INTEGRATED BREADBOARD 3: ROVER CAPABILITY EVOLUTION WITHIN SFR MISSION CONTEXT AND FUTURE PLANETARY TECHNOLOGY TESTING PLATFORM, AS A SERVICE

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ABSTRACT

The Integrated Breadboard 3 (IBB3) constitutes a challenging project executed by Airbus Defence and Space (ADS) for the European Space Agency (ESA). It consists of developing the autonomous capabilities of a rover prototype equipped with a robotic arm, in the context of the Sample Fetch Rover (SFR) mission. This rover is meant to not only autonomously traverse long distances, with limited localisation error, but also to fetch sample containers (i.e. Returnable Sample Tube Assemblies or RSTAs) in depots designated beforehand. The IBB3 architecture, born in the context of the SFR mission, is also conceived as a generic system to provide testing capabilities as a service. It comprises the Field Trials Rover System (FTRS) platform, the Mission Manager System (MMS), the Mobility system (MOB), and the RSTA Acquisition System (RAS). This publication details these software and hardware subsystems. Additionally, it presents results of development of the described platform, and its testing capabilities.

1. INTRODUCTION

The development of the IBB3 lasted around 9 months, and took advantage of work on previous breadboard activities. Its predecessor, IBB2, was tested during the Field Trials of September 2022 in Leighton Buzzard, UK [1]. The IBB2 focus was the integration of autonomous navigation functionalities like the Absolute Global Localisation (AGL) and the Autonomous Navigation mode (AutoNav). The greatest achievement during the 2022 test campaign was a 300 metre autonomous traverse with FTRS using AutoNav navigation mode while AGL provided localisation corrections throughout.

The most notable improvement of IBB3 with respect to IBB2 was the physical integration of the robotic arm (see Fig. 1) to fetch RSTAs in depots (i.e. circular areas around the RSTA). This integration entailed re-assigning the existing on-board hardware to comply with the requirements of both mobility and arm subsystems, in terms of structural/mechanical integrity, power and computational resources.

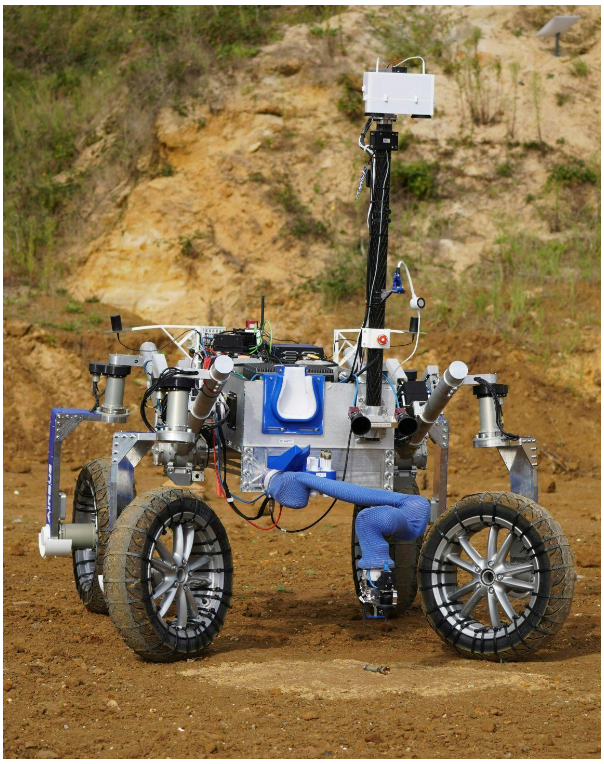

Figure 1. FTRS during the 2023 field trials campaign. RAS, installed in front of the rover, is testing a pickup of an RSTA while the front wheels are open to increase the workspace of the arm

On the autonomous navigation side, the improvements have been focused on the integration of Relative

Localisation (RelLoc), Sun Sensing Heading Estimation (SSHE), a breadboarding of Efficient Navigation [2], Navigation Corridors, the navigation in the depots areas using AGL-Depot functionality, and the control of the positioning and heading of the rover based on the RAS requirement to fetch the RSTA.

