DEVELOPING AND USING A FACILITY ENABLING CHARACTERIZATION AND QUALIFICATION OF PLANETARY EXPLORATION ROVER MOBILITY

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ABSTRACT

Evaluating the mobility performance of planetary exploration rovers through testing provides valuable information during the development phase and is required to verify the locomotion performance before flight. To enable this, not only representative mass-scaled models are needed, but also a dedicated test facility. To guarantee repeatable well-defined test conditions, an indoor test facility has been developed by Beyond Gravity (previously RUAG Space) under ESA R&D contract and used in ExoMars Locomotion sub-system phase B development activity [2,3]. This facility has then been enhanced under ESA and Airbus contract to enable the deployment, egress, and mobility verification of the ExoMars rover [4]. This facility has also been successfully used in i) early development phase of the ESA/NASA Sample Fetch Rover (project CHABLIS), ii) for testing walking robots of ETHZ and iii) evaluating lander generated ground noises disturbing seismometers. This paper describes the architecture, development, and operation of this rover mobility test facility together with major lessons learned.

1. FACILITY OVERVIEW

1.1 Soil and Obstacles

Different characterized Martian soil simulants can be accommodated within a 6x6x0.6m tilt platform. The following engineering soils with density as per [1] can be used in tests:

- ES1, Minex S6: 1250 kg/m³
- ES2, Siverbond D6DD: 1325 kg/m³
- ES3, SS3590 with gravel: 1575 kg/m³
- ES4, SS3590 and Minex S6: 2000 kg/m³

The soil depth needs to be sufficient to get proper motion performance. The determination of minimum soil depth has been established using single wheel testing [8] under the maximum load expected to be experienced during rover level testing. For the ExoMars rover, following minimum soil depths have been used:

- For ES1 & ES2 soil: ≥ 45cm
- For ES3 & ES4 soil: ≥ 35cm

Such depth allows minimizing quantity of soil to be procured as well as the overall weight to be lifted by the facility whilst accurately simulating Martian environment.

The obstacles shown in Fig. 1 (various sizes of half-spheres, cuboids and pyramids/cones) are labelled and accommodated with millimeter accuracy allowing comparison between different runs, motion scenario or vehicles. Each obstacle features an interface for a hook allowing manipulation with a crane.

Figure 1. Limestone Rock Obstacles

Figure 2. Limestone Bedrock with Obstacles

1.2 Tilt Platform

Thanks to a tiltable platform, the test facility allows setting slopes up to 26° with an accuracy of 0.1 degrees. A fixation on each side wall allows interfacing a lander with the egress ramps in different orientations. An exemplary configuration is shown in Fig. 2. Note that the room height is sufficient to test even the most demanding egress cases, such as the ExoMars Locomotion Verification Model (LVM). With its extension mast and located on an egress platform at full test bin tilt, it required room height of 7m.

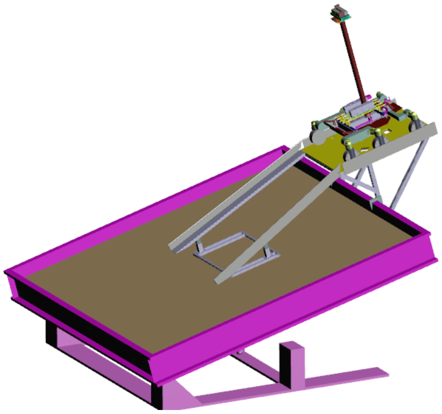

Figure 3. Tilt platform with dummy lander and ExoMars LVM

A second manual adjustable tilt platform can be accommodated within the bin to allow determining static stability exceeding 26° using the smooth motion of the tilt platform. A loss of stability is detected when one wheel starts losing contact with the ground (equivalent to zero load).

1.3 Motion Tracking

The central element is the VICON real time motion-tracking system that provides position / orientation, velocity and acceleration data of the rover, but also of its individual joints.

Together with the commanded trajectory and wheel speed, the rover velocity data can used to determine rover slip during post-processing phase. By interfacing the rover control system with the test facility using TCP or UDP protocol, the live rover slip can be determined and used as test success criteria or to stop a test when a given slip ratio is exceeded. The real time position information can also be injected into the navigation system for close-loop control testing. This enables rover testing without required dedicated perception sensors in early project phases or for off-loading the rover from its on-board navigation system for being more mass representative. The VICON system only requires accommodation of small targets on the rover body and each mobile element to be tracked.

