Review of International Space Station Mechanical System Anomalies

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Abstract

The International Space Station (ISS) when completed will consist of over 32 different mechanical systems utilized in more than 150 applications providing functionality for assembly, rotation and deployment of major components, and maintenance. Currently, a majority of these systems have been launched and either functioned or checked out on orbit, and all have completed preflight testing and flight readiness processing. Within the ISS program the Structures and Mechanisms (S&M) System Problem Resolution Team (SPRT) is responsible for the resolution of problems associated with all ISS mechanical system during qualification, pre-flight checkout and on-orbit operations. This activity combined with the shear number of complex mechanical systems on ISS has exposed the team to a great number of problems of interest to the Space Mechanism community.

The Problem Reporting and Corrective Action (PRACA) system is used to track, document, and approve the investigation and analysis, root cause determination, and corrective action and recurrence control for these problems. Formal SPRT's were formed in 2000. Since its inception the S&M SPRT has dipositioned over 350 ground and on-orbit problems. The PRACA database is used to store all problem records and can be used to generate reports on various metrics.

Figure 1. ISS on orbit

This paper will present the results of a thorough review of the mechanical system problems that have been addressed by the S&M SPRT. Metrics on the types and frequency of various problems will be presented. Problems with fastener installation and secondary locking features as well as tolerancing for thermal deformation and rigging are examples of the most common problems. The root causes will be categorized and the most prevalent causes will be discussed from a lessons learned perspective. Determination of root cause is often the most difficult part of a failure investigation and yields the most

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insight for determining proper recurrence control. Some of the recurrence controls put in place by the SPRT for these problems can be applied on other hardware programs. Examples include proper application of drawing call-outs for fastener installation, control of lubricants to preventing galling situations, and proper interface control for mechanisms. A summary of the problems that have had the most impact on the ISS program will also be reviewed. It is hoped that by providing the results of this investigation that the most common causes of ISS mechanical systems anomalies can be avoided in the development of future spacecraft mechanisms.

ISS Overview

The International Space Station when completed will be the largest and most complex space vehicle ever assembled. It will be made up of more than 18 individually launched major elements. There will be more than 35 different mechanical systems that will provide a wide variety of functions for the vehicle. Figure 2 shows the mechanical system topology for the completed ISS. Five different attach systems provide remote structural attachment for the major structural elements. Seventeen separate Common Berthing Mechanisms provide structural attachment and pressurized access between the habitable elements. Five Russian Docking Systems provide the same type of pressurized attachment between the US elements and the Russian elements. Four Segment-to-Segment Attach Systems and five Rocketdyne Truss Attachment Systems provide structural attachment between the major truss elements that make up the backbone of the station. Six Common Attach Systems provide locations to attach large exterior unpressurized elements and payloads to the ISS. Several different mechanical systems are used in the deployment of the solar arrays, radiators, and antenna. Two Solar Alpha Rotary Joints, two Thermal Radiator Rotary Joints, and the eight Beta Gimbal Assemblies (BGA) provide autonomous pointing of the solar arrays and radiators to support the power generation and heat rejection systems. Numerous other mechanical systems like the Mobil Transporter, Trailing Umbilical System and Hatches account for the more than 150 applications of complex mechanical systems on ISS.

