Testability Test Program Development Research

Jinpeng Yang[1], Guangyao Lian[2], Huijie Li[2], Bing Liang[2]
[1.] Army Engineering University, Shijiazhuang, China
Email: playanger@126.com
[2.] 32181 Force of PLA, Shijiazhuang, China

***Abstract*—In the equipment development stage, a testability verification test is required to test the testability index of the equipment to determine whether it meets the design requirements and decide to accept or reject it. Determining the protocol is one of the key techniques for the testability verification test, aiming to resolve the contradiction between the sample adequacy requirement and the constraint that the fault cannot be exhaustively injected. Based on a large number of domestic and international research status. This paper analyzes the advantages, disadvantages and applicable conditions of the existing experimental schemes. At the same time, this paper summarizes the key points of improving the current experimental scheme, and points out the development direction of further research.**

***Index Terms*—testability verification test, testability, sample size determination, fault injection, sampling test**

I. INTRODUCTION

In order to confirm the correctness of the test design and analysis, identify the design defects, check whether the developed products fully meet the test design requirements, it need to conduct the testability tests and evaluation in the process of equipment design and development[1]. The evaluation of testability verification test is based on the fault detection, fault isolation and indication results. The failure of the equipment to occur naturally does not meet the requirements of the specified sample. Therefore, it is necessary to introduce faults manually, that is, to perform a testability verification test based on fault injection in order to perform a prescribed test task. Many studies at home and abroad have emphasized the testability verification test based on fault injection [2].

The testability verification test is to extract he fault samples of the equipment, and detect and isolat the fault samples. The test results are analyzed according to the statistical model to confirm the testability level of the equipment. However, on the one hand, since the fault injection is limited by the structure of the product, the package, and the depth of access to the fault injection system, it is difficult to introduce a large number of samples when it is impossible to inject the fault[3];on the other hand, due to the sufficiency of statistical test samples, too small sample size will lead to the reduction of the credibility and accuracy of the test results[4]; there is a contradiction between fault injection and the principle of sample adequacy. The above contradictions are issues that need to be considered in the development of a test verification test program.

Therefore, this paper will synthesize the current research status of the testability verification test program at home and abroad, summarize the key technologies of the research on the test plan, and discuss the future development direction

II. RESEARCH STATUS OF TESTABILITY VERIFICATION TEST PROGRAM

A. Classification of test schemes

At present, the testability verification test scheme usually adopts the methods of the US military standard MIL-STD-471A notice 2, ADA report, GJB2072-94, GJBZ 20045-91 and so on[5-8]. Based on these criteria, some researchers have conducted extensive research on the improvement and optimization of testability validation protocols. According to the type of test, these schemes can be divided into success or failure type fixed sampling test plan, minimum acceptable value test plan, success or failure truncated sequential test plan, and testability verification test plan based on Bayes theory. According to the distribution type, it can be divided into a verification method based on binomial distribution and a verification scheme based on normal distribution.

B. Test plan based on binomial distribution

The test plan based on the binomial distribution and the formula for judging the acceptance/rejection are more difficult to solve, but more accurate results can be obtained by using a computer or a data table. The trial scheme based on the binomial distribution mainly has the following three experimental schemes.

(1)The success or failure fixed sampling test plan [1, 2].The idea of a typical success or failure test plan is to randomly extract n samples for testing, F of which fails. Specify a positive integer C , if $F \le C$,it is considered qualified; if $C < F$,it is considered unqualified [1].

The probability of passing or failing is based on the product failure detection rate and isolation rate level, which can be calculated by statistics. In the success or failure fixed sampling test scheme, the probability of product success is q, then in n trials, the probability of F failures is:

$$P(n,F\mid \text{q}) = \binom{n}{F}(\text{1-q})^F \text{q}^{n-F} \tag{1}$$

Among them, $\binom{n}{F}$ is a binomial coefficient, $\binom{n}{F}=\frac{n!}{(n-F)!F!}$.The probability of passing $L(\mathrm{q})$, that is, the sum of the probabilities of failures of 0, 1, 2... C in n test samples.

