Proceeding of the 7th International Symposium on Artificial Intelligence, Robotics and Automation in Space:
i-SAIRAS 2003, NARA, Japan, May 19-23, 2003

Validation Plan for SPDM Task Verification Facility

Ou Ma
New Mexico State University, Las Cruces, NM 88003-3450, USA, oma@nmsu.edu

Jiegao Wang, Misra Sarthak, Michael Liu
MD Robotics Ltd., 9445 Airport Road, Brampton, Ontario, Canada L6S 4J3, mliu@mdrobotics.ca

Keywords: STVF, SPDM, Validation, Contact Dynamics, Hardware-in-the-loop Simulation, Space Station, Simulator.

Abstract

This paper describes a plan and the technical rationales behind the plan for validating a complex, hardware-in-the-loop simulation facility, the SPDM Task Verification Facility (STVF). The facility is being developed by the Canadian Space Agency for the purpose of verifying the contact dynamic performance of the Special Purpose Dexterous Manipulator (SPDM) performing various maintenance tasks on the International Space Station. Because the real SPDM cannot be physically tested for 3D operations on the ground due to gravity effect, STVF uses a high-fidelity SPDM simulation model, known as the "truth model", to drive its hardware for contact operations. The objective of the R&D work described in this paper is to develop a methodology and procedure to demonstrate that the complex hardware-in-the-loop facility preserves the dynamics of the truth simulation model of SPDM for space-representative contact robotic tasks.

1. Introduction

SPDM (Special Purpose Dexterous Manipulator), shown in Fig.1, is a 15-degree-of-freedom, two-arm, advanced space robot, recently developed by MD Robotics Ltd. of Canada for the Canadian Space Agency (CSA). The robot will be used for external maintenance of the International Space Station. Like the other Space Station manipulators, SPDM cannot perform general 3-D tasks on the ground due to gravity. As an alternative, the Canadian Space Agency is developing a special hardware-in-the-loop simulation facility – *SPDM Task Verification Facility* (STVF). The primary purpose of STVF is to verify the dynamics (especially contact dynamics) of the robotic tasks to be carried out by SPDM on the Space Station. It will also be used for the development and verification of the robot's operation procedures, crew and ground personnel training, and mission analysis [1-2]. The facility is in the final integration and test stage and will be delivered in 2003 and launched in 2006.

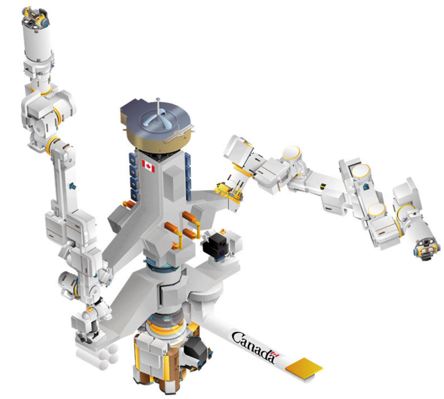

Figure 1: Special Purpose Dextrous Manipulator (SPDM)

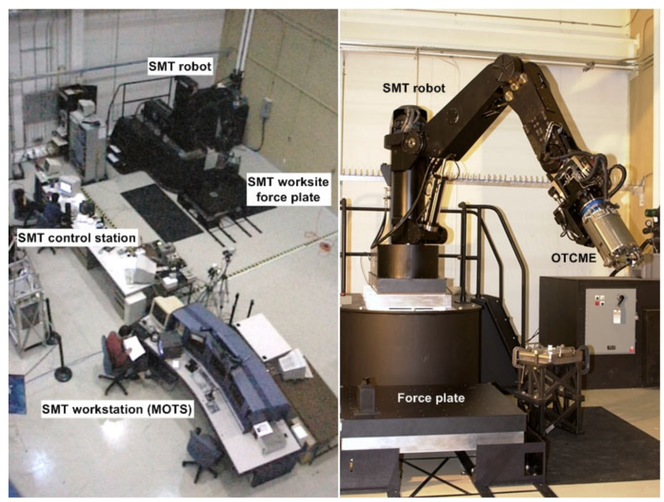

Figure 2: SPDM Task Verification Facility (STVF)

STVF is an integrated space-representative robotics simulation facility combining both software- and hardware-simulations. The software--simulation of STVF is performed based on the math model of SPDM hardware and its control software (flight code). The hardware-simulation uses a high-stiffness, hydraulic-drive ground robot, which is driven by the software simulator, to mimic SPDM performing a robotic task using a realistic payload and worksite hardware. The loop between the software- and hardware-simulations is closed by feeding the physically measured contact forces into the software-simulator [2-3]. The greatest challenge of STVF is to guarantee that the ground robot will dynamically behave like the simulated space robot during various delicate contact tasks.

