SAMPLE FETCH ROVER GUIDANCE, NAVIGATION AND CONTROL SUBSYSTEM - AN OVERVIEW

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ABSTRACT

Building on ExoMars heritage in Airbus, Sample Fetch Rover (SFR) is part of the NASA/ESA Mars Sample Return (MSR) Campaign, aiming to pick up and then return samples to the Mars Ascent Vehicle (MAV) in a timely manner. This paper gives an overview of the Guidance Navigation and Control (GNC) subsystem developed to fulfil these challenging mission constraints. After detailing the mission, the GNC scope and its constraints, this paper is giving an understanding of the GNC design as well as the Verification and Validation (V&V) philosophy, before presenting preliminary results.

1. SFR MISSION

The MSR Campaign is a response to the long-running scientific objective to better understand Mars. By acquiring and returning to Earth a rigorously documented and uncontaminated set of Mars samples, scientists will have access to the full breadth and depth of analytical science instruments available in terrestrial laboratories, unlocking new possibilities in exobiology, interplanetary geology and supporting our search to the origins of life [1].

Mars Sample Return is a joint NASA/ESA campaign consisting of three missions working in close collaboration to return samples from Mars to Earth by the early 2030s, as detailed in the Figure 1.

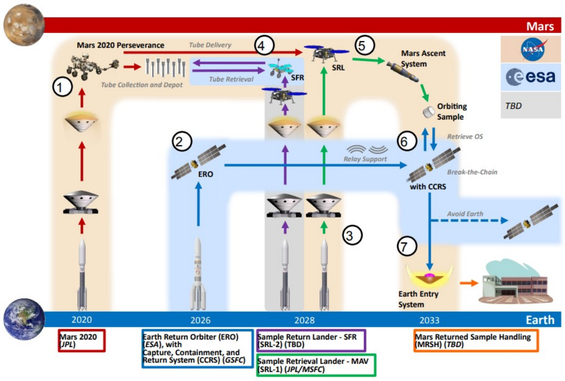

Figure 1. MSR Mission Concept as of April 2022 (credit: NASA)

The MSR architecture involves a total of five campaign elements: four flight elements and one ground element. Each campaign element consists of one or more functional elements. The four flight elements are:

- Caching rover mission, developed by NASA-JPL (Mars 2020 project), currently operating on Mars;
- First Sample Retrieval Lander (SRL-1) mission, consisting of a NASA/JPL developed lander with a MAV as well as ESA provided Sample Transfer Arm (STA);
- Second Sample Retrieval Lander (SRL-2) mission, carrying a SFR;
- ESA provided Earth Return Orbiter (ERO) mission.

In December 2018, Jezero Crater (JEZ) was selected as the Mars 2020 landing site. Due to the large traverse range of Mars 2020 it is possible that it will drive far enough that another landing site closer to the eventual depot location will be chosen for the SRLs. In particular, the science team has expressed interest in driving towards the Northeast Syrtis-like terrain found in the so-called "Midway" ellipse (MDW) [7].

As part of this campaign, SFR (Figure 2) is tasked with driving from the SRL-2 landing site to a sample depot, where the samples have been placed by the Mars 2020 rover, collecting the samples, and delivering them to the SRL-1 landing site. SFR is therefore currently required to be compatible with both JEZ and MDW landing ellipses.

SFR is being developed by Airbus Defence and Space Ltd. (herein referred as Airbus), as an experienced prime contractor having developed and delivered, together with industrial partners, the ExoMars rover.

The MSR campaign schedule is strict due to the orbital constraints which define short time windows for the MAV and ERO to bring back the samples from Mars to Earth. In that context, SFR has to ensure its mission is carried out swiftly and reliably. Autonomy, including the Guidance Navigation and Control (GNC) system, is a key element for mission success, enabling the rover to traverse large distances in the challenging Martian environment, to find the sample depot with minimal ground intervention, and hence to minimise idle time.