$$\mathrm{L(q)}=\sum_{F=0}^{C} P(n,F\mid q) \tag{2}$$

In the project, the manufacturer and the user will agree on four indicators of the party: design requirement value q0 of the failure detection rate and isolation rate, the minimum acceptable value of the failure detection rate and the isolation rate q1, the manufacturer risk α (the probability of failure when the quality level is reached), and the user risk β (the probability of passing the quality level is the limit quality). When the producer and the user negotiate and determine q0, q1, α, β, the following two formulas can be used to determine the test scheme and find the value of n and C.

$$\alpha = 1 - L(q_0) \tag{3}$$

$$\beta = \mathrm{L}(q_1) \tag{4}$$

For the convenience of practical use, (N, C) can be easily obtained by querying the data table [x].

This method is applicable to the infield fault injection test and can verify the test parameter values with the risk requirements of both parties, but it does not apply to the situation where there is a confidence level requirement.

(2)Minimum acceptable value test protocol [1, 2]. At the same time, the test plan considering the four parameters q0, q1, α and β is the standard sampling plan. The lowest acceptable value scheme considers only the lowest acceptable value q1 and the user risk β among the four parameters. After q1 and β are selected, N and C can be obtained by substituting the following formula.

$$\mathrm{L}(q_1) \le \beta \tag{5}$$

This equation has an infinite number of solutions, but it is still possible to look up the table [1] to find a suitable solution. When the minimum acceptable value q1 and the user risk β are selected, a series of test schemes that meet the requirements can be obtained by looking up the table. When the preferred scheme fails, the sample size can be increased, and the next scheme is selected to continue the test until it is determined (N, C).

This method is applicable to the infield fault injection test to verify the minimum acceptable value of the test parameters required by the confidence level, and is not applicable to the requirements of the manufacturer.

(3)Success or failure type censored sequential test plan [1]. The success or failure truncated sequential test protocol used in the test is also based on the binomial distribution. GB 5080.5-85[4] gives the sequential test plan data table according to the selected q0, D, α and β It can find the relevant parameters of the test protocol. Where: h(FD) is the total coordinate intercept of the test chart; s(FD) is the acceptance and rejection rate of the test chart; Nt(FD) is the number of censored test; Ct(FD) is the number of truncation failures [1]. A graphical representation of the success or failure truncation sequence is shown in Figure 1.

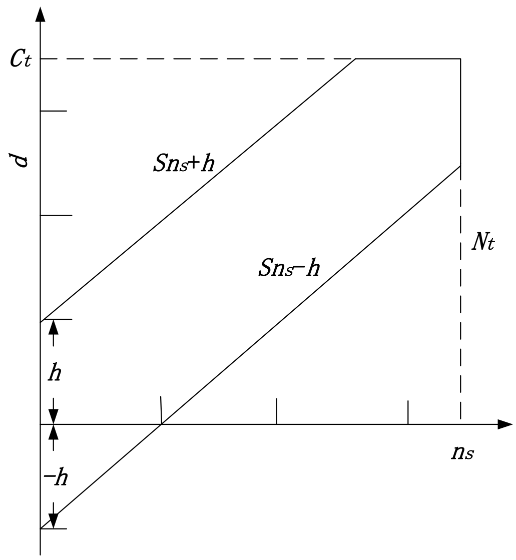

Figure 1 Censored sequential example

When $d \le s(FD)n_s - h(FD)$, It make a qualification criterion; when $d \ge s(FD)n_s + h(FD)$, It make a non-conformity criterion; when $s(FD)n_s - h(FD) \le s(FD)n_s + h(FD)$, It continue the test. Based on this, the number of test samples can be obtained [1].

The method is applicable to the in-field fault injection test to verify the test parameter values with the risk requirements of both parties, but it is not applicable to the situation with the confidence level requirement, and the determination process of the test plan is very complicated.

C. Based on the normal distribution protocol

(1)The Program of MIL-STD-471A notice 2 [1, 2, 5].The scheme is based on the estimation of the normal distribution interval, as shown in equation (6).

$$R_{U,L} = R \pm Z_C \sqrt{\frac{R(1-R)}{n}} \tag{6}$$

Ru, RL is the upper and lower confidence limits of the testability indicators evaluation. R is the point estimate of the indicator evaluation, is the design value of the test index when judging the acceptance or rejection. F is the number of failures. n is the determination test sample size. Zc is the confidence factor. The program does not give a sample size determination method. If it is determined by the maintainability verification test, the sample size should be no less than 30.