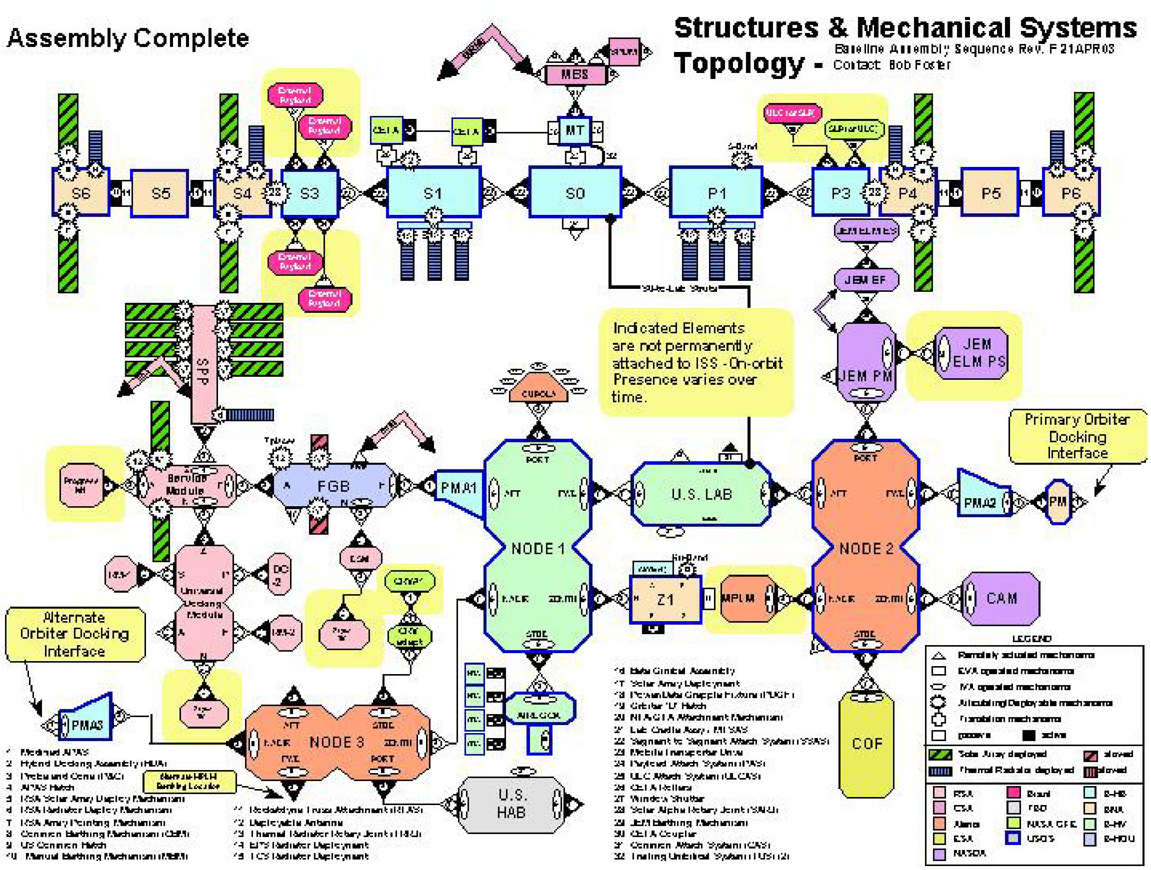

Figure 2. Mechanical System Topology

Introduction

The PRACA system has been used since 1997 to track, document, and approve the investigation analysis, root cause determination, corrective action, and recurrence control for all hardware problems on ISS. The S&M SPRT manages the resolution of all structural and mechanical system problems. Since its inception the S&M SPRT has worked on over 350 problems ranging in severity from galled fasteners on the ground to failed deployment systems on-orbit. The PRACA database can be searched for key words or other field identifiers and is used for trending of system problems on the vehicle.

Problem Reportability Criteria

Most hardware non-conformances are not considered to be PRACA reportable. Hardware discrepancies that occur during the manufacturing process are usually dispositioned through a local Material Review Boards with standard repair procedures. A PRACA reportable problem is anomalous hardware performance that occurs during Qualification or Acceptance testing, or after delivery of the hardware from the contractor to NASA while the systems are being readied for launch, or occur during or after activation on-orbit. PRACA reportable problems that occur on the ground are investigated and worked until the hardware is either brought back to print or to a waiverable condition where it can be assured to meet all system requirements. On-orbit the problems are worked until the hardware can be repaired or an acceptable condition can be found so the hardware can continue to function and meet most of its performance requirements until a future time when a repair can be implemented.