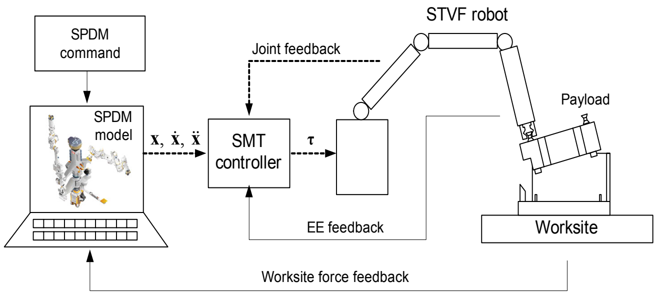

Figure 3: Concept of the STVF

In order to achieve this goal, many advanced robotics technologies have been used in the facility such as torque-controlled joint servos, computed torque control with Cartesian linearization, robust control, high bandwidth and precision force sensor and vision censors, etc. The STVF development team has theoretically and experimentally shown in principle that such an integrated hardware-in-the-loop simulation facility is capable of achieving its design goal [3]. However, since the theoretical proof and the experimental demonstration reported in [3] were limited to 2-dof systems only, the final conclusion about its validity for the real SPDM system will have to rely on the validation exercise after the facility is fully integrated.

The authors were responsible for developing a plan to validate the STVF [4]. The objective of the work is to develop test methodology and procedure to validate that the facility is capable of accurately simulating SPDM on-orbit behaviour during contact tasks. One of the main challenges we are facing is to quantitatively define and measure what we intend to check. Another main challenge is that we will have to develop the quantitative criteria (tolerances for acceptable errors) for judging a test as pass or fail. Based upon two decades of experience in validating space robot simulations and upon the specifics of the STVF and SPDM systems, we developed a series of validation test concepts and procedures. The complexity of these tests gradually increases from free-space motion, partially constrained motion to full ORU contact tasks. We also developed two levels of criteria for judging the validation test results. The development is an open process keeping the STVF developers and users as well as the SPDM developers and users in the loop, so that we can maximize ideas, expertise, and experience from different directions and therefore, result in an optimal validation plan. The paper first addresses the main challenges of the validation, starting from the next section. It then describes the validation methods including the main test concepts and their objectives. Finally, it discusses the criteria to be used to judge the pass or failure of individual test cases.

2. Validation Objectives and Major Concerns

The primary goal of the validation process is to experimentally demonstrate that the STVF preserves the SPDM on-orbit dynamics. That is, the STVF hardware robot is capable of precisely reproducing dynamic characteristics of SPDM as if it is in space performing both contact and noncontact robotic tasks. To achieve this goal, we have to clear all the concerns in the principles of STVF by both experimental and analytical means. The major concerns in this regard are as follows:

1) It is very difficult to precisely model all the hardware components of the hydraulic STVF robot, which have many nonlinearities and uncertainties. As a result, the computed-torque (Cartesian linearization) feed-forward loop may not be able to fully compensate the nonlinear dynamics of the hardware robot.
2) Without contact, the STVF system reduces to a master-slaver system and thus, its capability of tracking the SPDM simulation responses can be easily validated through experiment. However, with the presence of contact, the contact-force feedback loop makes the system no longer a master-slaver system although it is still expected that the simulation model will remain the "master". It is a natural concern that the force feedback loop might change the dynamic characteristics of the SPDM unless both robots (the SPDM in simulation model and the STVF robot in hardware) have the same impedance at their tips. This has to be demonstrated.
3) The STVF robot is designed to track the motion of the simulated SPDM regardless of its tip force-moment because the real contact force-moment is measured from the worksite of the hardware robot only as opposed to from its tip. In other words, the closed-loop system has to be able to reject any kind of force exerted on the tip of the STVF robot while it is still smoothly tracks the simulated SPDM motion. For example, when the STVF simulates an unloaded, free-space motion of SPDM, the dynamic responses of the STVF robot should remain the same, no matter what kind of payload hanging on its tip or what kind of force exerting on its tip.

3. Approaches and Considerations

Before designing validation test cases, we must first decide what validation approaches are to be used and what are the most important technical issues to be addressed in the validation.