1.1. Architecture of IBB3

IBB3 is the first Airbus rover breadboard and field trial campaign of the SFR mission that simulates a complete end-to-end operational element. The Operations (OPS) layer (contained within the green box labelled MMS in Fig. 2) consists of a frontend software solution, called 3DROCS/3DROV [3], developed by the software company Trasys International. This software provides the operator with a graphical interface, and a backend named the FTRS Task Manager (FTM) which handles all interfaces between 3DROCS/3DROV and the MOB and RAS applications. 3DROCS/3DROV facilitates the operator planning rover activities in advance as well as their execution during a test. Moreover, it handles the receiving and processing of telemetry to display the rover in a 3D scene. The FTM implements the logic required for rover activities that involve multiple subsystems working together, as well as the sending and receiving of telecommands/telemetry and the monitoring of events.

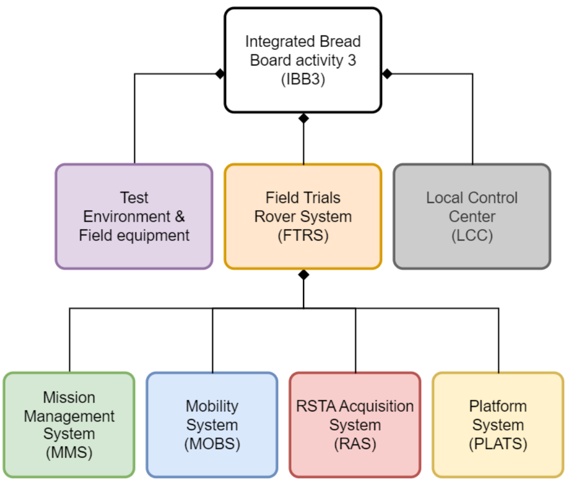

Figure 2. General chart of the IBB3 system

The paper presents in more detail the evolution of the rover platform and its subsystems, together with a summary of its integrated capabilities. It also introduces the concept of the integrated service for testing planetary use cases.

2. FIELD TRIAL ROVER SYSTEM (FTRS)

The FTRS, depicted in Fig. 3, is a four-wheeled mobile platform equipped with two sets of stereo cameras for visual localisation and navigation tasks. All four wheels have independent steer and drive control, making FTRS capable of performing generic Ackermann (including crabbing) and point turn manoeuvres. The total mass is 142kg, distributed among all four wheels with the front left taking slightly more than the others. The FTRS physical platform is composed of three main assemblies:

- **Main Tub.** It is built upon an aluminium-honeycomb open tub structure made of five 20 mm thick panels. This tub hosts all the computing and power conditioning items, as well as the power and data harness. Two apertures with brushes are placed at each side of the tub to allow cables to reach external components, while minimising dust ingress, and four cooling fans are used in continuous operation.
- **Mast.** It comprises a Carbon Fibre Reinforced Polymer (CFRP) tube, two sets of stereo cameras, a Pan-Tilt Unit (PTU), and a WiFi antenna. Each camera unit is monocular, so two are assembled together onto a plate to form a stereo bench, with a baseline of 15 cm between cameras. While the Navigation Camera (NavCam) assembly is placed on top of the PTU to control its orientation, the Localisation Camera (LocCam) assembly is in a fixed position at the bottom of the mast, pointing 18° downwards.
- **Locomotion Subsystem.** Developed by MDA, it comprises two side bogies linked by a transverse mechanical differential arm mounted on the rear face of the vehicle, the motor controllers, four wheels, and the PLC units host the locomotion logic. It is attached to the underside of the Main Body via a bolted connection with the flat deck in between the two rocker joints.

The FTRS features a differential GNSS (dGNSS) system, using the Real-Time Kinematic (RTK) positioning technique to provide accurate reference position and attitude. A base station provides live RTK corrections via radio link to the GNSS receiver onboard the rover. This unit is mounted on the rear electrical boxes and is connected to two antennas placed on separate brackets spaced 1m apart to also provide true heading measurements.

