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Preparation for Advanced Space Robotics Simulations in MOTS (the MSS Operations and Training Simulator)

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ABSTRACT

The Mobile Servicing System (MSS) Operations and Training Simulator (MOTS) is an established MSS simulation system in the International Space Station program. It has been designed and prepared to support anticipated training and operations activities that require a holistic operational perspective and quick and reliable responses. To date nominal sessions for general training and evaluation of flight files and procedures for operational scenarios have been supported. More challenging roles lie ahead. To properly accomplish these roles the MOTS must demonstrate a superior capability to produce representative performance conveniently, cooperatively, and with confidence. To perform conveniently the MOTS must be proven to support user interaction and data access by an easily controlled interface and to support new and varied activities. To perform cooperatively the MOTS must be proven to interface with external systems as elegantly as the MSS itself must interface with other ISS components. To perform confidently the MOTS must be proven to properly represent MSS performance in detail, proof that can only be obtained with respect to flight performance and data. Therefore the MOTS must be prepared to validate to flight data in real time. These are the key elements of advanced space robotics simulations.

Figure 1: The ISS Expedition 4 Crew, Cosmonaut Yuri Onufrienko and Astronauts Daniel Bursch and Carl Walz, enjoying the first MOTS based training in March 1998.

1. Introduction

Canada is contributing the comprehensive Mobile Servicing System (MSS) robotic system to the International Space Station (ISS) Program. The MOTS simulates end to end performance of this system as it completes a variety of robotics tasks. The initial MOTS configurations are described in References 1 and 2.

The MSS Operations and Training Simulator (MOTS) was initially specified in 1994 to provide "a high-fidelity, full function, kinematic and dynamic software simulation of the MSS Space Segment in on-orbit configurations" for the Canadian Space Agency. It provides sufficient representation of Canadian Mobile Robot Servicer (MRS) component performance in the flight environment to enable Crew and Mission Controller training and operations analysis, and was first used for formal Astronaut Training in March 1998 after an initial familiarization period. The MOTS continues to be enhanced to better represent evolving on-orbit MSS systems, indeed the incorporation of relocatable flight software components continues as those components become available. It is now appropriate to consider detailing advanced applications that can be supported from this platform, the foundations for which are native in MOTS design and architecture.

The MOTS support facility features a replica of the International Space Station (ISS) Robotics Work Station (RWS) as the primary physical interface at which the on-orbit human machine interface is emulated. The real-time simulation includes flexible multi-body dynamics, contact dynamics, thermal behavior, power consumption and distribution, telemetry generation, video distribution, camera control, and robot control of the MSS. The 3D visualization of on-orbit camera views includes real-time simulation of visual effects, such as, camera out of focus, depth of field, exposure control, vertical smear and blooming. Currently, elements of flight control software are being integrated to replace the original simulated modules. The simulator will eventually feature all of the high-level flight control software. The MOTS also supports planned hardware-in-the-loop simulation to the degree necessary to support SPDM Task Verification Facility (STVF) requirements.

Located at the Canadian Space Agency premises in St. Hubert, MOTS is being used by training staff and international astronauts in preparation for missions to the ISS, and by MSS operations support personal for mission

planning and development. MOTS is the CSA's primary tool supporting the operations and utilization of the MSS and hence will interface with other local ground support facilities, such as the Space Operations Support Centre (SOSC), which in turn interfaces with the Mission Control Center at the Johnson Space center in Houston.

2. Overview

The MOTS was originally procured as a complete system consisting of the simulation software and the host equipment and peripherals. It has since become more appropriately identified as a software system that is now hosted on a variety of SGI platforms ranging from a 2 processor Octane to a 20 processor Onyx. The MOTS provides an interface to a physical RWS, or provides users with functionally representative RWS components in software, including the Display and Control Panel (DCP) and flight displays with pages populated with graphics and digital information from high fidelity software models which represent system behaviour. When a simulation is running, the models provide human computer interface responses that represent the actual system. It also provides a realistic simulation of the operating environment through the reproduction of appropriate lighting and video performance. Video camera images are represented by computer graphics that are generated from a database of Space Station visual objects with a customized high performance visual renderer as shown in **Figure 2**.