PRACA Review

A detailed review of all S&M PRACA's was performed. The root cause of each PRACA was noted and categorized. It was found that most PRACA's could be grouped into one of 9 types. Figure 3 gives a percentage breakdown for these nine categories. As can be seem tolerancing errors and design errors account for almost 40% of the PRACA reportable problems that occurred in the structures and mechanical systems. Manufacturing type problems made up 15%. Fastener problems and environment/procedure problems accounted for 9% and 8% respectfully. Test and STE related problems each accounted for 4% of the PRACA's. Panel Retention makes up 2% with the other miscellaneous problems making up 23%. While the miscellaneous category makes up a significant number of anomalies, there did not appear to be any recurring themes although each one represents a problem that had to be worked with the implementation of a corrective action and recurrence control.

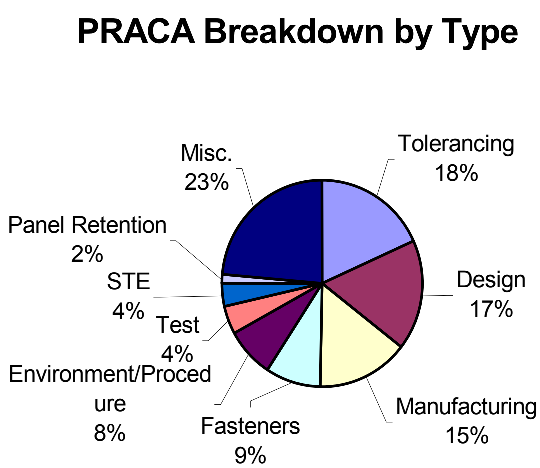

Figure 3. Problem Reporting Breakdown

Lessons learned from each of the major categories

For each of the major categories the root causes, corrective actions and recurrence controls were reviewed for lessons learned that could be useful in reducing the risk of similar failures on other space flight mechanism programs. An attempt was made to provide lessons learned that affected the highest number of PRACA's in each category.

Tolerancing

This category was used to capture failures attributed to insufficient design tolerancing for either thermal or mechanical deflections. For example, several moving mechanical assembly binding failures, which occurred during environmental testing, were caused by a lack of sufficient clearances. Root cause investigations determined that adequate tolerances had not been provided to account for the thermal expansion coefficient differences of the various components in the systems. Also, other hardware anomalies were found to be caused by poor mechanical tolerancing of moving components. In several cases, limit switch rigging tolerances did not account for the mechanical tolerances and run out of the interfacing mechanical components, resulting in the failure to achieve consistent and repeatable limit switch activation.

Most of the problems resulting from tolerancing errors could have best been prevented with good design reviews and more rigorous design analysis. It was found in a majority of these problems that the complexity of either the thermal or load environment was not considered in the original design. Whenever complex or even simple mechanical systems are being reviewed careful attention should be made to tolerances that could be affected by temperature or loads. In several problem reports, the root cause was not accounting for sufficient clearance in moving mechanical interfaces for the growth or contraction of components under the environment they were being designed to operate. In other cases, the orientation of the system in a gravity environment or unloaded condition affected the operation of the mechanism and resulted in anomalous performance. In several cases, failure to provide adequate margin for manufacturing tolerance build up resulted in failures of the units under test. A detailed design tolerance analysis accounting for manufacturing and worst case thermal and mechanical conditions can be used to mitigate the risk of having hardware failure in test or in operation.

Design

Failures attributed to design were characterized by problems in the detailed parts of the hardware. For example several cases of rotating components with out proper use of washers or bushing resulted in failure of the mechanism during testing. Also, interferences with fillets or other components, or having wiring routed too close to moving components resulted in test failures and the need to redesign hardware. Included in this category are failures attributed to insufficient strength of a fastener or other retention devices that should have been caught during design reviews or analysis. Failure to provide adequate design features to protect against galling, contamination, or to provide proper force or torque margins are also included in this category.