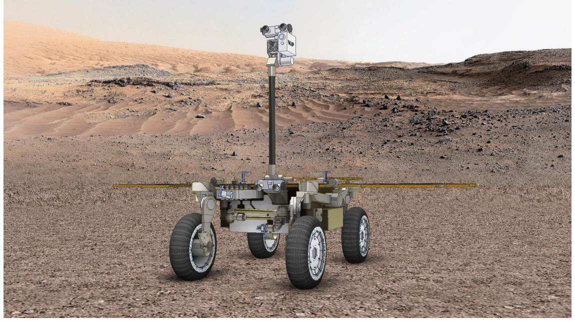

Figure 2. Artistic rendering of the Sample Fetch Rover (copyright: Airbus)

2. SFR GNC SUBSYSTEM SCOPE

In this mission context, the GNC subsystem has responsibilities and design drivers to keep the rover safe, thus preventing loss of the mission. Secondly, to fulfil mission objectives, the rover needs to traverse efficiently over long distances and perform accurately, both to reach the depot, and driving inside it.

Moreover, the solution is typically constrained by system level design drivers (e.g. available sensors, bandwidths, other subsystems volume, mass or power budgets), industrial maturity/heritage of underlying components, mission operational concept, etc.

To provide the required autonomous capabilities, the GNC includes components such as: rover mobility, platform localisation, perception, terrain modelling, terrain evaluation, mapping, path evaluation (both planning new paths and checking pre-planned ones) and additional support and interfacing modules, covering a large functional scope in the system.

In order to ensure mission success, high level requirements have been defined to cover the GNC scope detailed above.

3. HIGH-LEVEL REQUIREMENTS

Rover safety in the Martian environment

There is a critical need for the GNC to guarantee the safety of the rover while operating autonomously. Indeed, the challenging Martian environment presents numerous potential dangers including grounding out, terrain collisions (e.g. by Solar Arrays), sand traps, steep slopes and any situation leading to loss of control or an unsuccessful completion of a planned manoeuvre. Furthermore, additional dangers potentially encountered during operations must be covered. This criterion includes topics such as the safety during operations and the pose estimation accuracy. Therefore, the GNC shall:

- Identify areas of terrain that could compromise safety of rover and plan around them;
- Provide accurate rover localisation over a traverse
- Provide necessary safety checks to mitigate uncertainties.

Efficient traverses

As previously stated, the ability for SFR to traverse efficiently is mission critical to ensure a timely delivery of samples to the MAV. Hence, the GNC shall achieve traverses that are:

- Uninterrupted and with the highest level of autonomy of the platform to ensure a high average speed;
- Accurate over a multi-sol autonomous traverse to specific locations (e.g. the depot) defined in an absolute Mars reference frame.

Moreover, once the depot is reached, the GNC should also ensure safe operation within the sample depot to autonomously place the rover in the best position to retrieve the sample.

System-level design constraints

As stated, the GNC subsystem is also constrained by the platform it is implemented within. Thus, this criterion covers the impact of the GNC design on the overall system, including the energy consumption by the GNC system alone per metre of traverse and constraints or requirements on the available processing environment, sensors and actuators. Being efficiently implemented within the design constraints of the overall system requires the design to:

- Minimise the addition of extra hardware (e.g. sensors or actuators) with associated mass, volume and energy impact;
- Minimise the energy consumption per metre of traverse;
- Minimise the development risk and therefore impact to the programme cost and schedule.

