VALIDATION PROCESS OF THE STVF HARDWARE-IN-THE-LOOP SIMULATION FACILITY

Éric Martin, Michel Doyon, Yves Gonthier, Christian Lange

Canadian Space Agency, 6767 route de l'Aéroport, St-Hubert (Qc), Canada, J3Y 8Y9

eric.martin@space.gc.ca, http://www.space.gc.ca

ABSTRACT

As a partner in the International Space Station (ISS), Canada is responsible for the verification of all tasks involving Dextre, also known as the Special Purpose Dextrous Manipulator (SPDM). Those verifications cannot be performed using only software simulators since the accuracy of current contact dynamic models are yet to be confirmed. Instead, a solution involving hardware-in-the-loop simulation was retained. With this option, the space hardware is simulated while the contact dynamics is emulated using a rigid robot performing the tasks. Using this approach, the Canadian Space Agency developed the SPDM Task and Verification Facility (STVF). The approach suggested to validate STVF is based on first building confidence by comparing experimental results with pure simulation results for cases easy to model. Then, the complexity of the experimentations is increased. Preliminary test results presented in this paper show that STVF is performing well.

1. INTRODUCTION

Canada's contribution to the International Space Station (ISS) is the Mobile Servicing System (MSS) [1]. A major component of the MSS is Dextre, technically known as the Special Purpose Dextrous Manipulator (SPDM). While the Canadarm2 (Space Station Remote Manipulator System) will assemble the ISS, Dextre will be required for performing maintenance tasks. Essentially, Dextre will manipulate the Orbital Replacement Units (ORU), the components of the ISS systems replaceable on orbit. Dextre will operate directly connected to the ISS or to the tip of Canadarm2. Both Canadarm2 and Dextre are tele-operated by an operator located inside the ISS. Due to the important flexibility in the Canadarm2/Dextre system, all insertion/extraction tasks involving Dextre will be done using only one arm with the other arm grasping a stabilization point.

The cost and risks associated with the execution of robotic tasks around the ISS require that all procedures be verified on Earth prior to their execution in space. The main difficulty in emulating a space robot on ground is the fact that space manipulators cannot support their own weight on Earth. A possible option is to use hardware-in-the-loop simulation (HLS) as done by the Canadian Space Agency (CSA) [2], the German Space Center (DLR) [3] and the National Aeronautics and Space Administration (NASA) [4]. In this regard, CSA has developed the SPDM Task Verification Facility (STVF). One of the main technical challenges with the STVF was the verification of the feasibility of the insertion/extraction tasks. Simulation is a viable tool to validate the functionality of a space manipulator [5]. A faithful model of the space robot is available, but accurate modelling of contact dynamics is difficult to obtain due to the complex nature of the physical phenomenon during the interaction.

The strength of the hardware-in-the-loop simulation method developed at CSA is that the performance remains constant from very simple contact tasks to very complex contact tasks (e.g. 6 DOF, multi point with friction, etc.). Still, this approach imposes performance limits for the impact part of a contact task. This limit is related to the bandwidth of the controller and to the accuracy of the sensor system implemented in the hardware-in-the-loop system. Therefore, STVF should always represent the steady state case of any contact tasks while contact with impact will be exact up to the controller bandwidth.

The validation is an important aspect in the development of this testbed. Although the facility was already verified to comply with the system requirements during its acceptance, it still needs to be validated to show that it really represents the Dextre dynamics. In order to validate the facility, the simulator of the space robots must be validated which was not the case during the verification process of the acceptance. In the ideal case, we would compare the system with flight data. However, Dextre will not be launched before the end of the STVF validation process. We can also use simulated contact models. When colliding bodies have very simple contact geometries, theoretical models can be derived such that simulation results are in close agreement with the experimental data, both for the impact and steady state. However, when the geometries are more complex, it becomes difficult to evaluate if the simulation results

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are consistent with the reality. This is the rational behind the development of STVF. Thus, comparison with complex contact model simulation is obviously not an option for the STVF validation.

The suggested approach for the validation of STVF is to first build confidence by comparing experimental results with pure simulation results for cases easy to model. This paper will describe in details the various test cases being considered for the validation. Preliminary test results will also be presented.