Although under initial review this category appeared to be a case of 20-20 hindsight, further review resulted in some interesting lessons learned. The most striking of these was that the failures were primarily caught during qualification or acceptance tests. The ISS program was forced by budgetary constraints to waive the requirements for many tests and thus relied on design reviews and analysis as substitutes. In review of the resulting hardware performance, many years later, it is clear that often times this is a risk that may result in unsuspected hardware failures. Many design errors or deficiencies can only be found in test, and whenever analysis or inspection is used in place of those tests, a higher degree of rigor is required to assure that design errors are caught. Another lesson that should be drawn from this category is that design reviews need to include a thorough peer review. In several cases simple design errors, that senior designers would have caught, were missed and only caught in subsequent testing. It is felt that many of these could have been prevented by having adequate review by senior designers and analyst. Detailed design checklists could be used to help systematically review new design for errors that had been found in previous designs. Design to minimum risk criteria when applied correctly can help identify areas in a design that need close review.

Manufacturing
Failures assigned to this category had root causes in the manufacturing process either from failure to detect a mis-manufactured part or the inability to manufacture to the tolerances called of on the drawings. Poor identification of mandatory inspection points (MIP's) on drawings was determined to be a root cause on several PRACA's. Also, reliance on very tight tolerancing to achieve system performance lead to parts or assemblies that could not be manufactured to print and ultimately had to be accepted with waivers.

The primary lesson learned from this category should be the integration of design and manufacturing engineers in the early development of a mechanical system. In several cases the original design placed unrealistic reliance on very tight manufacturing control to assure systems performance. When these requirements were unable to be met, redesigns and reanalysis were required to assure systems performance requirements could be met. In several cases operational limits had to be imposed to assure that the hardware could perform. Other cases involved the failure to detect mis-manufactured parts until later testing. The recurrence control for all of these problems was the addition of mandatory inspection points to the detailed design drawings. The addition of MIPs to any drawing should be reviewed to assure that dimensions that are critical to system performance are carefully checked during manufacture and not left for acceptance testing to catch. Unless identified as a MIP, most detailed part dimensions are not as rigorously checked by quality inspectors.

Fastener
This category includes all cases where fasteners failed because either galling or the loss of a secondary locking feature caused a failure of a mechanism. For example, to meet payload safety requirements all safety critical fasteners must have a verified secondary locking feature. This means that during installation the running torque of most interference type locking elements have to be verified. On numerous occasions the loss of these locking features resulted in significant rework. This does not include times when a standard repair was used to replace the locking element. In many cases modified or non-standard repairs were needed. This category also includes failures where cycling of multiple use fasteners resulted in galling. The root causes in these cases was attributed to a lack of or wear out of a lubricated threaded interface.

This category seems at first to be mostly simple problems, however because it resulted in almost 10% of the postproduction problems on ISS it is worthy of review for lessons to reduce the risk of recurrence on future development projects. The use of secondary locking features is common in spacecraft design and on most structural applications there are few problems because they are normally single use applications and failures can be handle with standard shop repairs. However, on many ISS applications, fasteners are required to be installed and removed numerous times in the preparation and use of the hardware. This resulted in many occurrences of failed locking features that cause significant delays and costly repairs. Many of these problems could have been avoided if the original designs had accounted for the need to replace locking features as part of the normal processing of the hardware. Some ISS designs utilized easily replaceable fastener locking features and avoided this type of problem. Another cause of a significant number of failures was the lack of proper lubrication of the fastener or insert. Careful attention should be made to assure that galling does not occur at the threaded interface between fastener and insert or nut, especially on designs that may require several installation/removal cycles. In several PRACA's the root cause was determined to be insufficient lubrication, or breakdown of existing lubrication over several fastener cycles. The corrective action in many of these cases was to either add a more durable lubrication or add lubrication to both the fastener and insert.