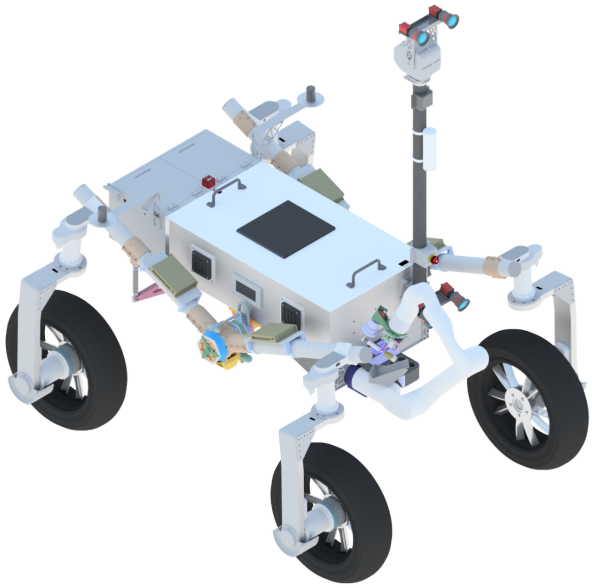

Figure 3. FTRS design in the frame of IBB3 project

The FTRS is powered by two LiPo batteries (22Ah, 488Wh) in a hot-swap configuration, meaning they can be individually swapped with a fresh battery without removing power to the system. During a comprehensive test, one set of batteries will last approximately 2.5h. The FTRS can also be powered via the facility AC mains supply through a 50m long tether.

3. MISSION MANAGEMENT SYSTEM (MMS)

The MMS is in charge of designing, preparing and executing the mission. It is in turn formed of two interconnected components: the Ground Control Software (GCS) and the FTRS Task Manager (FTM). The GCS is based on the 3DROCS and 3DROV software modules. The main objectives are to increase the user awareness of the system behaviour, to improve the understanding of the activity plans (i.e. sequence of activities to be performed and sent to the rover) and to provide a unified interface for strategic and tactical planning. 3DROCS and 3DROV are tightly coupled together, but they have different execution targets: while 3DROCS is executed on the operator's computer, 3DROV is executed on the FTRS On Board Computer (OBC).

3DROCS is the Graphical User Interface (GUI) that allows operators to perform the following tasks:

- To design long range traverse paths and format them into path files that are later sent to the rover.
- To monitor in real time the telemetry of the rover. This serves to visualise the evolution of the rover traverse as it is being performed, with information about RelLoc, Absolute Global Localisation (AGL) and Ground Truth.
- To decode the rover telemetry for assessment and analysis.

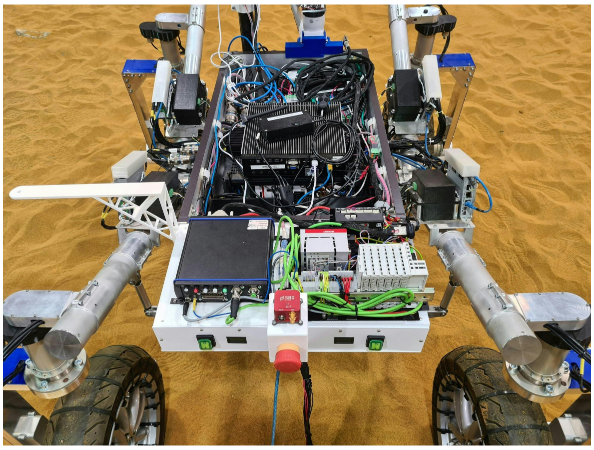

Figure 4. FTRS platform seen from the rear

While 3DROV is responsible for executing commands and activity plans issued by the operators through 3DROCS, commanding the execution of actions and supervising the completion of these actions.

The FTM software serves as an interface between 3DROV and the FTRS nodes, which are described in the next section. FTM executes the main functions of FTRS for both Traverse and Fetch operations and provides all the necessary functionalities to command and monitor rover operations. FTM can also be used through a user interface, bypassing 3DROCS.

3.1. ROS Network and nodes

The FTRS implements a distributed architecture with several processing nodes encompassing software execution on and off board the rover. The ROS2 middleware is used to provide the communication layer and functionalities that allow the software nodes to communicate with each other. In addition, rover data products are published on various ROS topics, which amongst them the GCS node subscribes to, displaying the 3DROCS GUI. In 3DROCS, the ROS actions are contained in a library divided into; FTM, MOB and RAS node functionalities, from which the operator can drag and drop any action to compose an activity plan.

MOB and RAS nodes are responsible for executing action level operations at subsystem level. These nodes can be directly commanded in activity plans. MOB nodes are used for executing commands, monitoring telemetry, algorithms and navigation mode logic.

