Application on the impact domain analysis of on-orbit maintenance in China Space Station

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Abstract. On-orbit maintenance is an important means to extend the service life and improve the reliability of the space station. As an essential part of maintainability analysis, impact domain analysis of on-orbit maintenance can find out the deficiency of maintainability design in advance and reduce the risk brought by maintenance. In this paper, the analysis method of the impact domain of the space station on-orbit maintenance is studied, and the working idea of "stage by stage, full coverage, focusing on key points" is put forward to adapt to the development and needs of China Space Station. The process, object, content, and analysis emphasis of the impact domain analysis for different development phases and different kinds of products are determined. The engineering practice shows that reasonable maintenance process and optimal design can be determined by the analysis of the impact area of on-orbit maintenance, which lays the foundation for the good maintainability of China Space Station.

1. Introduction

The space station provides a platform for long-term earth observation, astronomical observation and life science research in space orbit. The design life of space station including China Space Station is generally 10-15 years by international standard. On-orbit maintenance is an important measurement to extend the service life of the space station, ensure the safety of astronauts and reduce operating costs[1].

GJB 368B-2009 "General requirements for material maintainability program" and QJ 3124-2000 "Maintainability assurance requirements for aerospace product" stipulate that aerospace products should carry out maintainability analysis from performance analysis, thermal analysis, safety analysis, testability analysis, spare parts, tools, tolerance, emergency maintenance and other aspects. There are a lot of orbital replacement units (ORUs) in China Space Station, which brings out huge and tedious maintenance analysis work during the tight development cycle. In order to reduce the safety problems caused by insufficient maintenance risk identification [2] and the repetition of design and verification work, this paper presents an impact domain analysis method of on-orbit maintenance, which is also regarded as an independent maintenance work. The influences of electricity, gas, liquid, information and other aspects are collectively referred to as the maintenance impact domain. The impact domain analysis is always carried out from the early stage of development and has different key points from different kinds and levels of products. Through the analysis of impact domain of on-orbit maintenance, it can be comprehensively identified, including the impact on performance, function, reliability and safety of products at all levels, as well as...
formulating response strategies, improving maintainability design [3], so as to provide a design and verification basis for products at all levels.

2. Analysis method of impact domain of on-orbit maintenance
The impact domain analysis of on-orbit maintenance can be carried out from three dimensions, including time dimension, product level dimension and development stage dimension, as shown in Figure 1.

![Figure 1. Three dimensions of impact domain analysis of on-orbit maintenance](image)

Time dimension refers to the whole process of orbital maintenance task which is usually starting from finding fault until recovery after maintenance and task completion[4]. The dimension of product level refers to that the analysis of impact area of on-orbit maintenance shall cover three levels, namely ORU(single board / module, equipment, assembly), subsystem and system (cabin section, whole station). The dimension of development stage refers to the design, initial sample and formalized sample stage of model development. Time dimension determines the content of impact domain analysis, and product level dimension determines the object of impact domain analysis. The development stage dimension determines the focus of impact domain analysis.

2.1. Process of impact domain analysis of on-orbit maintenance
From the above three dimensions, we can determine the workflow of impact domain analysis of on-orbit maintenance, as shown in Figure 2. Among them, analysis objects can be determined by product level dimension, input information and analysis content can be determined by time dimension (i.e. maintenance process), and the focus of analysis can be determined by product level and development stage.
2.2. Objects of impact domain analysis of on-orbit maintenance

In order to reduce the risk, all ORUs in and out the cabin need to carry out influence domain analysis when conditions permit. However, there are so many ORUs in the space station that it will take a lot of time and energy if all ORUs carry out detailed analysis of the maintenance impact area. In this case, certain conditions can be selected to simplify the analysis process of some terminal items which have simple operation, spacious space, power supply and information interfaces.

This paper puts forward a working idea of "stage by stage, full coverage, focusing on key point" to meet the development demand of China Space Station. The whole analysis work is divided into three stages. In the first stage, all ORUs are selected conditionally to determine those products that need to be analyzed in detail. In the second stage, the analysis objects are selected and analyzed in detail. In the third stage, the single machine with technical state change and great influence will be reanalyzed and reconfirmed.

As we can see, in the above three stages of work, determining the principle for selecting the detail analyzed objects is the key to the work idea of "stage by stage, full coverage, focusing on key point". In this paper, taking China Space Station as a research object, the screening principles are determined, mainly including the following 4 items:

1) Impact domain analysis shall be carried out for all outer cabin ORUs;
2) In addition to the simple and independent preventive maintenance ORUs, other preventive maintenance ORUs need to carry out impact domain analysis;
3) ORUs which are close to the bulkhead or located in the cone section, structural neutral plate and other small operating space, as well as those may exist maintenance operation interference, need to carry out impact domain analysis;
4) Maintenance tasks those may lead to any function loss of the platform, or may need items of other subsystems to power on / off, as well as include operations of non hot pluggable connectors need to carry out impact domain analysis.