The scheme is simple and easy, but it has two disadvantages: one is that the larger the sample size, the less likely it is to pass the test; the second is the approximation method, when the index is greater than 90%, the evaluation error is larger.

(2)Test plan for GJB2072-94 [1, 2, 6]. In GJB2072-94, appendix C specifies a test protocol based on a normal distribution approximation.

When $0.1 \le R \le 0.9$, the one-sided confidence lower limit for the evaluation of test indicators is shown in equation (7).

$$R_L = R + Z_\alpha \sqrt{\frac{R(1-R)}{n}} \tag{7}$$

R_L is the one-side confidence lower limit, R is the point estimate for the indicator evaluation, n is the test sample size, Z_α is the confidence factor, and (1-α) is the confidence level.

When $R \le 0.1$ or $R \ge 0.9$, at the confidence level (1-α), the lower confidence limit RL of the test index is calculated as shown in equation (8).

$$R_L = \begin{cases} \dfrac{2\lambda}{2n-k+1+\lambda}; R \le 0.1 \\ \dfrac{n+k-\lambda'}{n+k+\lambda'}; R \ge 0.9 \end{cases} \tag{8}$$

Among, $\lambda = \frac{1}{2}\chi_\alpha^2(2k); \lambda' = \frac{1}{2}\chi_{1-\alpha}^2[2(n-2)+2]$.

When $RL \ge Rs$, it is received, otherwise it is rejected. This scheme gives a method for estimating the sample size, and the calculation is as shown in equation (9).

$$n = \frac{(Z_{1-\alpha/2})^2 R_S(1-R_S)}{\delta^2} \tag{9}$$

$Z_{1-\alpha/2}$is the 100th (1-α/2) percentile of the standard normal distribution, R_S is the required value of the test index, and δ is the allowable bias value.

This scheme has two advantages over the MIL-STD-471A announcement 2 scheme: one is that the RL estimate is more accurate, and the other is that the sample size estimate is given.

D. Test plan for estimating parameter magnitude [1, 2]

When the risks of both parties are not considered, the most common is the experimental scheme for estimating the magnitude of the parameters. The implementation of the program is divided into three major steps.

Step1: The sample size is determined. The required sample size is determined by the following three small steps.

(1)Minimum sample size estimate. The initial estimate of the sample size is as follows:

$$n_1 = \log_{R_L}(1-C) \tag{10}$$

$R_L$represents the lowest acceptable value of the test indicator. C is the confidence level. n_1 is an integer, indicating the amount of sample required to reach the RL each time the failure detection or isolation fails. Therefore, the test sample size should not be less than the n_1 value determined by the above formula. If the test sample size or the sample size of the existing data is less than the n_1 value determined by the above formula, then without analysis, it is certain that the lowest acceptable value of the specified lower confidence limit is not reached.

(2)Determine the minimum sample size required based on the test sample sufficiency principle. Fault isolation is to isolate the faults to the various units of the product as required, so the functional faults of the constituent units need to be verified to deal with the failure modes of the individual components of the product. In the testability verification test based on fault injection, it is necessary to ensure that each fault of each component has at least one sample. Therefore, according to the constraints of the sample adequacy criterion [4], the required sample size n_2 for the sufficient test is:

$$\mathrm{n}_2 \ge \lambda_U / \lambda_{\min} \tag{11}$$

Among, λ_U is the failure rate of the product; $\lambda_{\min}$ is the minimum value of the functional failure rate of the product component unit.

(3)Comprehensive comparison. In order to meet the above two requirements, the comprehensive test sample size takes a larger number in n_1 and n_2, which is:

$$\mathrm{n} = \max(n_1, n_2) \tag{12}$$

In the specific test, when n_2 is large, it can be determined directly according to $n=n_2$. When n_1 is large, samples can be added to a unit with a high failure rate until the total amount of samples is not less than n_1. Therefore, the sample size for the test should be equal to or greater than the value of n determined by this formula. However, this method is only applicable to situations where the risk of development is not considered.

