Clarification of performance metrics for SFR Breadboarding.

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1 INTRODUCTION

1.1 PURPOSE

This document describes how to calculate the performance metrics for both localisation and mapping breadboarding activities.

1.2 SCOPE

This document is issued to support the SFR Breadboarding TRR for localisation and mapping breadboards..

1.3 TERMINOLOGY

‘Visual Localisation’ (also just ‘Localisation’) in this document refers to the algorithm which takes as input a sequence of stereo image pairs, and outputs the estimated trajectory of the rover.

‘Mapping’ in this document refers to the process of processing stereo image pairs (up to 3) and outputting a model of the terrain observed, in the form of a point cloud.

2 DOCUMENTS

2.1 Applicable Documents

The following documents are applicable and are referred to as [AD xx] in the text:

	Title	Document Number	Issue
AD 01	Sample Fetch Rover Mission Requirements Document	ESA-E3P-SFR-RS-001	2.0
AD 02	MSR Sample Fetch rover A/B1 study breadboard and simulation requirements	ESA-E3P-SFR-RS-002	2.0
AD 03	Visual Localisation and Mapping Breadboarding Requirement Specification	SFR-ADSU-SYS-SP-000001	2

2.2 Reference Documents

The following documents are referenced for supporting information and are referred to as [RD xx] in the text:

	Title	Document Number	Issue
RD 01			

2.3 Acronyms and Abbreviations

AD	Applicable Document
ESA	European Space Agency
MAV	Mars Ascent Vehicle
MCR	Mission Concept Review
RD	Reference Document
SFR	Sample Fetch Rover

3 COORDINATE FRAMES AND CONVENTIONS

These conventions are identical to those defined in [AD 03] but are reproduced here for convenience.

3.1 CONVENTIONS

3.1.1 Quaternions

The quaternion q is defined as a 4 element vector $[q_1 \quad q_2 \quad q_3 \quad q_4]^T$ which can be written in complex number notation as:

$$q \equiv q_4 + q_1 i + q_2 j + q_3 k$$

where i, j, and k are hyper-imaginary numbers.

3.1.2 Naming Conventions for Translational and Rotational Transformations

For translational transformations provided within the datasets, the following naming convention is applied:

identifier_unit_frame

For example, ‘rbOriginPos_m_Ds’ refers to the position of the origin of the Rover Body frame (RB), in metres, with respect to the Dynamic Simulation frame (DS).

For rotation transformations, the following convention is applied:

att_q_*frame*To*frame*

For example, the quaternion ‘att_q_DsToRb’ defines a rotation that can be applied to a direction vector in the Dynamics Simulation (DS) frame to convert it to a direction vector in the Rover Body (RB) frame.

3.2 COORDINATE FRAMES

The following frames are used to define the position and orientation of the rover and cameras.

3.2.1 Rover Body (RB)

The Rover Body frame is fixed with the Rover and thus moves as the Rover moves (see Figure 3-1).

- All definitions are TBC;
- The origin O_{RB} is located in the plane of and at the geometric centre of the four body hold-down and release mechanisms (BHDRMs);
- The x-axis, X_{RB}, points towards the front of the Rover in the nominal direction of travel;
- The z-axis, Z_{RB}, points vertically upwards, antiparallel to the gravity vector when the RV is on flat, horizontal terrain; and
- The y-axis, Y_{RB}, completes the orthogonal right-handed set, and will lie to the left of the Rover.
- When deployed, the ground plane is located at Z_{RB} = - 540 mm, excluding elastic deformation of wheels / locomotion system.

