Chassis and Locomotion Breadboard Test Plan

CI CODE:

DTI EXPORT CONTROL RATING:  9E001, 9E002, 9A004
Rated by:      C Draper

Prepared by:  Date:

Rover Vehicle Team

© EADS Astrium Limited 2007

EADS Astrium Limited owns the copyright of this document which is supplied in confidence and which shall not be used for any purpose other than that for which it is supplied and shall not in whole or in part be reproduced, copied, or communicated to any person without written permission from the owner.

EADS Astrium Limited
Gunnels Wood Road, Stevenage, Hertfordshire, SG1 2AS, England
INTENTIONALLY BLANK
CONTENTS

1. INTRODUCTION ...........................................................................................................................................5

2. APPLICABLE DOCUMENTS ........................................................................................................................5

3. REQUIREMENTS REVIEW ..........................................................................................................................6
   3.1.1 Obstacle dominated requirements ...............................................................................................6
   3.1.2 Stability requirements...................................................................................................................6
   3.1.3 Soil dominated requirements........................................................................................................6
   3.1.4 Reference Terrain and Soil ..........................................................................................................8

4. ROVER CHASSIS CONFIGURATION........................................................................................................10
   4.1 Overview...............................................................................................................................................10

5. TEST ENVIRONMENT ................................................................................................................................11
   5.1 Obstacles ...............................................................................................................................................11
   5.2 Test Parameters .....................................................................................................................................11

6. TEST SEQUENCE ......................................................................................................................................12
   6.1 Basic functional checks ........................................................................................................................12
   6.2 Basic Locomotion tests ........................................................................................................................12
   6.3 Obstacle tests ........................................................................................................................................12
   6.4 Wheel Soil interaction ...........................................................................................................................12
   6.5 Cross slope locomotion ........................................................................................................................13

7. TEST MATRIX .............................................................................................................................................14

TABLES

Table 3-1 : Summary of Gradient requirements ................................................................................................7

FIGURES

Figure 4-1 : RCL-E configuration.....................................................................................................................10
Figure 4-2 : RCL-C Configuration....................................................................................................................10
Figure 4-3 : CRAB Configuration....................................................................................................................10
Figure 7-1 : Test Matrix (example) ..................................................................................................................14
INTENTIONALLY BLANK
1. INTRODUCTION

The Rover Chassis and Locomotion Breadboard forms an integral part of the Rover Breadboarding activities within the ExoMars Phase B1 activities.

The Locomotion Breadboard performs the fundamental locomotion and suspension functions necessary to support and implement the Rover.

When validated, the Locomotion Breadboard will be integrated with a "Navigation SW breadboard", to form a fully integrated Navigation & Locomotion Rover Breadboard.

2. APPLICABLE DOCUMENTS

<table>
<thead>
<tr>
<th>AD.1</th>
<th>EXM.RM.RQM.ASU.0001</th>
<th>ExoMars Rover Vehicle Chassis &amp; Locomotion Subsystem Requirements Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>AD.2</td>
<td>EXM.RM.SOW.ASU.0001</td>
<td>ExoMars Phase B1 Rover Vehicle Chassis &amp; Locomotion Subsystem Design * Breadboarding Statement of Work</td>
</tr>
</tbody>
</table>
3. REQUIREMENTS REVIEW

The following requirements are extracted from the top C&L Subsystem Design Requirement Specification [AD.1].

3.1.1 Obstacle dominated requirements

These are the most important ones with respect to the chassis comparison. In particular requirement

ASU-CL-906. Step obstacle

The Rover Vehicle shall be capable to surmount step-shape obstacles with a height of 0.25 m with a width larger than the chassis width, presented perpendicular to its driving direction under the following conditions:

a) horizontal terrain in front of the step consisting of soil of type B;

b) friction coefficient between the step and a metallic wheel equal to 0.3 to 0.5 for both the vertical and the horizontal portions of the step.

3.1.2 Stability requirements

Although all chassis types must comply with these requirements, there seems to be no intrinsic advantage or disadvantage of any of the architectures, since this is only defined by the footprint and centre of mass. There will be no test derived from these for the purpose of the chassis comparison.

ASU-CL-907. Static Stability

The C&L subsystem shall enable the Rover Vehicle to have a static stability angle of at least 40 degrees in all directions.

