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International Space Station Design for Dexterous Robotics - Inboard Truss Segments

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Abstract

Over 200 International Space Station external high maintenance items have been designed for replacement by a dexterous robotics system in addition to space-suited astronauts. Planning for dexterous robotics maintenance increases flexibility for space station operations with a robot able to execute many tasks in place of a suited crew member, lowering the number of hours crew must spend on Extravehicular Activity (EVA). The five inboard truss segments of the station – S3, S1, S0, P1 and P3 – include 122 of these robot compatible maintenance items or On-orbit Replaceable Units (ORUs). This paper describes the impact robotic compatibility has had on the International Space Station (ISS) design, reviewing the inboard truss items as examples. Diverse challenges exist to verify each genre of ORU meets the dexterous robotics requirements. Each individual ORU is a unique task since the positioning of cameras and the orientation of both the dexterous and supporting robotic arms are unique for each worksite. This paper describes results of analysis and testing conducted to determine requirements compliance of the ORUs, and a discussion of the expected capabilities of the Special Purpose Dexterous Manipulator (SPDM), which is planned to occupy the role of dexterous robot for the International Space Station. The purpose of compiling this experience is to suggest strategies for operation of the ISS, considerations for design of additional dexterous compatible hardware, and capabilities desirable in a dexterous robot for station operations.

Overview

The ISS contains a pre-integrated transverse truss structure to be assembled on-orbit from nine launch packages of one or two segments each. Each Integrated Truss Segment (ITS) contains numerous external electronic, power, structural and avionics units to sustain the operation of Space Station. These units last from 12 months to 100 years before they need to be replaced, and are designed as ORUs. The more common and shortest life ORU's have been selected for robotic replacement. The removal of a failed ORU and replacement with a new ORU is the typical activity the ISS dexterous robot, the SPDM, will be performing on the truss segments. The dexterous robot also performs tasks on non-removable hardware, such as opening access closures to ORUs or deploying and stowing certain mechanisms. ORU Manipulated Hardware (OMH) envelops all SPDM compatible hardware that are held to dexterous robotic requirements. On the five inboard truss segments (ITS S0, S1, P1, P3, and S3) there are 122 instances of these dexterous robot compatible OMH, including three manipulation tasks. Each OMH is located at a robotic worksite, a designated area for the robot to perform the task. A robotic worksite provides clear access to the OMH, visual cues, and a dexterous stabilization point to provide a reaction point for the forces reacted back into the structure. The inboard truss segments provide a total of 24 stabilization points to serve the 122 OMH worksites.

Reasons for Dexterous Maintainability

Early in the Space Station Freedom program (in July 1990) the amount of EVA required to assemble and maintain the space station was documented in the Space Station Freedom External Maintenance Task Team report, commonly known as the Fisher Price report [Reference 1]. The report concluded that 2284 hours of EVA would be required to assemble and maintain the space station. The report recommended that the space station transition from EVA to Extravehicular Robotic (EVR) maintenance, leading to a robotically maintained space station by the time assembly was complete. Other key recommendations from the report included commonality, graceful functionality degradation and verification of robotic functionality.

Starting from 100% robotic compatibility, Space Station Program working groups investigated parallel paths of designing hardware for robotic compatibility and negotiated which items were cost effective to make robotic compatible. The result included a set of robotic compatibility and interface requirements, maintained primarily in the Robotics System Integration Standards [Reference 2] and the Mobile Servicing System (MSS) to User Interface Control Document (ICD) [Reference 3]. These requirements were then made applicable to over 200 pieces of on-orbit removed hardware on the inboard and outboard transverse truss. With the cancellation of one of the two relocatable dexterous space station robots – the Flight Telerobotic Servicer (FTS) – these requirements now represent the capabilities and interface to the SPDM and a specific list of which ORU's would be included on SPDM's task list.

While SPDM and Station hardware designs continued to evolve in parallel, allocations of EVA and EVR time were inserted into the requirements at the segment level. Theoretically, these allocations could have driven additional EVR compatible items if a given segment exceeded it's allocation of EVA maintenance hours. In practice, efficiency of EVA operable tasks and the use of EVR maintenance of ORU's already on the EVR task list left sufficient allocation for all 5 inboard segments.

Space station hardware has entered final assembly, with the first EVR designated ORU's having launched in September 2000 on the first truss segment - Segment Z1.

Putting EVR Into Practice

The promise of EVR compatibility of Space Station hardware remains as it was in the Fischer Price report: to decrease the cost of space station operations, decrease the risk to the crew, and increase crew availability to science by lowering EVA requirements for space station external maintenance. The design of EVR compatible ORU's is complete and soon to launch. Once on orbit, changes will be more difficult, especially for the non-replaceable side of the ORU interfaces. In contrast to EVA, however, the maintenance agent in EVR can evolve to fill the gap. SPDM and follow-on dexterous robots may gain capabilities to increase the efficiency of EVR compatible ORU replacement, decreasing crew time requirements. Upgrades such as ground control and automation could take much of the external maintenance burden off of the crew. Increases in dexterous robot capability could expand the list of EVR compatible tasks beyond the current set.