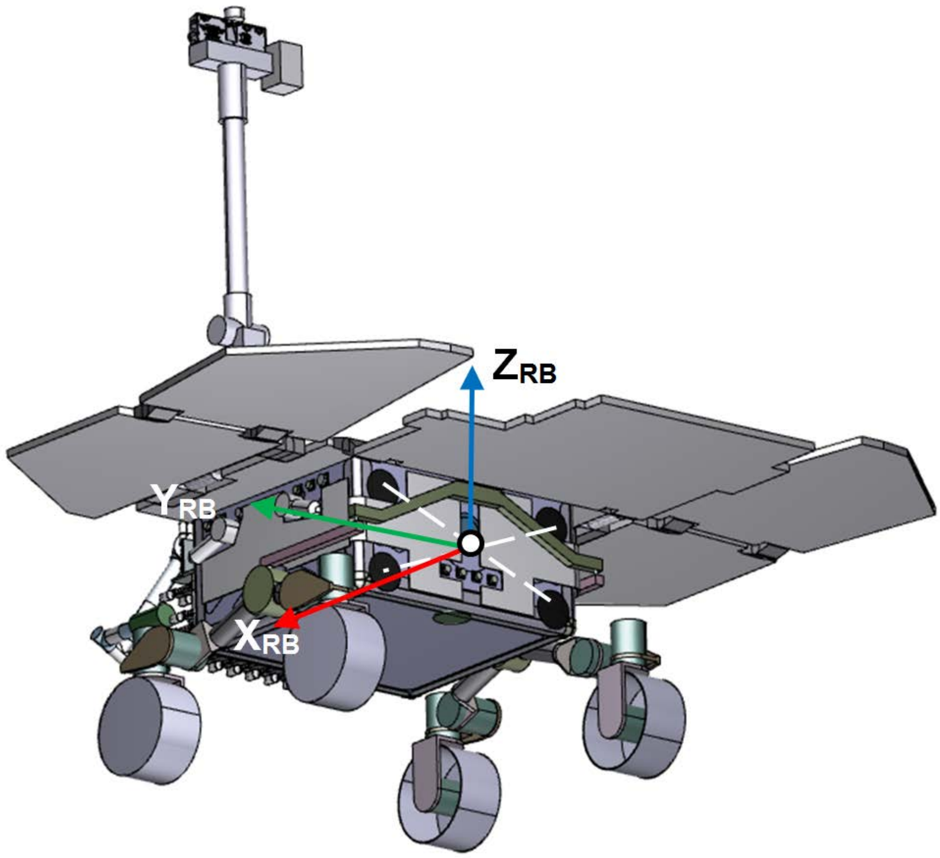

Figure 3-1: Rover Body Reference Frame

3.2.2 Deployable Mast Assembly frame (DMA)

The DMA coordinate system is positioned at the base of the mast. The origin is located at the base of the mast, at $\{X_{RB}, Y_{RB}\} = \{0.451\text{ m}, 0.317\text{ m}\}$.

The axes of the DMA frame are nominally aligned to the RB frame.

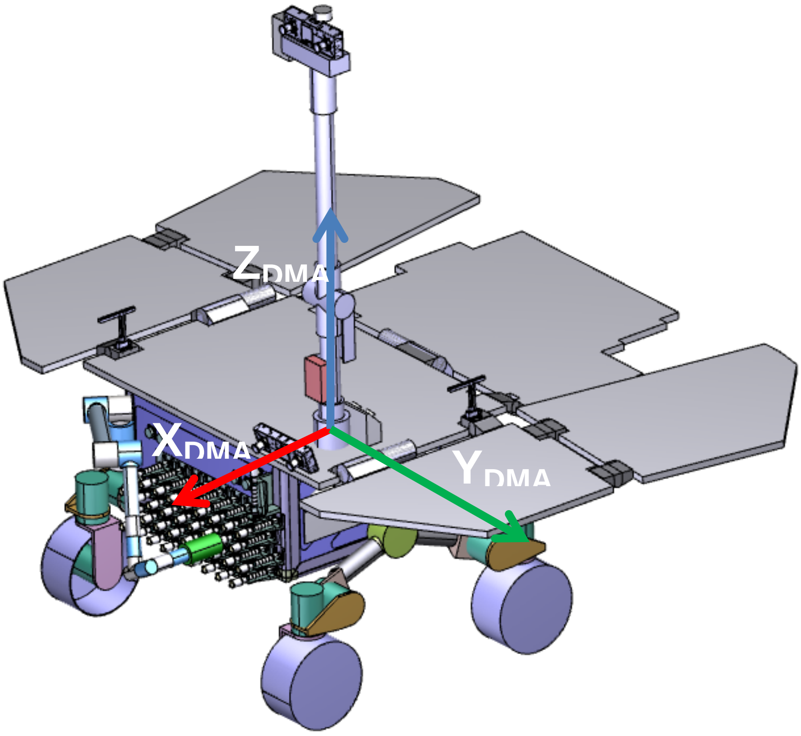

Figure 3-2: DMA Reference Frame

3.2.3 Stereo Bench Reference Frame

The stereo bench reference frame, is attached to the cameras stereo bench and is defined as follows:

- The origin, O_{SB}, is located at the middle of the segment linking the optical centres of the distortion-corrected left and right cameras.
- The x-axis, X_{SB}, is the projection of the distortion-corrected left optical axis ($Z_{O\ left}$) on the plane perpendicular to Y_{SB}.
- The y-axis, Y_{SB}, is in the direction from the distortion-corrected right camera optical centre to the distortion-corrected left camera optical centre.
- The z-axis, Z_{SB}, completes the orthogonal, right-handed set.