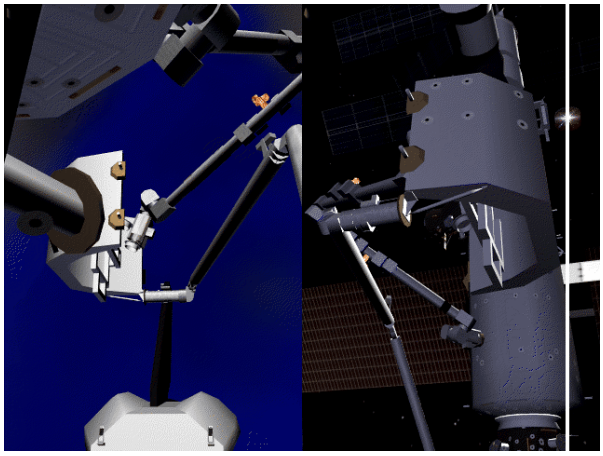

Figure 2: Flight 6a hand-off scenario captured in a multiplexed view from the Orbiter A and C cameras.

MOTS supports operations analysis by providing a complete set of real-time simulation and off-line data collection, conversion, and analysis tools. These tools can be used to verify system operating procedures, on-board displays, telemetry definitions, system models and performance data. The data recording and analysis function enables the user to analyze behaviour and isolate possible causes of performance deviations or equipment failure. The simulator also generates accurate command and telemetry data streams. These streams are used to stimulate and validate the ground segment monitoring facilities of the SOSC. The MOTS currently provides SRMS and SSRMS telemetry streams to the SOSC.

2.1 MOTS Hardware

The main hardware components required to support a formal MOTS simulation generally include at least a simulation host computer, a Robotics Work Station (RWS), at least one Simulation Work Station (SWS), a video distribution system, and a video or digital recording system.

An extensive trade-off study originally determined that a high-end Silicon Graphics Onyx™ platform provided the best multi-purpose host for this end-to-end simulation. It combines the multiprocessing power of a supercomputer with an advanced graphics architecture (Reality Engine). Its ability to support a comprehensive software driven visual environment coupled with the maturity of its parallel processing optimization were main considerations in this selection. The primary host computer is now equipped with twenty CPUs. A new Onyx platform utilizing the 400 MHz R-12000 processors and the "Craybar" based architecture would greatly enhance performance and is being considered for a host update in the near future.

The functional equivalent RWS seen in an earlier form in **Figure 1**, provides the crew with simulated camera views of the ISS environment on the flight video display monitors with data depicted on the flight Personal Computer System (PCS) laptop hosted user interface pages. The astronauts control the simulation via the PCS and a representative set of 3-degree-of-freedom hand controllers (one translational and one rotational) and a Display and Control Panel.

Simulation Work Stations (SWSs) enable support personnel to monitor and control all aspects of a simulator session and to perform such actions as inserting malfunctions, gathering data, and providing alternate or arbitrary viewing points such as **Figure 3**. An additional set of hand controllers is available at some SWS's to provide desired support or backup and to allow control of secondary manipulators such as the SRMS.

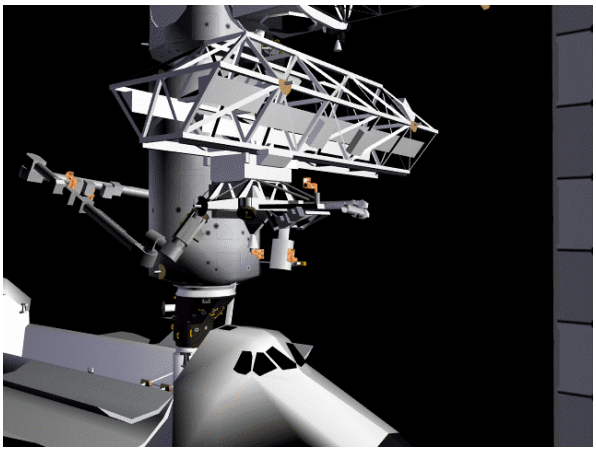

Figure 3: Initial berthing of the MSS Base System on the Mobile Transporter on the S0 Truss Segment during Flight UF2 by the SSRMS with SRMS camera views.

2.2 Simulation Environment and Software Tools

The simulator is built within CAE's off-the-shelf Simex simulation environment used in flight simulators everywhere. This environment has been enhanced to support and control this real-time multi-body dynamic simulation. The real time dispatcher schedules the execution of the models in specific processes at a specified rate. The dispatcher handles both synchronous and asynchronous processes.

