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Using virtual reality to support the product's maintainability design: Immersive maintainability verification and evaluation system

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ABSTRACT

Maintainability is an important characteristic of complex products. Good maintainability design can save substantial costs and reduce incidents and accidents throughout the product life cycle. Therefore, maintainability should be given full consideration in the early design stages. However, the current desktop tools are not effective to aid in maintainability design. Virtual reality (VR), a state-of-the-art of computer science, generates a virtual environment in which the user can have intuitive feelings and interact with virtual objects. In this paper, an immersive maintainability verification and evaluation system (IMVES) based on virtual reality is proposed. The goal of the system is to develop a cost-effective, rapid and precise method to improve the maintainability design in the early design stages. IMVES enables the user to interact with maintenance objects and conduct immersive simulations. Based on the developed methods, the data generated during simulation can be gathered to analyze the maintainability status. A case study applying IMVES into an aero-engine project is presented to demonstrate the effectiveness and feasibility of the system. Compared with desktop-based methods, the IMVES could provide a more efficient way to conduct a maintenance simulation. Furthermore, the credibility and objectivity of the maintainability evaluation are also improved.

1. Introduction

As the major capital goods that underpin manufacturing, services, trade and distribution, complex products play a critical role in modern industrial and economic progress [1]. These products greatly enhance the efficiency of human activities, whether for civil or military purposes. With a high use ratio and rapid technical improvement, these complex products generally are large scale and highly integrated, leading to the maintenance and support of these products becoming a big issue. Maintainability is an important built-in characteristic of complex products. From a high-level point of view, the maintainability can be defined as “the probability that a failed item can be restored to an operational effective condition within a given period of time” [2].

From a more operable perspective, maintainability refers to measures or steps taken during the product design phase to include features that will increase the ease of maintenance and ensure that the product will have minimum downtime and life cycle support costs when used in a field environments [3]. The issue to improve the maintainability is becoming increasingly more important than ever before because of the alarmingly high costs of operation and support and the incidents and accidents caused by incomprehensive maintainability design [4]. Good maintainability design enables the maintenance process to be conducted efficiently. Furthermore, good maintainability design can reduce costs throughout the product life cycle and reduce the incidents and accidents. Poor maintainability design will lead to the frequent replacement of components and long downtime of products; this outcome will lead to significant economic loss. The study shows that nearly 70% of the total product life cycle costs are determined in the early design stages [5], in which maintenance costs occupy a large part. and For example, the industry in the United States spends over $300 billion on plant maintenance and operations [6]. The annual cost of maintaining a military jet aircraft is approximately $1.6 million. Approximately 11% of the total operating cost for an aircraft is spent on maintenance activities [7]. Therefore, the cost of maintenance will be greatly reduced during the service stage if the product has a rational maintainability design, which will put great value on both users and enterprises. Another significant issue that needs significant attention is that the maintainability design is strongly associated with personnel security, especially for the fields that have a high degree of potential for accidents such as aviation, nuclear and mining industries. In civil

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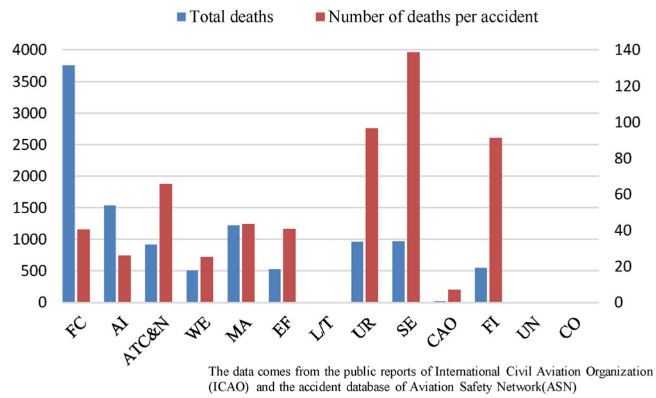

Graph 1. Comparison of the death toll due to various accident and incident factors.

aviation, maintenance is a crucial routine function in day-to-day operations. We investigated air crashes worldwide from 2001 to 2012. The incident and accident causes are classified as flight crew (FC), airplane (AI), ATC & Navigation (ATC&N), weather (WE), maintenance (MA), external factors (EF), landing/takeoff (L/F), unexpected result (UR), security (SE), cargo occurrences (CAOs), fire (FI), unknown (UN) and collisions (CO). Graph 1 shows the death toll caused by incidents and accidents, showing that the airplane is the second leading factor causing deaths (1539 deaths), and maintenance is the third leading factor in deaths (1220 deaths). Maintainability design has a strong correlation with both maintenance and airplane factors. Comprehensive maintainability design in early design stages of airplanes enables the maintainer to conduct the maintenance task in an efficient and comfortable way. The maintenance errors will be substantially reduced, meaning that the damages resulting from the maintenance errors will be kept to a minimum or totally avoided.