4. HERITAGE

The ExoMars Rover and other previous rover missions have had mainly in-situ scientific objectives. Their mission timelines are designed around reaching particular points of scientific interest with operators in the loop selecting interesting geological features on the way. The overall system is limited by the time necessary for operators and scientists to analyse terrain around the rover and update the mission plan accordingly while also providing an extra level of supervision over the safety of the rover. [2] [4]

Therefore, the GNC algorithms developed for ExoMars Rover were designed to traverse over extremely challenging terrain relative to the capability of the platform, whilst ensuring the safety of the rover at all times. However, they are not intended to be re-used without consideration of the different use cases for SFR. In particular, SFR will avoid challenging terrain as much as possible, maximising traverse speed. This is why ExoMars heritage is used as a solid foundation for the SFR GNC algorithms, with minimal adaptation as required for SFR, rather than being a direct and complete reuse. As the average traverse speed is a key factor, while terrain harshness is not, some tailoring of the GNC solution for SFR is required to reach the high-level requirements stated previously.

These design drivers have led to the creation of an additional, lighter-weight navigation mode (called FOPSA) for use in less challenging terrain. FOPSA is designed with the expectation of a greater level of uninterrupted autonomy of the platform during this mission.

Finally, SFR mission also provides challenges related to efficient and accurate operation, both over long traverses and over short drives within the depot, as detailed in the high-level requirements. This requires development of new modules related to on-board Absolute Global Localisation (AGL) that utilise orbital or a priori collected local data, as well as sun sensing functionalities for absolute heading estimation [8].

5. GNC DESIGN

Overall architecture of SFR GNC subsystem is presented in the **Error! Reference source not found.**. In navigation modes, stereo images are processed by the perception module producing a Digital Elevation Map (DEM) and some metadata characterising the terrain. Additionally, as a by-product, the Ortho-Rectified Image (ORI) is provided as a crucial input to the AGL module. Further along the chain, the terrain model is evaluated for multiple feature classes (e.g. slope, discontinuity, clearance) while the navigation map is produced containing fused information represented as a traverse cost. A navigation map is provided to the path planning algorithm, or path checking module, which outputs a sequence of safe path points to be followed by the driving stack (should ground command an unsafe path in HDD, the path checking will cause an abort, keeping SFR safe). The navigation layer provides following modes:

- **CheckPath** (used in Human Directed Drive (HDD) and in depot operations) - follows ground-defined paths, checking for safety;
- **AutoNav** (autonomous traverse to the target location) - evaluates terrain and plans a safe path towards a given target point;
- **FOPSA** (driving faster (on average) in benign terrain) - follows a global path constructed of waypoints evaluating and checking terrain in a lightweight manner and avoiding minor obstacles when necessary.

5.1. Locomotion

The Locomotion algorithms are responsible for commanding and processing sensor data from the Locomotion subsystem, which itself comprises the Fetch Actuator System for Traverse (FAST) and the Actuator Control Subsystem (ACTS) interface. The FAST has independently controlled steer and drive actuators for each of the 4 wheels. This allows the rover to perform both generic Ackermann manoeuvres, which combine conventional Ackermann manoeuvres with crabbing manoeuvres, and generic point turn

