and maintainability requirements. A case study is introduced at the end of this paper to demonstrate the feasibility of the proposed method in efficiently evaluating the maintenance space based on the layout design of the product components in the design stage.

Relevant to industry: For a large number of disasters caused by human errors in current industry, the result of this study contributes a guide to fully consider human factors in maintainability design through virtual environment and is beneficial to designers and engineers of industrial application fields.

1. Introduction

1.1. Background

Product designers must integrate all information about processes, tools, machines, tasks, and human operators to generate a design that is acceptable to all parties involved. Maintainability design is a major concern in the product design process. Well-designed maintainability can ensure service dependability, reduce the life cycle cost of the product, and improve comfort during maintenance. As most maintenance activities are performed by maintainers, issues related to human factors/ergonomics (HFE) should be considered in the maintainability design. However, while completing the design task, maintainability designers often have difficulty incorporating ergonomics information about human operators into their designs (Robert et al., 2000). Although such information on ergonomics exists for use in the maintainability design process, no proper method for using the information is available to designers. This study proposes a method for overcoming this deficiency by using swept volumes (SVs) to graphically represent ergonomics information in a virtual environment and consequently evaluate layout design.

As the actual space in which maintenance personnel work on failed units, maintenance space is an important factor of maintainability. Maintainers operate in an environment where interference between human and machine parts is a major concern. Sufficient operating room must be reserved to avoid collisions during the maintenance process. From the point of view of ergonomics, the space reserved for maintenance activities influences the operator's comfort and performance. Sufficient maintenance space for maintainers must be reserved to ensure ease of operation, safety, comfort, performance, and so on. Hence, layout design and maintenance space assessment are very important in the product design stage to improve maintainability and ergonomics.

The assessment of maintenance space is key in evaluating maintainability and in ergonomic design. However, the literature contains considerable discussions on methods for verifying maintenance space by using expert experience and visual sense. These methods are qualitative and influenced by subjectivity (Haiquan

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et al., 2011). To date, a proper quantitative solution is not yet available to verify the sufficiency of reserved maintenance space during the design stage. This research provides a quantitative and objective way to verify maintenance space with HFE considerations in a virtual environment with the use of SV.

The traditional way to verify whether adequate maintenance space is reserved relies on the physical prototype. This method is time consuming and leaves little room for change in the established design. The drawback of physical prototyping emerges when maintenance space needs to be verified in the early design phase. Virtual reality (VR) shows a way to overcome this problem. The application of VR in maintenance simulation to analyze layout in the early design phase and predict outcomes has been investigated for years. Virtual maintenance (VM) is a computer and VR-based application technology that simulates the maintenance process of an environment, including digital prototypes and virtual humans. A VM environment can reduce unforeseen defects caused by maintenance operations performed in a restricted space in the early design phase. This space restriction leads to movement constraints on the part of the operator, thus making contacts and clashes inevitable.

Adequate maintenance space has to be reserved in the early design stage to avoid collisions between maintainers and machine components. Therefore, we need to focus on the distance between workers and machine parts at every instant throughout the entire maintenance process. SV, which is an intuitive concept and defined as the infinite union of the instances of solids determined by poses taken during motion, is considered capable of representing the entire motion (Tsai, 2009). Calculating the distance between the maintainer and machine parts ensures that no collisions would occur between the SV and machine parts. Compared with the static discrete method that checks the distance between human and obstacle in every discrete time instant during motion, the SV method provides easier calculation and more reliable distance information.

1.2. Human factors/ergonomics

HFE can be treated as the application of the knowledge of human characteristics to system design. Dul et al. (Dul et al., 2012) defined HFE as “the scientific discipline concerned with the understanding of the interactions among humans and other elements of a system, and the profession that applies theoretical principles, data and methods to design in order to optimize well-being and overall performance.” HFE is “design driven” and should be evaluated as the fifth step in the user-centered design process described in ISO 13407 (Erik, 2013; Victoria et al., 2013). Ole et al. (Ole et al., 2011) introduced the concept of boundary objects, provided an improved understanding of the role of objects in participatory ergonomics design processes, and identified eight characteristics of boundary objects and their use, which can be referred to as the maintainability design process. The effective application of ergonomics in a workplace can create a balance between human operators and job design. Various studies have shown the positive influences of applying ergonomics rules to the workplace in different aspects, including machine, job, environmental design and axiomatic design (Azadeh et al., 2008; Abou-Ali and Khamis, 2003; Shikdar and Sawaqed, 2004; Taha et al., 2014). Awwad et al. (Awwad et al., 2004) developed a checklist to evaluate nonpowered hand tools based on basic features related to good ergonomic tool design. Lin et al. (Lin et al., 2005) developed a model for predicting the response of a power-threaded fastener-driving tool operator and the capacity to react against impulsive torque reaction forces for use in tool selection and ergonomic workplace design. Many studies have shown that an ergonomically deficient workplace can cause physical and emotional stress, low productivity, and poor working conditions (Azadeh et al., 2008; Cabrero-Canosa et al., 2003).