Because the system is based on IR technology, direct solar light is to be avoided within the test area.

1.4. Video and Data Synchronization

The main challenge has been to collect and synchronize video with data coming from various systems, including the rover itself. The data timestamping is based on a timecode generator providing LTC, VITC and IRIG-B. Dedicated development was needed to enable, at reasonable cost, the timestamping of multiple hi-resolution video cameras. Some commercial cameras allow accurate triggering or synchronized strobe with image per image movie reconstruction (e.g M-JPEG). This was used for the high frame camera with 60 fps capability but would saturate the bus for the required five other cameras accommodated in the room. The selected solution has been to select surveillance cameras with on-board video compression H.264. This allows to have a video size of approximately 40MB per minute compared to the 150 MB per minute needed for M-JPEG format.

However, the used video surveillance camera from Vivotek type IP8165HP does not have accurate triggering functionality. To allow synchronization, the LTC signal is recorded as audio signal and later post-processed to insert the timecode in the video signal. A dedicated software allows to reach an accuracy of ±1 frame at 25 fps.

Analog signals coming from triaxial accelerometers and the rover sensors like joint angle potentiometers are acquired and timestamped by the VICON Lock+ control box at 10Hz (position) up to maximum 2000Hz (accelerometers). A dedicated software has been developed using Visual C++ to collect all the data, transform the position in the appropriate coordinate system and post-processing the test results [5]. Additional test equipment like impacting plates or rover telemetry can be interfaced via TCP/IP and are timestamped by a Windows-based PC featuring a dedicated IRIG-B Time Code Receiver card.

It must be noticed that the accelerometers, potentiometers and 10Hz telemetry are synchronized by the Vicon Lock+. This means that, at a given time *t*, a set of data is available with milliseconds accuracy This is not the case for the video and the impacting plate for which the synchronization is to be done during the post processing phase using the time stamp.

2. COMMISSIONING

2.1. Position and Orientation

The time and effort needed to commission a planetary rover test facility with multiple fused high-accuracy sensing systems should not be underestimated. Laser distance measurement has been used to confirm the accuracy of the VICON system across the full test bin size and tilt. The number, location and focus of each camera have been optimized.

The standard calibration based on the VICON provided *light wall* has been used. However, this led to a position dependent absolute error exceeding the specification. Therefore, a dedicated larger calibration T-bar, featuring VICON markers at well-known locations, has been developed. This allows reaching 5mm position accuracy and 0.25° in orientation within the complete test volume.

2.2 Hub Vertical Displacement

In deployed configuration, the rover is considered a rigid body with known dimension. With those assumptions, and knowing the body position, orientation and bogie angles, the hub vertical displacement is calculated as follow:

1. Before each test, the VICON system is used to determine the soil surface using targets placed at various locations on the tilt platform. The test program reconstructs a soil-plane in the 3D space and stores it.
2. During the test acquisition, the (x,y,z) coordinates of the center of the wheels, expressed in the global coordinate system, is computed at each point in time using the rover forward kinematics.
3. Finally, the distance separating each wheel center point from the stored soil surface plane is calculated.

2.3 Rover Integration

For the ExoMars LVM, the chassis has been designed and produced by Beyond Gravity. It allows integration of the Bogie Electro-Mechanical Assembly (BEMA) [4] and is designed to correctly represent wheel load and Center of Mass. VICON markers are accommodated on each moving element. The chassis also houses the VICON Lock+, which allows recording analog signals (e.g. accelerometers, potentiometers) while minimizing the harness. Optimizing the external harness is important to minimize the external force disturbances on the rover, and has been conducted using a 6DoF force / torque sensor.

For SFR CHABLIS [6], accommodating the recording equipment on the rover chassis would exceed the overall mass budget. Therefore, it has been accommodated on a sled following the rover during the tests.

3. TESTING

3.1 ExoMars Breadboard BB2

In February 2017, ESA organized a confidence test using the DLR owned ExoMars Breadboard. This allow conducting significant number of tests on different soils and various control strategy specially to increase slope gradeability on soil ES2. In addition, the facility and test procedures were verified and optimized for the subsequent ExoMars LVM verification test campaign. A preliminary extrapolation of the results considering the larger LVM wheel has been performed. The main lesson learned is that early testing, even with not fully representative prototypes, provides valuable information about locomotion capabilities.