The software development environment features a suite of integrated tools to support the development of new simulation scenarios. It is integrated within the CAE simulation environment and is complimentary to the main simulation environment.

A simulation scripting tool is provided to allow the user to automate simulator runtime operations. Any user interaction with the simulator captured during a simulation run can be scripted. This capability is being expanded to support the execution of all system level tests that currently require substantial manpower to execute to completion. In this way regression testing can be conducted "overnight" in support of new version releases. This will ensure that all simulator functionality is checked and verified and is not impacted by new functionality or anomaly resolution. Recorded scripts can be run as they were recorded, on an accelerated basis, or as selected by an operator.

The video distribution system allocates simulated camera views to the video monitors available at workstations. The record and playback function captures key simulator data that enables the scene to be replayed within the simulator. It can record up to 4 channels of video and audio simultaneously on tapes, which can be replayed later either in real-time, frame-by-frame, or slow motion. The simulation can be restored to any point in the sequence, as controlled from the playback control page.

The data collection and analysis function gathers desired data at specified rates up to 1000 Hz during the real time simulation for post-simulation analysis. Data analysis provides integrated image processing, statistics, signal processing and mathematical capabilities.

The malfunction insertion capability during a simulation is another important function of the simulator. Specified malfunctions can be activated or deactivated manually, based on time or on events. The malfunctions themselves are stored in a malfunction database that contains all the malfunction commands and triggering parameters.

2.3 Simulation Models

The primary MOTS host computer consists of 20 processors supporting synchronized model execution across shared memory to obtain a real time deterministic simulation. Currently CPU allocation includes 1 CPU for the synchronous process, 8 for visual rendering, 7 for the 1000 Hz joint control systems, 1 for collision detection, 1 for contact dynamics, and the final 2 processors execute the remaining 15 processes that administer to everything from video-recording to GUI support.

Simulation models include malfunction and nominal behavior simulation of the system through faithful representation of equipment performance and are divided into two major categories: physical models and equipment models.

The physical behavior models consist of a flexible multi-body dynamics model, a power distribution model that determines the power status of the equipment, and a thermal model that computes the temperature of each MSS component based on the heat generated.

The equipment models consist of MSS equipment hardware control models and on-board software models. One example of such a model is the simulation of the software that resides in the robotics workstation. The model provides a 2-way communication between the on-orbit control pages; control panels; and handcontrollers, and the simulated MSS elements. Commands are forwarded to the lower level equipment models and telemetry and status information is returned to the robotics workstation.

A single point contact dynamics model supports general collisions, while a multi-point contact dynamics model supports SSRMS grappling payloads and berthing them to the Space Station. The simulator detects that manipulator activity is addressing a particular work site and the contact model changes automatically. The payloads supported vary in size and mass properties and can be as large as the space shuttle or as small as an EVA astronaut on a platform.

The incorporation of delivered flight software into the simulator is well underway. The capability to support Ada code within the simulator environment was added specifically to support Flight Software execution. All flight software appropriate for use will eventually be incorporated into the simulator. To date the current SSRMS Arm control System (SACS) and Joint Control System (JCS) have been incorporated. This activity has been greatly supported by the Prime Contractor, MD-Robotics, which has "encapsulated" the relocatable elements of this software with associated motor hardware components. The incorporation of the LEE Control System (LCS) is nearing completion and preparation for the incorporation of the Operational Control System or (OCS) is well underway.

2.4 Visualization Models

Within the Space Station the astronauts will operate the robot arm from one of two Robotic Work Stations (RWSs), where they will be presented with camera views displayed on three 10.4" flat panel LCD monitors. The lack of direct vision will challenge them to operate the arm mainly

through feedback provided by numerous cameras. The views produced by the cameras and displayed by the distribution system are therefore important to represent correctly. This is done by ensuring camera parameters are modeled correctly, and by including all camera effects such as auto exposure, blooming, smearing, depth-of field, and out-of-focus. The effects of the lighting environment are also very important, therefore a real-time shadowing capability is included that allows shadowing in selected views as desired. Shadowing is provided by projecting a shadow map and is therefore some what pixelated depending on the objects upon which the shadow is cast, and there is a significant performance impact when the option is enabled which can be as much as a 50% reduction in frame rate. These capabilities are implemented in a CAE-developed real-time visual renderer that, when coupled with tailored graphics objects, provides realistic camera views rendered at a rate of up to 30 Hz. The visual renderer relies upon a visual database of all ISS elements at various levels of detail and the data provided by the software simulation models. The rendered database provides an impressive lighting environment that faithfully emulates that observed in space.