1.3. Virtual reality

Since the 1990s, many studies have tested VM and proposed a number of solutions. Caudell and Mizell (Caudell and Mizell, 1992) proved the effectiveness of using a VR system to provide instructions for wiring a harness assembly. Real-time immersive virtual environments, such as the Workbench (Cutler et al., 1997) and CAVE (Cruz-Neira et al., 1993), have been used to assess the maintainability of virtual prototypes. Such environments are part of a complex VR system (Fernando et al., 2001) that supports assembly and disassembly operations in immersive virtual environments. Abate et al. (Abate et al., 2009) presented a solution combining VR techniques and haptic interaction to simulate the process of product assembly and maintenance in the aerospace industry; this solution is better than the object-oriented prototype system V-REALISM for maintenance training proposed by Li et al. (Li et al., 2003). VM systems have been widely applied in maintenance process simulation (Gomes and Zachmann, 1999), maintenance planning, and maintenance training (Leino et al., 2009). Other research models, such as the incomplete repair model and effective visualization model, are found in recent literature (Chen and Cai, 2003; Chabal et al., 2005; Kahle, 2007; Hu et al., 2011).

1.4. Swept volumes

Over the years, SVs have been extensively studied and used in a variety of applications, including ergonomics design, (Abdel-Malek et al., 2004), robot workspace analysis (Abrams and Allen, 2000), collision avoidance (Redon et al., 2004), NC tool path verification (Blackmore et al., 1997), and solid modeling in CAD (Abdel-Malek et al., 2001; Erdim and Horea, 2008). Researchers have proposed solutions to the mathematical formulation of SV by using the Jacobian rank deficiency method (Abdel-Malek and Othman, 1999; Abdel-Malek and Yeh, 1997; Blackmore et al., 2000; Shapiro, 1997), sweep differential equation (Blackmore and Leu, 1990), Minkowski sums (Elber and Kim, 1999), envelope theory (Martin and Stephenson, 1990; Rossignac and Kim, 2000), implicit modeling (Schroeder et al., 1994), and kinematics (Jüttler and Wagner, 1996). Given the complexity of computing the exact SV, algorithms that provide a polyhedral approximation of SV have been developed. Kim et al. (Ahn et al., 1993) and Lee et al. (Lee et al., 2002) studied an approximation of the general sweep for curved objects applied to font design. Weld and Leu (Weld and Leu, 1990) described a geometric representation of SV for compact n-manifolds applied to polyhedral objects. Baek et al. (Baek et al., 2000) studied a simple rotational sweep of an exact SV. Hüseyin and Horea (Hüseyin and Horea, 2008) proposed a generic approach to automatic contact analysis between a moving object and its envelopes to solve problems in the functional behavior of the corresponding mechanism determined by the design and manufacturing of higher pairs.

1.5. Aim

Considering human factors, virtual environment, and SVs, this study aims to achieve the following:

1. To combine HFE design with maintainability design
2. To overcome the shortcomings of the traditional maintenance space evaluation method based on physical prototyping

3. To use SVs to represent the activities of maintainers and evaluate the maintenance space design

The feasible applications of this study are as follows:

1 Product design improvement by meeting the requirements of maintainability and ergonomics
2 Analyses of maintenance procedure and support tools

1.6. Article structure

After the review of the literature on ergonomics, VR, and SVs that supports this research, we organize the rest of the paper as follows: detailed discussion of the proposed method, a case study applying the proposed method, and the conclusions drawn from the study and future work recommendations.

2. Method

2.1. Framework of the proposed methodology

Fig. 1 shows the overall framework of the proposed method. The framework consists of five parts: support data (in light coral color), virtual environment, verification method, output, and feasible applications. The descriptions of the modules are as follows:

Fig. 1 shows the overall framework of the proposed method. The proposed methodology is composed of five parts: support data (in light coral color), virtual environment, verification method, output, and feasible applications.

The **support data module** provides data, such as digital prototype, maintenance procedure, and human and ergonomics data, which are necessary for further research. Digital prototype, maintenance procedure, and human data are used to build the maintenance simulation, whereas the ergonomics data are used to build the evaluation criteria for each maintenance activity unit (MAU).

The **virtual environment module** provides the desktop VM platform to build and run the maintenance simulation.

The **verification method module** is the core of this research. Given that most maintenance operations are done by hand by the maintenance personnel, this research focuses on the activity of the maintainer's hand with or without maintenance tools. Maintenance operations are broken down into three MAUs: screw, twist, and translate. Two categories of SVs are established in this study: ***free SV*** and ***constrained SV***. The former is the largest SV of the maintainer's hand in a completely free space. It is equivalent to the maximum range of activity of the maintainer's hand. The latter is the actual SV of the maintainer's hand during the maintenance process as constrained by machine parts. The constrained SV is smaller than the free SV. By comparing the surface area and volume of the free and constrained SVs, the indexes that show the maintenance space status could be calculated. The quantitative evaluation criteria for each MAU are formulated based on the human and ergonomics data. By comparing the indexes with the quantitative evaluation criteria, the condition of the maintenance space could be obtained. Through maintenance simulation on a specific virtual platform, the constrained SV is derived and used to evaluate the maintenance space.