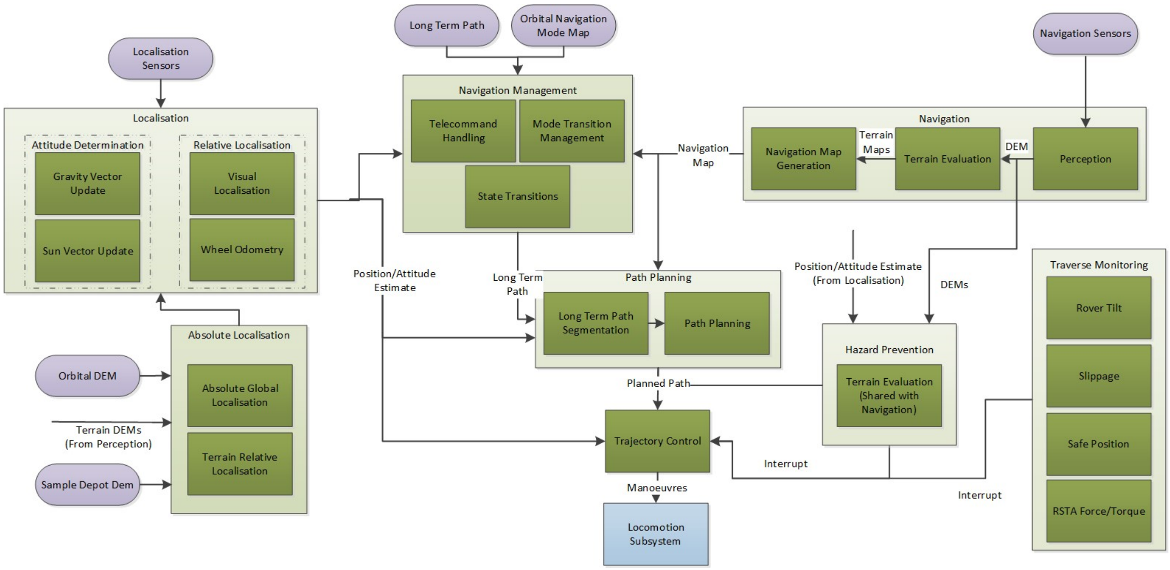

Figure 3. SFR GNC functional architecture

manoeuvres where the rover is able to rotate about any point between its left and right wheels.

The Locomotion Manoeuvre Control module (LocoMan) is responsible for converting body level Ackermann or point turn commands, provided by higher-level modules, into axis level commands for each of the steer and drive actuators.

5.2. Visual Odometry

While the rover is traversing, changes in position and attitude are estimated by Visual Odometry (VisOdo) similarly to ExoMars Rover [5]. Stereo image pairs are periodically captured by the Localisation Cameras (LocCams) from which VisOdo is able to track features identified in previous images, and produce an estimate of the change in rover position and attitude.

5.3. Roll and Pitch Estimation

The rover Inertial Measurement Units have accelerometers as well as gyroscopes. When the rover is stationary on the Martian surface, the measured acceleration allows for accurate determination of the gravity vector relative to the rover body, which is used to correct for drift in the rover roll and pitch as estimated by VisOdo. The accelerometer measurements are also used by the CoarseTilt module while the rover is traversing which provides an independent coarse estimate of rover tilt for FDIR.

5.4. Relative Localisation

The Relative Localisation module (RelLoc) is responsible for updating the estimated rover position and attitude throughout a traverse. It combines the high accuracy but lower frequency VisOdo updates with noisy, but higher frequency locomotion subsystem sensory data and IMU data for propagation purposes.

Gyro measurements are used to propagate rover attitude and the Wheel Odometry module (WheelOdo) uses actuator telemetry to propagate the rover position based on the current steer and drive configuration. When fusing VisOdo updates, care needs to be given to synchronisation, ensuring the VisOdo, WheelOdo & gyro data being combined correspond to the same time-window. Due to the non-negligible VisOdo processing time, part of the rover position and attitude estimate is always propagated while the rover is moving.

5.5. Trajectory Control

The Trajectory Control module (TrajCtrl) is responsible for ensuring the rover keeps to the path provided by the ground operators or Path Planning module.

For Ackermann manoeuvres, it uses the rover position and attitude estimated by RelLoc to calculate the current lateral error and heading error relative to the closest point on the path. It then applies corrective action via commands sent to LocoMan, adjusting the crab angle of the current manoeuvre to counter lateral error and adjusting curvature to counter heading error.

Similarly, for point turn manoeuvres, TrajCtrl calculates the rover's position error relative to the commanded position of the point turn and adjusts the manoeuvre's instantaneous centre of rotation to correct this.

These corrections keep the rover within a defined control corridor. If the rover exits the corridor at any point, TrajCtrl stops the rover and alerts the GNC system that the path must be replanned; this is then done without ground intervention.