This paper is an invitation to robot designers to increase robot maintenance capability of external space station ORU's, and to hardware designers to take advantage of the current operational design of EVR ORU's.

Impact of Dexterous Maintainability on Spacecraft Design

Generic EVR Compatibility Design Requirements

Dexterous maintainability places certain demands on design of hardware to be compatible with a dexterous robot. The design must, at a minimum, provide alignment guides with a capture envelope sufficient for consistent SPDM installation of the hardware, provide visual cues and controlled targets, verify indication of state to the operator, and require less within the capabilities of the robot. Certain configurations can be analyzed for an optimum output of force, but these configurations are not guaranteed on-orbit. Dexterous robot designers must keep in mind the limits of the telerobotic experience – no sensing of the hardware through the hands, no ability to feel any of the interfaces, and limited access to the hardware. The robot can only actuate bolts and interfaces purposely designed and intended for dexterous maintainability. All robotic tasks and hardware should provide for EVA contingency access, in the case where the robotic system fails or there is a problem during manipulation. Therefore all EVR compatible ORUs and tasks must also meet the standards for EVA compatibility.

Generic design for robotic compatibility includes provisions for alignment, targets, fastening, indicators, power connection, keying or hardware ID, grounding, thermal, grasp fixtures, and strong support structure. Automated (no operator-in-the-loop) removal and replacement is possible with unambiguous force/moment information fed back to the robot, allowing it to correct its own misalignments. Hard stops, which are indicated by rapid rising in force, are key in the insertion process by providing undeniable mechanical indication of the state of the box. The worksite of the ORU should basically provide a funneling alignment system, which brings the ORU from free space to the final hard dock position. The insertion process should be segmented to protect against damage to delicate connectors and surfaces on the ORU or worksite. The transition point is referred to as Ready-to-Latch. Prior to this point, the robot joint motions provide movement of the ORU. After this point, the robot's rotary drive tool drives a bolt head to bring the ORU to its final, attached state.

DDCUE/MBSU Coldplate Design

The DC-to-DC Converter Unit – External (DDCUE) (see Figure 1 - Flight DDCUE) and Main Bus Switching Unit (MBSU) are the two types of ORUs on the inboard truss segments that follow the outboard truss segment Battery Box style. The style is typically large square shaped boxes covered in white beta cloth for thermal protection, with thick black alignment stripes outlining the perimeter of the box and down the edges. The Battery Box was designed to use the micro-handle grasp interface (see Figure 2 – Micro-handle with Collocated Bolt and Status Indicator), collocated with an Acme screw for purposes of securing the ORU to the receptacle. The primary micro-handle is to be manipulated by the dexterous robot and is fortified with stiffeners to strengthen the honeycomb shell structure of the ORU. A secondary micro-handle is collocated with a secondary fastener to tighten down the ORU, as the primary micro-handle is located offset from the center of the box, directly above the connectors. As the robot drives the fastener, a mechanical status indicator located at each micro-handle interface, travels from LOCK and UNLOCK, providing status information for the fasteners.