4. MOBILITY SYSTEM

The IBB3 GNC solution is based on ExoMars GNC [6], SFR Unit BreadBoards (UBB), Delta GNC BB, IBB1, and IBB2 code base plus new developments. This code base is a combination of the functionalities of the various SFR UBB solutions and AGL capabilities. All of those modules have evolved following the changes in the SFR project baseline. Additionally, on top of this codebase, the CNES perception module was integrated, to produce a European autonomy solution known as A.C.AN (Airbus CNES Autonomous Navigation). Additionally, MOB includes the hardware interfaces to the locomotion subsystem and other GNC equipment and sensors. The use cases and requirements of IBB3 have resulted in the following stack of GNC functionality for the IBB3 field trials [5]:

The first set of functionalities listed below relate to the autonomous operation capabilities.

- Autonomous Navigation (AutoNav): This is the highest level of rover autonomy. The rover evaluates the terrain and thereafter plans and executes a safe and efficient path towards a given target point (e.g. this could be a waypoint or the final destination);
- Follow Path with Safety Assessment (FOPSA):This is an effort to increase traversing speed with a similar level of autonomy to AutoNav, but intended for benign terrains. The rover follows a global path constructed of way points while evaluating and checking terrain in a lightweight manner (with less perceptions and a longer driving distance between them) and avoiding simple obstacles when necessary;
- CheckPath (used in Human Directed Drive (HDD) and in depot operations): follows externally provided path checking its safety using navigation information.
- FollowPath: This provides the core path following functionality, for paths defined either by the operator or by the autonomous path planner.
- Absolute Localisation (AGL functions); This provides an onboard functionality to correct for the drift in VO pose estimation by correlating in-situ perception derived data products (Digital Elevation Map (DEM) and OrthoRectified Images (ORI)) against reference maps uploaded a priori, generated in mission from orbital imagery and / or from another rover (depending on where AGL is being used).
- Autonomous transition from FOPSA to AutoNav: if FOPSA is unable to find a path through the terrain (e.g. when the operator misjudges the complexity of the terrain);
- Navigation corridors: These provide constraints on where path planning may plan paths, and are explained in detail later.
- SSHE: An autonomous on-board function to update the absolute heading using a combination of sun imaging and gravity vector measurement. It is further explained later.
- Integration of RelLoc (including Visual Odometry), running in a closed-loop.

The second set of functionalities correspond to the lower layer which accepts a path sequence from any source (i.e. directly sent by operator via specific TCs or one produced by the autonomy navigation functionality). This part of the system provides FollowPath mode that is able to drive the rover following its input path. The key modules of this software layer are:

- Relative Localisation (RelLoc): gathers information from IMU, wheel odometry and visual odometry to estimate the relative localisation. In tests where the rover drove a 15-metre side square (i.e. 60 metres in total with 90 degrees turns) RelLoc showed a precision of 16 cm (0.26%).
- Absolute Localisation (AbsLoc): computes a rover roll and pitch measurement by averaging IMU acceleration when the rover is stationary.
- Trajectory Control (TrajCtrl): provides closed loop path following by adjusting rover-level commands to achieve the desired path.
- Locomotion Manoeuvre Control (LocoMan): converts the rover level control demands from TrajCtrl into axis (drive or steer) level control demands.

The Mobility Development Model Core executable (MdmCore) is the main application responsible for scheduling the rest of the system. It executes all