2.3. Content of impact domain analysis of on-orbit maintenance

Through sorting out the time dimension, i.e. the full maintenance process of an ORU, the content of the analysis of the maintenance impact domain is determined, as shown in Table 1.

First of all, collect comprehensive input information, including determining equipment failure criteria, sorting out maintenance related equipment, developing single machine maintenance process, defining equipment layout location, etc., to ensure the comprehensiveness of the maintenance
impact domain analysis. On this basis, the impact domain analysis is carried out from the system function, power supply impact, information impact, layout impact and other aspects. In addition, some equipment also need to analyze whether flight attitude control, thermal control, lighting, environmental control and other effects are involved.

**Table 1. Analysis content of impact area of on-orbit maintenance**

| Time dimension     | Content of impact domain analysis |
|--------------------|-----------------------------------|
|                    | System function | Power supply impact | Information impact | Layout impact | Others impact |
| ORU maintenance process | fault isolation | ✓ | ✓ | ✓ | ✓ |
|                     | status setting before maintenance | ✓ | ✓ | ✓ | ✓ |
|                     | access to maintenance work station | ✓ | ✓ | ✓ | ✓ |
|                     | remove the failure point | ✓ | ✓ | ✓ | ✓ |
|                     | installation of maintenance equipment | ✓ | ✓ | ✓ | ✓ |
|                     | status setting after maintenance | ✓ | ✓ | ✓ | ✓ |
|                     | status recovery after maintenance | ✓ | ✓ | ✓ | ✓ |

Note: Others impact included: flight attitude control, thermal control, lighting, environmental control etc.

2.4. Key points of impact domain analysis of on-orbit maintenance

The impact area analysis of on-orbit maintenance should start from the scheme stage and run through different stages of the whole process of aerospace model development, but the emphasis of each stage is different. The focus of the scheme stage is to investigate the influence of key products on function and layout as the basis of scheme design for product and system. The preliminary sample stage is to carry out a comprehensive analysis on the influence domain of on-orbit maintenance, including the influence of maintenance task on function, power supply, information, layout, etc., as the basis of maintenance manual and maintainability verification. The focus of the formal sample stage is to analyze those ORUs who have changed the technical status and surrounding layout so as to obtain an additional input for maintainability verification.

Generally, the impact domain analysis of on-orbit maintenance should be carried out from product, subsystem and system level by level. The analysis content described in section 1.2 of this paper is a complete set, and the analysis of products at all levels should be focused. The analysis of products focuses on the impact during the process from maintenance preparation, removal of ORU to installation and maintenance of spare parts. The analysis of subsystem focuses on the impact during the process from maintenance preparation, pre maintenance status setting, removal of ORU, installation and maintenance of spare parts to post maintenance status setting and confirmation. The analysis of the system focuses on the impact during the process from maintenance preparation, pre maintenance status setting, access to maintenance point, the influence on the platform work during
the process of disassembling ORU, installing maintenance spare parts, confirming the status setting after maintenance to recovering after maintenance.

3. Purpose and effect of impact area of on-orbit maintenance analysis

3.1. Purpose of impact domain analysis of on-orbit maintenance

By determining the product failure criteria, combing the equipment related to ORUs’ machine, power, thermal interface and layout, and combining with the ORUs’ maintenance process, the impact area of on-orbit maintenance can be analyzed from the aspects of system function, power supply, information and layout, while the following objectives can be achieved:

1) Confirm the rationality of ORU maintenance opportunity;
2) Confirm the effectiveness of ORU fault location;
3) Determine the workflow of system entering the maintenance mode;
4) Determine the system function changes after entering the maintenance work mode, and sort out the tasks and functions that the system cannot support after entering the maintenance work mode;
5) Determine the system level maintenance workflow and steps, including energy allocation, channel switching, attitude control, associated equipment and power supply, etc.;
6) Determine the suitable attitude for astronauts to operate and the movement process of mechanical arms, and confirm whether there is interference. Pay attention to the interaction between astronauts, mechanical arms and tools during the maintenance outside the cabin, as well as the transfer, storage of ORUs, and tools, auxiliary facilities during the maintenance inside the cabin;
7) Determine and improve system maintenance manual.

3.2. Effect of impact domain analysis of on-orbit maintenance

3.2.1. Optimize ORU maintenance process.

The impact domain analysis of on-orbit maintenance can grasp the situation that the maintenance task may lead to the suspension or degradation of some functions of the platform, so as to optimize the ORU maintenance process, determine the preventive and compensation measures to be taken during the maintenance, and the process should other cabins implement.

Based on the system functions, impact domain analysis of the ORUs related to energy, information and environmental protection functions should be regarded as the emphases to be carried out, especially the upstream power supply, information link and environmental thermal control equipment. It can be found that ORUs related to information and energy with more interfaces need to power on/off to the multiple associated equipment in the maintenance process, and these powers on/off equipment may degrade or even degrade the basic functions of the platform which has the impact of the loss.