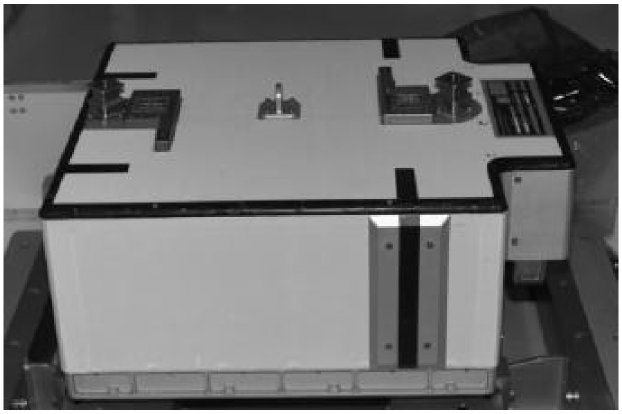

Figure 1 - Flight DDCUE

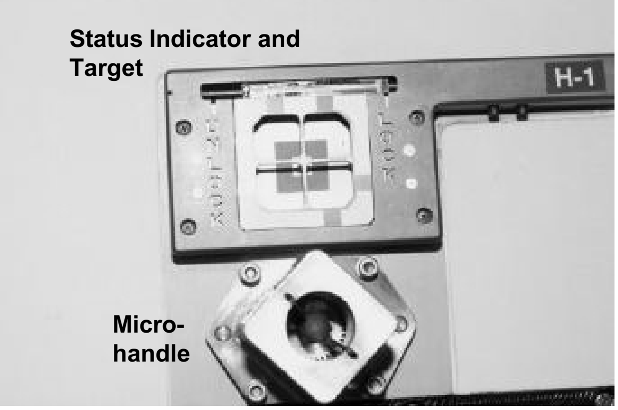

Figure 2 – Micro-handle with Collocated Bolt and Status Indicator

On the inboard truss segments, the MBSUs and DDCUEs are temperature controlled by an active cooling system (see Figure 3 - DDCUE and Cold Plate). The DDCUE and MBSU cold plates (or also referred to as receptacles) have a set of fins on the upper surface which mesh with fins on the underside of the DDCUE and MBSU. Four guide legs were added to the coldplate fin assembly to aid in installing the ORU – three long and one shorter. The guide legs were positioned close enough to prohibit the ORU from pitching or yawing excessively, which could place the fragile fin assemblies in danger of impact, but far enough apart to allow for self-correction in roll by a keying pin.

The tie-down posts on the MBSU and DDCUE coldplates fit tightly in matching cylindrical cavities (containing the Acme screw) on the undersides of the ORUs. Entrances into these cylindrical cavities are facilitated by coarse alignment bell-shaped openings, coated in a dry film lubricant, to aid the blind mating of the jackscrew onto the post. Three ball detents located even with the initial thread of the jackscrew inside the cylindrical cavity on the underside of the ORU provide a soft-dock mechanism at the point the ORU is ready to fasten. A push past the ball detents brings thread-to-thread contact a hard stop - indicated by a rapid rise in X-force. This hard stop indication, along with visual indication from the status indicator, informs the operator to commence fastening of the primary jackscrew. The jackscrew, essentially the fine alignment mechanism, takes over the insertion and brings the box to the fully mated position, independent of positional accuracy of the robot.

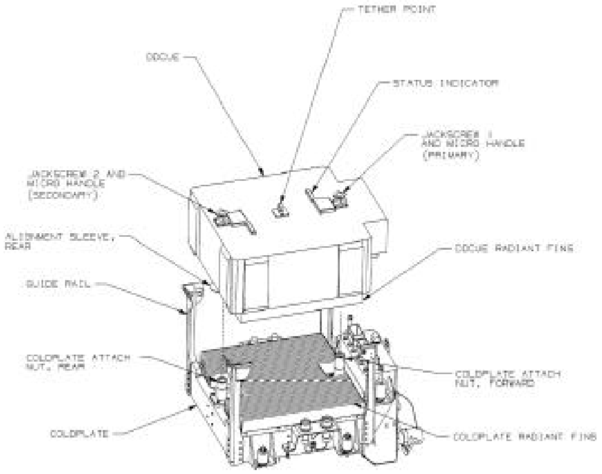

Figure 3 - DDCUE and Cold Plate

As a result from the robotic development testing done at Johnson Space Center (JSC) Robotic Systems Evaluation Laboratory (RSEL), the lower fourth guide leg was extended to be of the same height with the other three to eliminate parallax difficulties. The flanges on the tips of the guide legs were also extended to enhance ORU alignment earlier in the insertion, prohibiting initial rotational misalignments. These changes were included in the test article tested for verification purposes at the RSEL at JSC (see Figure 4 - MBSU Test Article). The changes were found to greatly increase the performance of the design in robotic capability.

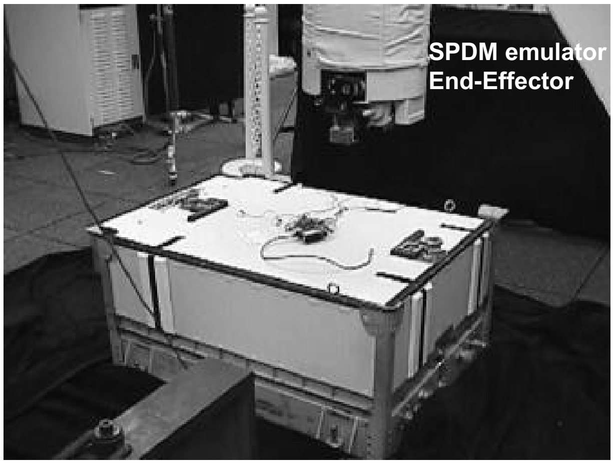

Figure 4 - MBSU Test Article

6B Box Design

The most common design of robotic compatible ORUs is the 6B external avionics box style (See Figure 5 - Flight 6B Box (MDM)). The External Avionics Box – 6B style – resulted from a design trade study of external avionics boxes, with the "6B" the designation of the chosen option. The 6B style ORU primarily contains electronics; and most are Multiplexers-Demultiplexers (MDMs). An entire family of 6B boxes exists, with varying electronic packages and corresponding mechanical size. The external robotic features of the 6B box are common amongst all, and are not dependent on size. This ORU type is present 32 times on the inboard truss segments, with non-EVR compatible locations also on Pressurized Mating Adapter 1 and truss segments P6 and Z1.

