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A NEW MAINTENANCE TIME MEASUREMENT METHOD BY VIRTUAL REALITY

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ABSTRACT

Virtual maintenance has emerged as one such technology which has attained maturity and gained acceptance in industry. The key contribution of virtual maintenance is to reduce the design cost and cycle. Currently, virtual maintenance verification focuses on these statically qualitative contents, and there is a big gap between virtual maintenance simulation time and actual maintenance time. This paper divides those causes for the gap into three parts, including integrity, determinacy and verisimilitude. A new virtual maintenance time measurement based on DELMIA has been raised aiming at reducing the effects of the verisimilitude causes. And qualitative and quantitative analysis has been combined together to improve products' maintainability.

Keywords: *Virtual Maintenance, Maintenance Time, Maintainability Requirement, Incident Matrix*

1. INTRODUCTION

The maintenance time verification of equipment based on physical prototype usually falls behind function and structure design. And this may causes higher cost and longer cycle. Virtual maintenance has been emerged as such a technology which has attained maturity and gained acceptance in industry and made a contribution to reduce design cost and cycle. Virtual maintenance time, as a parameter to guide maintenance design, is usually quite different from actual maintenance time. Based on the difference between simulation and actual operation, a new virtual maintenance time measurement has been raised to combine qualitative and quantitative maintenance factors together.

2. VIRTUAL MAINTENANCE PROCESS CHARACTERISTICS AND INFLUENCES TO VIRTUAL MAINTENANCE TIME

The maintenance time based on virtual reality may be not only influenced by virtual time, but also other factors. Through the literatures reading and summarizing, this paper has got the formal expression of virtual maintenance time, shown as follow:

$$T = f(T_s, E, H, M, \dots)$$

Here, T refers to the relatively accurate maintenance time,

Ts refers to the simulation time,

E refers to the actual maintenance environment factors,

H refers to these human factors,

M refers to virtual models.

These factors have been classified into three parts.

2.1 Integrity

Here, the integrity does not only contain integrity of virtual prototypes, but also integrity of maintenance process. Maintenance process refers to one that during which maintenance personnel takes maintenance operations with tools. Integrity of virtual prototypes refers to that virtual prototypes, to some extent, have the similar geometer size, function, motion characteristic and physical characteristics, including the constraints of space, time and degree of freedom in the maintenance process. As we know, before the simulation of a maintenance process, virtual prototypes are usually simplified in some degree to get a higher feasibility for computer simulation. Because of simplified prototypes during simulation, there is a big gap between simulation time and actual time of maintenance process. Therefore, the simplified prototypes should contain their information related to maintenance process, and not affect the simulation time.

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Integrity of maintenance process refers to that in the course of maintenance; maintenance personnel should dismantle maintenance objects with complete actions. Take process of opening a maintenance flap for example. Virtual human should dismantle the same number of screws in actual maintenance process. What's more, for process of screwing nuts, virtual human should screw the same degrees that as actual process do, but not screw several turn emblematically. In general, in the simulation of virtual maintenance process, virtual human should take maintenance operations what actual maintenance personnel take in real maintenance process. This may reduce the gap as much as possible.

2.2 Determinacy

Compared with traditional maintenance verification based on skilled maintenance personnel and actual prototypes, virtual maintenance verification based on virtual human and prototypes is usually done by maintainability or system designers. The simulation time is changeable because they do not know much about maintenance process. Therefore, man who takes virtual maintenance verification should communicate with designers and skilled maintenance personnel to get a well know about maintenance process information including maintenance tools, channels, procedures, postures, sequence, routes. Determinacy of maintenance process makes simulation time relatively unchangeable and precise.

2.3 Verisimilitude

Virtual maintenance is a term that applies to computer-simulated environments that can simulate physical maintenance process in the real world. Actually, there is still a big gap between virtual and actual environment. Compared with actual maintenance process, there is nearly no interaction between virtual human and maintenance environment, tools, objects. The shortness of verisimilitude makes simulation time inaccurate.

