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Virtual–real fusion maintainability verification based on adaptive weighting and truncated spot method

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Highlights

- Maintainability test is carried out in virtual–real fusion scenario with lower cost.
- The error of virtual–real fusion maintainability evaluation is reduced.
- The weights of real and virtual person test data are adaptively determined.
- Less time is consumed than the traditional virtual maintainability test.

Abstract

Maintainability is an important general quality characteristic of products. Insufficient maintainability will lead to long maintenance time and high maintenance cost, thus affecting the availability of products. Maintainability verification is an important means to ensure maintainability meets design requirements. However, the cost of traditional real maintainability verification method is very high, and the virtual maintenance method has insufficient verification accuracy due to the lack of large maintenance force feedback when the human body is moving. In order to reduce the evaluation error and test sample size, the paper conducts maintainability verification based on the mixed physical and virtual maintainability test scenarios. Aiming at the problem that traditional methods are difficult to deal with the real test information and synchronous virtual simulation information in the test process, this study proposes a virtual–real fusion maintainability evaluation algorithm based on adaptive weighting and truncated SPOT (Sequential Posterior Odd Test) method. It can weigh real test information and virtual human simulation information adaptively to obtain a virtual–real fusion maintainability test sample. Then, the SPOT method is used to evaluate the maintainability of small samples. The adjustment of valve clearance, replacement of air filter element and replacement of starting motor maintenance tasks of ship engine are taken as examples for demonstration. The virtual–real fusion and virtual maintainability verification methods are respectively used for verification, and compared with the physical maintenance scenario constructed by 3D printing, indicating that the accuracy of virtual–real fusion maintainability test verification is 89%, while the virtual maintainability verification is only 33%.

Keywords

virtual–real fusion maintainability, maintainability verification, adaptive weighting method, truncated SPOT method.

1. Introduction

1.1. Requirement analysis

Maintainability, like reliability, is an important general quality characteristic of products [23]. Insufficient maintainability will lead to long maintenance time and high maintenance cost, thus affecting the availability of products [5, 25]. Maintainability verification is an important means to discover the defects of product maintainability design and ensure that the qualitative and quantitative requirements of maintainability are met [16]. The traditional maintainability test verification is carried out on the physical equipment and real maintenance environment, so the verification is accurate, but the test cost is high and the test cycle is long [2], as shown in Fig.1. The virtual maintainability test is carried out on the digital prototype of the product as shown in Fig.2, which can reduce the requirements of the physical test prototype, which has become a highly concerned maintainability verification method [12]. Virtual reality technologies such as motion capture and data glove technology can be used to achieve the virtual maintenance operation by real human. However, in the process of maintainability test, there is always a lack of force feedback mechanism that can adapt to large scene and large maintenance force, and there will be

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various errors such as virtual environment positioning error, motion capture delay, collision feedback delay, etc. [27], which will greatly affect the accuracy of maintainability evaluation [6]. How to reduce the test cost while ensuring the maintainability verification accuracy is an important problem to be solved urgently.

1.2. Overview

In the past 20 to 30 years, many scholars have carried out a lot of new technology research to solve the problem that traditional maintainability verification depends on physical test and requires a high sample size. They mainly focuse on two aspects.

Fig. 1. The real maintainability verification

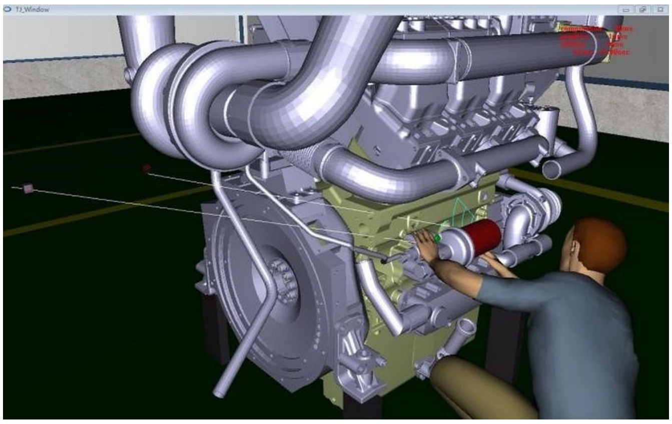


Fig. 2. The virtual maintainability verification

First, the maintainability test still uses the physical prototype, but the cost is reduced by less test times, and several new maintainability test data processing and verification methods are studied. The number of samples given in the maintainability standard is at least 30 [8, 20]. Miao et al. adopt the idea of segmentally weighted verification and propose the segmentally weighted verification (SWV) method to realize in-lab data verification. Then, the Dempster–Shafer evidence theory based integrative verification method is presented to solve the problem of in-lab and field data combination [19]. Wu et al. propose a novel prior distribution elicitation method for MTTR Bayesian demonstration. The test requires fewer samples than traditional methods that require no less than 30 samples relies heavily on expert experience and can be time consuming if performed manually [31].