The **output module** provides the output of the proposed method. The evaluation value of each MAU, the maintenance space

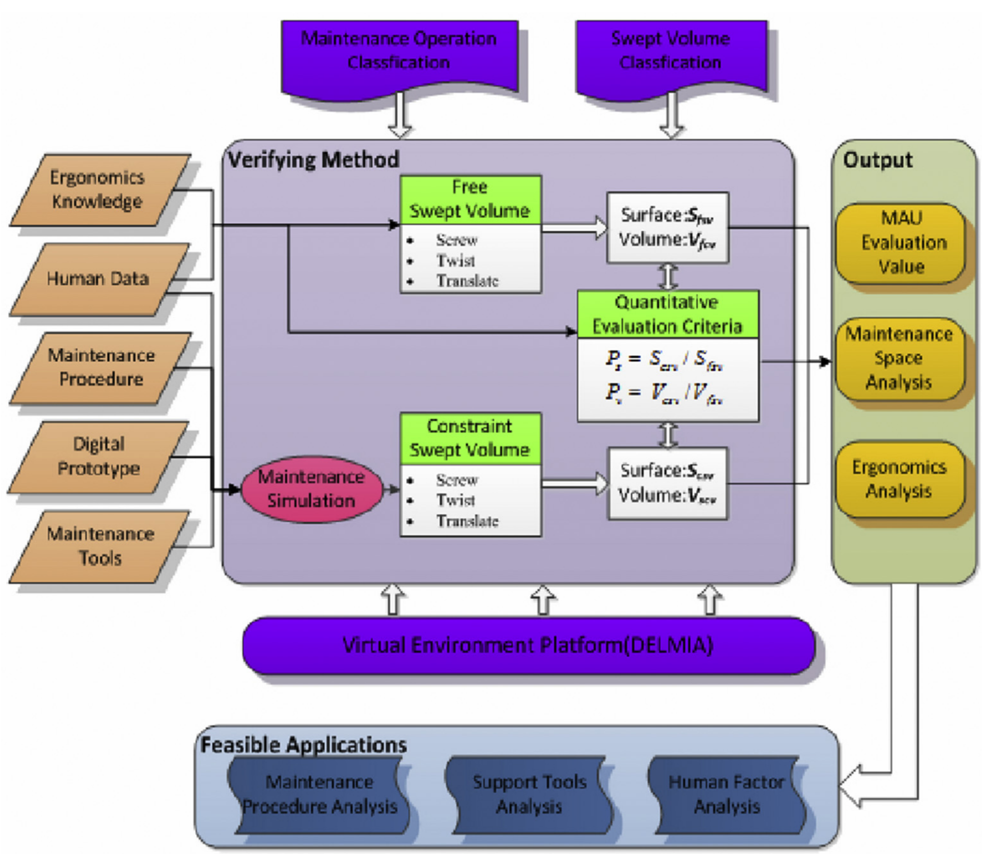

Fig. 1. Framework of the proposed methodology.

analysis, and the ergonomics analysis can be obtained through this method.

The **feasible applications module** shows the applications that the proposed method can support. These applications include maintenance procedure analysis, support tools analysis, and human factor analysis.

2.2. Hand and tool data

In product design, designers must consider the size of the maintainer's hand and the specific maintenance tool used in the repair process. The different hand sizes of maintenance personnel and the repair tools used lead to varying quantitative indexes of SVs.

The hand is the terminal part of the human forelimb and consists of the wrist, palm, four fingers, and thumb. The human hand is used for manipulative tasks. The human hand has 27 bones. The wrist, which joins the hand to the forearm, contains eight cube-like bones arranged in two rows of four bones each. The metacarpus, or palm, is composed of five long metacarpal bones. The four fingers and thumb have fourteen phalangeal bones (three in each finger, two in the thumb) (Esteban, 2007). The sizes of the maintainer's hand are obtained through statistical data or related standards. Table 1 shows the different sizes of people's hands in percentiles, and Fig. 2 shows the schematic diagram of the sizes.

According to the related principles of maintainability, a product should be designed in such a way that they can be maintained by standard tools as much as possible. The data on the sizes of standard tools should be based on industry standards, whereas the data on the sizes of specialized maintenance tools can be obtained in the tool manual or by actual measurement. The frequently used maintenance tools, such as screwdriver, pliers, and wrench, are shown in Fig. 3.

The data shown in Fig. 3 are only benchmarks that need to be updated based on the actual tool used.