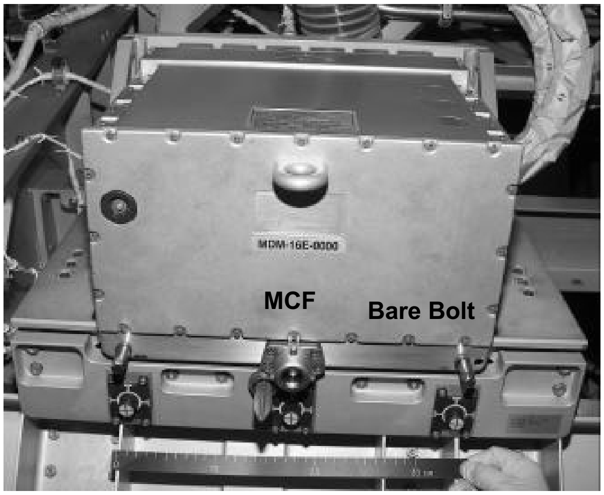

Figure 5 - Flight 6B Box (MDM)

The 6B Box ORU is optimized for robotic compatibility. One center bolt is collocated within a micro-conical fitting (MCF) (see Figure 5 - Flight 6B Box (MDM)) and drives the box in and out of its receptacle. Two side bolts, or bare bolts, tighten down the box for launch loads and maintain enough contact between the bottom plate and the receptacle radiator plate. These fasteners are not located near the center of the ORU as mentioned above but rather at the lower edge of it to aid in creating the preload necessary for conduction of excess heat through the receptacle radiator plate. All three fasteners mate with a spherical barrel nut to allow for slight misalignments at the Ready-to-Latch position and therefore have increased capability to capture during a nominal insertion. The bolts and spherical nuts are dry film lubricated to prevent wear during insertions and removals.

Two external guide pins extend out of the sides of the ORU which mate and align the ORU as they enter two triangular shaped coarse alignment guides on the receptacle (see Figure 6 - 6B Box Receptacle and Robotic Feature). A larger front pin (or cone) fits over a mating ring on the ORU and aligns the front of the ORU for the center bolt to be lined up with the mating nut on the receptacle. When those threads on the bolt reach the threads on the receptacle nut, a hard stop is reached, with a force indication fed back to the operator indicating to start the rotary torque drive. Prior to the mating of connectors in the rear of the ORU, a bottom wedge lip of the ORU will encounter spring-loaded Belleville washers and overcome clamping forces at the rear of the receptacle.