5.6. Sun Sensing Heading Estimation

The Sun Sensing Heading Estimation module (SSHE) is responsible for the following:

- Generating pan/tilt commands to find the sun in the FoV of the NavCam;
- Identify and localise the sun in the NavCam image and generate the sun vector in the Rover Body Frame from that information;
- Estimate the sun vector in MLG frame, based on the rover on-board time and the known rover location (longitude and latitude);
- Estimate the rover attitude (Rover Body Frame wrt MLG frame) and the rover heading in MLG frame, using sun and gravity (measured using IMU) vectors in both frames.

5.7. Absolute Global Localisation

The Absolute Global Localisation module (AGL) [8] requires products of the Perception module (DEM and ORI) to be able to correlate with reference data and estimates correction in reference to its internal position knowledge.

The AGL operates in two modes, depending on the phase of the mission: during the traverse to and from the sample depot, it allows the rover to be localised to better than 10 metres, to aid in following the long-term path. Within the depot itself, this allows the rover to be localised to better than a few tens of centimetres, which is required for effective tube pick-up.

5.8. Perception

The Perception module developed by CNES supplies the Navigation and AGL modules with Digital Elevation Maps (DEMs) and Ortho-Rectified Images (ORIs).

Perception generates disparity maps from stereo image pairs taken with the Navigation Cameras (NavCams).

Multiple disparity maps, taken from different camera pan angles, are then processed further to create a digital model of the terrain and merge different FoV into a single DEM and a single ORI.

The DEM (Figure 4), generated based on the disparity between the left and right camera images, are further processed by the Navigation module.

The ORI (Figure 5), generated from the camera images and the disparity map, are used as inputs only for the AGL module.

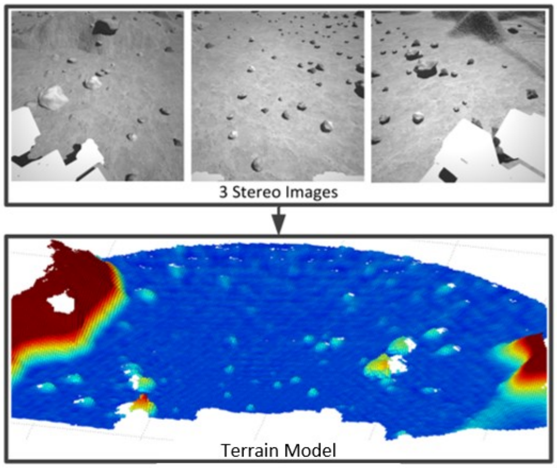

Figure 4. Perception generates a Terrain Model from NavCam stereo image pairs

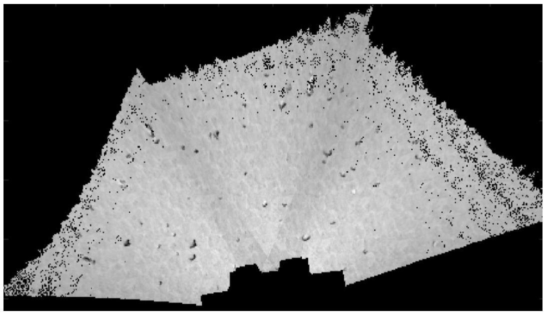

Figure 5. Example ORI generated out of integrated CNES solution

5.9. Navigation

The Navigation module is responsible for analysis of the terrain model provided by Perception. It assesses the safety and traversability of obstacles and outputs a Navigation Map (NavMap) for use in path planning.

To do this, it needs to assess various terrain features: slope, discontinuity, rover tilt, bogie angles, and clearance to the rover. Some of these are simple to calculate but others depend upon the kinematics and the estimated configuration of the rover in a particular part of the terrain. These are determined by iteratively placing a Rover Simplified Model (RSM) in various positions and headings on the terrain model.