The second is to adopt the virtual maintenance based test method, mainly focusing on how to improve the fidelity of human-computer interaction [10-12, 15, 24]. Desktop virtual maintenance is relatively simple [29]. In reference [24], a desktop virtual reality-based integrated system is developed for complex product maintainability verification. Guo et al. review the application of virtual reality technology in product maintenance, and deeply analyze the application field and effect, virtual reality hardware, development platform and current main research focus [12]. In reference [17], Luo et al. propose a method for quantitative evaluation of maintainability based on qualitative attributes of maintainability. The development of virtual reality technology can enhance the immersion and simulation fidelity of the maintenance process; thus, [10] and [11] combine the operation information of a real person and virtual information to carry out the maintainability evaluation and obtain higher evaluation accuracy. The difficulty of haptic and haptic interaction is a key problem in virtual reality [22]. The tactile feedback based on the data glove and the small force feedback of the hand under the fixed position are relatively mature [18]. Overtoom etc. provide a systematic overview of the literature assessing the value of haptic and force feedback in simulators teaching laparoscopic surgical skills [22]. It is still very difficult to apply the tactile feedback when the human body is moving [27]. The maximum feedback force is generally only 20N, which is difficult to meet the feedback needs of maintenance operations [21, 26]. So there are some researches on the modification of human model data by compensating for the influence of external factors on human motion[9, 28, 33]. For example, Grochow et al. propose an inverse kinematics method based on physical kinematics characteristics, which combine global nonlinear dimensionality reduction technology, Gaussian process latent variable model (GPLVM), and a priori kinematics model. It is suitable for correcting similar small-scale human motion data [9]. Seemann et al. propose a method to generate a modified new trajectory by projecting the observed position, velocity, and acceleration on the corresponding constrained manifold, ensuring the consistency of motion parameters [28]. Reference [33] proposes a hybrid method of real-time human motion capture using simplified marker sets and monocular video, then an improved inverse motion solver is used to estimate pose based on marker positions.

1.3. Focused questions

Through the analysis of the current situation, we can find that the current methods still have some limitations. For complex equipment, such as ship and aircraft, when the traditional physical maintainability verification method is used, even if only a small number of samples are needed, a very complex test scenario must be built in order to reflect the impact of complex cabin environment on maintainability with unbearable cost [12]. In addition, the current methods still lack universality in solving the problem of virtual maintenance fidelity, and are difficult to solve the impact of lack of force perception on maintenance time and comfort. Therefore, considering the economy and accuracy of product test, the combination of virtual and physical test has received more and more attention [1, 30, 32, 34]. In the early stage, we carried out research on the construction technology of maintainability test environment based on virtual–real integration scenarios [6]. The maintenance test operation is carried out on the physical equipment, whereas the maintenance obstacles and surrounding equipment with less operations use virtual prototypes. All virtual prototypes are presented through AR glasses, which can effectively simulate the real maintenance scene and produce a good sense of immersion, as shown in Fig.3.

In the previous stage, a virtual maintainability test information fusion method based on t-test and F-test was proposed [7]. This study is to solve the problem of large maintainability evaluation error due to the introduction of virtual prototypes based on the virtual–real fusion maintainability test mechanism. The evaluation information of real human and the evaluation results of synchronous virtual human in the process of immersive and virtual–real fusion maintainability test is fully considered. The fusion method is used to reduce the uncertainty, the virtual and real data-level fusion is realized through adaptive weighting, and the truncated SPOT method is used for verification.

Fig. 3. Schematic of virtual reality integration

The rest of this paper is organized as follows: In Section 2, the proposed maintenance index verification method based on virtual and real information fusion is presented and discussed. In section 3, the maintenance tasks of ship engine are taken as examples for demonstration. Finally, in Section 4 the conclusions are provided.

2. Maintenance index verification method based on virtual and real information fusion

By carrying out the virtual–real integration maintainability evaluation test, the real maintainability test information and the virtual human maintainability test information can be obtained. In the test based on virtual–real fusion scene, the maintenance human carries out maintenance tasks on real maintenance object, so the obtained maintainability data is close to the real maintenance data. Meanwhile, because other equipment and environments around the real maintenance object are presented in the maintainer's field of vision through AR glasses, there will be some real registration errors and time delays, so the maintainability data has some deviations. The errors can be effectively avoided by using the virtual human test information obtained by motion capture during the test process. Therefore, the real and virtual human test data in the virtual–real integration maintainability test has strong complementarity.