3.1 Validation Approaches

Based upon different types of reference sources for comparing to, we have four possible approaches, namely, “hardware vs analysis”, “hardware vs experiment”, “hardware vs simulation”, and “hardware vs flight” validations. Due to the high complexity of the STVF facility, it is impossible to analyze the integrated system dynamics unless we impose significant simplification and massive assumptions, which will, without doubt, add alternative uncertainties about the validity of the analysis results. Therefore, “*hardware vs analysis”* approach does not apply here. “*Hardware vs experiment”* approach requires other hardware test rigs as references and thus, it will likely be very costly, especially considering the fact that the reference test rigs have to be validated as well. “*Hardware vs simulation”* approach requires another validated simulator as reference. MDSF [5] is a good reference because the facility has been validated using all the above mentioned approaches and its SPDM model has been accepted as the truth model. “*Hardware vs flight”* approach is certainly the most favorable approach. However, the flight data will not be available until SPDM is launched hopefully in 2006 and many SPDM verification tasks should be done by STVF before the launch of SPDM. Therefore, the “hardware vs simulation” approach will be the best approach for now.

In order to be cost-effective, and also to meet CSA’s desired short schedule for an initial validation plan, it is proposed to generate the validation plan in four phases:

Phase 1: In this phase, preliminary validation concepts are developed by MDR and a draft validation plan is written and issued. This plan will contain initial test specifications, but not the validation criteria. This phase is characterized as a proposal phase.

Phase 2: In this phase, individual test cases and the related methods and procedure are developed by MD Robotics the basic concepts proposed in the preliminary validation plan from Phase 1 will thoroughly be reviewed by CSA and MDR together. As a result of the review, changes to the concepts and specifications will be made based on all the individual test cases and the related methods and procedure. SPDM simulations for all the planned test cases will be set up and tried on MDSF. Simulation results are studied in order to identify potential problems and understand the expected outcome. Besides, validation criteria will also be developed in this phase. This phase will be concluded with the delivery of the first version of the full validation plan. Among all the four phases, this phase is characterized as a major development phase. We have completed this phase.

Phase 3: In this phase, MDR will meet with CSA and will go through a thorough review and discussion of the validation plan developed in Phase 2. As a result of the review, modifications to the validation criteria and some test cases may be recommended and incorporated into the plan. The actual validation work may start during this phase, and initial report on the validation results will be issued.

Phase 4: After the launch of SPDM and the flight data being available, the MDSF-based SPDM model would be updated based on flight data. By that time, the SPDM truth model will no longer be an assumption but instead a reality. In turn, the validation plan will also have to be revised to reflect any new updates in the SPDM model. This phase will conclude with the final version of the plan together with the final report on the validation results.

3.2 Considerations

Three important aspects have to be considered when the validation plan is designed. They are SPDM system configurations, SPDM control modes, and SPDM motion trajectories. These are the important issues for evaluating the performance of the STVF system and the SPDM system. For all of the operation-related recommendations described in this section, satisfactory MDSF simulation study has to be conducted before the STVF physical tests can start. Pre-test simulation can discover many potential problems and help us to optimize the detailed test plan.

3.2.1 System Configurations

SPDM has two arms and it will be mostly operated while attached to the end of the Space Station Remote Manipulator System (SSRMS), a 17-meter long robotic arm, also called Canadarm2. There are, thus, three arms in the system, which can form many combinations of different multi-arm system configurations. For the same ORU (Orbital Replaceable Unit, a general name of a payload) task, the performance or dynamic response of SPDM may be quite different from one configuration to another. Although the validation test cases cannot cover all possible system configurations, they will have to reflect the most typical ones. The following are the recommended typical system configurations:

1) SPDM standalone or operating on the tip of Canadarm2
2) One of the SPDM arms is anchored to the Station and the other performs the task
3) Canadarm2 arm configuration is set to a real or close to real operational scenario

4) Each SPDM arm is in a configuration closest to a real operational scenario

Consideration is given to the worst SPDM arm configurations when planning the validation test runs. For STVF robot, this is not a concern because its operational workspace is only a small portion of the entire reachable workspace of the ground robot and hence, the robot can always be put in its best arm configuration for the testing.

3.2.2 SPDM control modes

SPDM has a variety of different control modes and features, which will be used in ORU tasks [6]. Those modes and features are listed below:

- Limp
- Standby
- SJRM – Single Joint Rate Mode
- MAM – Manual Augmented Mode
- OCPM – Operator Commanded POR Mode
- PPAM – Pre-stored POR Automatic Mode
- OCJM – Operator Commanded Joint Mode
- PJAM – Pre-stored Joint Automatic Mode
- FMA (feature) – Force Moment Accommodation
- Line tracking (feature)
- POHS (feature) – Position & Orientation Hold Selection.
- APPC – Arm Pitch Plane Change, a MAM feature.
- Singularity management.

The validity of STVF in one control mode does not necessarily guarantee that in another mode. It would be ideal if we can exercise as many modes as possible in the proposed validation test runs. Obviously, this is unpractical for the programmatic constraints. Therefore, the primary choice of the control modes for the limited test runs will be the MAM mode with or without FMA feature selected, because this is the basic control mode for ORU tasks. The POHS is also an important feature for the alignment before contact takes place.