2. STVF CONTROL APPROACH

The HLS testbed developed at CSA consists of a rigid robot with its control, a simulator for Canadarm2/Dextre dynamics and a visualization engine. The Dextre operator sends joystick commands to the Dextre simulator that predicts a corresponding motion response. The resulting Dextre endpoint motion then becomes a set point for the rigid robot controller. Real contact forces are measured using force/moment sensors and fed back into the simulator to allow the dynamic simulation engine to react to external contact forces. This concept, illustrated in Fig. 1, is very flexible since it can accommodate vibration of the space robot base or other phenomena. It can also be used to represent different space robots. The main difficulty in HLS is to have good performance, i.e. make sure the impedance of the ground robot is the same as the one of the space robot, while keeping the system stable in free space and in contact. This type of simulation creates instability problems similar to the case of force control with a force reflecting master/slave system in tele-operation.

The rigid robot (terrestrial robot) control synthesis is of prime importance in the HLS concept. Since the idea is to replicate the dynamics of the space robot with the terrestrial robot performing the contact task, the control algorithm must be such that the controlled terrestrial robot is transparent in the frequency band of interest for the analysis required. The control approach chosen by CSA consists in forcing the terrestrial robot to behave like the simulated space robot by using a Cartesian feedback linearization technique with acceleration input [6][7]. Cartesian position/velocity feedback is used in addition as a corrector to improve the system response within the bandwidth of interest. The control approach is illustrated in Fig. 1 and presented in details in [5]. It requires a stiff robot with high tracking accuracy, a good torque controller and the ability to implement or access the robot controller at the lowest level to achieve a fast sampling time. The robot of the STVF facility, shown in Fig. 2, is named SMT Robot for STVF Manipulator Testbed. The SMT Robot was specifically designed to meet these control requirements.

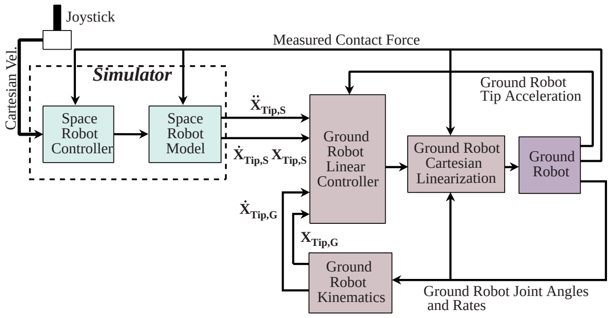

Fig. 1. Cartesian feedback linearization with acceleration controller.

Fig. 2. STVF Manipulator Testbed (SMT).

3. STVF VALIDATION TESTS

Fig. 3 depicts the steps and dependencies related to the STVF Validation. Each part of this diagram is described in details in the following subsections. A common element is that the position, orientation, translational and angular velocities at the tip of the SMT Robot will be calculated using its forward kinematics model and the measurements from the robot joint 23-bits absolute encoders.

3.1 Validated dynamics engine

The experimental results will be compared with the SPOTS results. SPOTS is a simulator developed by MDA Space Missions, the Canadian company that has developed the MSS. This simulator is considered the truth model of the Canadarm2/Dextre system. It is continuously improved as flight data becomes available. This detailed simulator runs in nonreal-time and therefore, it cannot be used as the driving simulator of the SMT Robot. Instead, the real-time simulator of the space robot uses the MSS Operation and Training Simulator (MOTS). This simulator was developed by CAE Electronics for CSA. It uses a dynamics engine based on SPOTS, but adapted to run in real-time.

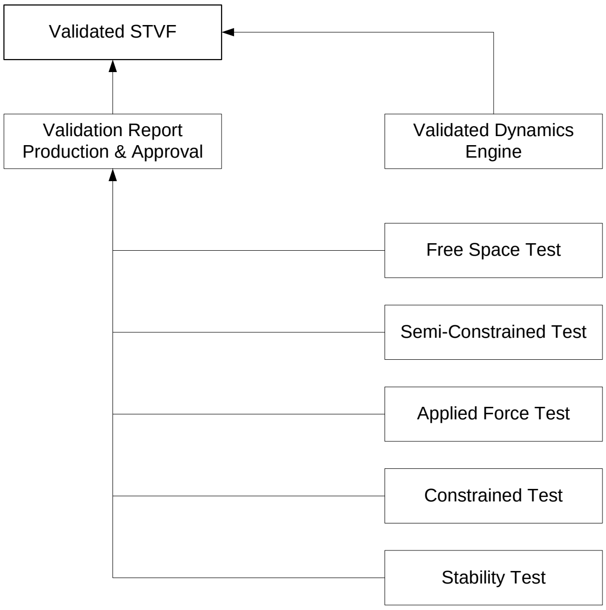

Fig. 3. STVF validation dependencies task.