First of all, temperature, humidity and illumination intensity in maintenance environment may give a big influence to maintenance personnel. On the other hand, in non-immersive environment, virtual human is assumed to repair in a constant environment. Secondly, compared with the decreasing rate of maintenance in actual environment, virtual human takes all maintenance actions in a constant rate. Thirdly, in the actual process of maintenance, maintenance personnel could use his vision, touch and experience to interact with maintenance tools and objects. But in non-immersive environment, all the movement of virtual human is predefined by designers and no interaction happens. In immersive environment, the interaction between human and models is quite different from actual environment because of the shortness of simulation facilities. Take the process of screwing a nut invisible for example. The skilled maintenance personnel could disassemble the nut with his sense of touch and experience. In immersive environment, shortness of verisimilitude and sensitivity of virtual gloves makes simulation time inaccurate. In non-immersive environment, virtual human is controlled by designers. Somehow, simulation time of screwing the nut is predefined. To sum up, the shortness of virtual reality itself gives rise to simulation and actual time.

To improve the accuracy of virtual maintenance time, we could take their factor above into account. As inputs of virtual maintenance simulation, integrity and determinacy factors are some qualitative requirements. Before immersive and non-immersive simulation, designers should know well about the maintenance process and eliminate the deviation of maintenance time brought by two factors. What's more, this paper presents a new method to reduce the deviation brought by factor of verisimilitude.

3. MEASUREMENT METHOD OF VIRTUAL MAINTENANCE TIME BASED ON INCIDENCE MATRIX OF MAINTENANCE QUALITATIVE VERIFICATION

For a certain maintenance action, we generally structure a maintenance process model, which could describe the actual process integrally, and add it's maintenance tasks time together to get the maintenance action time. Nowadays, the maintenance verification focuses on qualitative requirement. This paper presents a new method that combines qualitative requirement and maintenance time together, and reduce the gap between actual and virtual simulation time.

3.1 Classify Of Maintenance Qualitative Verification

Maintenance qualitative requirements contain visibility, accessibility, operating space, standardization, interconvertibility, modularization, error prevention and identification tag, ergonomic and maintenance safety. DELMIA, Digital Enterprise Lean Manufacturing Interactive Application, is a business software that widely used in manufacture's virtual disassembly. This paper

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researches how this five maintenance qualitative requirements, which are available in DELMIA, effect maintenance time.

3.1.1 Visibility

A good visibility means that in the course of maintenance, maintenance personnel could see maintenance tools, object and himself directly by his eyes. In DELMIA, vision cone method, which simulates human's view space, could give a vivid describe about if they are visible.

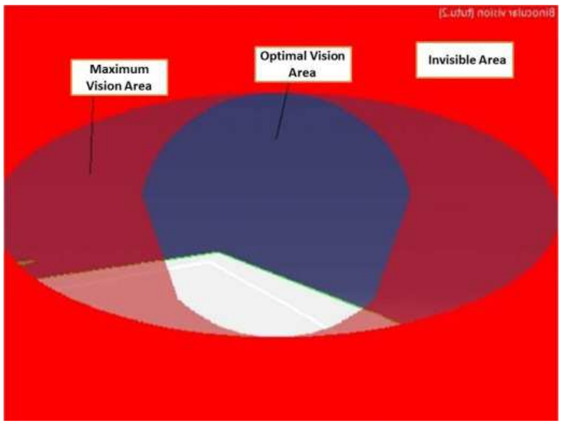

Figure 1 Vision cone

In this paper, degree of visibility is divided into three levels. And here are the detailed describe about each level:

LVL1: All maintenance objects and action keep in sight directly in the process of maintenance;

LVL2: Some of maintenance objects or actions sometimes are out of vision cone, or blocked;

LVL3: All maintenance objects and actions keep out of vision cone or are blocked and maintenance personnel could only finish his work all by sense of touch and experience.

3.1.2 Accessibility

Accessibility is a general term used to describe the degree, for maintenance personnel with different posture and tools, to get in touch with maintenance objects. In DELMIA, the envelope ball tool, shown in Figure 2, is used to access the degree of accessibility. Here are the detailed describe of each accessibility level.

LVL1: When maintenance personnel is in a natural posture, maintenance objects are all in the envelop ball. And for maintenance personnel, he could touch there objects easily.

LVL2: After changing to another posture, maintenance personnel could touch these objects. They could be included in the envelop ball.

LVL3: After changing postures, maintenance personnel could hardly touch these objects. They could only be at the edge of envelop ball.