The paper fully fuses the multi-source information in the test process to obtain the fused test samples, reducing the uncertainty of the underlying test data. In addition, in order to reduce the requirement for the number of test samples, the maintainability verification method based on small samples is studied. A truncated SPOT maintainability verification method based on the virtual–real fusion data is proposed, as shown in Fig. 4 to avoid the influence of motion capture error, virtual–real registration error, and tactile feedback error on the maintainability data in the virtual–real fusion maintainability evaluation test as shown in Fig. 4. Initially, for the same maintenance task, multiple maintenance tests are carried out in the virtual–real fusion scene, and the real test data and virtual human test data are obtained at the same time. Then, the adaptive weighted fusion algorithm is used to effectively fuse the two maintainability test datasets. Finally, the fused data are used as the field data, and the truncated spot maintainability verification method is used to analyze and verify the virtual–real fusion maintainability results to judge the rationality and effectiveness of the virtual–real fusion maintainability evaluation test scheme.

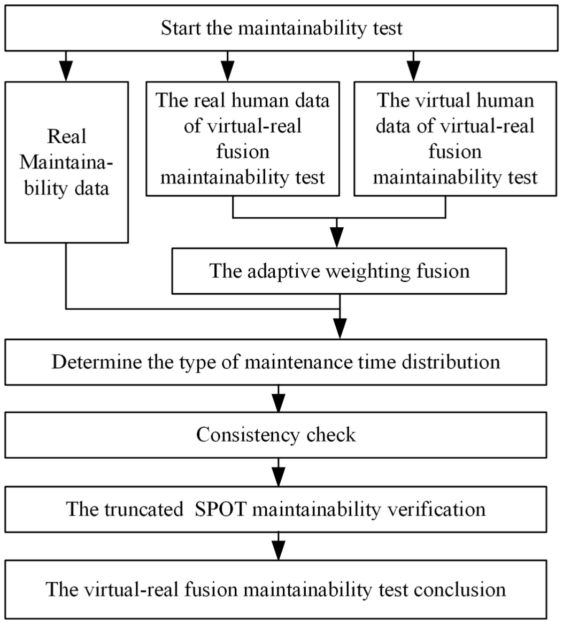


Fig. 4. Virtual–real fusion maintainability evaluation test method

2.1. Fusion method of virtual and real test data based on adaptive weighting algorithm

Inspired by the adaptive weighted fusion algorithm in the literature [13], this study regards the maintenance test results in different scenarios as the results obtained by different sensors measuring the same maintainability index in the maintenance process. The measurement results of the indicators are different. The adaptive weighted fusion method is used to perform data fusion obtained from different maintenance tests.

The real value of the maintainability index is assumed to be X. In the virtual–real fusion maintainability test, the maintainability index obtained by the real human evaluation is Xr, and the virtual human evaluation index obtained synchronously is Xx; their variances are σ_r^2 and σ_x^2, respectively. The corresponding fusion weights are φ_r and φ_x. According to the fusion model structure, we can obtain the following:

$$\begin{cases} X_R = \varphi_r X_r + \varphi_x X_x \\ 1 = \varphi_r + \varphi_x \end{cases}$$

The total variance is as follows:

$$\sigma^2 = E\left[\left(X-\overline{X}\right)^2\right] = E\begin{bmatrix} \varphi_r^2(X-X_r)^2 + \varphi_x^2(X-X_x)^2 \\ +2\varphi_r\varphi_x(X-X_r)(X-X_x) \end{bmatrix}$$

X_r and X_x are the maintainability data obtained in different maintenance scenarios; thus, they are independent of each other and are unbiased estimates of X, as follows:

$$E(X-X_r)(X-X_x) = 0$$

Therefore,

$$\sigma^2 = E\left[\varphi_r^2(X-X_r)^2 + \varphi_x^2(X-X_x)^2\right] = \varphi_r^2\sigma_r^2 + \varphi_x^2\sigma_x^2$$

The accuracy of the maintenance test data fusion results is inversely proportional to the size of the total variance. Therefore, when the fusion variance is the smallest, the accuracy of the fusion result is the highest. That is, the weights should satisfy the following:

$$\min \sigma^2 = \min\left((\sigma_r^2 + \sigma_x^2)\varphi_r^2 - 2\sigma_x^2\varphi_r + \sigma_x^2\right)$$