3.1.3 Soil dominated requirements

The following requirements are expected to affect foremost the wheel design. They are listed here for reference, but shall not be taken as a basis for the tests. Note that uneven load on the wheels, which is a result of non-vertical wheel displacement does have an effect in the case of drift soil with superimposed obstacles, however the main goal here is not to optimize the wheel-soil interaction, but the relative performance of the different chassis types.

ASU-CL-897. Maximum Speed

The C&L subsystem shall enable the Rover Vehicle to be capable of travelling at a maximum speed of at least 100 m/h in any given direction on Reference Terrain 1 defined in Annex 1, for fast, short duration recovery situations not lasting longer than 20 min (TBC).

ASU-CL-898. Gradeability – uphill #1

The C&L subsystem shall enable the Rover Vehicle to be capable of driving in a controlled and steady-state manner, over distances exceeding 2m, up a slope with an inclination of 25 degrees, on soil types A and B as defined in Para 3.1.4.

ASU-CL-899. Gradeability – uphill #2

The C&L subsystem shall enable the Rover Vehicle to be capable of driving in a controlled and steady-state manner, over distances exceeding 2m, up a slope with an inclination of 18 degrees, on soil types C and E as defined in Para 3.1.4.

ASU-CL-900. Gradeability – crosshill #1

The C&L subsystem shall enable the Rover Vehicle to be capable of driving in a controlled and steady-state manner, over distances exceeding 2m, up a slope with an inclination of 15 degrees, on soil type D as defined in Para 3.1.4.
The C&L subsystem shall enable the Rover Vehicle to be capable of driving in a controlled and steady-state manner, over distances exceeding 2m, on a cross-hill path, 90 degrees w.r.t. the uphill direction, on a slope with an inclination of 25 degrees, on soil types A and B as defined in Para 3.1.4.

ASU-CL-902. Gradeability – crosshill # 2
The C&L subsystem shall enable the Rover Vehicle to be capable of driving in a controlled and steady-state manner, over distances exceeding 2m, on a cross-hill path, 90 degrees w.r.t. the uphill direction, on a slope with an inclination of 18 degrees, on soil type C as defined in Para 3.1.4.

ASU-CL-903. Gradeability – crosshill # 3
The C&L subsystem shall enable the Rover Vehicle to be capable of driving in a controlled and steady-state manner, over distances exceeding 2m, on a cross-hill path, 90 degrees w.r.t. the uphill direction, on a slope with an inclination of 15 degrees, on soil type D as defined in Para 3.1.4.

ASU-CL-904. Gradeability – downhill # 1
The C&L subsystem shall enable the Rover Vehicle to be capable of driving in a controlled and steady-state manner, over distances exceeding 2m, down a slope with an inclination of 25 degrees, on soil types A and B as defined in Para 3.1.4.

ASU-CL-905. Gradeability – Downhill # 2
The C&L subsystem shall enable the Rover Vehicle to be capable of driving in a controlled and steady-state manner, over distances exceeding 2m, down a slope with an inclination of 18 degrees, on soil types C and D as defined in Para 3.1.4.

C: “distances exceeding 2 m” implies, in absolute terms, distances longer than one vehicle length. The total distance over which such movement can be maintained depends on energy availability.

ASU-CL-885. Point Turning Capability
The C&L Subsystem shall have Point Turning capability.
C: This capability is required to change direction safely and go back in case the Navigation System detects a dead-end situation.

<table>
<thead>
<tr>
<th>Soil type</th>
<th>Uphill</th>
<th>Cross-slope</th>
<th>Downhill</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>25°</td>
<td>25°</td>
<td>25°</td>
</tr>
<tr>
<td>B</td>
<td>25°</td>
<td>25°</td>
<td>25°</td>
</tr>
<tr>
<td>C</td>
<td>28°</td>
<td>18°</td>
<td>18°</td>
</tr>
<tr>
<td>D</td>
<td>25°</td>
<td>15°</td>
<td>18°</td>
</tr>
<tr>
<td>E</td>
<td>28°</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>F</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>G</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

Table 3-1: Summary of Gradient requirements
3.1.4 Reference Terrain and Soil

This section has been taken verbatim from the C&L Subsystem Requirements AD.1.