3.2.3 Motion speed and trajectory

For free-motion test, the maximum or the minimum speed is recommended. The maximum speed is commanded in order to have maximum observability of the dynamics and the minimum speed is for checking the sensitivity or resolution of STVF. Since the workspace of the STVF robot is limited to a 3D volume whose minimum side is only 0.6 m (in the horizontal plane) and maximum side is 1.32 m (in the vertical direction), it has to be ensured that the test motion trajectory is entirely within this volume. For a given workspace, higher speed will mean shorter operation duration. On the other hand, the total operation time should be long enough to allow for the reach of steady state and for the observation of low frequency behaviour of the system.

In the free space test, the SPDM brakes may be applied suddenly to maximally excite dynamic modes and show the system’s stopping performance. Such a test is challenging for STVF robot because it does not have joint brakes. However, the robot must have the capability of emulating SPDM dynamics in response to the application of its brakes.

For constrained-motion tests, commanded speeds will depend on specific constraint cases. Operational speed should be made lower when the constraint becomes stiffer. In general, the tip speed should be limited to the vernier level during a contact operation (≤10 mm/s for SPDM).

4. Test Cases

Based upon the foregoing discussion of approaches and considerations, a set of validation test categories is defined, as summarized in Table 1. Each test category consists of a number of test runs (cases) particularly designed for checking a special level of validity of the facility. These test cases in each of the test categories reflect different test conditions within the scope of that category. Each test run is identified using an ID name representing its test category and a number representing its run number. For example, AF-3 means the third test run of the applied-force test category.

Table 1: Summary of STVF validation test cases

Run ID	Test Category	Purpose	# of Runs
FS	Free-space test	Validate STVF capability of simulating SPDM free-space motion	7
RC	Rigidly constrained test	Validate STVF capability of simulating SPDM fully constrained motion	2
AF	Applied force test	Validate STVF capability of simulating SPDM dynamic response to applied tip forces (virtual contact motion)	4
SCD	Simple contact test	Validate STVF capability of simulating SPDM for simple contact tasks	5
ORU	ORU test	Demonstrate STVF capability of simulating SPDM for general contact tasks	2
OE	Operator Evaluation test	Get the operators’ feeling about the facility by Cooper-Harper rating (not used for judging the	2

		facility's validity)	
FT	Flight tests	Validate STVF capability of simulating SPDM for real ORU tasks	N/A
Total number of test runs			22

The planned test categories are illustrated conceptually by the diagrams in Figs.4-9.

