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On-Orbit Maintainability Verification Technology of Space Station

Zhen Lv*, Rong Fan, and Shuhong Feng

Aerospace System Engineering Shanghai, Shanghai, 201109, China

Abstract

On-orbit maintainability is one of the most important methods to extend the lifecycle of the space station, as it ensures the safety of astronauts and minimizes operating costs. Based on this, maintainability verification plays an extremely significant role in on-orbit maintenance and can verify the correctness and validity of the on-orbit maintainability. By conducting a comparative analysis and reviewing best practices both at home and abroad, this paper embarks on the mission of the China manned space station, combined with the requirements of objects, test items, and environment that need to be verified. The authors propose a ground testing by-step classification methodology and a simplified zero-gravity simulation separated space platform to accommodate the validation of the entire process on the orbital replaceable units.

Keywords: orbital replaceable unit; on-orbit maintainability; maintainability verification; ground testing; space station

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1. Introduction

At the beginning of the establishment of space stations, “Zarya”, the first space cabin, was launched by Russia on November 20, 1998 [1]. Space stations act as a platform for human beings to observe the earth and study astronomy and bio-science [2]. The lifecycle of a space station ranges from 10 years to 15 years on average. During this period, random faults may happen on any type of device. In this case, on-orbit maintenance is a very effective solution. On-orbit maintainability is regarded as a very important tool to extend the lifecycle of space stations, ensuring the safety of astronauts and lowering the maintenance costs [3-5]. On-orbit maintenance activity of International Space Station is shown in Figure 1.

Figure 1. On-orbit maintenance activity of the International Space Station

* Corresponding author.
E-mail address: lvzhen8212@163.com

Maintenance tasks are not equal to maintenance operation. A maintenance task always starts from the detection of the fault until the function recovery and completion of the task [6]. Engineers should perform maintenance design, analysis, and verification to ensure the process before the vehicle is launched [7], while maintainability verification acts as the critical step during the entire process of maintenance. Figure 2 presents the maintenance workflow and design projects.

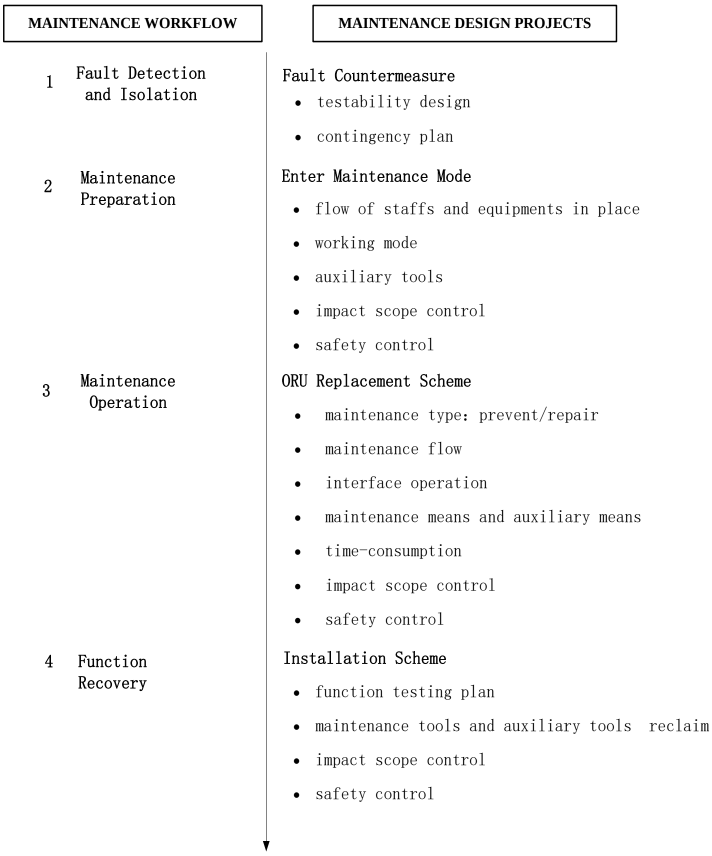

Figure 2. Work flow and design projects of the on-orbit maintenance

It can be broadly justified whether the quality and quantity targets of the maintenance work are compliant with relevant requirements [8]. Nowadays, several methods of maintainability verification have been studied and used, including analysis validation, simulation analysis, ground simulated testing, and on-orbit flight testing [9]. A proper method of maintainability verification depends on several factors, including the features of the spacecraft, the requirements of the maintenance, and the development of the project.