Regarding the significance of the maintainability of complex products, the maintainability design should be conducted more effectively in the early design stage. VR is a state-of-the-art of computer science. In many fields, VR has played effective roles both for academic research and industrial application [8]. In this paper, an immersive maintainability verification and evaluation system (IMVES) is proposed. The dual aims of IMVES are to verify the feasibility of applying VR to assist maintainability design and further, to develop a timely and effective approach to help the designer make better design decisions in early design stages. IMVES is purposefully designed to generate and conduct an immersive maintenance simulation, in which the designer can interact with virtual objects according to preplanned procedures, and the data related to the maintenance process can be collected to make further maintainability evaluations. IMVES has a general framework, which means it can be used in different design situations after proper modification. In addition to the description of the system architecture and functional components of the IMVES, this paper also describes two cases in which IMVES was used to help the designers to make design decisions for an aero-engine and a helicopter in the early design stages. Based on the analyses of the evaluation results by IMVES and later physical verification, the paper thus highlights that VR is feasible for practical product design and an effective approach to help designers make reasonable decisions.

2. The issues with current maintenance design methods-motivation analysis

Maintainability is a significant part of the design stages. For some large complex products, especially the weapons, maintainability design is even a compulsory design content that needs to be carefully conducted. At present, the industry design department has phased out expensive mental mockups, which will cause the maintainability to lag behind the whole design schedule. However, as the replacement, digital mockup (DMU) still has some efficiency problems. Among the industry sectors (including aerospace, aircraft and high-speed rail), mature simulation tools such as DELMIA (Digital Enterprise Lean Manufacturing Interactive Application) and JACK (a human modeling and simulation tool) have been widely used. Although these tools realize the visualization of the DMU and simulation of the maintenance process, this kind of maintainability design method produces unsatisfactory effects. The following major factors account for such low efficiency:

- Current design-aiding tools generally consist of desktop software. These tools can only display the DMU in a static way. Nevertheless, maintenance is a typical example of human-machine interaction, which is a dynamic process. A desktop-based view cannot oversee the design shortcomings that are exposed during the dynamic process, although these desktop tools can make some simulations where a virtual human can be involved. In other words, these tools still are "two-dimensional" to a certain extent.
- The desktop-based simulation has a low production efficiency, running counter to the speed requirement in new product development, which leads to maintainability design in a superficial way. The desktop-based simulation is commonly based on animation (the main aspect is key frame control). The elaboration level of the simulation depends on the quantity and accuracy of the key frames. To make the simulation delicate enough to reflect the real maintenance process, the designer must adjust the key frame many times. This kind of production method costs time and strength. A representative case is that, in one of our prior projects, we produced a simulation to simulate the process of pulling off a cable plug in satellite capture. The whole simulation play time is just approximately two minutes and thirty seconds. Despite knowing the Human Task Simulation module of DELMIA well, we still spent two whole days to produce the simulation to make it as precise as possible. For the common engineer, it is a heavy burden added to their design task.
- Traditional maintainability design methods rely too much on experience, which has considerable subjectivity. This issue is exposed throughout the desktop-based maintainability design process. The traditional maintainability design method is mainly simulation-based. Because designers cannot be involved in the maintenance process, they are just "cartoon-makers", and this lack of involvement in the maintenance process will lead to a situation in which, given the identical maintenance task, different designers will produce different simulations. Well-experienced designers can make a precise simulation that is close to the real maintenance process. Nevertheless, the simulation made by a less experienced designer may have large deviations, which lead to errors in the subsequent evaluation.

The potentials of VR could bring innovation to the current maintainability design method. With the assistance of VR, we can quickly duplicate a dynamic virtual environment that could be seen as the image of the real maintenance case. In the appropriate environment, the user, rather than a virtual human, can interact with the virtual environment. The advantages VR bring to virtual maintenance simulation are obvious: 1) The DMU can interact with the real user. 2) The simulation could be conducted rapidly because of the fundamental change in the simulation method. 3) The accuracy of the simulation could be greatly improved.

3. Related work

VR is the state-of-the-art in computer science. Using advanced display and interaction technologies, VR enables the user to have sensual perceptions and interact with the virtual object. Virtual maintenance (VM) serves an important role in maintainability design and