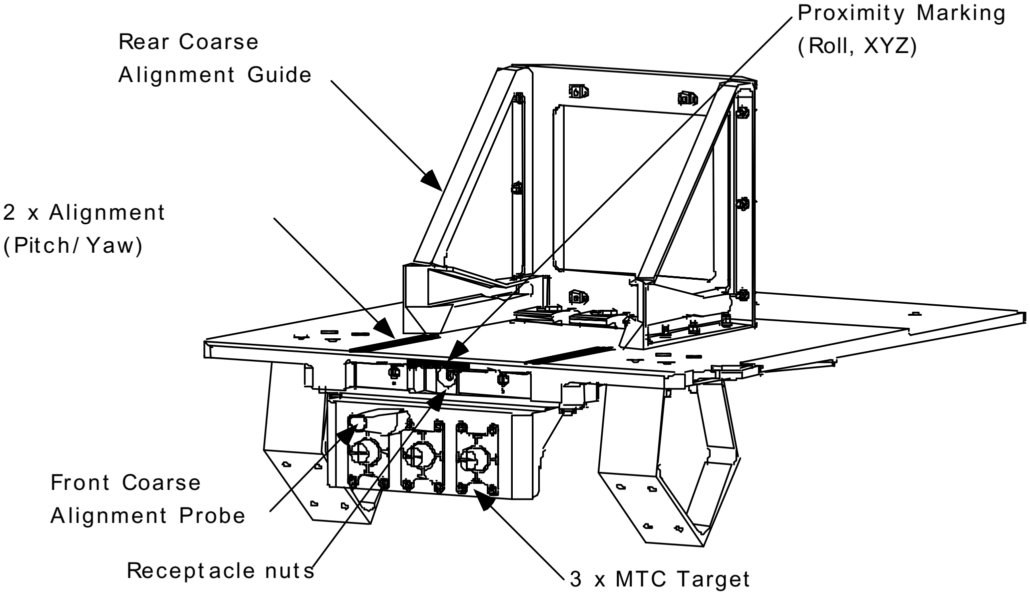

Figure 6 - 6B Box Receptacle and Robotic Feature

The receptacle also features alignment markings to aid in the installment of a new ORU while looking out the surrounding SPDM shoulder Left and Right cameras, along with the SSRMS available cameras. A marking is located on the front edge of the receptacle plate known as the Proximity Marking, to eliminate the chance an operator catches the rear edge of the ORU on the front edge of the receptacle while inserting. The proximity marking provides operators X, Y, and Z information from which they can start the two commands necessary for this type of ORU – a Z command until the operator has made contact with the ORU, then straight down to the Ready-to-Latch position. With these markings and alignment guides, the 6B box can be mated to its fully docked position via robotics.

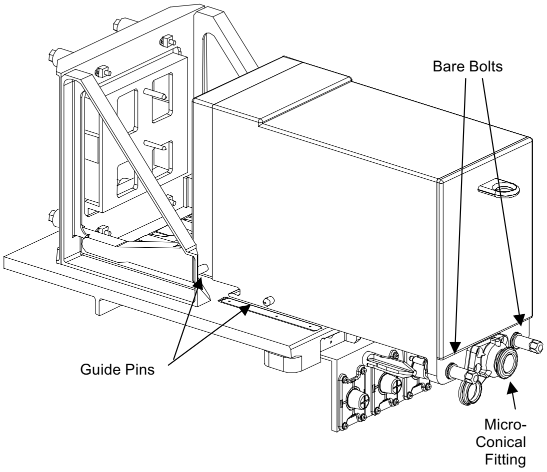

Figure 7 - 6B ORU and Features

No mechanical status indicator is present on the 6B boxes, however laboratory testing has proven its ability to feed back to the operator information at the key points of insertion. The targets provided adequate alignment for the end-effector to acquire the fasteners, and center target provided visual alignment for inserting the ORU. Torque and turns count provided enough information (along with the available visual cues) to the operator to indicate the box was fully seated. The turns count for these ORUs will be determined during testing of flight units.

The visual cues present on the ORU and mating worksite tested positive, by relaying rotational and translational alignment cues to the operator. The proximity marking ensured the rear lip of the ORU did not catch anywhere on the receptacle and controlled the initial approach into the guides. A problem could arise if the bare bolt tool is not fully seated on the bolts when the unfastening sequence initiates, and the operator inputs a removal command that pulls the ORU up out of the guides. An operational workaround was inserted into the on-orbit procedures for removal and replacement of a 6B box. The operator is to first initiate a clockwise rotation of the rotary drive, looking on the force display for a rapid increase in torque. With a torque indication, the operator is satisfied the socket has seated on the fastener and can commence the removal sequence for the bolt.

SPDA Doors Design

Remote Power Controller Modules (RPCMs), grouped in sets of six, constitute a Secondary Power Distribution Assembly (SPDA) in numerous locations along the truss segments. The RPCMs located on the upper center section of Segment S0 required a thermal shroud covering to protect the ORUs from direct sunlight. Since these RPCMs are robot compatible, their shroud, or covering, is required to be robot compatible. The RPCMs are to be covered at all times when not being replaced, therefore the common one-time EVA deployment of a shroud utilized elsewhere on S0 is not sufficient.

Figure 8 - Flight SPDA Door - Port

The resulting SPDA Doors (see Figure 8 - Flight SPDA Door - Port) are machined out of .625” thick aluminum plates, and are 35” long. The unit travels along a set of rails with roller bearings every 4” to facilitate the sliding of the doors. The doors feature steel wedge shaped brackets that interface with matching steel brackets attached to the rail assembly, housing a set of ball detents (see Figure 9 - SPDA Doors Soft Dock Mechanism and Rollers). These ball detents provide an adequate soft-dock force to capture the doors in either the fully open or fully closed position. The doors feature a micro-conical fitting (MCF) with a collocated MTC target (see Figure 10 - SPDA Doors MCF, Target, and Hard Stop). Two hard stops are provided to protect against ramming into the MCF of the other door and possibly damaging the grasp interface, and also to keep the doors captured in the rail assembly.

The doors are expected to float within the rail assembly while on-orbit in microgravity, however the robot may induce contact between the doors and the rails during capture and manipulation. The mating surfaces of the doors and rails have been finished to a maximum of 125 microinches surface roughness to reduce undesired frictional forces. The stationary rail brackets allow for easy entry of the door wedge brackets, and are designed to guide the wedge bracket to within capture of the ball detents.