3.1.4.1 Definition of Reference Terrain 1

- RMS slope of 10 (TBC) degrees measured on a 100 m horizontal baseline and 18 (TBC) degrees measured on a 10 m horizontal baseline.
- Surface Rock Distribution: Golombek & Rapp with the values for the Viking-2 landing site, i.e.:
  - Number of rocks per m$^2$ of diameter D and higher:
    \[ N(D) = L e^{-sD} \]
    with \( L_{\text{VL2}} = 6.84 \) and \( s_{\text{VL2}} = 8.30 \)
  - Fractional area covered by of rocks of diameter D and higher:
    \[ F_k(D) = k e^{-q(k)D} \]
    with \( k_{\text{VL2}} = 0.176 \) and \( q(k) = 1.79 + 0.152/k \)
- Soil Parameters: Reference case B: MPF Drift/Cloddy (para 3.1.4.2)
- Friction coefficient representative for wheel-rock contact (para 3.1.4.3)

3.1.4.2 Reference Soil Types and Soil Parameters

<table>
<thead>
<tr>
<th>Soil type</th>
<th>Bulk Density (kg/m$^3$)</th>
<th>Exponent of sinkage</th>
<th>Frictional modulus $k_\phi$ (N/m$^{n+2}$)</th>
<th>Cohesive Modulus $k_c$ (N/m$^{n+1}$)</th>
<th>Cohesion (Pa)</th>
<th>Internal Friction Angle (deg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type A: MPF All Cloddy</td>
<td>1550</td>
<td>1 $^{[2]}$</td>
<td>820,000 $^{[2]}$</td>
<td>1,400 $^{[2]}$</td>
<td>170 $^{[1e2,06,e8,010]}$</td>
<td>37 $^{[1e2,06,e8,010]}$</td>
</tr>
<tr>
<td>Type B: MPF Mixed Drift-Cloddy</td>
<td>1350</td>
<td>1 $^{[2]}$</td>
<td>820,000 $^{[2]}$</td>
<td>1,400 $^{[2]}$</td>
<td>220 $^{[1e11]}$</td>
<td>33.1 $^{[1e11]}$</td>
</tr>
<tr>
<td>Type C: MPF All Drift</td>
<td>1150</td>
<td>1 $^{[2]}$</td>
<td>820,000 $^{[2]}$</td>
<td>1,400 $^{[2]}$</td>
<td>530 $^{[1e9]}$</td>
<td>26.4 $^{[1e9]}$</td>
</tr>
<tr>
<td>Type D: MER-B Sandy Loam&quot;</td>
<td>TBD</td>
<td>1 $^{[2]}$</td>
<td>7,600,000 $^{[3]}$</td>
<td>28,000 $^{[3]}$</td>
<td>4 800 $^{[3]}$</td>
<td>20 $^{[3]}$</td>
</tr>
<tr>
<td>Type E: Physical Mars Soil Simulant DLR-A</td>
<td>TBD</td>
<td>0.63 $^{[4]}$</td>
<td>60,300 $^{[3]}$</td>
<td>2,370 $^{[4]}$</td>
<td>188 $^{[10]}$</td>
<td>24.8 $^{[4]}$</td>
</tr>
<tr>
<td>Type F: MER-B &quot;Slope Soil&quot;</td>
<td>TBD</td>
<td>0.8 $^{[5]}$</td>
<td>210,000 $^{[3]}$</td>
<td>6,800 $^{[3]}$</td>
<td>500 $^{[6]}$</td>
<td>20 $^{[5]}$</td>
</tr>
<tr>
<td>Type G: Physical Mars Soil Simulant DLR-B</td>
<td>TBD</td>
<td>1.1 $^{[4]}$</td>
<td>763,600 $^{[4]}$</td>
<td>18,773 $^{[4]}$</td>
<td>441 $^{[4]}$</td>
<td>17.8 $^{[4]}$</td>
</tr>
</tbody>
</table>

3.1.4.3 Wheel-Soil Interaction Parameters

|Friction Coefficient $\mu$ for Rocks-Metallic Wheels contact| assume 0.3 to 0.5 $^{[6]}$ |
|Shear Deformation Modulus $K$ | 0.8 to 2.5 cm $^{[1,3]}$ |