5.10. Path Planning

The Path Planning module (PathPlan) uses the finalised NavMap to perform one of two actions:

- Checking a ground planned path for safety in CheckPath mode by evaluating the NavMap at all points along the path and looking for forbidden (i.e. unsafe) obstacles;
- Planning a safe path through the terrain towards a ground-provided target position in AutoNav mode. This mode uses a variation of the A* algorithm [4] to find the lowest-cost rover dynamics compatible path through the NavMap (see Figure 6).

The checked or generated path is then output to TrajCtrl for execution by the rover's driving stack.

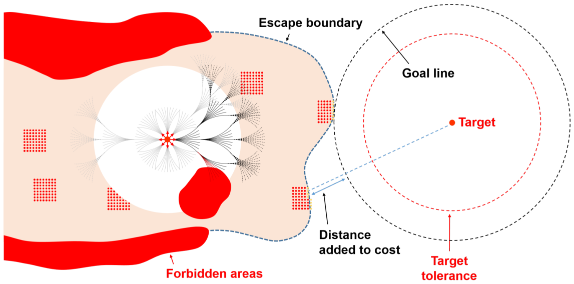

Figure 6. Path Planner uses the costed NavMap to search for the optimal path to the target

6. VERIFICATION AND VALIDATION

SFR GNC subsystem design and architecture is benefiting from Airbus experience on ExoMars, keeping the GNC functional stack as well as reusing most of the GNC HW architecture, while building on ExoMars' valuable lessons learnt.

However, modifications are required as detailed in Section 4. The design of those new elements, which are complex or critical has been advanced and de-risked through breadboarding activities.

The flow of activities for the Design, Development and Validation (DDV) of the GNC encompasses several streams and teams (both within the Airbus SFR project and within external suppliers). The main Airbus benches and their role in GNC DDV are summarised below:

- **OSE** (Offline Simulation Environment): Simulations are used to mature the design, provide confidence before the Functional Validation Bench (FVB) and support field trials;
- **FVB** (Functional Verification Bench): Simulations on this numerical bench validate the performance and debug software implementation of algorithms;
- **NSVF-SimOps/CCS** (Numerical Simulation Validation Facility - Simulation MMI for

Operations / Central Checkout System): simulations to confirm behaviour of GNC FSW within On-Board SoftWare (OBSW) is as expected;

- **ETM** (Electrical Test Model): Very few simulations exercising SW/HW interaction, used to confirm expected behaviour on real OBC;
- **GTM** (Ground Test Model): Flight like rover, real world tests, accepting reduced locomotion capability on Earth vs Mars.

6.1. Simulation environment

The SFR development and testing relies heavily on Airbus' OSE. The OSE has been mostly inherited from ExoMars development [4] and adapted to suit the project's needs.

Figure 7. Rendering of rover and terrain using PANGU

The OSE incorporates ESA's rover dynamics engine (GRDM) [6], locomotion subsystem and sensor models and uses PANGU [10] as photo-realistic scene rendering tool. PANGU is used to generate images of the Martian-like terrain as an input to rover's Localisation and Navigation camera models (Figure 7).

6.2. Unitary breadboards

The GNC Breadboarding activities were run in parallel with the Phase A/B1 study for Sample Fetch Rover. The breadboarding activities are designed to provide demonstration of the TRL (Technology Readiness Level) of any critical functions of the GNC, which have not yet reached TRL 5 or above.

The GNC Unitary BreadBoard (UBB) was intended to prototype the GNC navigation algorithms for SFR, demonstrating the capability to autonomously traverse terrains of varying difficulty whilst keeping the rover safe (Figure 8). The GNC needs to be able to efficiently traverse through an SFR relevant environment. The output of the UBB was a prototype of an autonomous Navigation system, which successfully demonstrated the achievement of TRL 5 at the end of 2019.