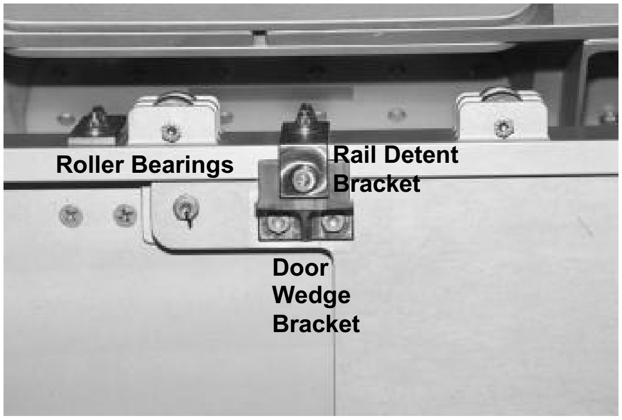

Figure 9 - SPDA Doors Soft Dock Mechanism and Rollers

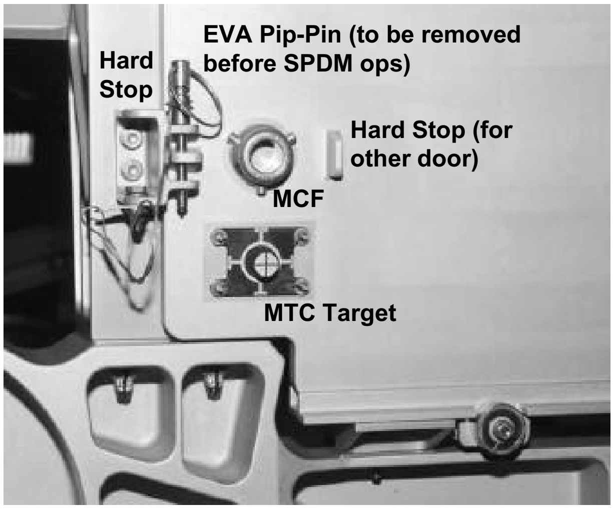

Figure 10 - SPDA Doors MCF, Target, and Hard Stop

For the alignment markings, or status indicators, only the fully open and fully closed position needed to be indicated to the operator. A simple, passive design was desired to provide indication of state through the SPDM's end-effector camera (the only view guaranteed on-orbit). The indicators are a series of black markings, labels affixed to the aluminum door. The simple design gives visual confirmation to the operator that the door is captured when the marking on the edge of the door is within the width of a similar marking on the rails.

Testing at the RSEL lab in Johnson Space Center proved to be quite difficult initially. The doors were to be tested in conjunction with the protected RPCMs beneath, which are at a 4° offset from the plane of the doors. The test article in the RSEL was situated with the RPCMs at 0° degrees from ground with the doors at the 4° offset. The test article door brackets and rail brackets were made out of aluminum alloy (instead of A286 Cres steel) in an effort to save cost, unaware of the impact it would have on the test results in the 1-G environment. The robot was tuned with a center of gravity algorithm to aid the robot in holding the 36" solid aluminum door evenly.

After immediate negative results from the robotic testing, the test article was modified to be more flight like to reduce the friction encountered in the 1-G environment. The rail surfaces were redesigned to a smoother finish on the flight article and subsequently altered on the test article. Finally, the rail brackets were positioned correctly and remade out of the correct steel material, along with the door brackets. These changes combined with the reorientation of the doors to 0° from ground with the RPCMs at the 4° offset yielded better results. The forces were still too high, so a vertical test was proposed and executed. With the doors in a vertical state (actuation direction parallel to the gravity vector), the forces to actuate closely matched the analyzed forces of 14lb. All force readings in the vertical state passed the requirement, while most of the force readings in the horizontal state exceeded the requirement. Although the vertical test did not involve the robot or an operator-in-the-loop, it proved the door mechanism required less than the 20 lb limit set by the Maximum Force requirement [Reference 2]. The robot in a 1-G environment was unable to actuate the doors in a smooth trajectory, inducing hardware contact not initiated by the operator. On-orbit, the doors will be able to translate more evenly than in a 1-G environment.

MT and Tether Shuttle Stops Design

Perhaps the most intricate design the SPDM will manipulate on the inboard truss segments are the Mobile Transporter (MT) Stop and the Tether Shuttle (TS) Stop. One each of these mechanisms is located on the edges of the two outer segments of the inboard profile (ITS Segments P3 and S3). The MT carries the Mobile Base System (MBS) or robotic base system along the truss segments for assembly and maintenance tasks. If there is a need to cross over to the outboard truss segments, the MT would need to cross the rotating Solar Alpha Rotary Joint (SARJ). To prevent the MT from accidentally running into the rotating SARJ assembly, two MT Stops have been located on the outer edges of the MT rails which do stay in place, and are left in the deployed position (see Figure 11 - MT Stop Test Article - Deployed). When the MT is prepared to cross the SARJ, it must first stow the MT Stop.