Step2: Test sample allocation. After determining the sample size, a certain number of samples need to be selected from the fault mode set and distributed to each component of the system. Reasonable sample allocation can accurately reflect equipment failure conditions and achieve accurate estimation of test indicators. In this scheme, the number of samples of the failure mode Fi is calculated as shown in the equation (13).

$$n_{Fi} = n\frac{\lambda_{Fi}}{\lambda_U} \tag{13}$$

n_{Fi} is the number of samples assigned to the ith failure mode, λFi is the failure rate of the ith failure mode, and λU is the failure rate of the product.

Step3: Testability parameter estimation. A point estimate using a test indicator or a one-sided confidence lower limit estimate. The calculation is as shown in equation (14) (15).

$$R = \frac{n-F}{N} \times 100\% \tag{14}$$

$$\sum_{i=0}^{F} \binom{n}{i} R_L^{\,n-i} (1-R_L)^i = 1-C \tag{15}$$

Where *R* is the point estimate for the evaluation of the test indicators, R_L is the one-sided confidence lower limit, *C* is the determined confidence level, n is the determined sample size, and *F* is the number of test failures.

E. Small sample test protocol

The traditional testability verification test program requires a large amount of fault samples. Bayes theory can make full use of pre-test information to make up for the lack of field test information, and can effectively reduce the sample size of test verification test under the premise of ensuring equipment quality. The testability verification test scheme based on Bayes theory first determines the test pre-test distribution based on the test pre-test information, and then solves the minimum sample and the maximum qualified judgment number by Bayes theory [9-11].

In engineering, the Beta distribution of the binomial distribution is generally selected as the prior distribution of the success or failure equipment:

$$\pi(P) = Beta(P;a,b) = \frac{P^{a-1}(1-P)^{b-1}}{\beta(a,b)}, 0 \le P \le 1 \tag{16}$$

Based on this, Bayesian theory can be used to obtain the posterior distribution of equipment test indicators. The testability test plan can be expressed as (N, C). N and C jointly affect the probability of passing the verification when the selected equipment test index is P. When the minimum acceptable value P_1 of the fault detection rate and the design requirement value P0 are determined, it can be solved by the constraint risk α and the constraint of the user risk β(N, C) [10-11].

The classic Bayesian method can significantly reduce the sample size, but still has the following shortcomings:

(1)The use of test pre-test information is equivalent to an increase in the test sample size, but the pre-test information must be accurate, and the multi-source of pre-test information may lead to unsatisfactory reliability and validity of the evaluation.

(2)The traditional Bayes sample size determination method can only determine the sample size of a single test type.

In response to the shortcomings of the classic Bayes method, many researchers have begun work on this, such as:

(1)For the classical Bayes sample size determination method, only the sample size of a single test type can be determined, and the problem of the design requirements of the integrated test plan is not satisfied. The design effect index is introduced in the literature [12]. The design effect is constructed by using the test virtual test credibility and the Bayes maximum a posteriori interval average length. The virtual and real sample equivalent model is established and converted into a physical test sample. A test-type virtual-solid combination test without virtual test cost is proposed [12].

(2)In view of the multi-source nature of pre-test information affecting the reliability and validity of the evaluation, when using Bayesian theory for reliability analysis, the literature [13] puts forward the idea of introducing support vector machine (support vector machine, SVM) theory to study the strategy of weight distribution of information from different sources in pre-test distribution and integrate information on pre-test information [13]. Literature [14] proposed a fusion method based on probabilistic model for multi-source heterogeneous pre-experience distribution and verified the effectiveness by simulation experiments [14]. In the literature [15], based on the credibility of the rocket-assisted torpedo test, weighted pre-test distribution and post-test distribution of multi-source pre-test information are constructed, and the fault detection rate index value is integrated and simulated. The experiment verified its effectiveness [15].

There have been some achievements in the study of the two main problems of the classic Bayes method, but there are certain deficiencies. How to fully and effectively use the pre-test information and establish a decision-making model for optimizing the testability verification test plan to effectively reduce the test sample size is a hot topic of research and an urgent problem to be solved.

III EXISTING PROBLEMS AND DEVELOPMENT DIRECTION

The advantages and disadvantages of the test protocol and the applicable conditions are shown in Table I.