Figure 4. ExoMars B2 DLR rover - Gradeability Test on ES3

3.2 ExoMars Locomotion Verification Model

With the ExoMars Locomotion Verification Model [4], the following tests have been conducted under ESA contract with Airbus being prime contractor:

- Dynamic Load
- Static Stability
- Modal Survey
- Static Slope Holding Test
- Gradeability Tests
- Wheel Walking Tests
- Obstacle Negotiation Tests
- Jamming Tests
- Buried Wheel Tests
- Path Deviation with Rock Obstacles Tests
- Deployment and Egress Tests

Figure 5. ExoMars LVM cross-slope on soil ES2, video including LTC and IRIG-B time

Before each test, the soil is levelled and prepared to the specified relative density. The soil levelling plate (visible in the background in Fig. 6) is rolling on the top of the sidewall. This allows relatively fast soil preparation while guaranteeing a constant soil depth and terrain flatness. This is crucial for hub displacement determination described in section 2.2.

Figure 6. ExoMars LVM Gradeability Test on soil ES2

A modular lander mockup platform with egress ramp is part of the test facility. To get a fully representative deployment and egress test, the ExoMars lander mockup provided by Roscosmos has been accommodated on the tilt platform using Kanya profiles. Egress with different orientations, ramp slopes and final drop heights onto both soft soil or hard rock obstacles have been conducted. During such tests, accommodation of near field additional cameras has been useful to accurately track wheel interaction and to optimize the egress.

Figure 7. ExoMars LVM egress test from lander platform. Image credit: ESA

3.3. SFR CHABLIS

In 2021 and early 2022, the SFR CHABLIS Mobility Breadboard Vehicle has been tested under contract with MDA. The test goal was to "… de-risk the SFR locomotion design concept and quantify performance limits and loads of the SFR through various mobility tests representative of expected scenarios. In addition, the CHABLIS is used to evaluate the performance of NASA's next-generation flexible Mars Wheel Tire Assembly" [6].

A total of 500 tests have been set-up including motion on hard bedrock accommodated within the tilt platform or on tiles with given rock distribution provided by NASA JPL shown in Fig. 8.

Figure 8. JPL tiles for locomotion testing

Over a period of 40 testing days, the following characterizations were performed:

- Gradeability Tests on Soils and Bedrock
- Slope Characterization tests on variable terrains
- Obstacle Negotiation Tests on variable soils
- Static Slope Holding
- Blocked Wheel tests
- Crevasse tests
- Diverse Maneuvers tests
- Life Terrain Tiles tests

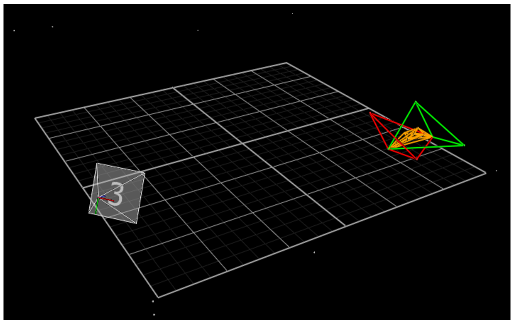

Figure 9. SFR CHABLIS 3D visualization in VICON

3.4 Hybrid Walking/Jumping Robot SpaceBok

In early 2020, SpaceBok [7], a collaboration between ETH Zurich and ESA/ESTEC, was tested. SpaceBok is a hybrid walking/jumping robot designed for fast traversal speeds in low-gravity planetary environments. The tests in Beyond Gravity's rover test facility allowed to test its motion performance on representative Lunar and Martian soils for the first time, and allowed to assess its slope gradeability performance.

Figure 10. ETH SpaceBok gradeability test

3.5 Walking Robot ANYMal

In early 2022, the ANYMal team from ETH Zurich's Robotic Systems Lab performed a series of motion test with this walking robot. The advantage here was that the performance of different motion control algorithms could be evaluated on a well-defined terrain and on a wide range of soil and obstacle types.

Figure 11. ANYMal test on hard bedrock.
Image credit: Robotic Systems Lab, ETHZ

4. CONLUSION

The capability to test in representative, repeatable and well-defined conditions, together with accurate data timestamping was the key to the successful verification of the ExoMars locomotion sub-system. More recently, a first prototype of the Sample Fetch Rover and other hybrid/walking robot prototypes for planetary exploration have been tested successfully.

In all motion tests, the facility's combination of testbed size, achievable tilt angles, multi-DoF Vicon-based motion tracking, video

synchronization and egress testing capability – which is unique in Europe – was key.
The facility is thus considered to be of high interest for the robotic space exploration community.

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