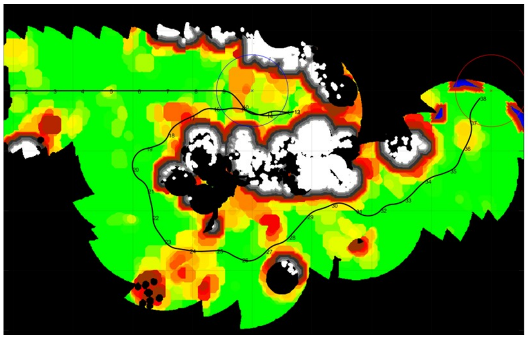

Figure 8. Simulation – UBB test - Planned Path overlaid on NavMap

The GNC UBB was capable of executing Processor-In-the-Loop simulations; hence the prototype GNC algorithms were run on an SFR flight-representative processor (GR740). While the algorithms were executed on the target unit, the simulator managed communication and provided all necessary inputs and executed output commands in the loop with the rover dynamics model virtually situated in the SFR-analogue environment (Figure 9).

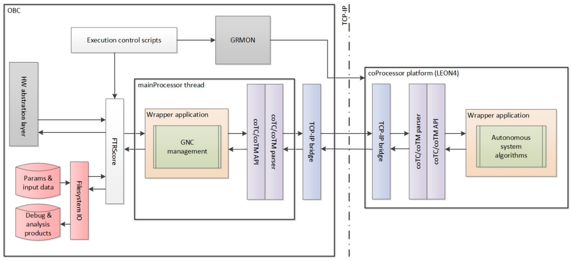

Figure 9. PIL architecture diagram: LEON (GR740) processor in the loop

The GNC UBB reused a significant part of the ExoMars AutoNav algorithms in order to support the design and validation of the critical functions. The reused ExoMars AutoNav algorithms have exceeded the target TRL 5 for SFR's UBB activities.

6.3. Integrated breadboards

The Integrated BreadBoards (IBBs) represent activity of integration and testing of prototypes of physical rovers. Within early phase of SFR project, two IBBs were planned:

- IBB1 - ExoMars-like platform in time when many SFR requirements were still immature but integration with real hardware platform was beneficial to prepare and learn to de-risk the next phase;
- IBB2 - first physical platform representing SFR-like kinematics and dynamics.

The IBB2 is composed of four main assemblies, as shown in the Figure 10:

- The Locomotion Sub-System (LSS), named CHABLIS, includes the two rocker bogies and motor controllers;
- The compliant wheels, developed by NASA, are made of a deformable mesh which adapts to the terrain's features [9];
- The main body including all the main IBB2 components and sensors;
- The mast used to place the Navigation and Localisation cameras in the required position.

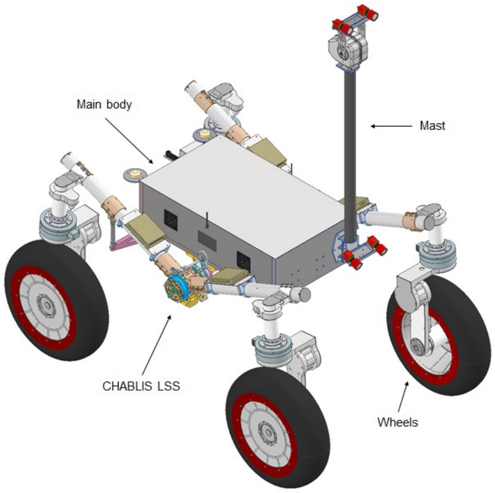

Figure 10. IBB2 main assemblies

The IBB2 GNC solution is based on development of the UBB code base. This code base is a combination of the architecture and functionalities of the SFR GNC UBB and AGL capabilities, on top of which, the new CNES perception module is integrated.
The resulting GNC sub-system will provide the following functionalities:

- FollowPath mode;
- AutoNav mode;
- CheckPath mode;
- FOPSA mode;
- AbsLoc (AGL functions).

The IBB2 GNC architecture presents the natural evolution of UBB and IBB1 developments. The core of the solution comprises the closed loop test harness, interfacing with the hardware abstraction layer that communicates with the rover hardware. This solution is capable to run flight-like architecture where the GNC uses the main processor to manage interfacing and execution and utilises the GR740 for more intensive computations related to navigation stack.