The rotational motion required by the MT Stop and the TS Stop are not typical tasks the SPDM has been optimized to achieve. The TS Stop has a required rotation of 90° without the use of a robotic extension tool, while the MT Stop requires a rotation of about 67°, and requires a tool. The SPDM can accomplish both motions, however the lateral force capability is still uncertain.

The MT Stop (see Figure 11 - MT Stop Test Article - Deployed and Figure 12 - MT Stop Test Article - Stowed) features a micro conical fitting collocated with a MTC target on a paddle offset from the pivot shaft by 2.4". The pivot shaft is made of steel, wet lubricated with Braycote 815Z, and rides through bronze bearings at the edges of the bulkhead. The MT Stop is spring loaded in both the y-direction (in and out of the bulkhead) and in the pitch direction, or counter clockwise about the pivot axis in the picture shown. Three protrusions from the bulkhead serve as hard stops. When the Stop is in the deploy position, it is resting against hard stop #1. To move the MT Stop to the stowed position, one would pull the MT stop away from the bulkhead about .5", rotate it CCW until the arm of the MT Stop hits hard stop #3, and then pushing back into the bulkhead and letting the Stop rest against hard stop #2. Alignment markings are being added to the design to increase visual confirmation of the engagement of the Stop against the bulkhead, and safety confirmation that the paddle will clear hard stop #2.

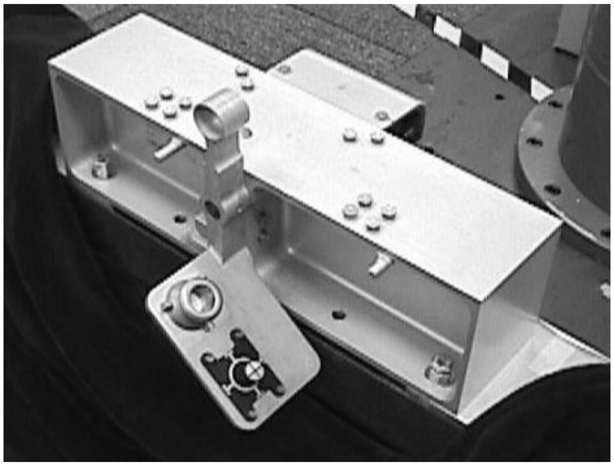

Figure 11 - MT Stop Test Article - Deployed

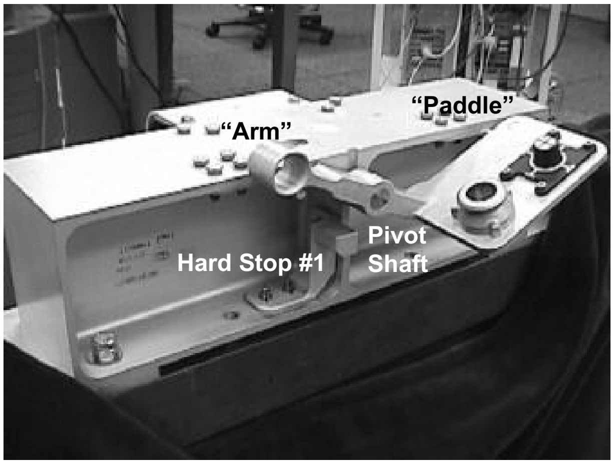

Figure 12 - MT Stop Test Article - Stowed

MT Stop testing found difficulty with deploying the Stop. The compression spring was deflected .15" due to the anodized key feature situated in between the stop and the bulkhead. The initial force to get the stop moving was above 20lb for most of the robotic runs. The micro-conical, or attach point, is offset from the pivot axis 2.4" which induced enough of a moment arm to hinder the robot's ability to slide the stop out. Considering the MT Stop, surrounding hard stops, and bulkhead are all similar in color, the operators had difficulty verifying the stop was able to clear the hard stop pins or engaged back to the bulkhead. The testing team suggested applying a white label to either the bulkhead or the hard stop pin to aid in visually clarifying the state of the MT Stop. These design suggestions are still pending. The anodized keying pin proved to be of no use, no camera view was able to identify the keying pin, nor verify whether it was engaged. The operators had the option to release the MT Stop and fly to the location of the keying pin with the end-effector and visually verify whether the MT Stop was fully engaged. This is undesirable as the operator must release the MT Stop in an unknown state, and possibly attempt to recapture if not fully stowed or fully deployed. With a working design, however, the Stop will only be in one of two predetermined states – deployed or stowed, as a result of the auto-rotate feature of the design.