By Lagrange multiplier method, we can obtain the following [3]:

$$\varphi_r = \frac{\sigma_x^2}{\sigma_r^2 + \sigma_x^2}, \ \varphi_x = \frac{\sigma_r^2}{\sigma_r^2 + \sigma_x^2}$$

Subsequently, $X_r(i)$ represents the result of the *i*-th group of maintainability tests based on the virtual–real fusion scenario, and $X_x(i)$ represents the result of the *i*-th group of simulated maintainability tests based on the virtual maintenance scenario. The average value of the first *k* groups of the maintainability test data is calculated as follows:

$$\overline{X}(k) = \frac{1}{2k}\sum_{i=1}^{k}(X_r(i) + X_x(i))$$

Then, the estimated variance of the *k*-th group of maintainability tests based on the virtual–real fusion scenario can be expressed as follows:

$$\sigma_{re}^2(k) = (\overline{X}(k) - X_r(k))^2$$

The final variance of *k* groups of maintainability tests based on the virtual–real fusion scenario is obtained as follows:

$$\sigma_r^2(k) = \frac{1}{k}\sum_{i=1}^{k}\sigma_{re}^2(i)$$

Similarly, the final variance value of the *k* groups of maintainability test based on the virtual maintenance scenario can be obtained as follows:

$$\sigma_x^2(k) = \frac{1}{k}\sum_{i=1}^{k}\sigma_{xe}^2(i)$$

Then, the fusion data X_R of *k* groups of maintainability test are obtained as follows:

$$X_R(k) = \frac{\sigma_x^2(k)}{\sigma_r^2(k) + \sigma_x^2(k)}X_r(k) + \frac{\sigma_r^2(k)}{\sigma_r^2(k) + \sigma_x^2(k)}X_x(k)$$

2.2. Maintenance time distribution type determination

Generally, the maintenance time obeys the log-normal distribution [14, 31], and the Kolmogorov method is used to test and analyze the real maintenance test data and the virtual–real fusion maintainability data to judge whether the log-normal distribution is obeyed. In the truncated SPOT method, the accumulated maintenance test data isused as the pre-test historical data, and the virtual–real fusion maintainability data is used as the field test data to verify the maintainability.

2.3. Consistency check

The variance and mean test method is used to test whether a significant difference between the real maintenance test data and the virtual–real fusion maintainability data. The two data parameters must be consistent to carry out maintainability verification.

2.4. Maintainability Verification

Let the maintenance time be *Y*, assuming that $Y_d = \ln Y$ obeys a normal distribution $Y_d \sim N(\theta, \sigma^2)$, where σ^2 known, or an estimate of its appropriate accuracy can be obtained from previous data. θ is an unknown parameter of the overall distribution and can be known by analysis and calculation based on real maintenance test data. According to the contract, the index value of the mean repair time (MTTR) is θ_0, the risk of the contractor is α, and the risk of the subscriber is β. The MTTR can be verified by the following methods.

The following assumptions are made:

$H_0: \theta = \theta_0$ $H_1: \theta = \theta_1 = \lambda\theta_0 > \theta_0$, $\lambda > 1$, where λ is the detection ratio agreed by the manufacturer and the subscriber. In general, $1.2 \le \lambda \le 1.5$.

For virtual–real fusion maintainability data time samples $X_d = (X_{d1}, \cdots, X_{dn})$, the post-test weighting ratio is obtained as follows:

Suppose: $H_0: \theta = \theta_0$, $H_1: \theta = \theta_1 = \lambda\theta_0 > \theta_0$,

where λ is the detection ratio, and $\lambda > 1$. In general, $1.2 \le \lambda \le 1.5$.

For virtual–real fusion maintainability data time samples $X_d = (X_{d1}, \cdots, X_{dn})$, the posteriori weighting ratio is obtained as follows:

$$O_n = \frac{P_1}{P_0} \cdot \frac{L(X_d \mid \theta_1)}{L(X_d \mid \theta_0)}$$

where $P_0 = \int_{-\infty}^{\theta_0} \frac{1}{\sqrt{2\pi v}} e^{-\frac{(\theta - \overline{Z_d})^2}{2S_{Z_d}^2}} d\theta$, $P_1 = 1 - P_0$.

The introduction of constants A, B, $0 < A < 1 < B$. According to Wald's point of view, $A = \frac{\beta}{P_0 - \alpha}$, $B = \frac{P_1 - \beta}{\alpha}$. The following judgment rules shall be adopted [4]:

(1) If $O_n \le A$, then the virtual–real fusion maintainability data satisfy the maintainability requirements, and the virtual–real fusion maintainability evaluation scheme is feasible.