In the maintenance process, the maintainer operates in a bounded environment that may cause depressive feelings and fear. Therefore, we need to leave some extra space to make the maintainer feel comfortable and safe. Corrections may vary depending on different maintenance environments.

2.3. Classification of maintenance operation

Maintenance operation can be divided into two categories: with tools and without tools. In the following, bare-handed maintenance operation is considered first, and the consideration of maintenance operation with tools can be derived from bare-handed maintenance operation.

2.3.1. Bare-handed maintenance operation

Once the data on the maintainer's hand are obtained, the free and constrained SVs of the hand can be determined. In this study, the subtle movements of fingers are ignored to a certain extent. In fact, from the maintainability perspective, subtle finger movements have little impact on product design. Therefore, we regard the maintainer's hand as a rigid body when the maintainer is performing a particular motion.

Table 1
Sizes of People's hands in different percentiles (mm).

Items	Sex					
	Male			Female		
	P5	P50	P95	P5	P50	P95
Hand length	173	184	197	165	175	186
Palm length	99	105	112	93	99	105
Hand width	76	83	89	71	77	83
Palm perimeter	190	205	217	180	185	189
Palm thickness	27	28	30	24	25	26

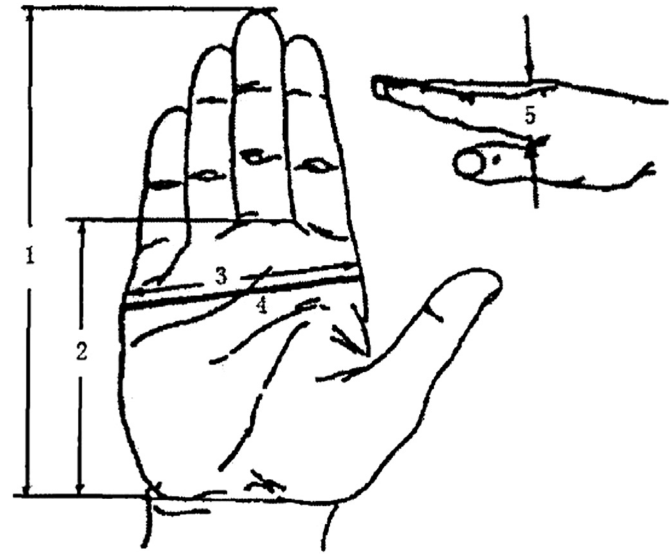

Fig. 2. Schematic diagram of hand sizes.

Considering that different operations may cause different types of SVs, the operation type should be classified. We divide the maintenance operations of the hand into three types, as shown in Table 2 and Fig. 4.

The free SV of the hand for each MAU should be established to determine the space that the MAU requires. The constrained SV of the hand for each MAU can be obtained by using the tools in the Human Task Simulation module in DELMIA(V5R18, Dassault Systeme) to determine the maintenance space based on the layout of machine parts. The SV of each MAU constructed in DELMIA is shown in Fig. 5.

The constrained SV of the hand for each MAU can be obtained by using the tools in the Human Task Simulation Module in DELMIA to determine the maintenance space based on the layout of machine parts. Fig. 5 shows the SV of each MAU constructed in DELMIA.

2.3.2. Maintenance operations with tools

The motion trail of maintenance operations with tools can be treated as the combination of the trajectory of the maintainer's hand and the tool used. The SVs of the maintainer's hand and the tool used can hence be determined. The SV of the operation is the Minkowski sum of the two kinds of SVs mentioned above. Let A and B represent the hand and tool, respectively. The SV of the operation can be defined by the following:

$$SV(\mathrm{A}+\mathrm{B}) = (SV(\mathrm{A}))\oplus(SV(B)) = \{a+b \mid a\in SV(A), b\in SV(B)\} \quad (1)$$

where SV(A) means the SVs of A and SV(B)means the SVs of B.

Fig. 6 shows an example of the generated SVs of a maintenance operation with a tool.

2.4. Evaluation method

2.4.1. Evaluation indexes

The free and constrained SVs for a specific maintenance operation need to be determined. To evaluate the room reserved by the

Fig. 3. Common maintenance tools.

Table 2
Types of MAU[a] of the hand.

Type	Description
Screw	Operation of the hand when the maintainer screws the screw bare-handed or uses the screwdriver
Twist	Operation of the hand when the maintainer uses a wrench and rotates the wrench from the center on the part to be maintained
Translate	Movement of the hand along a line without rotation

[a] MAU: maintenance activity unit.

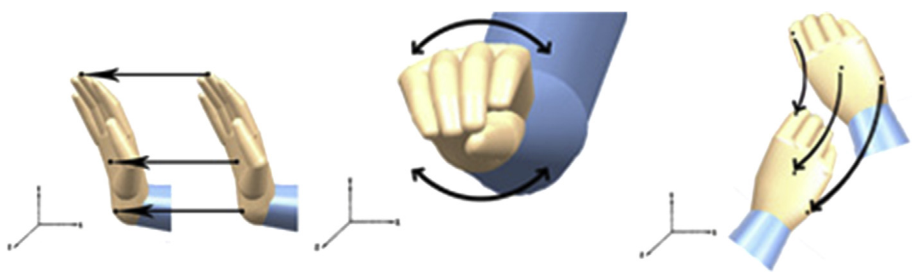

Fig. 4. Three types of MAU of the hand.