Environment/Process
This category was used to capture failures or hardware anomalies caused by the system being operated outside original design environments or operated in a manner not accounted for in the original design. Most of these failures or anomalies have happened on-orbit as a consequence of changes to the original design parameters and assumptions. Although this is not normally considered a design or hardware problem, this category represents an area where numerous hardware problems had to be worked and lessons learned can be drawn. These failures were a result of not assuring that original design assumptions were actually the environment or process that the hardware was to be operated in. Often it was found that early design assumption and operational baselines changed as the program matured. In

several cases the effect of the changes in either planning or updated environments was not properly assessed for its impact to already completed analysis and certification. This resulted in hardware being operated outside the design baseline. Corrective action included processes to assure that operational and environmental baselines used in design analysis and certification programs were carefully monitored, and that the cognizant design group reviewed any changes to operational plans or conditions. In several cases providing additional margin in the early design phase could have provided additional flexibility when changes were required later in the program

Test

These failures and anomalies were attributed to either test parameters not being meet or test procedures not being followed. In either case the flight hardware was subjected to excessive loads or temperatures and had to be reworked or reanalyzed. In several instance a component had to under go several repeat acceptance tests which was beyond the original qualification. Other problems resulted from an inability to perform the test as originally designed and specified. Several failures resulted from test procedures being poorly written and confusing to test operators.

The impact from this type of failure could have been reduced with more thorough reviews and verification of the tests that flight hardware was to be exposed too. In most certification programs the qualification environment is developed to certify the hardware for exposure to a given flight environment and either one or two acceptance test cycles. In several cases a flight unit for various reasons had to be reworked and then re-acceptance tested. When the original number of certified acceptance cycles was reached a great deal of extra analysis and sometimes limited retest was required to prevent over stressing the hardware. This could have been avoided if the original qualification had included more than one or two acceptance test environment. This should be considered especially on complex systems with a higher chance of needing repeated tests. On the ISS program many component level acceptance tests were eliminated and replaced with acceptance tests at the next higher system level. In cases like this a failure of any part of the system resulted in all components having to be exposed to another acceptance test cycle. Because these types of acceptance test were so critical, procedural or operator errors had a much more costly impact, and thus should have had more rigorous reviews and verification. The institution of "Won't Fail Reviews" prior to new tests has proven to be a useful tool in reducing these types of failures. A "Won't Fail Review" provides an independent thorough review of a procedure by independent experts who focus on risk areas in a procedure.

Special Test Equipment (STE)

This category was used to capture all failures where the root cause was determined to have resulted from a failure of the STE, either hardware or software. These failures resulted in flight hardware needing to be reworked or retested. Several times lack of quality control or fault tolerance in the STE resulted in damaged flight hardware. Poor design of the STE also was a contributor to several anomalies.

A factor in several of these cases was a lack of detailed design review of the STE. Because STE hardware often times has direct effect on the flight hardware it must have the same level of design and functional review as the flight hardware. Where potential damage to flight hardware exists fault tolerance in the STE is as important as the fault tolerance in the flight system. This is also true in the manufacturing of the STE. In one case, poor quality control of the STE almost resulted in severe damage to very critical and irreplaceable flight hardware.

Panel Retention – Failure of quarter turn or other captive panel fasteners

This category was used to capture all anomalies with the internal and external ISS panels. Most of these failures were attributed to improper strength of a fastener or improper procedures used in the original assembly or use on orbit.

Again this category at first seems too simple for discussion, but because of the number of occurrences and on-orbit impact it warrants further investigation. Most of the panels both internal and external to the ISS are removable for access to maintainable hardware or for assembly tasks. Difficulty in the original assembly of the panels before flight was not correctly identified as having the potential to also be a source of failure on-orbit. These types of failures have required an excessive amount of crew time for repair and rework. For future manned vehicle designs, care should be taken to provide very robust and easily replaceable fasteners for hardware like panels that will be frequently utilized by the crew.