2.5 Graphical User Interface

Users interface with the simulation through high fidelity replicas of flight GUI pages executed on a flight PCS and interfaced to the modeled system through the simulation database. This current practice of implementing exact replicas of flight GUIs though a third party user interface, in this case SAMMI, may be augmented with a direct interface to C++ coded replica pages. The C++ interface is generated by BX-Pro, another tool, as an alternate rapid prototyping technique under current investigation. Additionally an interface is being added to allow actual PCS laptops to be directly interfaced to the MOTS. This will be by RS232 interface and may then proceed to support a 1553 interface through an intermediate device or using ISP and HLA over a LAN. Interfacing these pages to the simulated models was accomplished through use of the equipment ICDs, and specifications that establish the means by which information is passed and commands are completed in the actual system.

3. Current Status

3.1 Convenient Performance – New Tasks

Convenient performance of any tool is an important measure of its utility. To demonstrate the native capabilities designed into the MOTS that can be expanded or manipulated to support new tasking may require lengthy and tedious consideration of all MOTS capabilities, features, and user interfaces. It is more appropriate to consider a recent representative task that was conducted in the MOTS to assist comprehension of the native simulation capabilities that are available to be utilized or enhanced for desired support.

An HTV crew capture trial was conducted using the MOTS in November 2000. In this trial the NASDA H2 Transfer Vehicle was modeled in the MOTS to the degree that it could be positioned for capture relative to the ISS within the constraints of a generalized control system. The HTV was then released into free drift while an astronaut performed a capture operation such as shown in Figure 4.

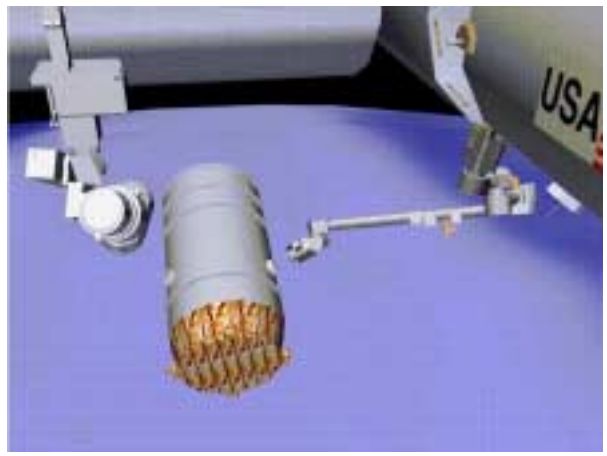

Figure 5: View of HTV Capture Trials from the P1 Truss "over-the-shoulder" of the P1 Truss lower inboard camera. SSRMS is based on Node2 with the HTV control system deactivated to permit free drift for capture.

The capability to support free flyers in MOTS is resident to the degree that any potential payload could be grappled and de-mated from the ISS and subsequently released and positioned as desired and controlled with the input of velocity parameters or flown by hand controllers, and otherwise influenced by collisions. These capture trials required that acceleration parameters be incorporated as well. Also required to support this activity was the HTV itself and the additional objects to support the Flight J1 environment including Node2 (a base for the SSRMS), P1, S1, and Hab and Jem structures to name a few. This additional capability was implemented in five weeks and included a convenient interface page depicted in Figure 5.

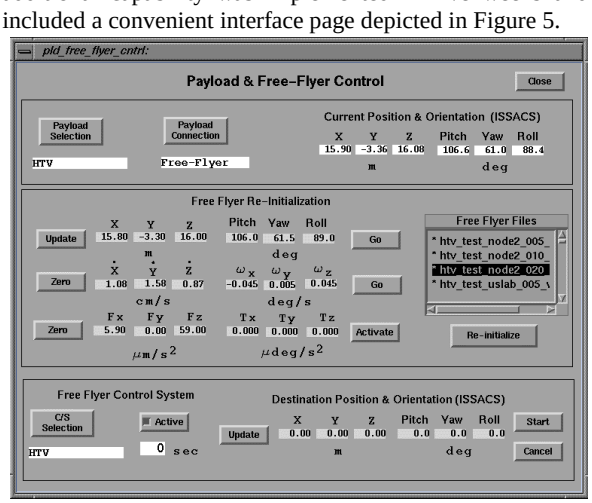

Figure 4: The simulation control page for Payloads allows the positioning of the payload and assignment of control system parameters to payload positioning.