Fig. 5. Swept volumes of MAUs.

layout design, we can compare the two kinds of SVs to check whether the maintenance space of the actual maintenance operation, represented by the constrained SV, is sufficient. Qualitatively, based on the knowledge data, a large constrained SV equates to a satisfactory maintenance space. To evaluate the maintenance space quantitatively, we define two indexes as the ratio of the surface area of the constrained SV to the surface area of the free SV and the ratio of the volume of the constrained SV to the volume of the free SV, marked as P_s and P_v, respectively.

$$P_s = S_{csv} \Big/ S_{fsv} \tag{2}$$

$$P_v = V_{csv} \Big/ V_{fsv} \tag{3}$$

where S_{csv} and S_{fsv} are the surface areas of the constrained SV and the free SV, respectively; and V_{csv} and V_{fsv} are the volumes of the

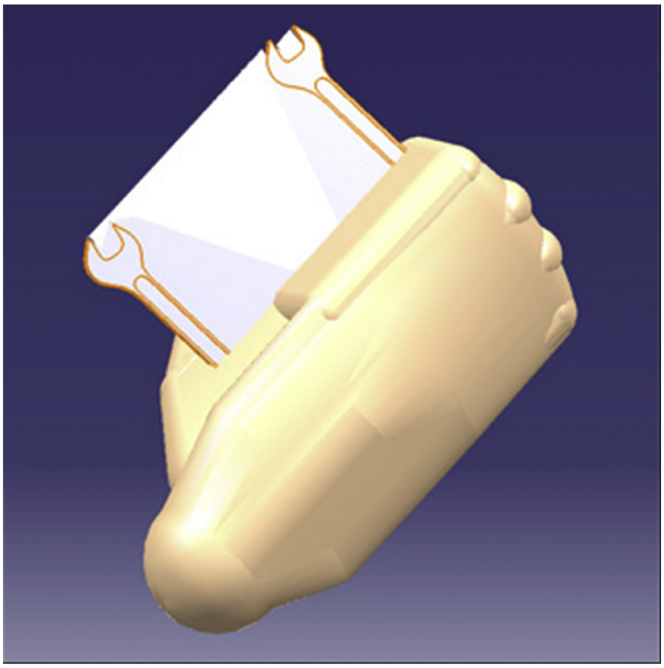

Fig. 6. Example of swept volumes of maintenance operation with a tool.

Fig. 8. Radial/ulnar deviation of the wrist.

constrained SV and the free SV, respectively.

2.4.2. Evaluation criteria

Different types of MAUs have different evaluation criteria. The evaluation criteria can be drawn from HFE knowledge. As most of the operations are performed by the maintainer's hand, the range of motions of the concerned articular of the hand should be considered.

Movements of wrist for flexion/extension are shown in Fig. 7. Fig. 8 shows the radial/ulnar deviation of the wrist. The ranges of motions for these movements (Table 3) are based on previous studies.

The data on the range of motion of each finger can also be obtained from previous studies. However, for most maintenance operations, the angle of fingers has little effect on the evaluation of maintenance space. In this study, all fingers are assumed to move within an appropriate range.

Table 3
Ranges of motions of the wrist.

Joint	Action	Normal(/degree)
Wrist	Extension/Flexion	70/75
Wrist	Radial/Ulnar	20/35

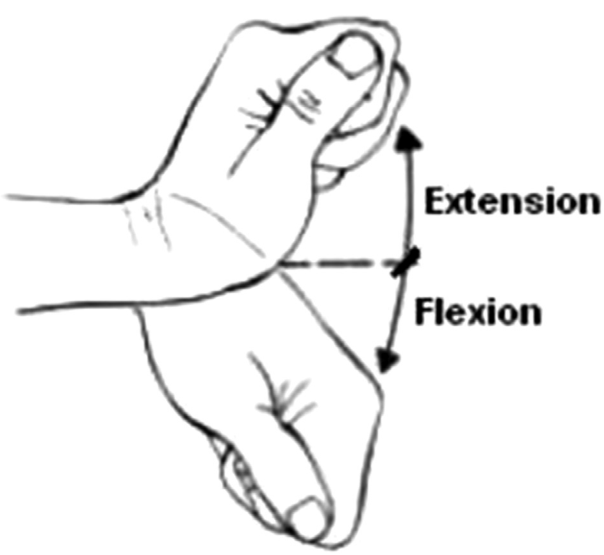

Fig. 7. Flexion/extension of the wrist.

Fig. 9. Palm arches.