The concept of the STVF system implies that the overall validity of STVF depends on the validity of the simulator used to drive the SMT Robot. As mentioned before, the dynamics model of the Canadarm2/Dextre system is implemented with MOTS. Therefore the validation of the dynamics models in MOTS is considered a dependency on STVF validation. MOTS validation is addressed in a separate validation exercise and it is validated against the SPOTS simulator also described above.

3.2 Free-Space Test

The objective of this test is to validate the STVF capability to simulate the Dextre dynamics responses in free space, through seven runs presented in Table 1. These runs were chosen to excite the dynamics model in the worst case situations and also to exercise many modes and features of the control system of the MOTS simulator. Because MOTS will already be validated by the time this test is executed, no problems are expected with respect to these control modes and features. Moreover, the performance of the SMT Robot in free space was verified during the acceptance tests of the STVF facility, and thus, no problems are anticipated. In all runs of Table 1, Dextre will be operated at the tip of the Canadarm2 unless otherwise stated by mentioning "standalone".

Table 1. Free space test runs description.

Test	Description	Purpose
1	Manoeuvring with maximum joint coarse rate and stop, unstabilized configuration.	Validate the worst case stopping distance.
2	Small command at rate sensor resolution level, standalone .	Validate SMT Robot tip velocity response to joint rate command as small as sensor resolution.
3	Manoeuvring from rest to high coarse Cartesian velocity with maximum payload.	Validate worst case Dextre manoeuvrability and POHS capability.
4	Manoeuvring in Cartesian position mode with line tracking at coarse speeds, unloaded.	Validate STVF response when Dextre is commanded in Cartesian position mode with Line Track feature selected.
5	Manoeuvring in Cartesian position mode with incremental pre-stored positions and orientations.	Validate the STVF response when Dextre is commanded in small incremental positions.
6	Manoeuvring in joint position mode with incremental pre-stored joint positions, unloaded and unstabilized.	Validate the STVF response when Dextre is commanded in small incremental joint positions.
7	Manoeuvring in Cartesian velcocity mode with the feature to change pitch plane.	Validate the STVF response when Dextre is commanded to rotate its pitch plane.

3.3 Spring-Constrained Test

In this test, the tip of the Dextre model in SPOTS and the tip of the SMT Robot are partially constrained by attaching a spring. The purpose of this test is to validate that the SMT Robot is capable of precisely simulating the Dextre dynamics responses when its tip is elastically constrained. It helps to verify whether or not the STVF maintains Dextre impedance when its tip contacts with a soft environment. This is the first and the easiest constrained-motion test case because:

1. Elastic constraints can be well characterized and analyzed;
2. Elastic constraints can be precisely modelled and simulated by the reference simulator (SPOTS).

However, the hardware spring must be pre-constrained prior to performing the test in order to reach a zone of linear spring tension. In simulation, this implies the initialization of some of the Dextre integrators to a non-zero value, which brings the difficulty of finding the appropriate initial conditions. For this test, Dextre is attached at the tip of the Canadarm2 with one arm braked and stabilized. The other arm is commanded to perform circular trajectories of its end effector, so that forces and moments are applied in all axes.

3.4 Payload-Loss Test

This test simulates a payload loss case. Its objective is to validate that the SMT Robot is capable of precisely simulating the Dextre dynamics response to simple and known external forces applied to its end-effector tip. For convenience, the two proposed runs are described in Table 2. For these runs, a 5 kg mass links the SMT Robot end-effector and the force plate through a pulley system, such that the resulting force applied to the end-effector and force plate is identical in magnitude. The force is applied along the longitudinal axis of the end-effector, in the vertical direction, and is suddenly release using a solenoid interface.

Table 2. Payload loss test runs description.