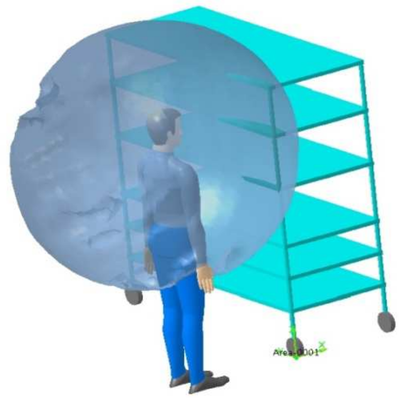

Figure 2 Envelope ball

3.1.3 Operating space

Operating space is a term that describes the degree of suitability for maintenance personnel's operations with the objects. In DELMIA, collision detection tool uses real time to analysis whether the space meets the requirements. In Figure 3, virtual human's left hand has been interfered with the cube. These red circles show where interferences happen.

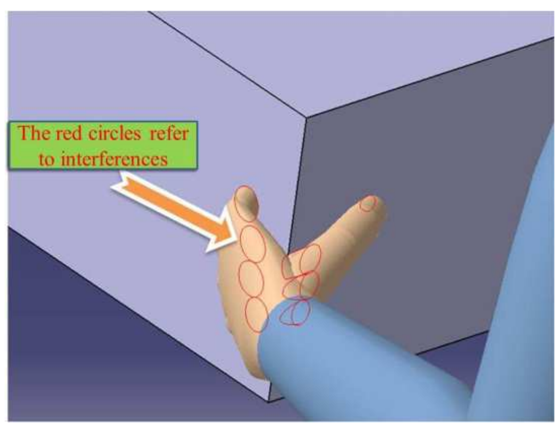

Figure 3 Collision detection

Here are the rules of operating space classify.

LVL1: When the maintenance personnel is in a natural posture, his arms and tools have a plenty space for operation and do not interfere with nothing.

LVL2: After maintenance posture changing, the number of interferences between maintenance personnel's body and objects has decreased. And

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for maintenance personnel, he could finish the work more easily.

LVL3: After maintenance posture changing, there is still much interference. For maintenance personnel, he must try his best to refrain from the interferences and finish the work with more attentions.

3.1.4 Maintenance safety

Maintenance safety is a term that describes how dangerous sources influence maintenance process. Dangerous sources are something with special characteristics that maintenance personnel should keep a certain space from and make the maintenance process more complex. In general process of maintenance, it could be divided into three parts, thermal, electrical and mechanical dangerous sources.

Thermal dangerous sources are things with thermal radiation, flame, high or low temperature. Also, maintenance personnel should keep away from electrical dangerous sources, like electrified components, electrostatic phenomenon, short-circuit, high-voltage and overload, and mechanical dangerous sources, like cusp, sharp edges and rough surface.

The rules to classify the maintenance safety are shown below:

LVL1: There is no dangerous source in the maintenance space and route, and the maintenance operation will be done safely.

LVL2: Some dangerous sources have existed in the space and for maintenance personnel have to operate carefully to avoid interferences with them.

LVL3: Some obvious dangerous sources in the narrow space and maintenance personnel have to operate with some specific protective equipment.

3.1.5 Working posture

Working posture refers to the posture that an individual is required to adopt due to the layout of a workstation and/or the nature of the task. Poor working posture is a common ergonomic hazard in the course of maintenance and can cause fatigue, discomfort and injury risk. The working posture in the course equipment maintenance can generously be divided into stoop, kneeling with one or both kneels, crouching, lying on front, lying on back, etc. In DELMIA, RULA (Rapid Upper Limb Assessment) is a survey method developed for the use in ergonomics investigations of workplaces where work-related upper limb disorders are reported. This tool requires no special equipment in providing a quick assessment of the postures of the neck, trunk and upper limbs along with muscle function and the external loads experienced by the body. According to the color of virtual human's body, in Figure 4 we could get to know how well the working posture is. The green shows that the posture is comfortable and can be accepted in a short time. The yellow shows that the posture is relatively uncomfortable and should be changed in time. The orange shows that the posture is certainly uncomfortable and should be avoided in the course. The red shows that the posture is unaccepted or even dangerous.

Figure 4 RULA of virtual human

Here in this paper, we have concluded three rules for RULA classify:

LVL1: During the course of maintenance, the results of RULA are always green. For maintenance personnel, he is in a comfortable posture without tiredness.

LVL2: During the course, there are some unavoidable yellow or orange sometime in RULA results.

LVL3: During the course, some unavoidable red exist in the results. For maintenance personnel, his working rate may be obviously decreasing.

What we need to say is that these rules and classify above are not always suitable for different fields. For a certain kind of work, a corresponding rules and classify should be founded before analysis.

