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Compensation-based methodology for maintenance time prediction in a virtual environment

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ABSTRACT

This study presents a novel compensation-based methodology for maintenance time prediction in a virtual environment during the early stage of product design. According to the work procedure in assigning maintenance tasks, a maintenance process simulation is generated on the virtual maintenance platform by following the simulation principle. The basic compensation time or ratio is acquired by analyzing the relationship between practical human motions and corresponding virtual human motions. After that, the compensation principle is confirmed based on the generated simulation principle. Finally, the simulation time and compensation time are approached according to the compensation model to obtain the predicted time. The obtained predicted time of several cases are accurate to a certain extent compared with feedback information.

1. Introduction

Maintenance time is a fundamental quantitative parameter in maintainability design and has considerable influence on product availability. Thus, maintenance time prediction, which can be conducted in the experiment, design, and manufacture phases, is an important part of the product life cycle. However, maintenance time prediction cannot be performed effectively in actual operation situations, and current maintainability experimentations waste considerable time, manpower, and material resources. Predicting maintenance time at an early stage is important in maintainability design, particularly for new products.

Traditional maintenance time prediction mainly covers six typical methods, namely, the probability simulation method, function level method, sampling prediction method, regression analysis method, time-accumulated method, and comparative analysis method [1–7]. The probability simulation method predicts the maintenance time systematically according to the maintenance activity distribution. This method can obtain a comprehensive and detailed prediction result but is complicated in calculation and dependent on basic data. The function level method has simple operations that predict the maintenance time according to the existing maintenance activity table and product level table. However, corresponding data are usually outdated and need to be added and amended for new products. The sampling prediction method samples enough replaceable units and assesses the maintenance work by referring to corresponding check tables. This method predicts the maintenance time with empirical equations and obtains increasingly detailed prediction results with product design.

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The regression analysis method [8] analyzes the relationship between maintenance time and equipment character on the basis of necessary experiments on similar product or statistical data. This method establishes models by using regression analysis to predict the maintenance time for new or improved products. The prediction precision of this method depends on the similarity between existing and new products and the relationship between system design and maintainability design. The time-cumulated method [9] confirms the necessary time of each maintenance project, task, and activity according to historical experience or existing data and diagrams. This method predicts the maintenance time by accumulating or averaging under a given procedure. The basic standard time in this method is obtained mainly from electronic equipment that needs to be amended for other types of products. The comparative analysis method selects a component whose maintenance time is known as a basic reference and predicts the corresponding maintenance time of other units compared with the selected basic reference. This method relies on little design information, thus making this method suitable for various products. The abovementioned traditional methods mostly focus on electronic equipment and extensive application in other types of products, such as mechanical products. These methods lack basic maintenance work time or maintenance activity information. They also have different requirements in data form, high computation complexity, and low operation efficiency.

In recent years, some improved or innovative methods with the characteristics of integration, intelligentization, and visualization have been presented to provide more approaches for maintenance time prediction. First, integration focuses on the combination of existing traditional methods because a single method cannot fulfill the requirements properly to predict the maintenance time of complex products that contain both electronic equipment and mechanical equipment. Various integrations make these improved methods highly adaptable when launching maintenance time prediction for different objects. In actual implementation, proper method selection for integration depends on experience, and an inappropriate integration may lead to an unexpected result. Second, intelligentization provides a new direction in maintenance time prediction. Methods such as language simulation and artificial intelligence are adopted to predict time, thus providing effective approaches for realization. These methods include real-time simulation [10,11], systematic simulation [12,13], Monte Carlo simulation [14], and genetic algorithm [15,16]. Some intelligentization methods, such as the Bayesian network [17], tree network [18], nerve network model [19], fuzzy neural network [20], hidden Markov model [21], and multilayer perception model [22], are also used in software maintainability prediction. However, these methods involve long programming times and have low degrees of visualization. Third, visualization transforms data into graphs or images that display the transformation on-screen on the basis of computer graphics and image processing technologies, thus providing an innovative approach for data processing and representation. A maintenance flow diagram is established to conduct maintainability design analysis on the basis of product structure and possible fault information [23]. The established diagram is also adopted for maintenance process simulation and maintenance time prediction. Petri net technology is used to establish an executable specification tool theory model that combines visualization and formalization for maintenance time simulation and prediction [24]. Colored petri net is used to establish a simulation model for maintenance time prediction by considering the disassembling process sequence and system fault model [25]. Other network models, such as the critical path method [26], graphical evaluation and review technique [27], and generalized reliability analysis simulation program [28], are also presented in maintenance time prediction. In the visualization domain, the continuous development of computer graphics and computer-aided design technologies, particularly virtual reality technology, has increased research interest on product simulation, interaction, and analysis. The advantages of virtual reality systems can be summarized as follows. A virtual prototype provides a visual process to protect product design against hardware limitations. Moreover, a virtual prototype can be operated and tested in a virtual environment to assess product performance, thus decreasing physical prototype requirements and corresponding development costs.

The corresponding historical data of maintenance time is also fundamental in maintainability prediction [29], and several mathematical methods have been adopted for data processing and maintenance time prediction. A maintenance prediction method that consists of graphic evaluation, likelihood parameter evaluation, and Sharpiro–Wilk normal distribution validation is proposed on the basis of the principle of statistical modeling [30]. The demonstration method of maintenance time with random weighted method is also studied [31]. Aircraft maintenance historical data and life cycle cost information are used separately for aircraft design, including maintenance time prediction from the perspective of maintainability [32,33].

Virtual maintenance technology, as an extension of virtual reality technology in the maintainability domain, provides a creative, intuitive, and holistic way to conduct maintenance task simulation and analysis by a virtual prototype in a virtual maintenance environment [34–36]. The applications of virtual maintenance for each stage of product design has been increasing recently [37–40]. Virtual maintenance can intuitively represent the entire maintenance process, including human manipulation, cooperation, and tool operation. Virtual maintenance also provides a reasonable basis for maintainability analysis, such as visibility, accessibility, operation space, and maintenance safety [41]. Therefore, flaws can be exposed during the early stage of product design to avoid the hysteresis of conventional ways.

In the virtual simulation domain, simulation time inaccuracy is universally recognized because of the following reasons. (1) Objectivity: in a virtual simulation environment, the movement principles of virtual humans or virtual products, such as motion frame-based movement, scripting programming-based movement, motion capture-based movement, and reproduced-based movements, exist objectively. Once a virtual platform is selected for simulation, all simulation processes are generated under the movement principle. The movement principle does not fully reflect the corresponding real conditions, such as the pretightening force in bolt assembly, the collision among products, and the flexible component movement. (2) Subjectivity: the simulations generated by different designers significantly vary, even for the same maintenance process. For instance, a human motion can be generated by 5 or 10 motion frames. Both two situations reflect the same human motion,