The hand arches of the palm are shown in Fig. 9. When the hand arches the palm, the metacarpal bones of the index and the middle fingers are constant, whereas the metacarpal bones of the ring and small fingers rotate about their respective carpometacarpal joints.

For a certain maintenance operation, the motion of relative joints should be within a certain range. The maintainer may feel uncomfortable if the rotation angle of a joint is too large. If the maintenance space is too small, the maintainer has to adjust the position of his/her joints to finish the job in an uneasy way. Fig. 10 shows comfortable and uncomfortable palm arches.

Based on the discussion above, we divide the results of the maintenance space evaluation into three levels: good, normal, and bad. At each level, the values of P_s and P_v lie within a certain range. The specific evaluation criteria for different MAUs are drawn from the ergonomics requirements (Table 4).

2.4.3. Hierarchical evaluation method

After the evaluation result of each MAU is obtained, the results must be combined. Normally, the maintenance task is the combination of the MAUs of the maintainer. A rule to follow in combining the evaluation results is that if one or more evaluation levels are bad, then the total evaluation result is bad. If all the evaluation results are not bad, the factors P_s and P_v of each MAU are equally important, whereas for a specific maintenance task, the MAUs are not. Different weights are allocated to different MAUs. The weight factor is decided by the ratio of the time of the specific operation to the time of the maintenance task. It is calculated as

$$\alpha_i = \frac{t_i}{t_{task}} \tag{4}$$

where α_i is the weight factor of the ith MAU, t_i is the time that the maintainer spends on the specific maintenance operation, and t_{task} is the total time of the maintenance task.

Given the weight factors of the maintenance operations, we can calculate the evaluation criteria interval for the maintenance space (Table 5).

The evaluation score of the maintenance space for the maintenance task is the weighted average of the evaluation scores of the maintenance operations. It is calculated as

$$g_{task} = \sum_i \alpha_i (g_{is} + g_{iv})/2 \tag{5}$$

where g_{task} is the evaluation result of the maintenance space for the maintenance task, and g_{is} and g_{iv} are the evaluation scores of P_s and P_v of the ith MAU, respectively.

In this study, we defined the free and constrained SVs for each MAU in the maintenance process. The evaluation criteria are formulated based on the ergonomics requirements. Each MAU is quantitatively evaluated to verify whether the maintenance space is sufficient and to detect defects in the product design that need to be improved to enhance maintainability.

Table 4
Evaluation criteria of different maintenance operations.

Operation type	Evaluation level	P_s	P_v
Screw	Good	>0.85	>0.8
	Normal	0.6–0.85	0.5–0.8
	Bad	<0.6	<0.5
Twist	Good	>0.8	>0.75
	Normal	0.6–0.8	0.5–0.75
	Bad	<0.6	<0.5
Translate	Good	>0.9	>0.9
	Normal	0.7–0.9	0.7–0.9
	Bad	<0.7	<0.7

P_s: The ratio of the surface area of the constrained SV to the surface area of the free SV.
P_v: The ratio of the volume of the constrained SV to the volume of the free SV.

3. Case study

Based on the techniques we presented, we used part of the maintenance process for the auxiliary power unit of the Boeing 737 as an example. The maintainer must unscrew six screws by using a wrench (Fig. 11). The qualitative results of the evaluation of the maintenance space for this task can be obtained by using the visual with the digital prototype data, whereas the quantitative results are obtained by using our proposed method. We demonstrate that the proposed method is feasible and efficient.

First, we simulated the maintenance process in the virtual environment of DELMIA (Fig. 12). The virtual man used is a P50 person. No collision was assumed in the simulation. The task of unscrewing was decomposed into three maintenance operations: approach, unscrew with a wrench, and leave. These operations correspond to the three MAUs: translate, twist, and translate.

Sequential maintenance operations in the task of unscrewing: (a) approach, (b) unscrew, and (c) leave.

Once the simulation was constructed, we ran the simulation to obtain the constrained SVs of the three basic maintenance operations of the hand and recorded the time of each operation. The time data were used to calculate the weight factors of the basic maintenance operations. We could easily observe through the simulation that a sufficient room was reserved for the maintenance operations of approaching and leaving, whereas not enough

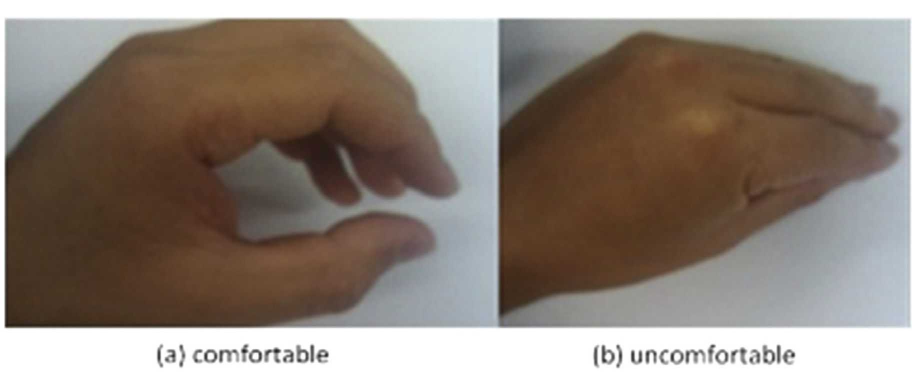

Fig. 10. Different palm arches.