TABLE I.
COMPARISON OF TEST VERIFICATION TEST PROTOCOLS

Sample size determination method		advantages	disadvantages	Applicable conditions
Test plan for estimating parameter magnitude		(1) The qualification criteria are reasonable and accurate (2) Consider the characteristics of equipment (3) Give the parameter estimate	(1) Analytical work	Applicable to situations with confidence level requirements, not applicable fo α and β requirements
Based on the binomial distribution	Success or failure type sampling	(1) The qualification criteria are reasonable and accurate (2) clearly defined n and c	(1) No parameter estimates are given (2) Failure to consider the characteristics of equipment	Applicable to infield fault injection test, verifying the test parameter values with risk requirements of both parties, not applicable to the situation with confidence level requirements
	Lowest acceptable value	(1) The qualification criteria are reasonable and accurate (2) Consider the characteristics of equipment	(1) Only consider the minimum acceptable value	Applicable to the infield fault injection test to verify the minimum acceptable value of the test parameters required by the confidence level, not applicable to the requirement of α
	Success or failure truncation	（1）Eligibility criteria are reasonable and accurate （2）Small sample size requirement	(1) No parameter estimates are given (2) The test plan determines complexity	Applicable to infield fault injection test, verifying the test parameter values with risk requirements of both parties, not applicable to the situation with confidence level requirements
Based on the normal distribution	MIL-STD-471A	(1)Simple and easy	(1)No sample size determination method	Applicable to situations with confidence level requirements, not applicable for α and β requirements
	GJB2072-94	(1)Simple and easy	(1)Evaluation accuracy is not enough	
Small child	Protocol based on the Bayes	(1) The qualification criteria are reasonable and accurate (2) Significantly reducing the amount of test sample	(1) Only the sample size of a single test type can be determined (2) The multi-source nature of pre-test information will affect the reliability and validity of the assessment.	Applicable to infield fault injection test, verifying the test parameter values with risk requirements of both parties, not applicable to the situation with confidence level requirements

According to the survey and related data, the current experimental scheme for estimating the parameter magnitude is the most common. However, the testers have to carry out a large amount of analysis work before the test, and there are a large number of hardware limitations such as the difficulty of injection, the danger of fault injection, etc [16-18]. There are two main factors leading to the above situation:

(1)The advantages and disadvantages of the existing experimental schemes, there are limitations on the use conditions, the success or failure of fixed-sampling sampling, the lowest acceptable value and the success or failure truncated sequential test scheme cannot significantly reduce the sample size; Bayes method which can significantly reduce the sample size cannot obtain the ideal reliability and validity due to the information fusion problem of multi-source prior information.

(2)With the development of electronic technology, the problem of modularization, miniaturization, high integration and module packaging on the product makes fault injection more difficult. The sample size of the fault injection test should be as small as possible, and the formulation of the fault injection test plan should be more elaborate. In the process of gradually implementing the two-level maintenance support system, the application of the Line Replaceable Module (LRM) will make the above restrictions more prominent [19-21].

In view of the above general situation, further research in the following aspects is of positive significance:

(1)The information fusion technology of multi-source pre-test information in the experimental scheme based on Bayes theory should be further studied. And establish a more perfect model on the expression of a priori information and posterior information mapping, and improve the reliability and validity of the evaluation results based on Bayes theory. Future mature Bayesian-based protocols may significantly ease the conflict between sample sufficiency and small sample size.