Our designed architecture allows iterative development and integration of the system. The GNC algorithms can be tested interchangeably in simulation or connecting to the hardware via an abstraction layer and the GNC algorithms can be executed as a separate process or in PIL setup.

6.4. Field trials

Using the IBB2, field trials will be conducted in a planetary representative environment (i.e. analogous terrain to the mission). Indeed, building on lessons learnt from ExoMars and ADE [11], field trials are integrated early in the SFR programme.
These field trials will allow representative tests in real world conditions, providing confidence in functionality with an integrated HW/SW system.

Figure 11. IBB1 testing of the GNC subsystem in the Mars Yard in Airbus facilities in Stevenage [UK]

The initial shakedown tests of IBB2 will be conducted in Airbus Mars Yard (Figure 11), while a more thorough test campaign will be conducted in a local quarry, all before bringing the rover to the Mars analogous site like Atacama Desert.

6.5. Formal Verification

As a next step to previously detailed testing, a formal V&V approach [3] is followed, using an FVB to test performance through stochastic measures, as well as to obtain early functional verification results.
Higher level benches will then follow, as detailed in Section 6, until the GTM, a fully integrated flight representative model, which will confirm functionality and general behaviour (despite some limitations such as gravity representativeness).

7. EXAMPLE RESULTS

During UBB and IBB1 campaigns, a generic set of tests was established representing scenarios analogous to the SFR mission elements. Those tests are used for Unitary Breadboards testing including functionalities such as:

- GNC UBB campaign;
- IBB1 demonstrations;
- Integration of CNES perception solution;
- AGL interfacing;
- Sun Sensing testing.

Most of the mentioned breadboards were also tested in PIL setup to verify integration and build confidence in modules performances.

Figure 12. IBB1 field trials replacement location (Airbus car park)

Figure 11 presents shakedown tests of IBB1 conducted in the autumn of 2020 and Figure 12 shows replacement of field trials cancelled due to COVID-19 travel restrictions. Multiple critical functionalities as well as fully integrated autonomous solution prototype were tested, including long traverses. The IBB1 campaign provided valuable lessons learnt to be utilised in IBB2 preparations.

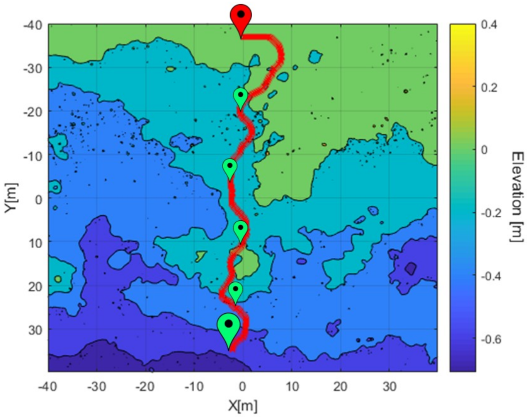

Figure 13. UBB test: multiple waypoints are reached in Processor-In-the-Loop (PIL) using GR740 board in the simulation.

Figure 8 and Figure 13 show simulated and executed in PIL setup, UBB test from local and global perspectives. Presented UBB test is a complex traverse, in terms of both terrain and distance to be driven (i.e. 74 m). It goes through two particular terrain stripes. Between -10 m and -20 m on Y there's a high Cumulative Fractional Area (CFA) of 6% and between 10 and 20 m on Y there's a slope stripe of 2-9 deg.

8. CONCLUSIONS

With a substantially different mission profile in comparison to ExoMars, SFR is bringing significant challenges to the GNC subsystem in terms of performance and autonomy. Building on Airbus' ExoMars heritage, an efficient GNC subsystem has been designed with Airbus' partners, showing promising preliminary results on both simulators, with and without PIL, and breadboards.

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