The stereo bench frame only applies to the cameras after distortion correction has been applied. The SB coordinate system is illustrated in Figure 3-3 (along with the stereo baseline).

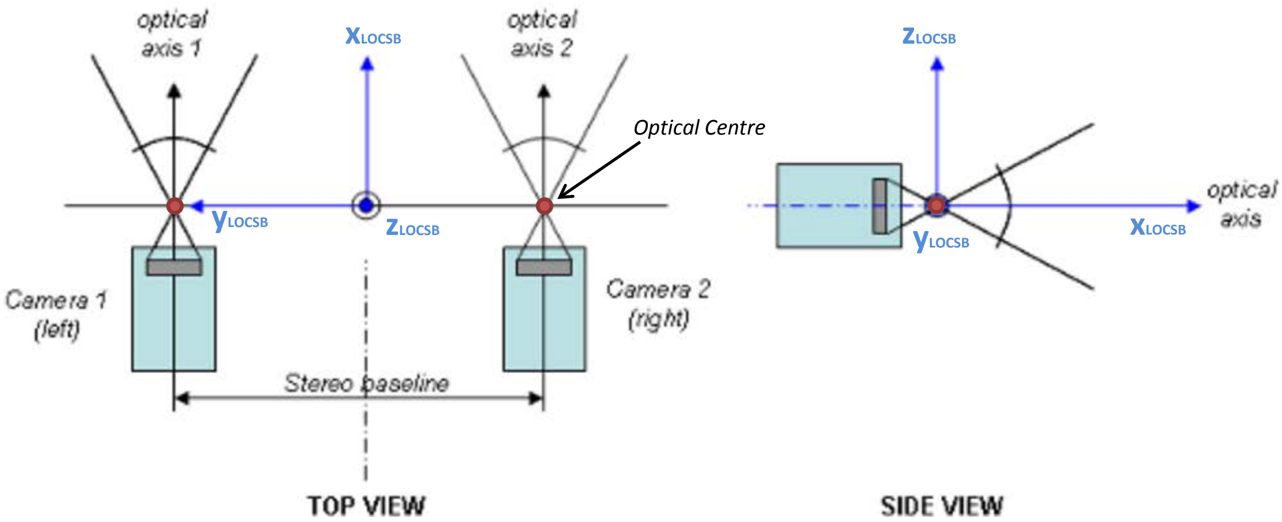

Figure 3-3: Stereo Bench Reference Frame

3.2.4 Localisation Camera Stereo Bench Reference Frame (LOCSB)

The Localisation Camera stereo bench reference frame (LOCSB), is an instance of the Stereo Bench Reference Frame (See section 3.2.3), with the origin as stated in section 3.2.3 defined for the Localisation Camera Stereo Bench.

3.2.5 Navigation Camera Stereo Bench Reference Frame (NAVSB)

The Navigation Camera stereo bench reference frame (NAVSB), is an instance of the Stereo Bench Reference Frame (See section 3.2.3), with the origin as stated in section 3.2.3 defined for the Navigation Camera Stereo Bench.

3.2.6 Navigation Cameras Translation / Rotations

The NavCam orientation can be manipulated via use of the PAN and TILT actuators (Figure 3-4)