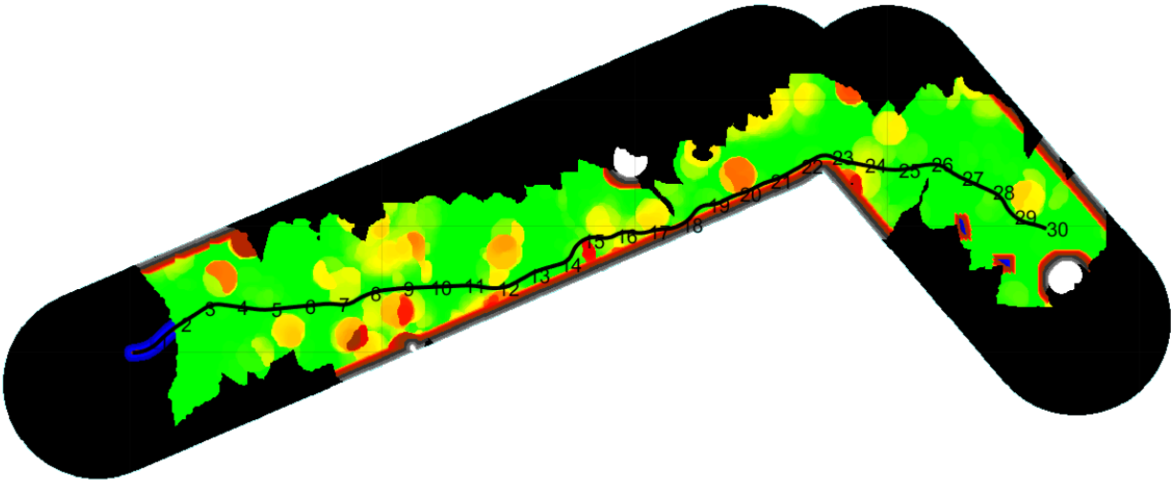

Figure 5. Navigation Corridor (area within the black contour) The white region defines the area set to non-allowed by the operator. Other colours within the black area are part of the navigation map (green are safe areas, orange-red are more costly areas, white are forbidden areas)

software managers provided by the GNC management module and controls all external interfaces. The GNC algorithms can also be tested and developed using the simulation environment, which shares a common code base with the MdmCore. In the flight system, the processing of the GNC architecture is split between the main processor for real time modules (like TrajCtrl) and the co-processor for autonomy processing. Previous campaigns have successfully performed Processor in the Loop (PIL) testing with the autonomy system running on a flight representative processor [7]. For increased speed of development and greater flexibility, the IBB3 trials are run without this PIL functionality. The integration of RelLoc showed a precision of 16 cm (0.26%) after driving a 15-metre side square, i.e. 60 metres in total, without use of AGL localisation.

A Navigation Corridor (see Fig. 5) is a stadium shaped area defined by a starting point, an end point, and a half-width. This area, set by the operator, prevents the rover from laterally drifting further than an operator-defined distance from the nominal path. In other words, the Nav Corridor ensures that the rover will not navigate outside of the area which the operator has assessed to be acceptable for the mission. It can be noted that the trajectory control has a similar functionality basis but at a smaller / more precise scale: it constrains the maximum drift of estimated position from the planned path. As a reminder, the path is either planned on board in autonomous navigation modes of operation, or defined by the operator when commanding the rover using lower levels of autonomy such as CheckPath.

With regards to SSHE, it is a GNC sub-functionality added for IBB3 allowing to generate a precise, absolute rover heading by measuring the local sun and gravity directions and comparing these measurements against the expected directions in the global frame. The SSHE performance was tested in the Airbus car park during shakedown tests. The assessment of the precision was achieved thanks to a GNSS heading reference. The rover heading computed by SSHE has been validated against averaged dual antenna GNSS data. Due to the nature of the algorithm the worst achievable precision is expected at the highest sun elevations (as the sun vector approaches being collinear with the gravity vector). Next to a series of measurements with different sun elevations, a worst case test was carried out in July with a sun elevation of just over 60 degrees, which is the highest possible elevation the sun can reach in the south of England. The heading error under these worst case conditions did not exceed 0.7 degree for any measurement.

Finally, the integration with RAS-BB has added a new user of some core GNC functionality, e.g. for acquiring images of the workspace using the NavCams. The core of the solution comprises the Processor In the Loop (PIL) closed loop test harness, interfacing with the hardware abstraction layer that communicates with the real rover hardware. This solution follows a flight-like architecture [7] where the GNC uses the main processor to manage interfacing and schedule execution, and utilises the co-processor for more intensive computations related to navigation stack.

5. RSTA ACQUISITION SYSTEM

The RSTA Acquisition System (RAS) [4], depicted in Fig. 6, consists of the hardware and software necessary to perform the detection and acquisition of the sample tubes. The Acquisition Management Software (AMS) is in charge of scheduling and managing all the commands and data products within the RAS subsystem (image acquisition from the cameras, arm poses, gripper open/close). The Vision Based Detection Software (VBDS) is in charge of the detection of the RSTA within images taken by the NavCam (showing the scene from a top-down perspective) and the wrist mounted RSTA Detection Camera (RDC). The RSTA Storage Assembly (RSA) is the physical storage where the RSTA has to be stored after being picked up. Finally, the Arm and Gripper Subsystem (AGS) is composed of the following elements: the robotic manipulator, the gripper, the RSTA Regrip Bracket (RRB), the RDC and the AGS Server.