In view of the above impact, it is necessary to analyze the impact and degree of shutdown of associated equipment in detail, optimize the maintenance process, and reasonably arrange the sequence of power on and power off. At this time, it is possible to change the routine way of removing the faulty parts by first powering off all the associated equipment and then unplugging all the connectors of the faulty products at one time. Instead, it is necessary to take the optimization measures to cut down the shutdown time of the key associated products and reduce the impact of maintenance on the platform as much as possible. For example, unplug one connector of the faulty product and power on the associated product immediately, and then repeat as follows.

Most of the ORUs in the energy category are power generation and energy storage equipment, and maintenance often leads to the decline of power supply capacity. At this time, it is also necessary to determine which products are affected and how much platform power is reduced according to the scope and extent of influence, so as to optimize the maintenance process, carry out energy allocation and load reduction from the system level, and determine the closed load list and power on / off sequence according to the power output of the power channel in combination with the safe working mode of the platform.
3.2.2. Optimize aircraft assembly layout.
In order to ensure that astronauts can efficiently and facilitate finish the maintenance task on-orbit, it is necessary to optimize equipment layout according to ORU's maintenance strategy, working mode, fault impact degree, etc. ORUs with regular maintenance and high fault severity level shall be arranged close to the aisle as far as possible to facilitate maintenance.

In addition, layout impact analysis can find problems such as small operation space, poor visibility and accessibility, interference of equipment, etc., so as to provide reasonable adjustment suggestions for aircraft assembly design. Meanwhile, considering that there are more than one position for astronauts to maintain the same equipment on orbit, Jack software can be used for simulation analysis [5] to complete the analysis of equipment layout influence area in order to obtain more comfortable maintenance position and optimize the layout design of limit device. Figure 3 shows two positions for the maintenance of the same equipment. The left picture shows the maintenance in the aisle, and the right picture shows the maintenance in the aisle. Through analysis, it is more comfortable to stand in the aisle for maintenance, with better visibility and accessibility.

![Figure 3. Comparative Analysis of different maintenance positions of the same equipment](image)

3.2.3. Strengthen product environment adaptability.
When the ORUs related to the environment is maintained, it will have an impact on the astronaut's cabin activity environment; when the ORUs related to thermal control is maintained, it will carry out a severe environmental resistance assessment on the equipment adopting active thermal control measures; when the ORUs related to power supply is maintained, it will bring environmental impact on the downstream equipment which controls the temperature through power on, especially ORUs outside the cabin. Because some ORUs interfaces are many and complex, or interference equipment needs to be removed, or offline detection and fault location are needed after removal, the maintenance time of one ORU may be long, which is a serious test to the equipment environmental adaptability.

When analyzing the impact area of the above problem, the power supply path of the equipment should be analyzed first. If there is only one power supply path, further environmental adaptability analysis shall be carried out to confirm whether the equipment temperature can be guaranteed during the maintenance task. Special attention should be paid to the top equipment of the distribution channel with more downstream equipment. The downstream load should be analyzed one by one until the lowest level, especially the equipment exposed outside the cabin such as lighting equipment, propulsion pipeline, adapter, etc.

4. Conclusions
Based on the demand of China Space Station maintainability, this paper determines the analysis project of on-orbit maintenance impact area, and studies its implementation methods. Considering the large number and complex influence of ORUs in China Space Station, the work idea and specific implementation method of "stage by stage, full coverage and emphasis" are put forward. Engineering practice shows that on-orbit maintenance impact domain analysis can effectively
identify the possible risks in system design, aircraft assembly design, product design and other work, optimize the design of system, equipment and ORU maintenance process, as well as provide a strong guarantee for the development of space station.

The maintainability of the space station is of great significance and has a long way to go. The results of on-orbit maintenance impact domain analysis must be integrated with product development at all levels to play a practical role in ensuring the high reliability and long life of China Space Station.

Acknowledgments
The work described in this paper was supported by a grant from Shanghai Science and Technology Commission excellent technical leader program project (No 17XD1423500).

References
[1] S H Feng, Z Lv and Y Meng 2019 Research and Practice of Oriented On-orbit Maintainability Ground Verification Technology J. Quality and Reliability 3 35-40
[2] Safety Centered Maintainability for ISS Payloads 2000 Maintainability Handbook. Astrium
[3] W Zhang and Q L Xia 2014 Study on Design and Verification Method of Space Station Maintainability J. Manned Spaceflight 20(2) 134-8
[4] ECSS-E-TM-10A2010 Space engineering Logistics engineering
[5] Z Lv, R Fan and S H Feng 2019 Study on On-orbit Maintainability Verification Technology of Space Station J. International Journal of Performability Engineering 15(1) 66-75