(2) If $O_n \ge B$, then the virtual–real fusion maintainability data do not satisfy the maintainability requirements, and the feasibility of the virtual–real fusion maintainability evaluation scheme is poor.

(3) If $A < O_n < B$, then proceed to the next step.

① If $A < O_n < C$, then the virtual–real fusion maintainability data satisfy the maintainability requirements, and the virtual–real fusion maintainability evaluation scheme is feasible.

② If $C < O_n < B$, then the virtual–real fusion maintainability data do not satisfy the maintainability requirements, and the virtual–real fusion maintainability evaluation scheme is poor.

3. Demonstration

3.1. System construction

Taking a ship engine maintainability verification as a typical research case, the simulation environment of the real rear auxiliary engine room is shown in Fig. 5. The diesel engine is shown in Fig. 6, which is mainly composed of crank connecting rod mechanism, valve structure, fuel system, lubrication system, cooling system, and starting system.

The diesel engine needs to replace the fuel filter, air filter element, and other consumables, and the cylinder head needs to be opened to adjust the valve clearance. In addition, the starting motor has a certain failure rate; thus, it should be designed with good maintainability to ensure the rapid maintenance of the crew. Here, three maintenance tasks are selected to carry out the maintainability test: replacing the air filter element, replacing the starting motor, and adjusting the valve clearance.

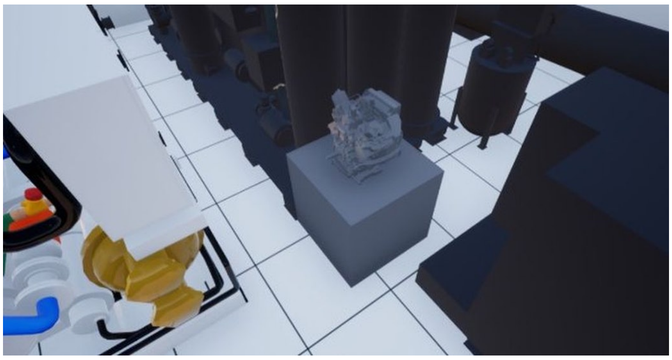


Fig. 5. Simulation of real rear auxiliary engine room environment

Fig. 6. Diesel engine to be studied

The main purpose of the example is to verify the maintainability verification method of virtual–real fusion. Three test methods are compared. The first is the real physical test. The real prototype is maintained and operated by real human, which represents the most accurate test conclusion. The second is the virtual–real fusion test verification, which uses the data obtained from the real operation of the physical prototype and virtual environment, and carries out the sequential verification of the data fusion method proposed above. The third method is to operate the virtual prototype by human. Although the tactile and force senses are not mature enough, this test can simulate the operation process to a certain extent.

Due to the high cost of carrying out live maintenance tests, and the test operation also has certain safety risks, the main equipment of the ship's auxiliary engine cabin is obtained in the laboratory by using the complete digital model of the ship's auxiliary engine compartment and 3D printing. The space layout is carried out according to the relative position relationship of each equipment in the real cabin, so as to simulate the real ship's cabin maintainability test scenario, as shown in Fig.7.

3.2. Maintainability verification of valve clearance adjustment task

(1) Test operation and data acquisition

Fig. 7. 3D printed cabin equipment

Prior to adjusting the valve clearance, the cylinder head, which is connected with the engine body through three No. 10 fixing screws, is removed. Therefore, the maintenance tools include No. 10 hex wrench and slotted screwdriver. The operation steps of the maintenance process are shown in Fig.8.

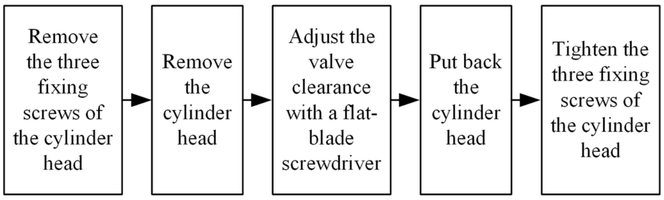
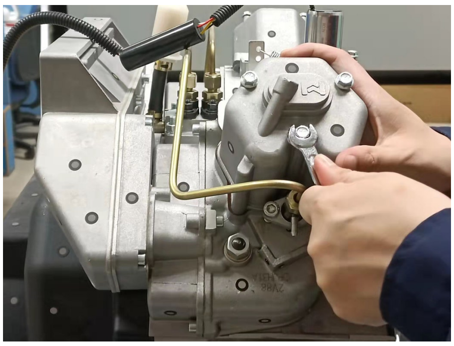