3.2 The measurement method of virtual maintenance time based on the incidence matrix

This section presents a new measurement method of virtual maintenance time based on the incidence matrix, which has combines the maintenance time and there five factors above together.

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3.2.1 Breakdown of virtual maintenance works

Generally speaking, a maintenance work is composed of many maintenance tasks, like preparation, approaching, detection, isolation, decomposition, changing, trimming, handle, etc. In general virtual environment, the maintenance work time is usually the sum of maintenance tasks time, which is measured by MTM (Methods Time Measurement). In this method, there are 13 therbligs, including reach, move, grasp, turn, apply pressure, release, position, disengage, eye time, crank, body transports, body motion, simultaneous and combined motions. All human's movements could be composed by the therbligs. According to survey and statistics, MTM has got the time of each therbligs. After combining therbligs' time together, we could get the maintenance work time.

Compared with the actual maintenance environment, we should find out how the factors may influence maintenance time. However, the workload of virtual maintenance verification may be larger and inefficient if we start from the therbligs layer. Aiming at the availability, we have studied how therbligs combination, called maintenance therbligs, is influenced in this paper.

According to a large number of literature reading and survey, we have got a new maintenance work framework, shown in Figure 5. What's more, the maintenance therbligs in this framework may just be suitable for aviation equipment maintenance. For other equipment and products, we should get some maintenance therbligs with better applicability.

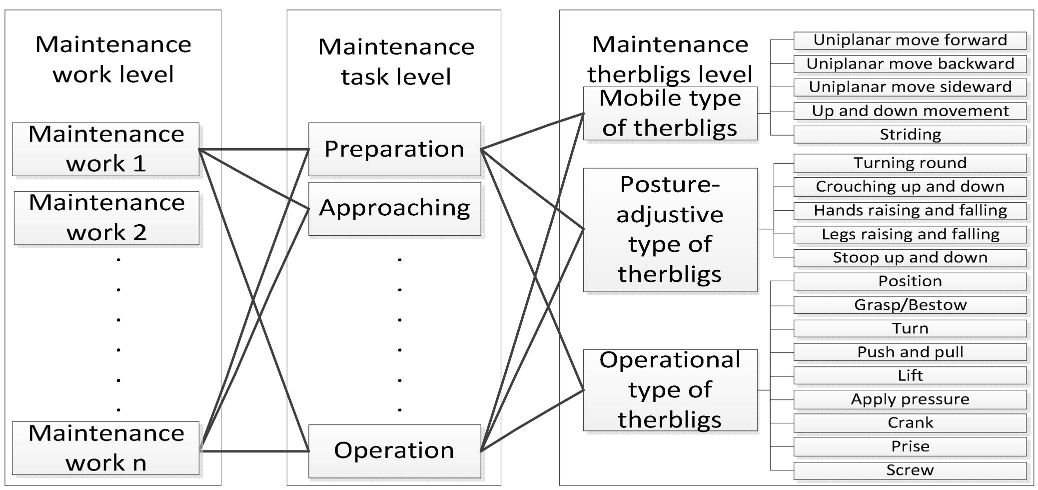

Figure 5 Breakdown of maintenance work

During the course of virtual maintenance, fault detection and isolation, which is an important component for maintenance time, could not be simulated with general virtual reality software. We could get to ascertain fault detection and isolation time according to the quantitative requirement of testability.

3.2.2 Incidence matrix of maintenance therbligs time

This paper has structured an incidence matrix that shows how maintenance therbligs time is influenced by different status of maintainability quantitative requirements. To count the influence coefficient, we use control variable method. In actual maintenance environment, we keep skilled maintenance personnel working in relatively constant situation. With mass of statistical data got in actual maintenance process, we could get the mean value and variance of therbligs time

$$A = \frac{\bar{t} - t_s}{t_s}$$

$$\bar{t} = \frac{1}{n}\sum_{i=1}^{n} t_i$$

$$\sigma^2 = \frac{1}{n}\sum_{i=1}^{n} (t_i \quad \bar{t})^2$$

Here, A refers to the influence coefficient,

ti refers to actual maintenance therbligs time in the certain status of a maintainability quantitative requirement,

$\bar{t}$ refers to the mean value of ti,

σ2 refers to the variance of ti,

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ts refers to virtual maintenance therbligs time,

n refers to the statistical number of actual time.