(2)Sample allocation study considering multiple factors. The existing fault sample allocation scheme is mainly based on the failure rate stratified sampling allocation scheme. Although this method can effectively reflect the fault condition of the subject, but it is still possible to ignore other influencing factors, resulting in a sample set is not reasonable because of considering the single factor. A comprehensive consideration of multiple influencing factors in sample allocation can optimize the sample set of test validation tests to some extent. At present, researchers have conducted research on sample allocation methods that consider multiple factors. These studies use weighted ideas when considering multiple factors, which effectively improves the sample structure and improves the accuracy of index estimation. For example, He Yang considered the number of failure modes, the failure rate, the sum of fault diffusion strength and the degree of damage, and proposed a multi-factor based allocation scheme [22]. Zhang Xishan co-ordinated the effects of failure rate, fault impact, mean time to repair (MTTR) and test costs in the proposed integrated weighted allocation method [23]. Deng Lu et al. defined the concept of fault attributes, and considered five factors of failure rate, hazard degree, severity, spread degree and detection difficulty in the fault attribute [24]. Yu Siqi et al. constructed a replaceable unit contribution hierarchy model based on five factors: failure rate, hazard degree, detection isolation time, maintainability and test development cost, and he proposed a sample allocation scheme based on contribution [25]. However, due to the differences of the subjects and the limitations of the experimental stage, these programs have significant differences in the factors considered, and there is no more general allocation algorithm, which makes it difficult to implement the project application method considering multiple factors. Proposing an engineering-weighted allocation scheme is an urgent problem to be solved.

(3)A breakthrough has been made in the technology of fault injection. On the one hand, the optimal deployment of the fault injection point can be studied. The existing fault injection method is to analyze the fault mode (top event) first, and then randomly inject the fault (bottom event) from the board level component. The contribution of different bottom events to the top event is different. If the fault injection point is randomly selected without selection, it will lead to equipment damage, fault injection failure and evaluation distortion [26]. On the other hand, the fault transfer characteristics can be utilized. Simulate injection of fault signals or monitor simulated fault signals based on bus [27] outside the package module. And use certain isolation means or improve the fault-tolerant mechanism design of the product to achieve safe or even non-destructive injection of some fault injection points that may cause harm. This allows more samples to be implemented on the hardware, mitigating the need for a small sample size.

(4)The fault injection point of the fault injection cannot be implemented for the physical position limitation caused by the package, and an equivalent fault injection point is found to perform the fault injection test. In [28], a fault-state and fault-fault transfer characteristic analysis model based on Bayesian reliability propagation algorithm is established and a location inaccessible fault injection method based on the fault model is proposed [28]. This point can also be studied from the improvement and establishment of the fault tree model. Researchers have adopted dynamic fault tree models or introduced ambiguity and gray correlation into the fault tree model when studying reliability and fault analysis which can improve the objectivity of reliability calculation, improve reliability and safety, and better analyze failure modes, etc [29-31]. Successfully finding equivalent fault injection points can also achieve more samples and alleviate the need for small sample sizes.

IV CONCLUSION

Based on a large amount of data, this paper makes a comprehensive summary, comparison and analysis of the existing test verification test program, points out the existing problems, and forecasts the direction of further development.

REFERENCES

[1] Z. Tian and J. Shi, *Analysis and Verification of System Test Design*. Beijing: National Defence Industry Press, 2003.

[2] J. Shi, *Testability Design Analysis and Verification*. Beijing: National Defense Industry Press, 2011, pp. 276-289.

[3] T. Li, J. Qiu and C. Liu, “Failure sample distribution scheme for test verification test based on failure rate,” *Acta Aeronautica Sinica*, vol. 30(9), 2009.

[4] J. Shi and R. Kang, “Research on testability test scheme based on general adequacy criterion,” *Acta Aeronautica Sinica*, vol. 26(6), pp. 691-695, 2005.

[5] MI-STD-471A, *Maintenance management outline for system and devices*. U.S. Government Printing Office. 1983.

[6] L. Yu and F. Wu, “Inspection method of mean time to recovery taking the risk of both sides into account” *Tactical Missile Technology*, 2012.

[7] E. Lieblein and C. Wang, “US Department of Defense Software Initiative - Situation Report,” *Systems Engineering and Electronics*, vol. 1, 1987.

[8] D. Oksoy, “An Exact Analysis of the Method-One Maintainability Demonstration Plan in MIL-STD-471,” *IEEE Transactions on Reliability*, vol. r-21(4), pp. 207-211, 1972.

[9] L. Deng, A. Xu, W. Li, et al, “Testability verification test scheme based on Bayesian Theory,” *Journal of Nanjing University of Science and Technology*, vol. 6, 2014.

[10] A. Ahmed, “Bayesian using extension of Jeffreys Estimator of weibull distribution based on Type-I and II cnsored data,” *Trends in Applied Sciences Research*, 2014.