This page allows for payload designation and assignment and permits parameters to be applied directly and zeroed, updated, or re-initialized as desired. It also permits predefined data sets to be recalled, previewed, and applied. It also enables selection of desired control systems if supplied as well as the disabling of the control system (release to free drift) and counts the ensuing time that elapses until a valid capture is detected. An auto-sequence capability is also provided to allow the payload to be positioned in that manner if desired.

The resident data collection capability was also utilized to plot 50 parameters at 10 Hz for the average 90 seconds for which data capture was required for each of the 160 runs performed. The conduct of this exercise, as with many activities, provides the opportunity to assess model performance under varied conditions. In this case the testing of the simulation performance supporting captures specific to free flyers resulted in a more robust and better representative model of the full snare, grapple, and rigidize sequence as it applies to any target.

3.2 Cooperative Performance – Co-joined Simulations

Many partners in the ISS program are involved in robotic operations of their own, all supported by various means. Inevitably cooperation between the partners will necessitate cooperation between facilities and organizations as combined flight operations are undertaken. Ground based simulation is a fundamental component in preparation for any such activity. The MOTS architecture currently employs High Level Architecture (HLA) to allow the MOTS numeric processing and visual rendering to be separated to different computer systems. The concept of a number of various different agencies executing software models of their own robotic systems and all linking together in a shared common visual scene that is available at all sites is very appealing. The ability to execute simulations remotely is also very appealing due to the high cost of specialized computer systems which are required to host the precise simulations. In an ambitious program such as the ISS it may become desirable for operators to run remote simulations to avoid the demanding travel that becomes an issue in widespread international endeavors. Current architectures employed in the MOTS and other systems will lend themselves well to support these kinds of progressive activities.

3.3 Confident Performance - Validation

Simulator validation is a potent issue that can only be fully resolved by exhaustive comparative assessments against definitive performance data, which to date is not available for the MSS. Most who will not be satisfied with anything less then corroboration with the "Real Thing" must consider that it may take a while for the "Real Thing" to reveal itself.

The most important items in the MOTS requiring validation are the dynamics and control system solutions. The dynamics resolver in the MOTS has a long and distinguished pedigree dating back to the simulation systems that supported the origin of the SRMS at SPAR Aerospace. The product of SPAR's effort eventually became known as the Manipulator Development Simulation Facility (MDSF), though it may be better labeled a Manipulator Simulation Development Facility. This VAX based simulation system included a highly capable dynamics engine that contributed to the establishment of design parameters and the control system for the SSRMS. This MDSF-NRT (for Non Real-Time) was then expanded to an MDSF-RT (Real-Time) and eventually ported to a Convex C-220 and subsequently to the IBM 6000 series with SGI handling the graphics. Then with the MOTS project came a port to SGI equipment. It was critical to maintain commonality with the MDSF because the MDSF-NRT had been firmly established as the "Truth" model for SSRMS simulations. It was clear that this capability would be much more practically incorporated then duplicated. Without benefit of current control systems the MOTS proceeded to establish full system simulation capability with initial Fortran models. The MOTS performance was constantly compared with known MDSF-RT and NRT performance. Ultimately potential Flight Software was implemented in MOTS and its performance compared with current MDSF-NRT performance in a detailed validation that compared inputs and processing in addition to the outputs of the two simulation systems. The product is a set of validation performance plots that is not exact, but so close that it is difficult to characterize the difference at times. **Figure 6** illustrates the match found between the MOTS performance (in blue) and the MDSF-NRT performance (in red) for this 100 second Manual mode dynamic tip linear velocity plot for one axis. This plot is representative in that most plots match at least this well, note the match in amplitude and phase considering that the full y scale is $12*10^{-5}$ metres.

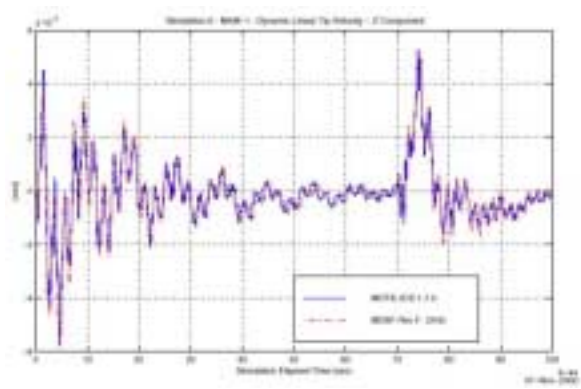

Figure 6: A typical MOTS Real-Time vs MDSF Non Real-Time performance validation plot.