This paper embarks on the mission of the China manned space station. It proposes the by-step classification on-ground testing methodology after reviewing and comparing the existing maintenance validation methodologies. Meanwhile, it also establishes a zero-gravity simulation separated validation platform that accommodates the internal and external cabin ORU. In addition, it enhances the feasibility, availability, and economical efficiency of the work of maintainability verification.

2. Requirement Analysis of Maintainability Verification Task

2.1. Requirement Analysis of Verified Objects

Maintainability verification is a tool to verify whether the maintenance work can suffice the requirements of the key performance indicator. Verified objects are always referred to as the whole products with the designated feature and can be maintained on-orbit.

To ensure the safety and reliability of the spacecraft during its long working period on-orbit, the maintainability verification of a manned space station must resolve the following two major issues.

One issue is enormous verified devices. Given the occasional failure of electronic products, as well as the abrasion and stuck of institutional products, it is common to put the on-orbit maintenance functionality on the design of important device and function that include GNC (Guidance Navigation Control), energy, environmental, and thermal control, as well as information management and astronaut residence support. There are different impacts and maintenance timing even between the same types of ORUs. To the electronic device, the validation must be separated due to the different related downstream equipment. To the fluid pipeline equipment, the validation also has to be separated because of the layout. Different layouts mean different visualization and accessibility. Therefore, the quantity of ORUs for an independent-flight-spacecraft can be up to hundreds, which means there will be thousands of ORUs on the space station. Strictly, verification for each ORU cannot be substituted for other ORUs.

The second issue is the difficulty in testing and verification. It is a challenge to maintain the ORU including a single board of electronic products, fluid pipeline equipment, institutional products, equipment with precise installation, and large external cabin ORU. The maintenance should be verified thoroughly on the ground, which should take the requirements for the astronaut and manipulator into consideration as well as the complexity of the operations and environment restrictions [10]. It should be mentioned that verification on the ground is not equal to equipment assembly. The order of equipment assembly is prioritized by the comfortability of the operation. Meanwhile, for an aircraft in orbit, many of the key equipment cannot be shut down. It is more important to keep the station working than to make the operations convenient.

All figures should be numbered with Arabic numerals (1, 2, ⋯ , *n*). All photographs, schemas, graphs, and diagrams are to be referred to as figures. Line drawings should be good quality scans or true electronic output. Low-quality scans are not acceptable. Figures must be embedded as pictures into the manuscript and not supplied separately. Lettering and symbols should be clearly defined either in the caption or in a legend provided as part of the figure. Figures should be placed at the top or bottom of a page wherever possible, as close as possible to the first reference to them in the paper. Large external cabin ORU maintainability needs two astronauts, and manipulator assistant is shown in Figure 3.

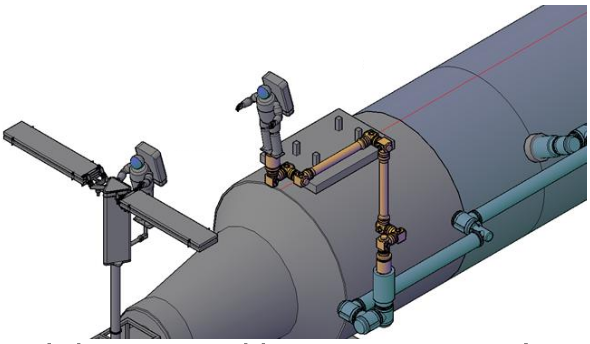

Figure 3. Large external cabin ORU maintainability requires two astronauts and a manipulator assistant