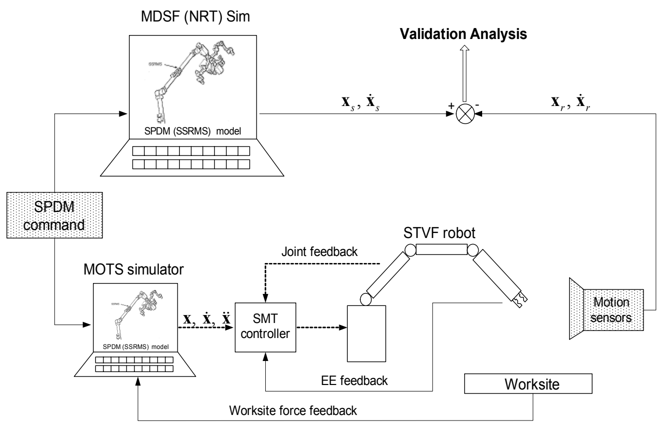

Figure 4: Concept diagram of the free-space (FS) test

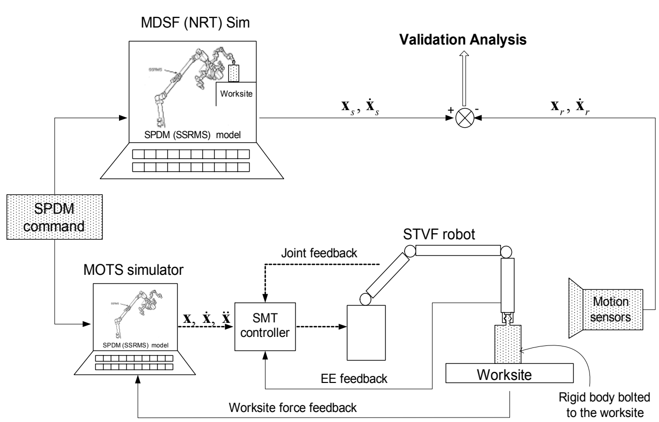

Figure 5: Concept diagram of the rigidly-constrained (RC) test

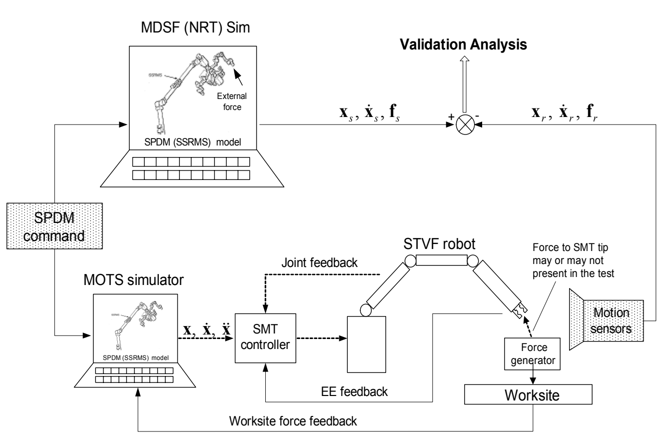

Figure 6: Concept diagram of the applied-force (AF) test

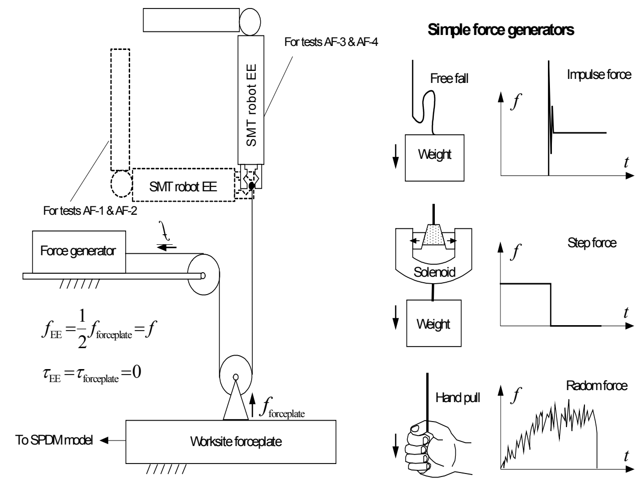

Figure 7: Examples of applied-force generator for AF tests

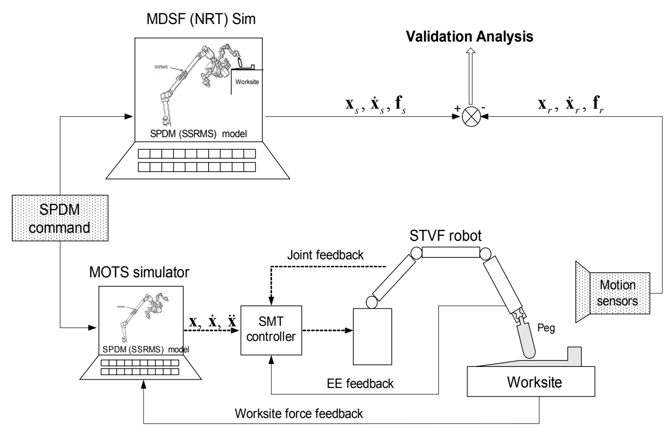

Figure 8: Concept diagram of simple-contact (SCD) test

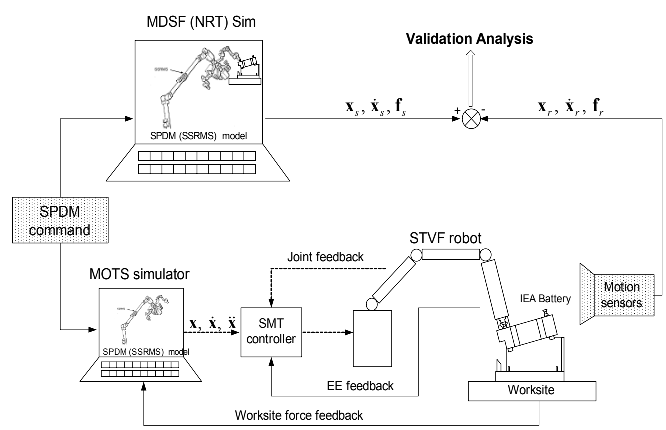

Figure 9: Representative ORU (ORU) test

In each diagram the top path represents the pure software simulation performed by MDSF and the bottom path is the software-hardware combined simulation done by STVF. Their output results are compared against the validation criteria defined in Section 5.

The complexity of the test categories varies from the simplest free-space test (Fig.4) to the most complicated full ORU test (Fig.9). It is very important to understand that this specially designed “from-simple-to-complex” test strategy is necessary for understanding and final judgement of the complex STVF dynamics system. Because of the lack of validated ORU contact-dynamics model parameters, we cannot immediately jump to the ORU test without going through simpler and much more understandable test cases first. These intermediate test categories include the rigidly constrained test, the applied-force test, and the simple contact test.