Other Miscellaneous
Failure that could not be placed into one of the above categories, and the total number of similar events was less then 5. More categories were used in the initial review of the PRACA's like corrosion, configuration control, and unexplained anomalies, but none of them resulted in more than 4 occurrences and thus were grouped into the miscellaneous category.

PRACA's with Largest Program Impact

The original purpose of this review was to determine the types of problems that occurred most frequently in a large program like ISS. It became clear during this review that it would also be beneficial to discuss some of the failures that have had the largest impact or potential impact to mission objectives, cost or schedule.

Figure 4. Photo of BGA and 4-Bar Assembly

BGA Hinge Lock Failure and Excessive Deployment Force (PRACA 2389 & 2435)
This failure occurred during the deployment of the first solar arrays on the P6 element of ISS. During activation of the element a four bar mechanism is used to rotate the solar array mast canisters and blanket boxes from a launch position to an on-orbit position. Locking features at the base of four bars engage when full rotation is achieved. The deployment force on-orbit was significantly higher than expected and not all locks could be properly engaged. An exhaustive investigation revealed that insufficient control of the manufacturing tolerances allowed binding to occur in the mechanism which increased the required force to deploy and caused the hinge lock to malfunction. Also, a design feature that relied on friction to maintain alignment of critical parts failed when subjected to the binding loads. A redesign was undertaken to correct this on the remaining six solar array four bar mechanisms along with tighter control of the assembly process and functional checks to verify deployment forces.

Beta Gimbal Assembly (BGA) High Current (PRACA 2685)

The BGA is a direct drive mechanism located at the base of each of the ISS solar arrays and is used to rotate the array toward the sun. During early operation of the first two arrays on-orbit, higher than expected current spikes were noted. As time and cycles accumulated these current spikes eventually reach the maximum limit and a stall condition on the joint. These stalls have been recovered from and managed through a combination of operational procedures to limit the rotation required from the joint and planned rotation reversals. Although the root cause has not been absolutely determined an intensive investigation has narrowed the failure to the bearings and/or lubricant. It is believed that an anomaly in the lead based lubricant has cause some form of debris to be generate in the bearing causing erratic torque ripple that over time can lead to torque requirements beyond the motor capability. Rotation reversal has continued to be an effective means to regain rotation capability. A preplanned period of reversing rotations have reduced the frequency of the stalls and appears to date to be an effective means of controlling the anomalous performance. Without a definitive root cause it is hard to draw conclusive lessons from this experience, however it cannot be ignored that the bearing design was changed after development life testing had been completed, and that the original life testing did not include any of the environmental effects that the bearing would see on orbit. Cost and schedule were factors in the decision not re-performing the tests.

Solar Array Deployment Anomaly (PRACA 2397)

This failure also occurred during the deployment of the first solar arrays on the P6 element. As the arrays were being deployed, dynamic motion in the panels caused a failure of the blanket tension mechanism. This failure was attributed to small stiction forces between the solar array panels where silicon surfaces were in contact. Although the arrays were functionally tested on the ground, the effect of these forces was masked by ground support equipment and the effect of operating in a 1-G environment. Failure to recognize the effect that these small forces would have on the system resulted in a significant failure on-orbit. Only after the on-orbit failure occurred did detailed dynamic analysis demonstrate the effect. No preflight analysis of this type had been conducted. If this type of analysis had been conducted prior to flight, it would have identified a lack of force margin in the blanket tensioning system that was also a contributor to the on-orbit failure.

Hatch Handle Improperly Stowed (PRACA 3348)

The handle on the ISS common hatch is used to operate the latches on the hatch. After use, the handle is stowed in a position so that it does not interfere with the mechanism. The stowage procedure relies on crew training to assure that this is performed properly. As was the case on orbit, an improperly stowed hatch handle almost caused the loss of access to the airlock. A non-standard work around luckily allowed access to be regained and new procedures are in place to assure the condition does not happen again. In review of the failure it was determined that the design does not adequately protect against the miss stow of the handle. Adequate design features to prevent the miss operation of the hardware were not provided. Anytime that operator training is required to prevent what could be catastrophic consequences design solutions should be found to minimize the chance that they could occur. In this case guards are being added to the hatch to preclude improper hatch handle stowage.