Accordingly, while designing the on the ground maintainability testing method and plan, factors including category, quantity, interface form, layout, and the challenges of on-orbit maintenance the designer should be considered to ensure reasonable project planning. To avoid fundamental changes in the product design and layout in the final project phase caused by maintenance plan adjustment, it is important to arrange the typical ORU verification at the very beginning, which usually is ORU of energy, environmental, and thermal control products as well as worse layout equipment.

2.2. Requirement Analysis of Verified Items

In general, hierarchy of ORU can unfold in three levels, including product, subsystem, and system (aircraft). The validation of the product level relies on mechanical, electric, fluid, gas, and thermal interfaces, as well as the maintenance scheme of the product. The validation of the subsystem level relies on its working mode, maintenance tool, impact, and time consumption, as well as interfaces between this product and others, which belong to the same subsystem. The validation of the system level focuses on breakdown isolation, maintenance working mode setting, maintenance flow, system recovery, ORU transfer, maintenance impact of the whole aircraft, and maintenance tools arrangement.

Compared with the validation of the product level, verified items of the subsystem, even the system level, are obviously much more complex, involving breakdown isolation, separation of electricity and information, maintenance mode shift in-and-out of the aircraft platform, as well as maintenance operations, support, and time consumption. Therefore, verified items can be classified into some types. One type proves the ORU maintenance process, operation design and space, tools, and time consumption. The typical method is the flume experiment. The other type of verified items proves the default location, power supply and information separation design, maintenance working model, and scope of maintenance impact, and it usually combines with the integrative test.

2.3. Requirement Analysis of Verification Environment

The environment needed by on-orbit maintenance relies on a weightless environment and workplace.

The weightless environment is the critical factor to be considered during on-ground maintenance verification. Due to the power of the acting force and counter-acting force, astronauts must use a handle and stopper while performing maintenance work. It is shown in Figure 4 that there are many handles and stoppers in the cabin that are throughout the whole activity area.

Figure 4. Handles and stoppers in the cabin

The relative position between the astronaut and the apparatus, operation pit, and maintenance tools is different from the regular on-ground maintenance operation. In addition, because of the limited operation around the ORU, the coverage of the maintenance tool, standing position of astronaut, and operation scope are confined in a certain area. The serious limitations of activity space and visibility range are also applied to the maintenance program of external cabin ORU when the astronaut is in a spacesuit.

Therefore, when a maintenance verification plan is designed, it should simulate the scenario of human beings, apparatuses, and tools in a weightless environment to reflect the ORU layout environment, i.e., the astronaut visibility scope and activity area to ensure the testing result is the most similar as that in reality.

3. Analyses of Maintenance Verification Methods

To stimulate the weightless environment of astronauts and ORU, on-ground testing methods have been extensively studied at home and abroad, among which such testing can be divided into mock tests and digital simulating tests. Digital simulating tests include computer picture simulation and VR simulation [11-12]. Mock tests include neutral buoyancy tank, parabolic flight, gas floating platform, hanging maneuver, drop tower, 1-g simulation, and hypobaric chamber [13-14]. This paper shows the comparison with the testing object, verified items, and the environment by some powerful methods.

As mentioned above, the quantity of ORUs for an independent-flight-spacecraft can be up to the hundreds. Almost all the ORUs should have their maintenance scheme under the cabin environment verified. If we use the maintenance verification methods in Table 1, long testing time consumption and excessive costs will not be avoided. Therefore, a proper on-ground maintenance verification method should be studied urgently to meet the requirements of the China space station. Figures 5-7 show the different laboratory methods.