From the past validation experiences, we believe that a total of 22 formal test runs would be adequate. Among the total runs, 7 are free-space runs, 4 are free-space but applying tip force runs, 9 are constrained or contact runs, and the final 2 are operator-in-the-loop test runs. In our opinion, the 14 runs in the RC, AF, SCD, and ORU test categories are most important. Each of the test categories has been defined in the validation plan. All the test cases are detailed in the validation plan. Because of the space limitations, we cannot describe them in details here.

5. Pass/Fail Criteria

In the validation process, the maximum allowed tolerances for the errors between the target simulation output and the reference simulation output will have to be established. These error tolerances are usually referred to as validation criteria. Validation criteria have to be carefully developed and agreed upon by the technical community including the SPDM developers and users. This section describes the validation criteria and how they are applied to the validation process.

5.1 Comparison Methods

There are two kinds of basic comparison strategies in the validation process. One is performance-based and the other is task-based. The performance-based comparison checks the detailed dynamic performance along the time history of the simulated operations. Typically, it compares the transient peaks, steady-state values, frequencies, and phase differences of the simulated dynamic responses against the corresponding quantities of a reference simulation or physical test. The task-based comparison checks whether the simulated task is accomplished as expected without looking into the detailed time histories of the corresponding dynamic performance. It compares only the major operational status such as success (e.g. ORU is inserted) or fail (e.g. jammed or missed), final misalignments, total time of operation, maximum load, etc. Obviously, the performance-based strategy is more precise but it requires more engineering analysis work, especially when one needs to distinguish errors from dynamics model and those from numerical process and/or measurement systems. The task-based strategy, on the other hand, is relatively easier to apply because it avoids looking into detailed dynamic responses. As a result, it is more suitable for gross type of validation. The task-based comparison is, in fact, more suitable for validating contact dynamics (CD) simulations with complex contact interfaces, because in such cases detailed dynamic responses are extremely difficult to predict, understand, and analyze.

5.2 Validation Criteria

Corresponding to the two comparison methods described in Section 5.1, two different levels of validation criteria are proposed, namely,

- Task-based validation criteria
- Performance-based validation criteria

The task-based criteria are designed for task-based comparison method. The performance-based criteria, on the other hand, are designed for performance-based comparison method. The main motivation for defining the two levels of criteria is to maximize the validation tests or runs with limited budget/time. As we know, for contact operations, the analysis and interpretation of simulation results will be more difficult and time consuming. On the other hand, contact dynamics responses vary significantly from one case to another. A small number of runs will not be sufficient to cover necessary aspects but a large number of tests may not be realistic for cost and time limitations.

The foregoing fact motivated us to develop the two-step validation procedure as described in Fig.10. At first step, a large number of runs were screened by the task-based criteria. At the second step, only a selected number of the runs, which have passed the first step, will be screened by the performance-based criteria. In other words, all the validation runs will have to pass the task-based criteria and only a small part of all the validation runs are required to pass the performance based criteria. Of course, the failed runs in both steps will have to be investigated and re-tested.

5.2.1 Task-Based Validation Criteria

The task-based validation criteria represent a high level of engineering judgement for contact tests. There are no existing references available for this type of criteria although this kind of high level checking has been practiced in the past. Based on the past experiences of CD validation and the specific nature of ORU contact tasks, we define a set of the task-based criteria for contact tasks, as given in Table 2. It should be pointed out that the task-based validation criteria do not suitable for validation of noncontact tasks because they have much less uncertainties than their contact counterparts. For the noncontact test cases, the performance-based criteria defined in Section 5.2.2 should always be used.

Please note that the criteria regarding the final misalignments depend on the contact geometry interface and thus, their values vary from one ORU to another. However, it is not difficult to compute them if one knows the geometry data of the contact interface of the ORU of interest. In fact, during a test, one may not have to really measure and check the final misalignments. Because the criteria were designed just to guarantee the ORU within the envelope of the bolt drive, the above computed criteria must be satisfied if the ORU can be bolted down to its final place using normal end-effector driving torque.