The TS Stop uses a direct interface with the SPDM end effector, an H-fixture, collocated with a MTC target (see Figure 13 - TS Stop H-Fixture and Target). Use of the 13" Robot Micro-Conical Tool (RMCT) on a MCF would have exceeded the robots kinematic capabilities due to the increase of pitch rotation at the shoulder of the SPDM. The TS Stop also operates via hard stops, with visual confirmation available for indication of state. The operator approaches and grasps the H-handle, pulls left .36 inch, encounters a hard stop, then initiates the pitch rotation. The alignment markings, as well as views of the detail TS Stop worksite, visually verify the TS Stop has disengaged from the longeron and is thus ready to rotate and stow. The spring assembly within the TS Stop is wet lubricated with Braycote 601 E/F and has performed as expected during testing. Separate sets of alignment markings are used for the stowed and deployed state (see Figure 14 - TS Stop Test Article - Deployed and Figure 15 - TS Stop Test Article - Stowed), with the visible gap in between giving the operator the most information as to the state of the OMH.

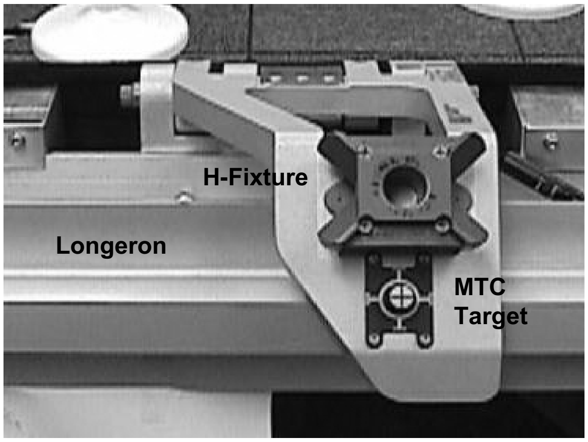

Figure 13 - TS Stop H-Fixture and Target

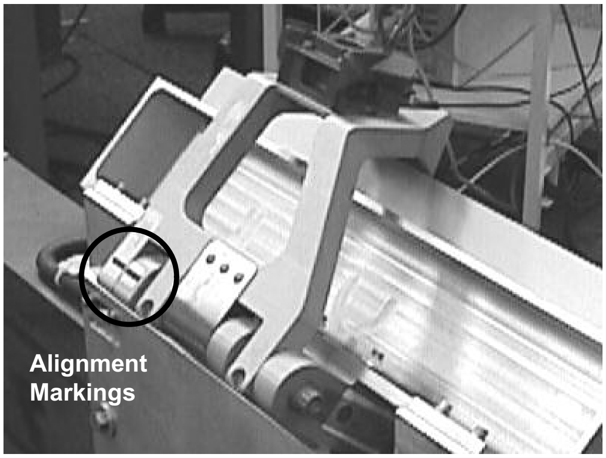

Figure 14 - TS Stop Test Article - Deployed

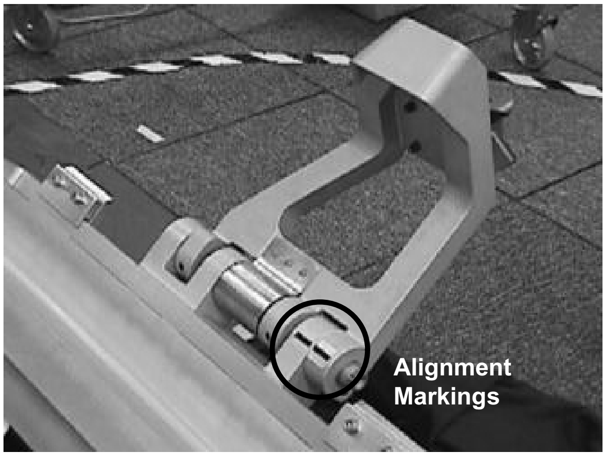

Figure 15 - TS Stop Test Article - Stowed

Both the MT Stop and TS Stop require more than 10lb of force to actuate in the y-direction (published SPDM capability) as designed, with the MT Stop at 14 lb and TS Stop at approximately 15 lb. To build additional confidence in the robot's capability to manipulate these items, Boeing has added additional lubricant to the rotating shaft of the MT Stop, as the actuation force is extremely sensitive to any side loads induced on the pivot axis. The TS Stop seems to be less sensitive to unintended moments and thus can be robotically manipulated with less than 20lb as seen in the testing.

Conclusions

Extensive groundwork has been laid by the ISS EVR program to provide EVR capability to reduce the impact of EVA maintenance on crew time and ISS operational cost. The first fruits of this work were launched Station assembly Flight 3A, and on nearly every flight after that. From this point, two directions will help towards a common ground of operability:

1) Accelerate on-orbit experience with SPDM and other EVR systems to confirm theories of microgravity operations and raise confidence in EVR capability prior to depending on it; and
2) Develop additional EVR agents and tools to complement and augment planned SPDM capability both to expand the number of EVR tasks and to ensure reliability of successfully completing EVR tasks.

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