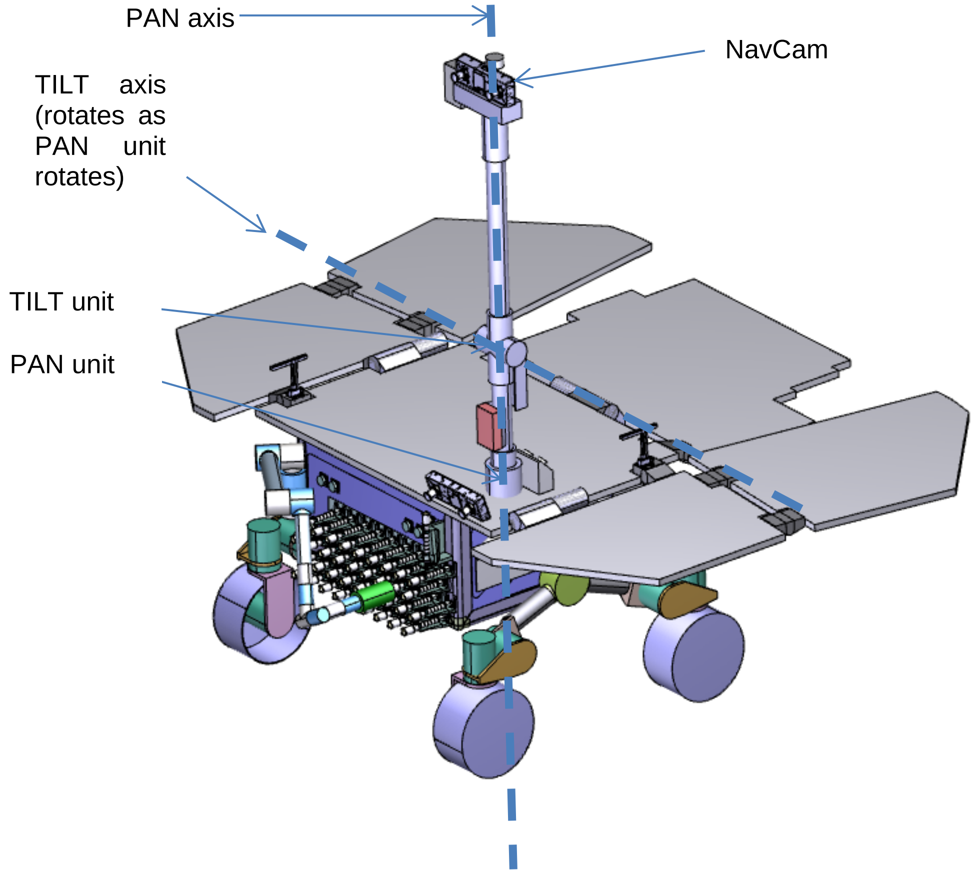

Figure 3-4: PAN and TILT Axes

The PAN axis is located at {X_{RB}, Y_{RB}} = {0.451 m, 0.317 m} and is aligned to $Z_{RB.}$ (See also section 3.2.2, Deployable Mast Assembly frame (DMA))

When the PAN angle is 0°, the TILT axis is aligned to Y_{RB} and is located at {X_{RB}, Z_{RB}} = {0.451 m, 0.594 m}.

The axis about which the tilt actuator rotates (nominally Y_{RB}) is itself rotated about the Z_{RB} axis as the pan actuator rotates so that it can then rotate around an arbitrary vector lying in the {X_{RB}, Y_{RB}} plane.

Note: This information is for reference only; the mapping datasets will contain the transformation between the Navigation Camera stereo bench frame (NAVSB Frame, section 3.2.5) and the local map frame (LM Frame, section 3.2.7.2)

3.2.7 Simulation Frames

3.2.7.1 Dynamics Simulation Frame (DS)

The DS frame is the frame in which the simulated world is defined. It is fixed with respect to the simulated gravity field and the simulated terrain.

- The origin O_{DS} lies at the centre of the simulated terrain.

- The z-axis, Z_{DS}, lies vertically upwards, anti-parallel to the simulated gravity vector.
- The x-axis, X_{DS}, lies parallel to the terrain's digital grid x axis and is tangential to the simulated local geodetic horizontal in an eastern direction.
- The y-axis, Y_{DS}, lies parallel to the terrain's digital grid y axis and completes the orthogonal right-handed set. It is tangential to the simulated local geodetic horizontal in a northern direction.

Therefore, if the rover position is [X_{DS}=0, Y_{DS}=0, Z_{DS}=0] and orientation is defined as a unit quaternion then the Dynamics Simulation frame (DS) coincides with the Rover Body frame (RB).

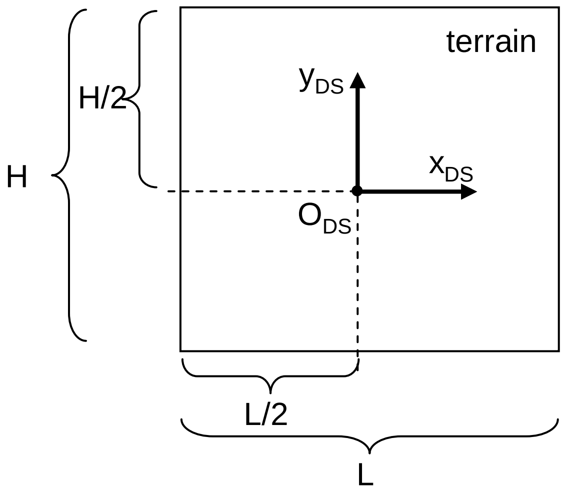

Figure 3-5: Dynamics Simulation Frame

3.2.7.2 Local Map Frame (LM)

The Local Map frame defines the reference frame in which the world around the rover is assessed. It is related to the local position of a point on, or close to, the Martian reference ellipsoid. For the purposes of the Mapping function, it defines the frame in which the terrain is to be perceived lies.