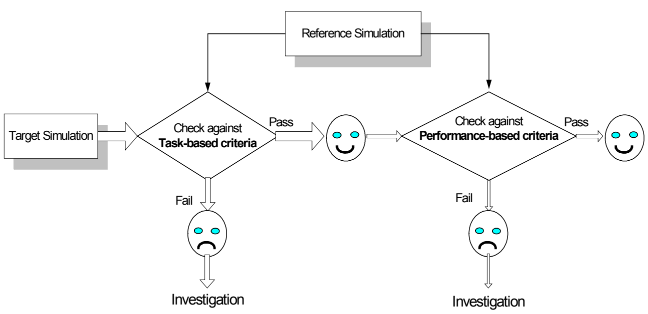

Figure 10: Two levels of criteria in the validation process

As a matter of fact, the above-mentioned two-step process has been practised in our past validation works at MDR for Canadarm and Canadarm2. It is also a very common practice for hardware testing.

The purpose of defining comparison criterion regarding time comes from such a fact that we observed situations in our past hardware test where an ORU task was completed but it took a substantially longer time (i.e., many times longer) than it should be. The long operation time was caused by some kind of temporarily jamming or slow creeping in the course of the ORU insertion or extraction. Obviously, if such a case happens, we would consider the task unsuccessful although the ORU may have eventually been pushed into its target position. The only criterion that is capable of catching this kind of problem would be the time criterion. We define the time criterion to be 30% because we think a human operator would not be able to notice that level of time error unless he or she is specially trained with the sense of timing.

Table 2: Task-Based Validation Criteria

Quantity	**Criteria (error tolerances)**
Overall	The main trends of dynamic responses look similar without significant & unexplainable abnormalities from operator's point of view.
Final Misalignments	If the task requires follow–on bolt driving, the final misalignments should be within the envelope of the bolt head.
Jamming	Following the reference (whether jamming or not) within 30% differences in time.
Bouncing	Following the reference within 30% differences in time.
Maximum POR load	Force: 40% or 20N whichever is larger Moment: 40% or 10Nm whichever is larger
Final POR load	Force: 10% or 10N whichever is larger Moment: 10% or 5Nm whichever is larger
Completion time	The total time used to complete the task must be within 30% difference.

5.2.2 Performance-Based Validation Criteria

Some performance-based validation criteria have been developed in MD Robotics Ltd. (formerly Spar Aerospace Ltd.) for Canadarm and Canadarm2. However, these criteria are of very limited use in the scope of this validation plan because, comparing SPDM to Canadarm2 or Canadarm, there are significant differences in size and the nature of their tasks plus both Canadarm2 and Canadarm criteria are for free-space (noncontact) motions only. Therefore, validation criteria for closed kinematics chains and for the intermittent contact regime encountered during ORU replacement tasks have to be defined from scratch.

Based on the above mentioned validation experience for Canadarm [6] and the specifications of the SPDM [7] and Canadarm2 [8], we derived a set of STVF performance-based validation criteria for unconstrained motion, as shown in Table 3. The derived criteria numbers have been rounded to the nearest 0.001 meters (i.e., mm) for linear quantities and 0.01 degrees for angular quantities, which is a similar fashion having been used in the development of the Canadarm2 sim-to-sim validation criteria. The rationale behind the derivation is discussed in details in reference [4].

For contact operations or constrained motions, there are no any documented criteria available from past practice for references. Generally speaking, the tolerance on a transient peak for a contact motion should be higher than that of a noncontact motion because the transient motion caused by contact/impact is more unpredictable than the free-space motion. On the other hand, the tolerance on a steady state for a constrained contact motion should be lower than its noncontact counterpart because the physical constraint in the contact helps to reduce the deviation in dynamic motion. It should be pointed out that, for a constrained motion, if a geometry constraint in the contact interface is tighter than the position or orientation criteria (tolerances) given in Table 3, then the former should be used to replace the criteria from the table. This is because the physical constraints in geometry cannot be violated.

In fact, the Canadarm's validation criteria were not finalized until years after the launch of the arm [6]. The Canadarm2 validation criteria had also been developed over a course of several years. Similarly, the unprecedented validation criteria for contact motion being proposed in this section are still preliminary at this moment. Further improvements to the criteria based on additional rationale and more supporting evidences are expected in the future.