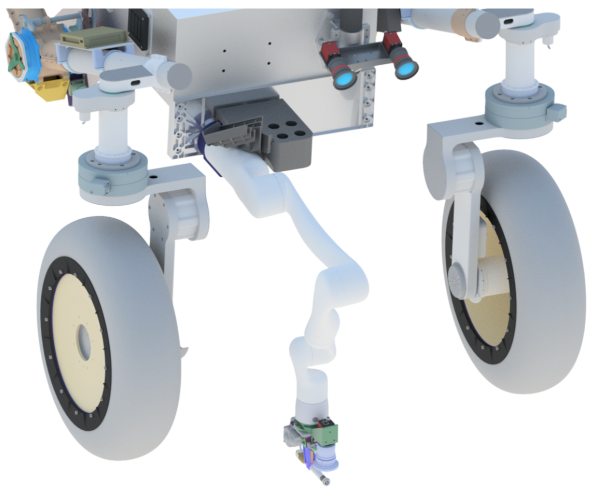

Figure 6. IBB3 design zoomed on the RAS: RSA slots are next to the attachment of the RAS, the RDC camera is in light blue attached to the wrist of the RAS, the gripper at the end of the arm with a RSTA tight in

All the presented functions and equipment of RAS are necessary to perform the end-to-end sequence from the identification of the RSTA on the ground to its safe storage onboard the rover. This sequence comprises a series of steps that start when the rover approaches a position close enough to the RSTA. These steps include:

- The identification of the RSTA in the scene in front of the rover.
- The planning of the gripper poses to grasp the RSTA.
- The deployment of the manipulator and its gripper to the RSTA and grasp it.
- The re-grip of the RSTA at the RSTA Re-grip Bracket to facilitate insertion into the storage location.
- The insertion of the RSTA into the RSTA Storage Assembly.

Integration of the RAS onto the FTRS platform proved to be challenging. The integration resulted in an increase of the mass and volume of the rover, which was already close to the allowable limit. To reduce mass, adaptations to the rest of the platform (e.g. in particular the reduction of the mass of the legs) had been done to compensate for the addition of the arm mass. In addition to mass, the FTRS introduced constraints to the workspace of the arm, limiting pickup capability. Moreover, the FTRS had to share the onboard resources (e.g. OBC, ROS network, onboard services, power, data sharing). Finally, having two subsystems, RAS and MOB, on the same platform halved the time available for each team to test and validate the system, which required a strong coordination within the wider IBB3 team.

6. DEVELOPMENT AND TEST ENVIRONMENT

Alongside the development of the different subsystems of IBB3, efforts have been made to establish a reliable development and test environment. It started with the creation of an integrated IBB3 team gathering the following disciplines:

- The Mobility team in charge of developing the GNC solution for the MOB system.
- The RAS team in charge of developing the robotic arm system.
- The Software team in charge of the overall integrated and embedded OBC and services, as well as the development of the FTM.
- The Operations team in charge of specifying the requirements for 3DROCS/3DROV software, and the elaboration of the test procedures.
- The Platform team, in charge of the physical evolution of the FTRS.
- The Management team, in charge of the organisation of the test campaign.

The first phase of development and testing was performed within the Airbus Mars Yard in Airbus Stevenage (see Fig. 7). The ceiling of this facility is tiled and provides a reliable ground truth usable to assess the quality of the relative and absolute localisation GNC solutions. To facilitate better collaboration, a mesh network was deployed in the Mars Yard, with the rover OBC part of that network. Thus allowing a very short reactive loop for the developer to update code on the FTRS. Within this project, modern development practices have been deployed, for example the Mobility algorithm developments were validated through a Continuous Integration chain.

Figure 7. Mars Yard Facility in Airbus Stevenage, UK

The GNSS subsystem, acting as the ground truth for IBB3, has also been updated. The IBB2 system used a dGNSS method to provide centimetre level (relative) accuracy between the base station and the rover by placing an EMLID Reach RS+ unit on each. This, combined with the onboard IMU/GNSS Antenna data from an SBG Ellipse-D, provided both heading and position information. For IBB3, the base station was upgraded to an EMLID Reach RS2+. This device is a multi-band GNSS receiver with Networked Transport of RTCM (Radio Technical Commission for Maritime Services) via Internet Protocol (NTRIP) corrections. As shown in Fig. 8, the Internet was provided by a Starlink receiver, which allowed testing with the rover in remote areas. The NTRIP corrections also allow for centimetre level (absolute) accuracy of the base station. The base station then transmits RTK corrections through a pair of RTK-specific radios (one at the base station and one on the rover) to the SBG unit to provide centimetre level (absolute) accuracy for the ground truth position. The heading is then calculated by fusing data from two GNSS antennae and an integrated IMU in the SBG unit, giving a heading truth with a precision of better than 1 degree, essential to assess the quality of the SSHE functionality.