Table 5
Evaluation criteria for maintenance space.

Evaluation level	P_s	P_v	P_{total}
Good	$>0.85\alpha_1 + 0.8\alpha_2 + 0.9\alpha_3$	$>0.8\alpha_1 + 0.75\alpha_2 + 0.9\alpha_3$	$>0.825\alpha_1 + 0.775\alpha_2 + 0.9\alpha_3$
Normal	$0.6\alpha_1 + 0.4\alpha_2 + 0.7\alpha_3$ $-0.85\alpha_1 + 0.8\alpha_2 + 0.9\alpha_3$	$0.5\alpha_1 + 0.25\alpha_2 + 0.7\alpha_3$ $-0.8\alpha_1 + 0.75\alpha_2 + 0.9\alpha_3$	$0.55\alpha_1 + 0.325\alpha_2 + 0.7\alpha_3$ $-0.825\alpha_1 + 0.775\alpha_2 + 0.9\alpha_3$
Bad	One or more evaluation level is bad.		

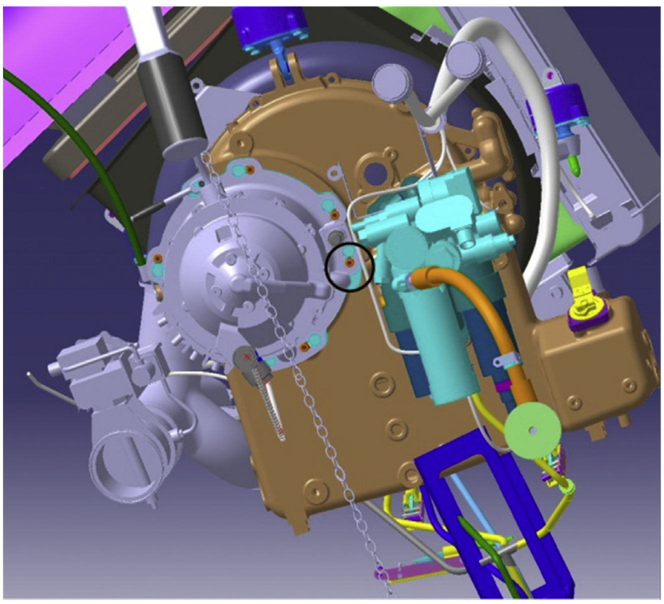

Fig. 11. Digital prototype of auxiliary power unit.

maintenance space was reserved for the operation of unscrewing the screw. To evaluate quantitatively the maintenance space, the constrained and free SVs of the unscrewing operation were constructed, and the quantitative indicators, namely, the surface area and volume of the SVs, were calculated.

The evaluation criteria of the operations in the unscrewing task are listed in Table 6. Information on the maintenance task, including the three sequential basic maintenance operations, time spent on each operation, weight factors of each operation, and the surface areas and volumes of the constrained and free SVs, is shown in Table 7.

The large values of the two indexes, i.e., the surface area ratio and volume ratio, for each basic maintenance operation equate to good evaluation results. The maintenance space meets the requirement for operating Screw 6. We take Screws 1 and 3 as examples to demonstrate the analytical process. The analysis process for the other screws is similar to that for Screw 1.

Screw 1: The values of the surface area ratio and volume ratio for Approach and Leave show that the constrained SVs of these two basic maintenance operations are the same as the free SVs; thus, the maintenance space is large enough for the maintainer to operate as if in a free space. For the basic maintenance operation of unscrewing, the value of the surface area ratio falls within the normal range, and the value of the volume ratio is good. These results show that enough space is available for the unscrewing maintenance operation. After combining the results of the two indexes for each basic maintenance operation, the total result is good; thus, enough maintenance space is reserved for the entire process of unscrewing Screw 1.

Screw 3: The values of the surface area ratio and volume ratio for Approach and Leave show that enough space is available for approaching and leaving Screw 3. However, for the basic maintenance operation of unscrewing, the values of these two indexes are

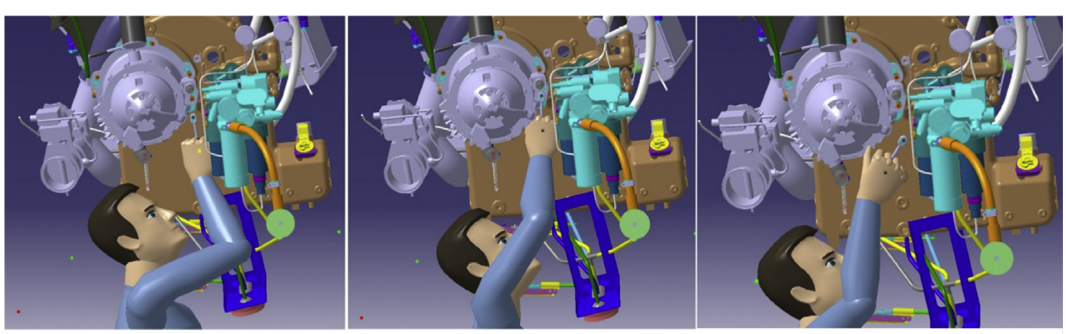

Fig. 12. Sequence of the maintenance process.