Test	Description	Purpose
1	Dextre on Canadarm2 configuration. Arm 2 is braked and stabilized to the station; Arm 1 is initially in position hold and an external force is applied on its tip. Then, the arm is commanded to move along the axial direction of its end effector. The external force is suddenly removed after the tip reaches the commanded rate.	Validate that the SMT Robot does have the dynamic characteristics of Dextre in response to an external force supposedly applied to the tip of Dextre but physically applied to the forceplate only. Verifies impedance of the SMT Robot against that of the Dextre truth model (SPOTS). Force is applied along the end-effector axis.
2	Same as Test 1 but the same external force is simultaneously applied to the tip of the SMT Robot.	Same as Test 1, but also verifies disturbance rejection capability. Force is simultaneously applied to forceplate and end-effector.

3.5 Constrained Test

The objective of this constrained test is to demonstrate that the SMT Robot does not modify the Dextre dynamics, and that hardware-in-the-loop simulation with SMT Robot has the same dynamics behaviour than the SPOTS simulator which should be the same as the real Dextre. This test is setup such that the modelling accuracy of the contact model is irrelevant. In first place, the equivalent of a hardware-in-the-loop simulation (HLS) is setup, involving MOTS and the SMT computer cluster, as usual. However, instead of having the SMT Robot contacting the force plate to generate contact forces and moments, a special software will be running on the SMT computer cluster. This software will:

1. Emulate a simple, but representative contact model (e.g. Arm Controller Unit (ACU) and its worksite, rough version). This model must comply with the 1 kHz hard real-time constraint;
2. Compute in real-time the forces and moments resulting from the MOTS position and velocity commands, and feedback these forces and moments to MOTS;
3. Log the resulting forces and moments in a set of files to become the reference data for this experiment.

This experiment is described in the top part of Fig. 4. Subsequently, the SMT Robot is inserted in the HLS simulation, as shown in the bottom part of Fig. 4. The same contact scenario is run, but this time the positions and velocities are measured/derived from the SMT Robot position encoders. These data are fed to the same contact model and the calculated forces and moments are sent to MOTS. If the SMT Robot transfer function is sufficiently close to unity within the bandwidth in which contact operations are performed, the contact model outputs should correlate with the reference data obtained in Step 1. Since in both cases the same contact model is used, it is not necessary to have a validated contact model to perform the test. As long as the contact model can be run in real time, this method should give quantitative results to evaluate the performance of the system for more complex contact cases. Finally, it is important to mention that no physical force is applied at the tip of the SMT Robot in the course of this test. We simply assume that the disturbance rejection capability of the robot will have been addressed in the Payload Loss Test. This includes the force plate hardware and its associated data acquisition system.

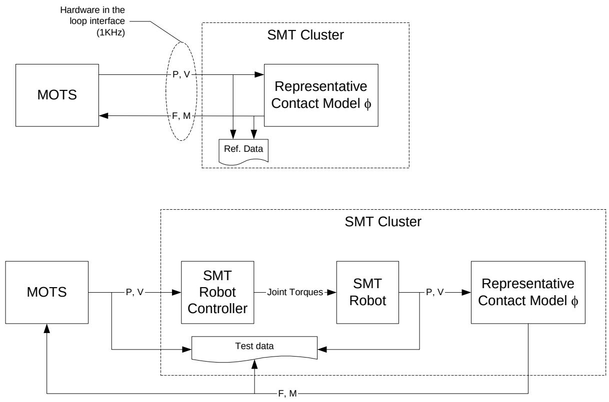

Fig. 4. Constrained test principles.

3.6 Stability Test

The last proposed test is a stability test where the gains of the Dextre control system are selected such that Dextre is unstable. It consists in making sure that the SMT Robot, when operated in HLS, is also unstable in this case. The purpose of this qualitative test is to demonstrate that possible unstable on-orbit Dextre configurations will not be unnoticed. In other words, an unstable Dextre configuration should also be unstable on STVF. This test emphasizes the safety of the STVF concept. Actually, the SMT Robot in HLS mode may be less stable than Dextre. So an unstable condition in STVF will not necessarily be replicated on Dextre, but an unstable condition on Dextre will certainly be replicated on STVF.