Table 1. Comparison of on-ground maintenance verification methods

Method	Object	Item	Environment
1-g simulation (low accuracy, low cost)	Verify different types of ORU; certain area representing whole layout	Maintenance operations	Normal environment, 3D activity space
Hypobaric chamber (low accuracy, low cost)	Testify parts of maintenance scheme	Partial maintenance operations, partial maintenance supporting	Low pressure environment, 3D activity space
Gas floating platform (high accuracy, high cost)	Microgravity maintenance scheme	Maintenance operations	Microgravity; 2D activity space
Hanging maneuver (high accuracy, high cost)	Broad testing objects, almost representing layout	Maintenance operations, maintenance time, partial maintenance support	Microgravity, 3D activity space
Neutral buoyancy tank (higher accuracy, higher cost)	Broad testing objects, fully representing layout	Maintenance operations, maintenance time, partial maintenance support	Microgravity, 3D activity space
Computer picture simulation (high accuracy, low cost)	Broad testing objects, almost representing layout	Maintenance operations, maintenance time	Microgravity, 3D activity space
VR simulation (high accuracy, low cost)	Broad testing objects, almost representing layout	Maintenance operations, maintenance time	Microgravity, 3D activity space

Figure 5. Neutral buoyancy tank, ESA European Astronaut Center, Cologne, Germany

Figure 6. ESA’s maintenance verification in Airbus A300 with microgravity environment

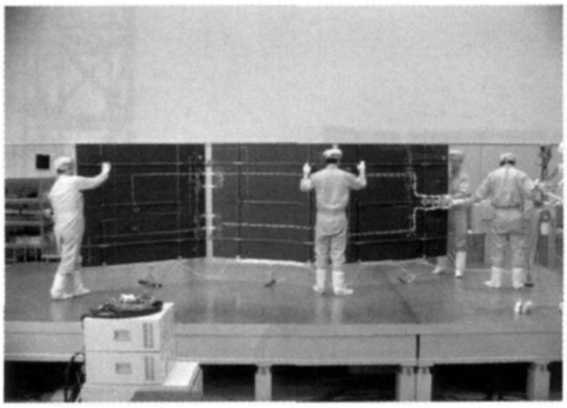

Figure 7. Japanese solar array maintenance test on gas floating platform

4. Study of Maintainability Verification Methodology

4.1. Study of By-Step Classification On-Ground Testing Method

Regarding the analysis results of maintenance verification requirements, this paper proposes a by-step classification on-ground testing method to accommodate the maintenance programs of enormous and complex ORUs.

This by-step classification method is based on detailed analysis of the tasks, while classified by verified objects, verified items, and verified methods. It can optimize the accuracy, cost, and time consumption of on-ground tests by extended objects and items while choosing the most proper method mentioned in Chapter 3 step by step.

The by-step classification on-ground testing method includes four steps, as follows.

The first step is to focus on typical ORUs, which should have earlier phase verification. These typical ORUs are defined by curbing ORU maintenance type, interface, and the difficulty of identification, usually including energy equipment, information equipment, and fluid pipelines. Visibility and attainability can be verified in this step, which usually takes place throughout computer picture simulations [15].

The second step is to focus on ORUs with difficult operations, such as those with complex operations and narrow operating space, as well as large-scale equipment. Maintenance operations and the scope of impact can be verified in this step for ORU and its tools, which usually occurs throughout computer picture simulation plus on-ground testing (e.g. 1-g simulation, hanging maneuver), as shown in Figure 8.

Figure 8. Maintenance of ORU with difficult operations by hanging maneuver

The third step is to focus on all kinds of ORUs at least with complex operations and small operating space. Maintenance verifications are performed in the simulated cabin environment. The maintenance procedure, operation, time consumption, scope of impact, and certain part supporting can be verified in this step, which usually takes place throughout 1-g simulation, hanging maneuver, and VR.

The fourth step is to face as many ORUs of the space station as possible. All the verified items mentioned in Section 2.2 should be verified. The hanging maneuver, neutral buoyancy tank, VR, and other methods can be used.