7. INTEGRATED SERVICE FOR TESTING PLANETARY USE CASES

On the one hand, all the developments were focused to comply with the requirements of the ESA IBB3 project. On the other hand, each design solution was implemented to be as generic as possible, more importantly, sustainable and adaptable to different mission contexts.

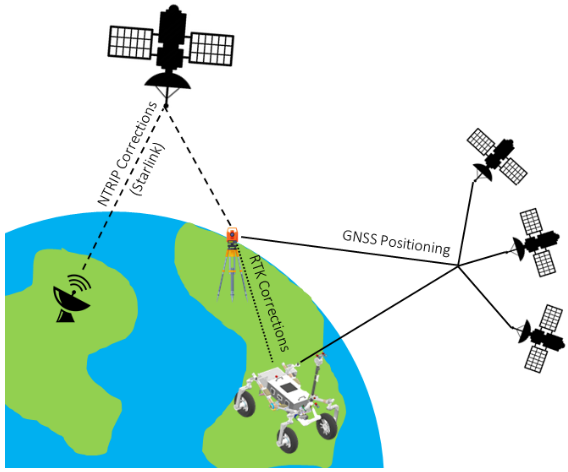

Figure 8. GNSS-RTK ground truth design

From the platform point of view, the FTRS offers a comprehensive rover system in terms of power supply, structure modularity (e.g. the adaptation of the FTRS platform to integration the RAS, the modification of the legs to reduce mass and adapt to new wheels) and safety considerations (multiple emergency stops). From the OBC point of view, considerable effort has been invested in separating the different subsystems libraries and source code (i.e. GNC algorithms, MdmCore, VBDS server, AGS servers, FTM software, cameras servers, locomotion server), thanks to a highly comprehensive Interface Control Document (ICD) defining the interfaces between all the components in the OBC. These parts were then integrated with the ROS network, delivering a modular architecture to exchange data between the subsystems.

The RAS has been designed and developed in full autonomy before integration on to the FTRS, allowing a high level of adaptability for other potential missions requiring manipulator activities.

Moreover, the development strategy was to opt for a strong agile approach (e.g. the teams performing two-week sprints to react as soon as possible in case of deviation or adjustment of priorities). The computational setup (Continuous Integrations (CI) chains for softwares, MdmCore, GNC algorithms) as well as the simulation environment offered a powerful testing environment to adapt quickly to different contexts and requirements of new developments.

Finally, as described in Section 6, the IBB3 project evolved in a comprehensive test environment, allowing an accurate assessment of the different functionalities of the rover, to which was added the operational layer brought by the use of the 3DROCS/3DROV software.

8. CONCLUSION AND OUTLOOK

The IBB3 project became a natural continuation of the rover breadboarding activities carried out by Airbus Defence and Space and agreed with ESA to develop an operational concept in the frame of the SFR mission. This continuation was made possible via not only inheriting the progress made in the previous iterations of IBB, but also thanks to the integration of multiple disciplines including software, robotic arm, mobility and operations. The decision to integrate all those disciplines, in addition to the agile development environment, delivered a highly dynamic team enabling the project to be highly reactive. The deliverable outputs being; a self-contained & modular FTRS rover, commandable through a high level user interface software; successful field trials which delivered many significant learnings about the end-to-end system capabilities and its behaviours; valuable experience in operating such a planetary robotics mission.

Organising such a multi-disciplinary project proved challenging but in turn allowed to achieve the fulfilment of its plethora of requirements. The extensive testing plan in the Mars Yard and car park environments throughout the course of the final months of the project was translated into the rapid development, refinement and validation of the many functionalities, getting the platform ready to successfully conduct the IBB3 field trials in September 2023 near Leighton Buzzard in the UK [5].

For future iterations of the presented system, planned improvements to the robustness are envisaged to deliver a test platform, field trials infrastructure & test-delivery team that can be offered as a service. The whole architecture proved a flexible and adaptive solution to autonomous traverse and mobile manipulation. Moreover, the workflow developed during the project, combined with Airbus' dedicated robotics and rover test facilities, provides a strong environment ideally suited for the testing of future robotics activities.

9. ACKNOWLEDGEMENT

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