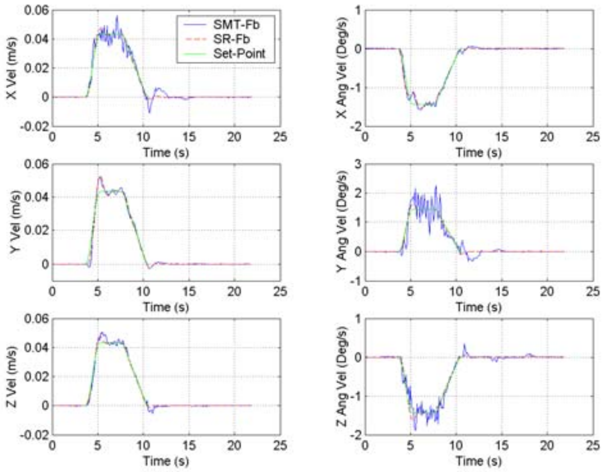

Fig. 5. Free Space Test – Velocity profiles.

4. PRELIMINARY TEST RESULTS

In this section, preliminary results are presented. Although the validation did not start yet since the validation of the MOTS simulator is not completed, preliminary results were generated. The results are good and no problems are anticipated during the validation.

4.1 Free-Space Test

The first set of results presented were generated by manoeuvring one Dextre arm at maximum vernier velocity, 7.5 cm/s, and ramping it down to zero, while carrying a 100 kg payload. This test is similar to the Test 1 of Table 1 except that it was executed in Cartesian Velocity mode instead of Joint Velocity Mode. The linear and angular velocity profiles are presented in Fig. 5. The green line is the velocity setpoint for Dextre (SR for Space Robot), the red line is the actual velocity of Dextre and the blue line is the velocity of the SMT Robot trying to track Dextre (red line). It is apparent that the velocity tracking is very good. The translational and rotational errors for this manoeuvre are presented in Fig. 6. The maximum deviation observed is 3.3 mm in translation and 0.1 degree in rotation, which is well below the allowed limits, respectively 15 mm and 0.5 degree.

4.2 Spring-Constrained Test

The second set of results was generated for the Spring-Constrained Test, as described in Subsection 3.3. The results are presented in Figs. 7 to 9. Fig. 7 shows the position of the end-effector of the SMT robot (blue line) superposed with the one of Dextre obtained in pure simulation (green line).

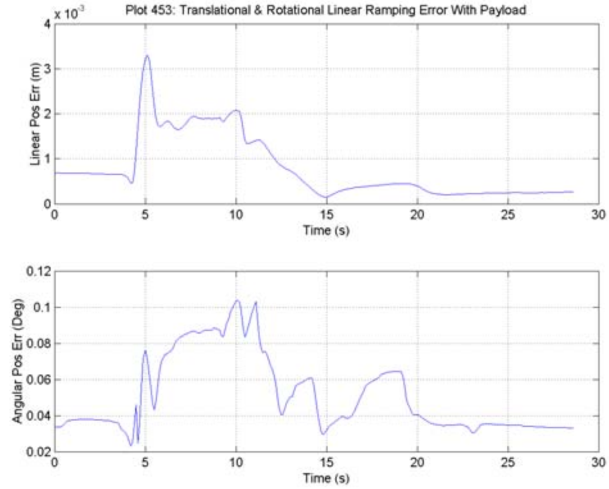

Fig. 6. Free Space Test – Translational and rotational errors.

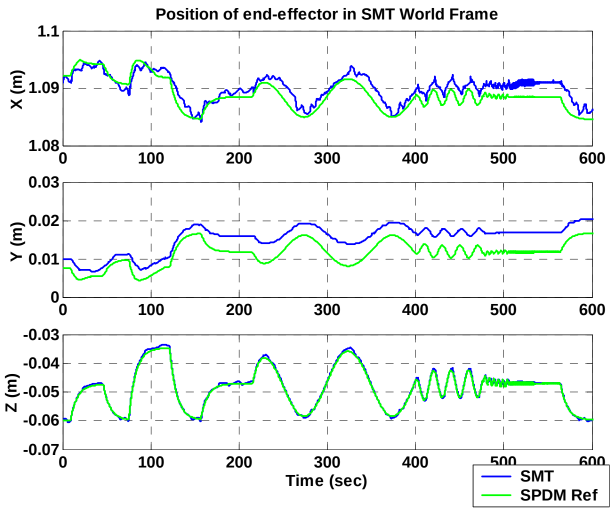

Fig. 7. Spring-Constrained Test – Position of End-Effector.