Comments

1. The values with reference [1] originate from the Mars Pathfinder (MPF) mission [RD 2] whereby the numbers following the character e refer to the Experiment Numbers considered.
2. Values with reference [2] originate from [RD 3]. Since there are no experimental Mars data for n, k, and kc Lunar values have been adopted, which happen to have a simple value for n and therefore simple units for k, and kc.
3. The shear deformation modulus is based on Lunar data [RD 3] but depends on the normal stress and on the wheelsoil contact patch [RD 4], therefore a range is given.
4. Values with reference [4] are based on Martian soil stimulant experiments performed at DLR, Germany [RD 5]. Terramechanical soil data based on Mars Exploration Rover mission observations in 2004 have been published in [RD 11] and [RD 12].

5. For the rock-wheel friction coefficient $\mu$ it is assumed that the Coulomb friction model applies and that there is no hooking of the wheel on to rock surface roughness features, which in reality may occur for short instances.

References


4. ROVER CHASSIS CONFIGURATION

4.1 Overview

The Rover Locomotive Breadboard is intended to be form and fit comparable with the Flight design. The size of the Locomotion Breadboard is by default the Baseline scenario (Soyuz), but is subject to formal decision prior to commitment to the BB Build.

While compliance with the overall Flight configuration is achievable (within practical constraints for physical size, CoG, configuration etc), a representative Mass for the breadboard is difficult to achieve. Martian gravity is ~33% of earth’s so the mass of the Rover when on the martian surface will be only 33% of its earth mass. This results in a challenging situation when measuring and/or assessing the wheel soil interaction in an earth environment.

Reference configurations are shown below for likely wheel configurations

![Figure 4-1 : RCL-E configuration](image1)

![Figure 4-2 : RCL-C Configuration](image2)

![Figure 4-3 : CRAB Configuration](image3)
5. TEST ENVIRONMENT

5.1 Obstacles

For the chassis evaluation of the stability (both static and dynamic) the following tests shall be performed.

For these tests the soil type may initially be neglected, as the tests investigate the ability of the chassis to overcome specific obstacles challenges - relating to “hang-up” “leg-rearing” and “Toppling” behaviours.

For these specific tests the soil type is considered to be of minor importance, however the load balance differences between the models may only become visible when there is sufficient slip and trench digging. The Chassis will be locomoted on sandy ground (the sand must be a few cm deeper than the grousers).

1. Step:

   ![Diagram of a step]

   - $l$ [mm] TBD
   - $h$ [mm] TBD
   - The length will allow 4 wheels on the top of the step.
   - This is a Fundamental requirement.
   - Smaller length should allow both front and both rear wheels to be on the lower plateau.

2. Truncated pyramid:

   ![Diagram of a truncated pyramid]

   - $l$ [mm] TBD
   - $h$ [mm] TBD
   - $\alpha$ [°] TBD
   - The length of the obstacle shall be short enough so only one wheel will be effected at a time.

3. Shifted truncated pyramids:

   ![Diagram of shifted truncated pyramids]

   - $d$ [mm] TBD
   - $h$ [mm] TBD
   - $\alpha$ [°] TBD
   - Testing of asymmetric obstacles. There is no direct requirement, but this test may reveal some important differences between the chassis types in more realistic cases.

4. Cross-hill driving on slope with a single truncated pyramid on the high side:

   ![Diagram of cross-hill driving on slope]

   - Slope TBD °
   - $h$ [mm] TBD (obstacle)
   - Test shall be performed driving forward and backward (sideways along the slope, not up or down), with the higher wheels driving over an obstacle like the ones in the former tests.
   - The specific slope is to be set as high as feasible (either by experiment or by analysis), in order to emphasize the differences in the chassis types.

5.2 Test Parameters

For each test case the following shall be noted as a minimum:
1. Terrainability (e.g. fail/pass).
2. Wheel slip (for each wheel).
3. Energy consumption.
4. Slew from original course (e.g. from straight line).
5. Depth of trench digging (although this may remain a qualitative assessment, better reported on image or video).

Video images shall be captured where-ever possible, to aid post-test assessments.