4 PERFORMANCE METRIC COMPUTATION

4.1 General Points

4.1.1 Subtrajectories

In order to evaluate the performance of a localisation algorithm across as many conditions as possible, it is possible to look at multiple sections of a longer trajectory to determine the performance. This can be achieved by starting at an arbitrary frame (N) and progressing along the trajectory until the conditions associated with the requirement have been met, at frame N+*x* (e.g. 5m traverse).

The difference between the change in ground truth and the change in estimation along this section of trajectory between frame N and N+*x* can be determined at this stage.

This process is then repeated starting from a different point in the trajectory. Choosing the next frame as the starting point (N+1) provides the most data, but also leads to a lot of overlapping subtrajectories. For this activity, a spacing of 10 frames between subtrajectories is recommended. This process repeats until the end of the trajectory.

From the difference in the actual and estimated measurements along all of the valid sub-trajectories the mean distribution and standard deviation can be obtained, and the mean+3sigma calculated.

4.1.2 Error over a subtrajectory

Care should be taken when extracting subtrajectory performance measures from a longer test. If the starting frame is in the middle of the trajectory, then there will already be some accumulated error in the estimate at that point. This should be taken into account when calculating how much error the estimation has made over the subsequent subtrajectory.

4.1.3 Standard Deviation

Standard deviation is calculated including Bessels correction.

$$s = \sqrt{\frac{\sum (x - \bar{x})^2}{n - 1}}$$

4.2 Localisation Performance Requirements

4.2.1 Timing Performance

Timing performance is measured in seconds. This is the time (wall-clock time) elapsed on the target hardware (GR740 development board) between the processing API being invoked and the function returning with an estimate.

A common mechanism for obtaining elapsed time on the target hardware development kit has been defined by the development kit supplier (TAS-UK)

4.2.2 RAM Consumption Performance

The supplier shall propose a suitable methodology for measuring RAM consumption during execution.

4.2.3 Estimation Accuracy Performance

4.2.3.1 3D Position Error

3D position error is measured in meters.

The error vector is calculated as the Cartesian difference between the estimated displacement and the actual displacement of the Rover Body frame origin, measured in the Dynamic Simulation frame (‘world’ frame).

3 Sigma Calculation

To obtain a single scalar quantity for mean+3sigma position error from the individual 3D errors resulting from each subtrajectory, the following steps should be taken.

‘mean’ is calculated as the Cartesian norm of the mean of all position error vectors.

$$mean = norm\left(mean\left(\overrightarrow{error_{pos}}\right)\right)$$

‘sigma’ is calculated as the norm of the vector comprised of the standard deviation on each axis of the DS reference frame.

$$\sigma = norm\left(std\left(\overrightarrow{error_{pos}}\right)\right)$$

In other words, assuming that all error vectors are defined in the DS frame (as defined above) then the standard deviation of the vector of the X, Y and Z components are taken separately, and then the norm of the resulting vector is taken.

4.2.3.2 Attitude Error

Attitude error is measured in degrees, and is an unsigned quantity.

Attitude error is calculated as the magnitude of the shortest-path rotation between the estimated and actual attitude. Assuming that the rotation between estimated and actual attitude is defined as a quaternion, this is calculated from the scalar part of the quaternion.

3 Sigma Calculation

The mean of all attitude errors is calculated, and the standard deviation of all attitude errors is calculated in the standard way.

4.2.3.3 Heading Error

Heading error is the attitude error, measured in degrees about the vertical axis of the global frame

Heading can be calculated as the angle between the X axis of the dynamic simulation frame and the projection of the Rover Body frame X axis onto the DS frame X-Y plane.

i.e. if the Rover Body X axis vector (expressed in the DS frame) is [X_{RB}^{DS} Y_{RB}^{DS} Z_{RB}^{DS}] then the heading is atan2(Y_{RB}^{DS}, X_{RB}^{DS}).

3 Sigma calculation

Heading error is a signed quantity. As such, the absolute value of the mean of all heading errors is calculated, and the 3 sigma value is added to this.

$$mean + 3\sigma = abs\big(mean(error_{head})\big) + 3 * std(error_{head})$$

Where $error_{head}$is the vector of heading errors from all subtrajectories.

4.3 Mapping Performance Requirements

4.3.1 Timing Performance

See section 4.2.1

4.3.2 RAM Consumption Performance

See section 4.2.2

4.3.3 Mapping Accuracy Performance

4.3.4 Error in the output point cloud

The error in the output point cloud is measured in meters.

The error shall be computed (for each point in the point cloud) as the Cartesian norm of the difference between the position vectors of the actual position of the point (as defined by the ground truth) and the estimated position.

$$pointErr_n = norm\big(pos_n^{ref} - pos_n^{est}\big)$$