International Journal of Industrial Ergonomics 54 (2016) 154–163

Contents lists available at ScienceDirect

International Journal of Industrial Ergonomics

journal homepage: www.elsevier.com/locate/ergon

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

Dong Zhou [a], Jiayu Chen [b], Chuan Lv [c, *], Qingyuan Cao [b]

[a] State Key Laboratory of Virtual Reality Technology and Systems, BeiHang University, Beijing, China
[b] School of Reliability and Systems Engineering, BeiHang University, Beijing, China
[c] Science and Technology on Reliability and Environmental Engineering Laboratory, Beijing, China

ARTICLE INFO

Article history:
Received 17 April 2015
Accepted 12 June 2016
Available online 18 June 2016

Keywords:
Maintainability design
Ergonomics
Maintenance space design
Swept volume
Virtual maintenance

ABSTRACT

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

* Corresponding author.
E-mail address: tiancaishizhizhu@gmail.com (C. Lv).

http://dx.doi.org/10.1016/j.ergon.2016.06.003
0169-8141/

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