Table 6
Evaluation criteria for unscrewing operations.

Evaluation level	1	2	3	4	5	6
Good	>0.8569	>0.8597	>0.8663	>0.8571	>0.8620	>0.8621
Normal	0.6138–0.8569	0.6195–0.8597	0.6325–0.8663	0.6142–0.8571	0.6241–0.8620	0.6242– 0.8621
Bad	One or more evaluation level is bad.					

Table 7
Data of the studied maintenance process.

Screw no.	Task operation	MAU	Time cost	α_i	Surface area		Volume		g_{is}	g_{iv}	g_{task}	Result level
					Constrained SV	Free SV	Constrained SV	Free SV				
1	Approach	Translate	2.15	0.215	0.985	0.985	0.990	0.990	1	1	0.917	Good
	Unscrew	Twist	5.75	0.575	1.075	1.295	1.015	1.152	0.830	0.8811		
	Leave	Translate	2.10	0.21	0.985	0.985	0.990	0.990	1	1		
2	Approach	Translate	2.55	0.234	0.875	1.150	0.900	1.005	0.761	0.896	0.8033	Normal
	Unscrew	Twist	5.85	0.537	0.950	1.295	0.955	1.152	0.734	0.829		
	Leave	Translate	2.50	0.229	0.8755	1.150	0.900	1.005	0.761	0.896		
3	Approach	Translate	3.20	0.275	1.985	2.233	1.685	1.855	0.889	0.908	–	Bad
	Unscrew	Twist	5.25	0.45	0.740	1.295	0.570	1.152	0.571	0.495		
	Leave	Translate	3.20	0.275	1.985	2.233	1.685	1.855	0.889	0.908		
4	Approach	Translate	2.10	0.214	1.675	1.675	1.555	1.555	1	1	0.8899	Good
	Unscrew	Twist	5.60	0.572	0.895	1.295	1.065	1.152	0.691	0.924		
	Leave	Translate	2.10	0.214	1.675	1.675	1.555	1.555	1	1		
5	Approach	Translate	3.10	0.251	2.450	2.450	1.985	1.985	1	1	0.8926	Good
	Unscrew	Twist	6.25	0.506	0.985	1.295	1.025	1.152	0.815	0.7606		
	Leave	Translate	3.00	0.243	2.450	2.450	1.985	1.985	1	1		
6	Approach	Translate	2.75	0.252	2.155	2.155	1.865	1.865	1	1	1	Good
	Unscrew	Twist	5.50	0.505	1.295	1.295	1.152	1.152	1	1		
	Leave	Translate	2.65	0.243	2.155	2.155	1.865	1.865	1	1		

evaluated as bad, which means that the space is too small to complete the unscrew operation. Based on the evaluation criteria in Table 5, the total evaluation result for Screw 3 is bad. Therefore, designers must adjust the design of Screw 3 to ensure that enough maintenance space is reserved to operate in it.

By analyzing the two indexes of each basic maintenance operation in this case study, we can obtain the results of the maintenance space evaluation and find the limitation in the layout design of the failed unit. The method proposed in this study is useful and efficient.

4. Conclusions and future work

Designers must consider the HFE during the maintainability design process. As an important component of maintainability design, maintenance space evaluation should be influenced greatly by the HFE requirements. The traditional way to verify the adequacy of maintenance space relies on the physical prototype and expert knowledge. This traditional evaluation method is time consuming and influenced by subjectivity. Recognizing the difficulty that designers face in integrating ergonomic design with maintainability design, this study proposes a new method for evaluating the maintenance space in a virtual environment by using the SV combined with HFE knowledge. The proposed method can overcome the drawbacks of traditional methods. The maintenance process is divided into three operations corresponding to the three MAUs. For each MAU, free and constrained SVs are defined and consequently constructed. The evaluation criteria are drawn from HFE knowledge. By evaluating the surface area ratio and volume ratio of each basic maintenance operation, we can analyze and verify whether sufficient maintenance space is reserved. The proposed method is proved feasible and efficient by validating it via a case study.

Several areas may be improved in future work. The classification of maintenance operations used in this study is rough to some extent. The movement and adjustment of the maintainer's fingers have not been considered. The evaluation process can be improved and made comprehensive by considering finger movement. However, further study is needed to carry out these improvements.

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