Verified items can be classified into operation tests and impact tests. Then, by classifying the testing environment, testing plans and methods can be nailed down (as mentioned by Table 1). The detailed classification method is shown as Table 2.

Table 2. Four steps of by-step classification on-ground testing method

	1st step	2nd step	3th step	4th step
Verified object	Different kind of product	Complex operating equipment, narrow operating space equipment, large-scale equipment	All kinds of ORU esp. Complex operation, small operating space based on simulated cabin environment	Maintenance operation and procedure for all kinds of ORU in cabin environment
Verified items	Visibility and attainability	Maintenance operation, maintenance tool, scope of impact	Maintenance procedure, maintenance operating, time consumption, scope of impact, certain part supporting	Maintenance procedure, operating design and space, tool, time; default identification, power supply and information separation design, maintenance working mode, scope of impact.
Verified method	Computer picture simulation	Computer picture simulation + on ground testing (1-g simulation, hanging maneuver etc.)	1-g simulation, hanging maneuver, VR	Hanging maneuver, neutral buoyancy tank, VR
Product illustration	Preventive maintenance ORU, fluid loop equipment, external cabin ORU	Greater impact scope, passably meet visual and attainable requirement, specialized tools	Cover the verified object in 1st step and 2nd step. Can make adjustment with reference to the current layout.	To cover ORU as more as possible

4.2. Simplified Partial Testing Platform

The verification of maintenance operation is the critical part of maintenance verification. It can mainly prove the ORU maintenance process, operating design, space, tools, and time consumption.

Based on the factors illustrated in Table 1, it is understood that the hanging maneuver and neutral buoyancy tank can simulate 3-D activities in the weightless environment with high accuracy but at a higher cost, which means it cannot perfectly meet the verification needs of the China space station. This paper proposes a simplified zero-gravity simulating partial testing platform that considers the adoptability, effectiveness, and cost of the lifecycle. It can verify the maintenance operation, space, and tools for the internal and external cabin ORU.

The zero-gravity simulating partial testing platform simplifies the internal and external cabin environment. The platform includes the internal cabin environment stimulated platform, external cabin environment stimulated platform, and zero-gravity hanging system for astronauts, products, and tools, as shown in Figures 9-11.

Figure 9 describes the zero-gravity hanging system. The system is designed as a passive balanced system, including a fixed pulley, tether, and balance weight. It has four degrees of freedom, which are upper and lower, front and rear, left and right, as well as rotational freedom.

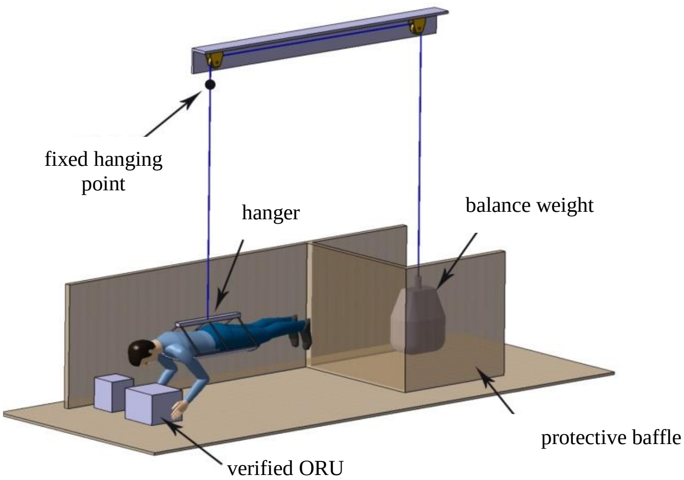

Figure 9. Zero-gravity hanging system

The internal cabin environment stimulated platform needs to build a cabinet on the ground as shown in Figure 10. The external cabin environment stimulated platform is built like a semicircle arcs cabin, along with obligated common interfaces on the surface as shown in Figure 11.