Table 3: Performance-Based Validation Criteria

Measured Quantity	Tip Constraint	State	Criteria (sim-to-test)		References (sim-to-sim)	
			Relative	Absolute	SSRMS	SRMS
POR Position	Unconstrained	Peak		0.013 m	0.06 m	0.061 m
		Steady-state		0.006 m	0.03 m	0.031 m
	Constrained	Peak	15%	0.026 m	unavailable	unavailable
		Steady-state	5%	0.004 m	unavailable	unavailable
POR Orientation	Unconstrained	Peak		0.53 deg	1.0 deg	1.0 deg
		Steady-state		0.20 deg	0.2 deg	0.2 deg
	Constrained	Peak	15%	1.00 deg	unavailable	unavailable
		Steady-state	5%	0.20 deg	unavailable	unavailable
POR Linear Velocity	Unconstrained	Peak		0.005 m/s	0.015 m/s	0.015 m/s
		Steady-state		0.001 m/s	unavailable	0.003 m/s
	Constrained	Peak	30%	0.010 m/s	unavailable	unavailable
		Steady-state	10%	0.001 m/s	unavailable	unavailable
POR Ang. Velocity	Unconstrained	Peak		0.05 deg/s	0.05 deg/s	0.05 deg/s
		Steady-state		0.02 deg/s	unavailable	0.025 deg/s
	Constrained	Peak	30%	0.08 deg/s	unavailable	unavailable
		Steady-state	10%	0.02 deg/s	unavailable	unavailable
POR Force	Unconstrained	Peak			unavailable	unavailable
		Steady-state			unavailable	unavailable
	Constrained	Peak	30%	15 N	unavailable	unavailable
		Steady-state	10%	5 N	unavailable	unavailable
POR Moment	Unconstrained	Peak			unavailable	unavailable
		Steady-state			unavailable	unavailable
	Constrained	Peak	30%	8 Nm	unavailable	unavailable
		Steady-state	10%	3 Nm	unavailable	unavailable
Dominant Frequency	Unconstrained	Frequency	30%		15%	25%
		Phase shift			unavailable	unavailable
	Constrained	Frequency			unavailable	unavailable
		Phase shift			unavailable	unavailable

The criteria for unconstrained motion were derived with slight adjustment
The criteria for constrained motion were proposed based on R&D CD validation and SPDM test experiences
Legend:
Unconstrained -- motion direction along which no physical constraints exist, i.e., noncontact motion
Constrained -- motion direction along which a physical constraint exists, i.e., contact motion
Peak -- The transient peak of the highest motion wave; peak value should be averaged from several data points
Steady-state -- the steady-state in the final motion period

6. Conclusions

A plan and the associated methodology for validating the SPDM Task Verification Facility (STVF) are described in this paper. Because of the complex nature of the facility, a two-step approach has been proposed; one is at a gross, higher level and the other at a more detailed low engineering level. The strategy of planning the validation tests is to start from simple and well-understood cases, gradually extend the complexity of the tests, and finally to the most representative ORU contact cases. The validation test cases were particularly designed to address the main concerns and issues regarding the design and operation of the STVF system. Finally, a set of validation criteria (error tolerances) has been developed based on the objectives of this validation and the experiences of past simulation validations, as well as the specifics of the STVF and the SPDM systems.

Acknowledgements

This work would have been impossible without the technical support from the STVF development team led by Dr. Jean-Claude Piedboeuf and Dr. Eric Martin of the CSA, the STVF sponsor and operations team led by Dr. Alan Robinson, Dr. Banu Kalaycioglu, and K. Pudwalski of CSA, the SPDM systems experts R. Mukherji, J. Dunlop, R. Carr, Dr. K. Buhariwala, Dr. R. Ravindran, and Dr. P. Nguyen of MD Robotics.

References

[1] Piedboeuf J.C. et al., Special Purpose Dexterous Manipulator (SPDM) Task Verification Facility (STVF) System Specifications, *Canadian Space Agency Document: CSA-SS-SG-0008, Draft 4.0*, 1999.

[2] Dupuis E. and Piedboeuf, J.C., Special Purpose Dexterous Manipulator (SPDM) Task Verification Facility (STVF) Design Document, *Canadian Space Agency Document: CSA-SS-DD-0008, Draft 6.0*, 2001.

[3] Carufel J.De, Martin E., and Piedboeuf J.C., Control strategies for hardware-in-the-loop simulation of flexible space robots, *IEE Proc. Control Theory Appl., Vol.147, No.6*, Nov. 2000, pp.569-579.

[4] Ma O., Liu M., Buhariwala K., SPDM Task Verification Facility (STVF) Validation Plan, *MD Robotics Document: MDR-SS-PLN-7076, Revision 1*, July 2002.

[5] Ma O., Buhariwala K., Neil R., Maclean J., and Carr R., "MDSF - A Generic Development and Simulation Facility for Flexible, Complex Robotic Systems", *International Journal of Robotica, Vol.15, No.1*, pp.49-62, 1997.

[6] Palmer B. Chiu, Shuttle Remote Manipulator System Simulation Validation Plan, *NASA Document: JSC-37938*, 1998.

[7] Fullford P., Special Purpose Dexterous Manipulator (SPDM) Specification, *MD Robotics Technical Document: SPAR-SS-SG-2899, Revision C*, 1999.

[8] Space Station Remote Manipulator System (SSRMS) Specification, *MD Robotics Technical Document: SPAR-SS-SG-0379, Revision G*, 1995.