Table *1*

How to get a virtual maintenance time? Firstly, we should divide the maintenance work into some basic maintenance therbligs. At maintenance

After a large number of calculations, we have got all the influence coefficients of different maintenance therbligs in different situations, shown in

therbligs layer, we could use these influence coefficients in the incidence matrix to revise the simulation time. The equation below shows how to get the maintenance task time.

$$T_{Task\,j} = \alpha_1\left(1+\sum A_{1i}\right)T_1 + \alpha_2\left(1+\sum A_{2i}\right)T_2 + \cdots + \alpha_{20}\left(1+\sum A_{20i}\right)T_{21} + T_j'$$

Here, TTaks j refers to time of the maintenance therbligs j,

α_j refers to time that the maintenance therbligs j appears,

A1i 、 … 、 A20i refer to the influence coefficients,

T1、…、T20 refer to maintenance therbligs time,

Tj' refers to the compensation between maintenance therbligs in the maintenance task j.

To get the virtual maintenance work time, we could also combine the maintenance task time and compensation together, shown in the equation below.

$$T = \sum_{j=1}^{10} \beta_j T_{Taks\,j} + T'$$

Here, T refers to virtual maintenance work time,

β_j refers to time that the maintenance task j appears,

$T_{Taks\,j}$ refers to time of the maintenance task j,

T' refers to the compensation between maintenance tasks.

4. CASE STUDY

This section takes a certain virtual maintenance process of meteorological radar control unit as an example, and proves the practicality of the corrective method. In the virtual course, a virtual human may pick a tool up in his hand, walk to the maintenance position, stoop down and strip the control unit. What makes it complex is that the unit is assembled in a narrow cabin with a small cap. The virtual human should finish the strip with a bad visibility and operating space. The entire virtual maintenance environment and the characteristics of control box are shown in Figure 6

4.1 Virtual maintenance time with MTM

After investigating the actual maintenance course, we have simulated it with DELMIA in which human operation time is measured by PTS. As a relatively easy maintenance work, it could be directly broken down into several maintenance therbligs which are mentioned in Figure 5. A relatively accurate maintenance therbligs time is shown in Table 2.

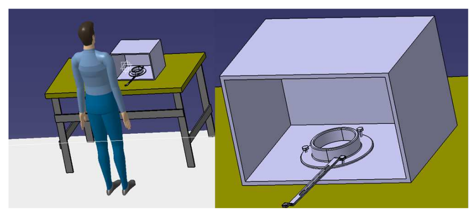

Figure 6 Visibility and operating space of the control unit

4.2 Corrective virtual maintenance time

The incident matrix, shown in **Error! Not a valid result for table.**, is used to correct the maintenance time. As a matter of fact, maintenance time is only influenced by the visibility and operating space. According to the rules, the visibility of control box could be classified into level 2 and operating space into level 3. The influence coefficients in **Error! Not a valid result for table.**and equations in section III are used to correct maintenance therbligs time. The corrective time is also show in Table 2

4.3 Comparison

According to a survey, we have got actual maintenance time date of the control box, shown in Table 2. Putting three groups of date of time together in Figure 7, we could obviously see how the incident matrix improves the efficiency of virtual maintenance time. Compared with virtual time based on PTS, the gap between corrective time and actual time is much smaller. Of course, there is still a gap between actual time and corrective time, which is caused by the factors like actual environment and human. However, influence coefficients used to correct maintenance therbligs time make the simulation time much more efficient and improve the availability of corrected MTM.

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Table 1 The incident matrix of influence efficient