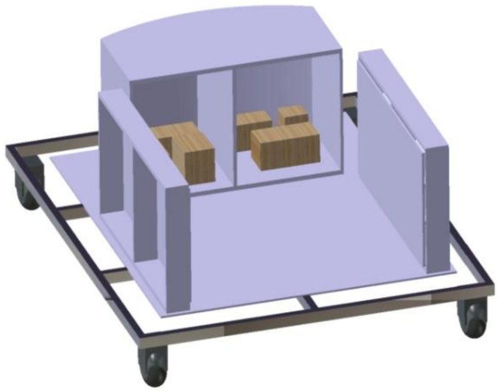

Figure 10. Internal cabin environment stimulated platform

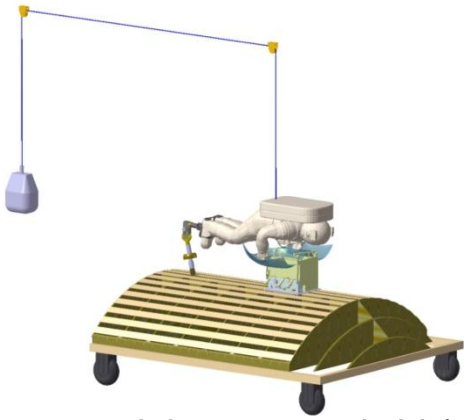

Figure 11. External cabin environment stimulated platform

4.3. Engineering Practice of Maintenance Verification

Different methods of maintenance verification have been used in the maintenance program for the China space station.

As expressed in Table 1, earlier phase verification should be arranged for typical ORUs of different kinds by computer picture simulation. Figure 12 shows the maintenance simulation of a lithium-ion battery. According to Figure 12, it can be concluded that the non-positive operation of ORUs has poor accessibility. Therefore, ORUs with non-positive operation should be verified one by one.

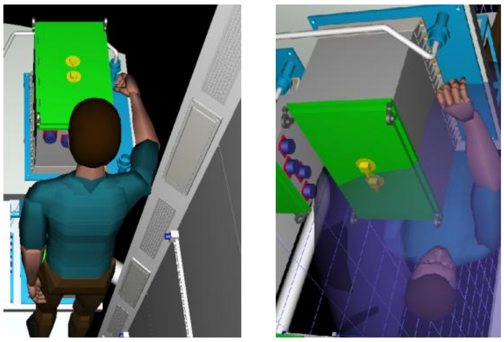

Figure 12. Maintenance verification by computer picture simulation

The zero-gravity simulating partial testing platform can be used for the second step verification in Table 2. In fact, this platform has already been practiced in real work. Figure 13 shows the maintenance verification by an engineer.

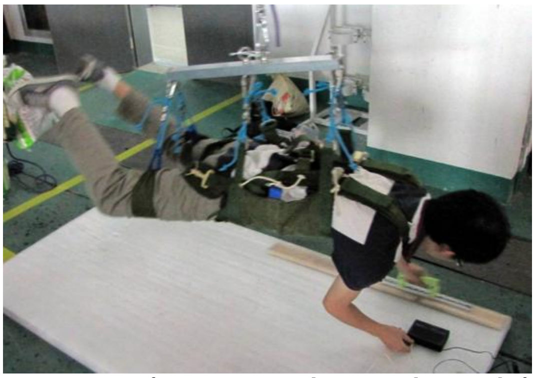

Figure 13. Practice of zero-gravity simulating partial testing platform

Then, maintenance verifications in the simulated cabin environment can be arranged. It is not necessary to equip all real products (the same configuration as launched) at the beginning. Figure 14 shows the first round of maintenance operation verification in the internal cabin environment.

Figure 14. First round of maintenance operation verification in internal cabin environment

After several rounds of improvement, the products with the same configuration launched can be equipped for testing. Then, the fourth step in Table 2 can be arranged to verify all the items using different tests and methods.

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