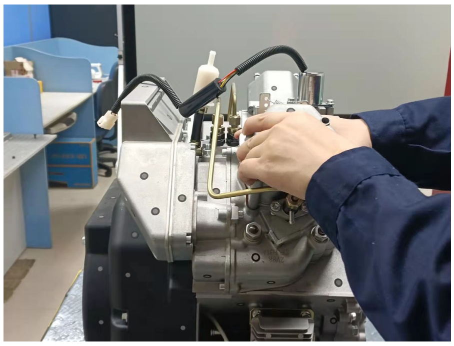
Fig. 8. Operation steps of adjusting the valve clearance maintenance

The operation method of the main process is shown in Fig.9.

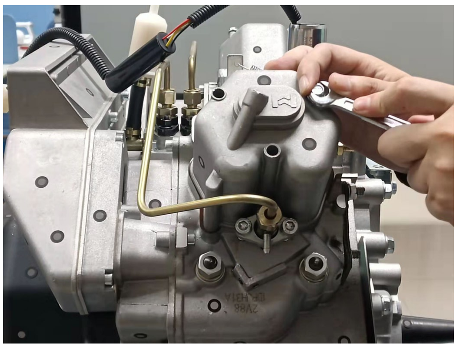
The human and virtual human maintenance data can be obtained at the same time by carrying out the virtual–real fusion maintainability test, the process is shown in Fig.10. The virtual maintenance data can be obtained by correcting the errors of the virtual human data, considering the various errors in the virtual–real fusion test. At the same time, the real maintainability test and virtual simulation test are carried out to compare with the virtual–real fusion test, as shown in Fig.11 and Fig 12.



a) Remove the screws



b) Remove the cylinder head



c) Adjust the valve clearance

Fig. 9. Adjustment of valve clearance Service procedure

Fig. 10. The virtual–real maintainability test

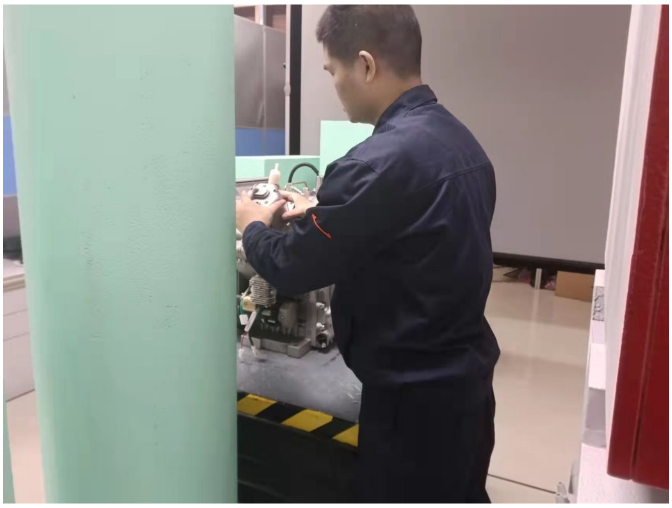


Fig. 11. The real maintainability test

Fig. 12. The virtual maintainability test

The virtual–real fusion maintainability test is conducted repeatedly for 10 times to reduce the randomness of the single maintenance test and ensure the reliability of the test results. At the same time, 10 real maintainability tests and virtual simulation tests are carried out to facilitate comparison and analysis with the virtual real fusion test. The maintainability test results are shown in Table 1.

(2) Virtual and real data fusion

Table 1. Adjustment of valve clearance maintainability test results

	Real maintenance time /s	Virtual–real fusion maintainability data		Virtual data time /s
		Human maintenance time /s	Virtual human maintenance time /s	
1	342	355	353	403
2	358	379	367	394
3	359	307	331	440
4	360	329	342	469
5	348	363	359	431
6	353	398	377	373
7	364	350	353	356
8	356	324	340	413
9	347	359	357	410
10	356	387	371	378

According to the adaptive weighted fusion algorithm in Section 2.2, the fusion test data are calculated according to the real maintenance data and the virtual maintenance data, and the fusion results are shown in Table 2.