			Visibility/A1			Accessibility/A2			Operation space/A3			Maintenance safety/A4			Working posture /A6		
			1	2	3	1	2	3	1	2	3	1	2	3	1	2	3
Mobile type of therbligs	Uniplanar move forward/T1		0	0.03	0.06	0	0	0	0	0.02	0.05	0	0.22	0.46	0	0.45	0.90
	Uniplanar move backward/T2		0	0.02	0.05	0	0	0	0	0.03	0.06	0	0.31	0.65	0	0.51	1.21
	Uniplanar move sideward/T3		0	0.04	0.09	0	0	0	0	0.07	0.14	0	0.23	0.46	0	0.48	1.12
	Up and down movement/T4		0	0.07	0.15	0	0	0	0	0.06	0.14	0	0.25	0.49	0	0.49	1.09
	Striding/T5		0	0.06	0.11	0	0	0	0	0.09	0.20	0	0.25	0.48	0	0.52	1.22
Posture-adjustive type of therbligs	Turning round/T6		0	0.04	0.10	0	0	0	0	0.05	0.12	0	0.05	0.13	0	0.65	1.42
	Crouching up and down/T7		0	0.06	0.12	0	0	0	0	0.06	0.16	0	0.07	0.14	0	0.64	1.35
	Hands raising and falling/T8		0	0.09	0.21	0	0	0	0	0.08	0.18	0	0.10	0.23	0	0.48	1.03.
	Legs raising and falling/T9		0	0.11	0.26	0	0	0	0	0.10	0.23	0	0.12	0.25	0	0.53	1.21
	Stoop up and down/T10		0	0.15	0.32	0	0	0	0	0.13	0.25	0	0.17	0.36	0	0.53	1.31
Operational type of therbligs	Hand operation	Position/T11	0	0.10	0.26	0	0.11	0.28	0	0.21	0.45	0	0.22	0.48	0	0.26	0.51
		Turn/T12	0	0.22	0.49	0	0.23	0.51	0	0.26	0.56	0	0.35	0.79	0	0.38	0.80
		Apply pressure/T13	0	0.03	0.08	0	0.13	0.26	0	0.21	0.46	0	0.25	0.51	0	0.27	0.56
		Crank/T14	0	0.16	0.36	0	0.26	0.56	0	0.31	0.65	0	0.41	0.86	0	0.42	0.91
		Grasp and bestow/T15	0	0.25	0.55	0	0.33	0.69	0	0.28	0.59	0	0.39	0.84	0	0.40	0.86
		Lift/T16	0	0.36	0.81	0	0.45	0.96	0	0.48	0.99	0	0.38	0.79	0	0.41	0.91
		Push and pull/T17	0	0.38	0.86	0	0.49	1.00	0	0.46	0.95	0	0.41	0.88	0	0.46	0.95
	Tools operation	Position/T18	0	0.12	0.32	0	0.26	0.56	0	0.23	0.41	0	0.20	0.45	0	0.31	0.65
		Prise/T19	0	0.09	0.21	0	0.13	0.27	0	0.26	0.56	0	0.16	0.39	0	0.25	0.56
		Screw/T20	0	0.25	0.56	0	0.29	0.61	0	0.32	0.65	0	0.32	0.68	0	0.36	0.81

Table 2 Three groups of maintenance time

Num.	Maintenance therbligs name	Time based on MTM/DELMIA	Level of visibility	Level of operating space	Corrective time	Time in actual course
1	Stoop down	0.18	1	1	0.18	0.21
2	Grasp	0.39	1	1	0.39	0.40
3	Stoop up	0.39	1	1	0.39	0.37
4	Turning round	0.988	1	1	0.988	1.11
5	Uniplanar move forward	2.652	1	1	2.652	2.74
6	Stoop down	0.109	1	1	0.109	0.16
7	Tool position	0.827	1	1	0.827	1.02
8	Tool crank	12.996	1	1	12.996	13.95
9	Tool position	0.945	2	2	1.0584	1.02
10	Tool crank	12.996	2	2	16.245	17.35
11	Tool position	1.174	3	3	1.550	1.63
12	Tool crank	12.996	3	3	20.274	22.35
13	Bestow	0.59	1	1	0.59	0.48
14	Grasp	0.46	1	1	0.46	0.54
51	Stoop up	0.109	1	1	0.109	0.18

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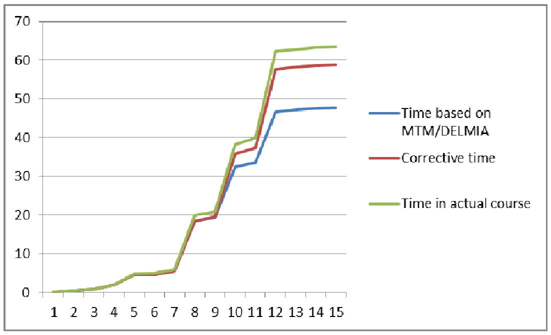

Figure 7 Comparison of the three kinds of time

5. CONCLUSION

Based on the characteristics of current virtual maintenance verification, this paper provides three kinds of factors, integrity, determinacy, verisimilitude, which makes the gap between virtual and actual maintenance time. To reduce the influence of verisimilitude, a new method that revises maintenance therbligs time by classifying the maintenance qualitative requirements was proposed. Next research, we would study how continuous factors, like temperature, humidity and sense of touch, influence the distribution of maintenance therbligs time and influence between maintainability in maintenance environment and human perception. A relatively accurate maintenance time could direct the maintainability design early and particularly.

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