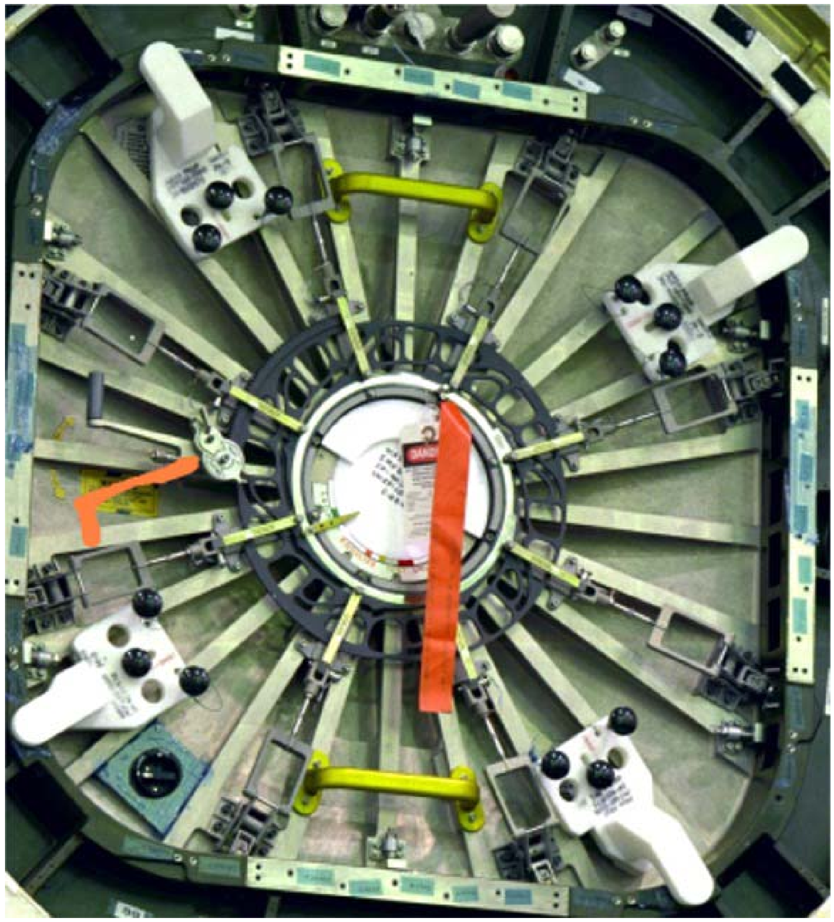

Figure 5. Photo of common hatch. Incorrect handle position in red.

Conclusion

Every failure should be looked at for lessons learned to prevent the same problem from recurring. This report attempts to look at the failures on ISS not on a case-by-case basis, but rather from a more global view of the identifying the most frequent types of failures and their root causes. A program as large as ISS affords the unique opportunity to do this because of the large number of mechanisms all being managed by one team. It was found that what appear to be the simplest of problems like tolerancing and fastener design are still the most common problems in the development and operation of spacecraft mechanisms. A large number of design problems were not identified until qualification and acceptance tests were performed, reinforcing the validity of these tests even in the face of cost and schedule pressures. Care must be given in design reviews of even the simplest mechanisms that adequate attention is paid to details especially when they can directly affect system performance. Mandatory inspection points should be called out to assure all critical dimensions are check and functional tests should always try to replicate the environmental conditions that the hardware must operate in. It is hoped that these results will be used to focus designers of future spacecraft mechanical system to be sensitive to the most common failures that have been experienced on ISS.