Consider that the NRT simulation against which the MOTS is compared does not have any timing constraints and therefore it is not necessary to cut off any frequencies. In NRT convenient use may also be made of mechanisms which could not be considered in a real time operational environment such as the disabling of dynamics while the control system initializes. The MOTS includes current Flight

Software Ada code for both the Arm Control System and the Joint Control Systems. The JCS and its associated motor hardware and dynamics routines execute as dedicated 1000 Hz processes across 7 CPUs (1 for each joint), and must be synchronized with SACS execution and Common Data Base access.

The validation that can legitimately occur in advance of actual system performance is limited in any case, therefore preparations are underway to quickly compare simulator performance with actual system performance. In this concurrent mode of operation the MOTS will receive actual system commands and resultant performance data by telemetry available through NASA. This command information will then drive a simulation session the results of which are compared with received response data adapting to the latency of the received information by noting the embedded times. The MOTS will concurrently generate performance plots to track the fit of the actual vs the MOTS generated responses. The deviation would be tracked and may be corrected by real time modification of simulation parameters to achieve better fits as the activity progresses. In this way anything the SSRMS does in orbit will contribute to the validation of MOTS performance. It is important that this be conducted in real time because there will not be adequate opportunity to conduct post flight analyses in the case of the ISS, it must be monitored and addressed as it performs.

The MOTS has proven to be a useful platform on which to verify the performance of operational procedures with flight software, in an operationally representative environment. Several adjustments of flight procedures and reconfiguration files have been precipitated by MOTS simulation sessions.

3.4 Concurrent Simulation

Concurrent simulation is the simulation of an activity currently underway. This activity will aid real-time validation and will also allow for ready operational support. As the SSRMS is positioned and proceeds with a maneuver, planned or otherwise, the simulation can be placed in a slave mode following actual SSRMS commanding and movement. It can be slaved to actual operational data to position Joints, etc, or allowed to proceed using only actual commands and determining the resultant output. Either way the simulation can be monitored to ensure close representation of actual performance and periodic configuration. Where the actual system reaches some sort of decision point or impasse the simulation may be used to try out the intended activity. The current status of the simulation is saved to enable instant recovery at any time, and then a trial sequence may be undertaken. This trial would allow a user to verify desired trajectory parameters are satisfied and that the SSRMS arrives at its objective with desired joint configurations sufficient to support activities at a new work site. This would permit support personnel to advise flight crew on the best way to proceed.

4. Future Plans

The MOTS remains the backbone of the ground segment facility at the Canadian Space Agency and is important for the success of the Canadian Space Program. It is a modular simulator that enables the addition of new components and interfaces to other facilities. MOTS must always stay in synch and up-to-date with Space Station planning and construction. New visual objects and fidelity and simulation components are constantly being added and tuned to ensure the MOTS continues to provide a faithful simulation of the International Space Station.

The MOTS has proven the capability to support simulations of the Special Purpose Dexterous Manipulator (SPDM) and the 60 flexible bodies required for such an environment. The SPDM Task Verification Facility (STVF) will depend upon hardware-in-the-loop simulation from the MOTS to place the Robot supported contact dynamics in the proper control environment. Within the STVF a real robot will reproduce the SPDM end-point motion resulting in real contact forces between mock-ups of the SPDM payloads, known as Orbital Replacement Units (ORUs), and the work-site. The real contact forces will then be fed back to the MOTS, which will be running the SPDM dynamics and control system models when they become available. Data is already exchanged between the simulator and the robot environment over a FireWire interface to achieve the necessary data exchange rate of 1000 Hz.

5. Summary

The MOTS currently plays a limited role in preparing astronauts for the operation of the MSS and verifying operations procedures. It provides a faithful simulation of MSS that is improving as model performance is enhanced, and actual behaviour is established. Expansion of this role is dependent upon proven performance for each scenario addressed. This will come with time as it is proven that the capabilities addressed here can be accomplished easily in a user friendly and flexible environment.

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