We can see that the experimental results are very close to the simulated one, without HLS, namely the green ones. The errors between the two curves are presented in Fig. 8. In all cases, the error is below the required limit of 6 mm (red lines). Moreover, the errors in X and Y are probably due to the inaccuracy in the identification of the spring model parameters, resulting in a scaling difference between the curves. This aspect will be improved during the formal validation. Finally, the measured forces (blue line) and calculated forces in pure simulation (green line) are presented in Fig. 9. The correlation between the two curves is excellent.

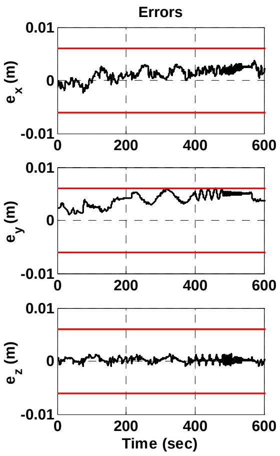

Fig. 8. Spring-Constrained Test – Error on Position of End-Effector.

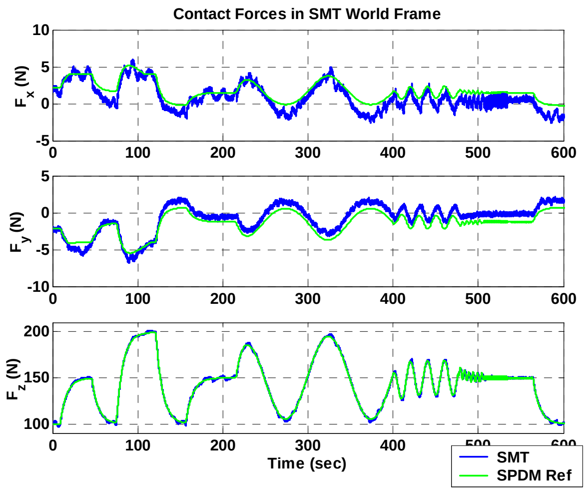

Fig. 9. Spring-Constrained Test – Contact Forces.

4.3 Constrained Test

The last set of results presented is for the constrained case. As described in Subsection 3.5, this test consists in the replacement of the force plate by a virtual contact model. To demonstrate the concept, the results presented in this subsection were generated using a simple sphere on planes contact model. Three perpendicular contact planes were modelled to create an inner corner of a cube. The SMT Robot was assumed to hold a sphere with a diameter of 6 cm. The three contact planes have a stiffness of 10^5 N/m$^{3/2}$ with a coefficient of restitution of 0.9 [8]. No surface friction was modelled in the planes to avoid numerical instabilities.

The commanded input velocity in the SPDM Frame is presented in Fig. 10 and the results in Figs. 11 to 13. The robot is first commanded to move along the longitudinal axis of its end-effector at a velocity of 5 cm/s. Once contact is established, the force stabilizes to –100 N (in SMT World Frame) as shown in Fig. 13. The robot is then commanded to slide on this plane along the Z direction with a velocity of 2.5 cm/s until it touches a second plane and that the force stabilize to 50 N. At that point, the robot is commanded to move in the X-direction with a velocity of 2.5 cm/s while holding the applied forces on the two contact planes until the robots hits the third contact plane and the force stabilizes to 50 N. Finally, the robot is commanded to increase simultaneously its desired velocity along the three axes thus resulting in an increase of the applied forces in the three contact planes.

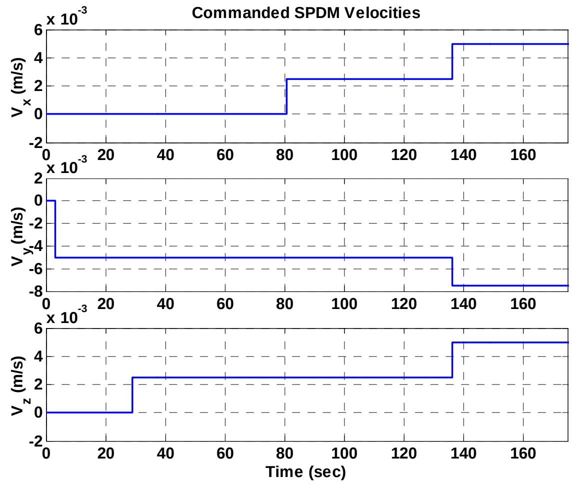

Fig. 10. Constrained Test – Commanded Dextre Velocities (in Dextre Reference Frame).