Table 2. Fusion results of maintainability test data

	$X_1(k)$	$X_2(k)$	$\overline{X}(k)$	$\sigma_1^2(k)$	$\sigma_2^2(k)$	$\varphi_1(k)$	$\varphi_2(k)$	$X_r(k)$
1	355	353	354.0	1	1	0.5	0.5	354.0
2	379	367	363.5	120.6	6.6	0.052	0.948	367.6
3	307	331	348.7	660.0	108.8	0.142	0.858	327.6
4	329	342	345.4	562.2	84.5	0.131	0.869	340.3
5	363	359	348.5	491.8	89.7	0.154	0.846	359.6
6	398	377	355	718.0	155.4	0.178	0.822	380.7
7	350	353	354.5	618.3	133.5	0.178	0.822	352.5
8	324	340	351.7	636.9	133.9	0.174	0.826	337.4
9	359	357	352.4	571.0	121.4	0.175	0.825	357.4
10	387	371	355.1	615.7	134.5	0.179	0.821	373.9

The comparison chart is drawn according to the test data and the fused data, as shown in Fig. 13.

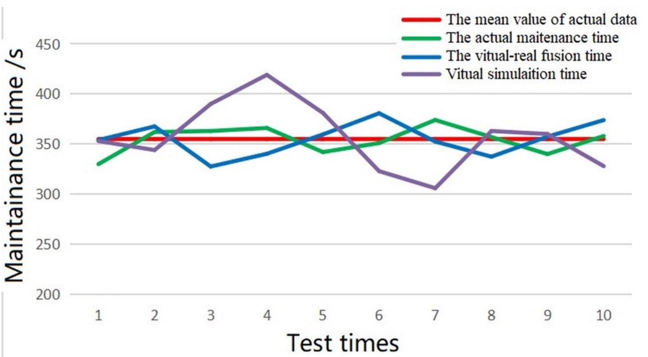


Fig.13. Maintenance data comparison

Fig. 13 shows that the virtual–real fusion data are closer to the actual maintenance data than the virtual simulation data, and the virtual–real fusion maintainability test can reflect the maintenance process more truly. Thus, the accuracy of the virtual real test data fusion method using the adaptive weighting algorithm is confirmed.

(3) Time distribution check

The real maintenance data in Table 1 are considered historical data, and the data $X_r(k)$ obtained by fusion in Table 3 are considered

Table 3. Kolmogorov test calculation table (historical data)

	$X_1(k)$	$X_2(k)$	$\overline{X}(k)$	$\sigma_1^2(k)$	$\sigma_2^2(k)$	$\varphi_1(k)$	$\varphi_2(k)$	$X_R(k)$
1	355	353	354.0	1	1	0.5	0.5	354.0
2	379	367	363.5	120.6	6.6	0.052	0.948	367.6
3	307	331	348.7	660.0	108.8	0.142	0.858	327.6
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8	324	340	351.7	636.9	133.9	0.174	0.826	337.4
9	359	357	352.4	571.0	121.4	0.175	0.825	357.4
10	387	371	355.1	615.7	134.5	0.179	0.821	373.9

field data to evaluate the virtual–real fusion maintenance scheme. Assuming that the historical maintenance time is $Y=(y_1,...,y_n)$, let $X=\ln Y=(x_1,...,x_n)$. Whether X follows a normal distribution should be checked.

The following can be calculated: $\hat{\mu}=\overline{X}=\frac{1}{10}\sum_{i=1}^{10}x_i=5.869$, $\hat{\sigma}^2=\frac{1}{9}\sum_{i=1}^{10}(x_i-\overline{X})^2=0.001396$. The sample values are arranged from small to large (repeated data are combined), and the frequency corresponding to each order statistic is n_i. Table 3.3 shows the calculation detail. The table indicates that $\hat{D}_n=0.1783$, and the significance level $\alpha=0.2$. The critical value table of Kolmogorov test indicates that $\hat{D}_{n\alpha}=0.3226$. Thus, it obeys the normal distribution, that is, the maintenance time obeys the log-normal distribution. In addition, the field maintenance time obeys the log-normal distribution.

(4) Consistency check

The maintenance time has been shown to follow a log-normal distribution; thus, only a parametric test is required. For the convenience of research, the logarithm of historical data and field data is considered (denoted as X_1, X_2, respectively) and transformed into normal distribution for further research.

As mentioned, $n_1=10$, $n_2=10$, $\overline{X}_1=5.869$ $S_1^2=0.001396$ $\overline{X}_2=5.871$ $S_2^2=0.002457$, and $\alpha=0.1$.

The variance $F'=0.5682$ is tested, and because $F_{0.95}(9,9)<F'<F_{0.05}(9,9)$, no difference is found in their variances. The mean value $t'=-0.0967$ is also tested, and because $-t_{0.95}(18)\le t'\le t_{0.95}(18)$, no difference is found in their mean value. Therefore, the historical data and the field data passed the consistency test.