[11] C. Chang, J. Yang and L. Hu, “Testability Evaluation Method for Complex Equipment Based on Bayes Theory,” *Fire and Command Control*, vol. 37(11), pp. 173-176, 2012.

[12] G. Liu, J. Qiu, et al, “Design of tested virtual reality test based on Bayesian,” *Journal of Test and Measurement Technology*, vol. 6, 2014.

[13] Y. Fan and Z. Tian, “Reliability analysis of small samples based on Bayes Method,” *Mechanical Strength*, vol. 28(6), pp. 463-466, 2014.

[14] B. Liu and S. Gong, “Probabilistic model method for multi-source information fusion in Bayesian reliability evaluation,” *Electronic Product Reliability and Environmental Testing*, vol. 29(1), pp.10-13, 2011.

[15] G. Xing, Y. Shen and B. Liang, “Bayes fusion evaluation method for fault detection rate based on multi-source pre-test information,” *Science Technology and Engineering*, vol. 12(15), pp. 3606-3609, 2012.

[16] C. Chang, J. Yang and J. Wang, “Test verification and application research of radar equipment,” *Journal of Computer Measurement and Control*, vol. 19(8), pp. 1943-1945, 2011.

[17] J. Shi, C. Ji and H. Li, “Analysis of test verification technology and application status,” *Measurement and Control Technology*, vol. 31(5), pp. 29-32, 2012.

[18] Y. Yin, C. Shang, Y. Ma, et al, “Test method for test verification of radar equipment based on fault injection,” *Journal of Computer Measurement and Control*, vol. 22(7), 2014.

[19] S. Glista, W. Burns and B. Lessard, “F-22 lessons learned: Line Replaceable Module (LRM) electrical connector—an

investigation of vibration-induced contact wear and electro static discharge hardening," *Asme International Mechanical Engineering Congress & Exposition*, pp. 327-340, 2009.
[20] P. Wang, R. Zhang, Y. Zhu, et al, "Research and Application of LRM Structure Technology," *Fire Power and Command Control*, 2014.
[21] *Requirements for employing standard electronic modules*. Military Standand MIL-STD-378F, 1989
[22] Y. He, H. Li and Z. Wang, "Multi-factor based testability verification sample allocation scheme for electromechanical equipment," *Electro-optical & Control*, vol. 1, pp. 97-100, 2015.
[23] X. Zhang, K. Huang, X. Yan, et al, "Integrated weighted Allocation Method for Fault Samples in Test Verification Test," *Journal of Computer Measurement and Control*, vol. 23(1), pp. 139-142, 2015.
[24] L. Deng, A. Xu and X. Zhao, "Sample distribution scheme for test verification test based on fault attributes," *Journal of Test and Measurement Technology*, vol. 2, pp. 103-107, 2014.
[25] S. Yu, B. Jing and Y. Huang, "Research on sample distribution scheme of test verification test based on contribution degree," *China Testing*, vol. 41(2), pp. 91-95, 2015.
[26] E. Kouwe, C. Giuffrida and A. Tanenbaum, Evaluating Distortion in Fault Injection Experiments. Ninth IEEE International Symposium on High-Assurance Systems Engineering (HASE'05). IEEE, 2014:25-32.
[27] L. Nie, J. Feng, A. Liu, et al, "Design of fault injection on ARINC429 Bus," *Electronics Optics & Control*, 2014.
[28] T. Li, C. Hu and X. Zhou, "Location inaccessible fault injection method based on fault transfer characteristics," *Journal of Aeronautics*, vol. 32 (12), pp. 2277-2286, 2011.
[29] H. Qian, J. Luo, W. Jin, et al, "Reliability assessment of DEH system optimization based on dynamic fault tree Analysis," *Electric Power*, 2014.
[30] Z. Zhou, D. Ma, X. Yu, et al, "Application of fuzzy grey relational analysis method in fault tree analysis," *Journal of Electric Machines and Control*, vol. 3, pp. 60-64, 2012.
[31] J. Ho, P. Jin and G. Cai, "Failure mode of reusable rocket engine based on fuzzy fault tree and factorization analysis," *Journal of Aeros.*

Jinpeng Yang: (1993.1-), male, master, study in Army Engineering University. The main study field is testability design.