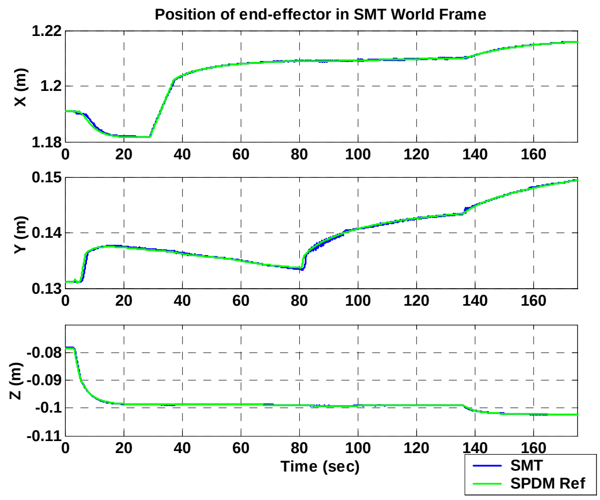

Fig. 11. Constrained Test – Position of End-Effector.

The same experiment with the same velocity profile was repeated in pure simulation, without HLS, using exactly the same contact model. From Figs. 11 and 12, we see that the tracking is very good and the error is well below the allowed limits shown in red in Fig. 12. The resulting contact forces are presented in Fig. 13. Again, the results are excellent with two superposed curves. We can see that small oscillations of the forces are observed when the SMT Robot hits the second contact plane. It seems to be related to numerical instabilities and could be fixed by reducing the contact stiffness. This will be investigated further during the validation of STVF.

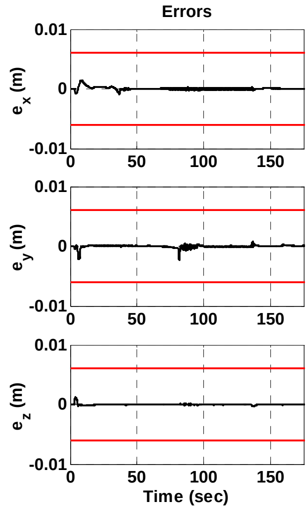

Fig. 12. Constrained Test – Error on Position of End-Effector.

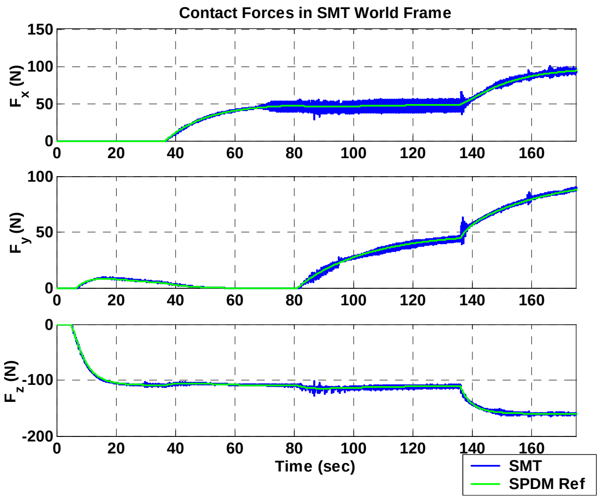

Fig. 13. Constrained Test – Contact Forces.

5. CONCLUSION

In this paper, we presented the approach suggested to validate the STVF facility. This facility was developed at the Canadian Space Agency to verify all the tasks involving contact that Dextre will need to perform in space. This approach is based on building confidence by comparing experimental results with pure simulation results for cases easy to model. The various test cases considered for the validation were described in details. Preliminary test results were finally presented for a Free-Space Test, the Spring-Constrained Test and the Constrained Test. In the three cases the results are within the allowed limits which is promising for the upcoming validation exercise.

6. ACKNOWLEDGEMENTS

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