(5) Maintainability verification

In $X\sim N(\theta,\sigma^2)$, the variance is estimated from the field data as $\tilde{\sigma}^2=0.002457$ and $\theta\sim\pi(\theta)=N(5.869,0.001396)$. The index value of MTTR is 355 seconds, and then $\theta_0=5.871$. Let $\alpha=0.2$, $\beta=0.15$, and $\lambda=1.4$, that is, $\theta_1=1.4\theta_0$.

The average repair time is verified according to the Bayes sequential probability ratio test method. The following can be calculated: $P_{H_0}=0.5199$ and $P_{H_1}=0.4801$. Then, we can obtain $\Lambda(X)=0.1821$ and $O_n=0.1682$. Then, $A=0.4519$ and $B=1.5905$. The fusion data satisfy the maintainability requirements because $O_n\le A$, and the feasibility of the virtual reality fusion maintainability evaluation scheme is good.

(6) Results comparison

The above are the virtual–real fusion maintainability verification results, and its correctness and superiority need to be compared with the real and virtual maintainability verification results. Both real and virtual test data are from Table 1. The maintainability verification adopts the method specified in the literature [20]. By calculation, the real test passes verification, while the virtual test data fails to pass the consistency inspection due to the scattered data, so it is impossible to judge the maintainability level of valve clearance adjustment. This shows that the result of virtual–real fusion is consistent with the real experiment and the virtual experiment can not get the correct conclusion.

3.3. Maintainability verification and comparison of other tasks

Using the same test process and method as above, the maintainability test is carried out for the replacement of air filter element and the replacement of starting motor maintenance tasks respectively, and the virtual–real fusion maintainability test is compared with the real test and virtual simulation test. The operation processes pictures are shown in Fig.14 and Fig.15.

Since only one verification conclusion can be obtained from 10 test repairs and corresponding data, 3 groups of tests are carried out for each maintenance task to verify the stability of the method, and each group of tests should compare the three test modes. The real maintainability test is the benchmark, and it is the correct data no matter whether the maintainability meets the requirements. If the virtual–real fusion maintainability verification and virtual maintainability verification are the same as the real test conclusion, then the judgment result is correct, otherwise, it is wrong. Table 4 lists the maintainability verification results of different maintenance tasks.

Table 4 shows that the accuracy rate of the virtual–real fusion test maintainability verification results is 88.9%, whereas that of the virtual simulation test maintainability verification results is only 33.3%. Evidently, the accuracy of the virtual–real fusion maintainability evaluation results is significantly higher than the latter and is closer to the real maintainability test evaluation results. Therefore, the virtual–real fusion maintainability evaluation for ship equipment has strong feasibility.

Further analysis shows the main reasons for the higher accuracy of the virtual–real fusion maintainability test verification are: (1) The real operation is carried out on the real object, and its force touch is consistent with the actual. (2) During the test, the maintenance environment is superimposed, which can reflect the influence of maintenance space on maintenance operation. (3) The fusion of virtual and real data are adopted to reduce data error further.

The main reasons for the low accuracy rate of virtual maintainability verification are: (1) Although it can simulate the maintenance environment and space, and has good test vision, it is difficult to establish touch and force sense, resulting in a large error compared with the actual maintenance operation. (2) Single test is difficult to reflect detailed operations accurately, such as screwing, wiping, etc. The test is subjective and unstable. (3) Just like the virtual-real fusion

a) real test

b) virtual–real fusion test

c) virtual simulation test

Fig. 14. Maintainability test of air filter replacement

a) real test

b) virtual–real fusion test

c) virtual simulation test

Fig. 15. Maintainability test of starting motor replacement

Table 4. Maintainability verification results of different maintenance tasks

Maintenance task	No.	Real test	virtual–real fusion test	virtual test
valve clearance adjustment	1	√	√	×
	2	√	√	√
	3	√	√	×
the air filter replacement	1	√	√	√
	2	√	√	×
	3	√	√	√
starting motor replacement	1	×	√	√
	2	×	×	√
	3	×	×	√
accuracy rate		100%	88.9%	33.3%

Note: "√" indicates that the maintainability satisfies the requirements, and "×" indicates that the maintainability does not satisfy the requirements.

maintainability verification, the complementary data cannot be fused, which leads to large errors in the verification data.

4. Conclusion

In this study, real and virtual maintenance data are fused by adaptive weighting algorithm, thereby reducing the influence of the errors in the virtual–real fusion maintainability test on the maintenance results. The experimental results show that the fused data are closer to the results of the real maintenance test. Then, the fusion data is evaluated and verified using the truncated spot method. The results show that the virtual–real fusion maintainability verification method has higher accuracy and stronger feasibility than the virtual simulation test.

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