6. TEST SEQUENCE

6.1 Basic functional checks
- Verification of EGSE communications,
- Operator safety features,
- Commaning of basic functional channels (eg 18DOF=18 inputs),
- Telemetry data functions (angles, currents, etc)
- Backdriving of Motors (the motors shall not backdrive..)
- Static stability test (stability up to 30<40˚ angles in each of the 2 major axis)
- TBD

6.2 Basic Locomotion tests
- Verification of basic locomotive movements
- Forward, / reverse functionality
- Maximum speed
- Turning point
- Wheel walking, and stowed locking (if such axis is implemented…)
- TBD

6.3 Obstacle tests
These tests verify the ability of the chassis to accommodate the obstacle height, given the weight distribution of the Locomotion Breadboard.
As such they provide valuable engineering value in understanding the relationships between mass distribution (both static and dynamic), chassis articulation, and hazard management. Obsticals are defined in Para 5.1

- Tests conducted on nominally flat surface with “soil” as defined as TYPE B in para 3.1.4
- Step (in both the Forward and Reverse directions)
- Truncated pyramid (in both the Forward and Reverse directions)
- Shifted truncated pyramids (in both the Forward and Reverse directions)

6.4 Wheel Soil interaction
Tests conducted on nominally flat surface with “soil” as defined as TYPE A in para 3.1.4
Measurement of the following parameters in both forward and reverse directions
- Wheel slippage
- Wheel trenching
- Efficiency of locomotion (eg Power/speed)
- Accuracy of locomotion direction
- etc
6.5 Cross slope locomotion

Tests conducted on ± TBD degree Inclined slope tests, “soil” as defined as TYPE A in para 3.1.4

Measurement of
- Cross axis deviation
- TBD
7. TEST MATRIX

An example of the Test results matrix is shown in Figure 7-1

<table>
<thead>
<tr>
<th>Test Number</th>
<th>Test description</th>
<th>Test Conditions</th>
<th>Results</th>
<th>Date/Operator</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Terrai n-ability</td>
<td>Wheel slippage</td>
<td>Energy</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>1.1.f</td>
<td>Step, forward</td>
<td>inclination 0°</td>
<td>l = TBD mm</td>
<td></td>
</tr>
<tr>
<td>1.1.b</td>
<td>Step, backward</td>
<td>inclination 0°</td>
<td>l = TBD mm</td>
<td></td>
</tr>
<tr>
<td>1.2.f</td>
<td>Step, forward</td>
<td>inclination 0°</td>
<td>l = TBD mm</td>
<td></td>
</tr>
<tr>
<td>1.2.b</td>
<td>Step, backward</td>
<td>inclination 0°</td>
<td>l = TBD mm</td>
<td></td>
</tr>
<tr>
<td>2.f</td>
<td>Pyramid, forward</td>
<td>inclination 0°</td>
<td>l &lt; TBD mm</td>
<td></td>
</tr>
<tr>
<td>2.b</td>
<td>Pyramid, backward</td>
<td>inclination 0°</td>
<td>l &lt; TBD mm</td>
<td></td>
</tr>
<tr>
<td>3.1.f</td>
<td>Shifted pyramids, forward</td>
<td>inclination 0°</td>
<td>l = TBD mm</td>
<td></td>
</tr>
<tr>
<td>3.1.b</td>
<td>Shifted pyramids, backward</td>
<td>inclination 0°</td>
<td>l = TBD mm</td>
<td></td>
</tr>
<tr>
<td>3.2.f</td>
<td>Shifted pyramids, forward</td>
<td>inclination 0°</td>
<td>l = TBD mm</td>
<td></td>
</tr>
<tr>
<td>3.2.b</td>
<td>Shifted pyramids, backward</td>
<td>inclination 0°</td>
<td>l = TBD mm</td>
<td></td>
</tr>
<tr>
<td>4.f</td>
<td>Cross-hill obstacle, forward</td>
<td>inclination______°</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4.b</td>
<td>Cross-hill obstacle, backward</td>
<td>inclination______°</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 7-1 : Test Matrix (example)
### DOCUMENT CHANGE DETAILS

<table>
<thead>
<tr>
<th>ISSUE</th>
<th>CHANGE AUTHORITY</th>
<th>CLASS</th>
<th>RELEVANT INFORMATION/INSTRUCTIONS</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>-</td>
<td>-</td>
<td>Initial Issue</td>
</tr>
</tbody>
</table>

### DISTRIBUTION LIST

**INTERNAL**

**EXTERNAL**

Configuration Management
Library