Concept, Development and Testing of Mars Rover Prototypes for ESA Planetary Exploration

Martin Azkarate, Levin Gerdes, Tim Wiese, Martin Zwick, Marco Pagnamenta,
Javier Hidalgo-Carrió, Pantelis Poulakis and Carlos J. Pérez-del-Pulgar

***Abstract*—This paper presents the system architecture and design of two planetary rover laboratory prototypes developed at the European Space Agency (ESA). These research platforms have been developed to provide early prototypes for validation of designs and serve ESA's Automation & Robotics Lab infrastructure as testbeds for continuous research and testing. Both rovers have been built considering the constraints of Space Systems with the sufficient level of representativeness to allow rapid prototyping. They avoid strictly space-qualified components and designs that present a major cost burden and frequently lack the flexibility or modularity that the lab environment requires for its investigations. This design approach is followed for all the mechanical, electrical, and software aspects of the system. In this paper, two ExoMars mission-representative rovers, the ExoMars Testing Rover (ExoTeR) and the Martian Rover Testbed for Autonomy (MaRTA), are thoroughly described. The lessons learnt and experience gained while running several research activities and test campaigns are also presented. Finally, the paper aims to provide some insight on how to reduce the gap between lab R&D and flight implementation by anticipating system constraints when building and testing these platforms.**

I. INTRODUCTION

SPACE robotics can be considered a niche field of engineering in which the conditions given by the space environment present particular constraints to the research activities conducted in the area. Space representativeness is in constant duel with research in terms of cost and flexibility in the process of design, manufacturing and testing. This is mainly due to the technologies and development tools employed in Space that lack the mass production and community that other engineering fields benefit from. Space environment is harsh and remote, and therefore difficult to access. Restrictions come not only by the available technology and components for Space, which sometimes can be years behind their terrestrial counterparts, but even more drastically in the system mass and energy, which leads to the need for highly optimised and customised systems. One of the first questions engineers are faced with on a space mission is whether they are capable of designing a system that fulfils the mission requirements within the given mass and power budgets. Space missions are also what we call single-shot opportunities. One cannot repair, except for certain fixes by software patches, nor usually repeat a mission, which again puts stringent requirements on system robustness and design margins. All these aspects have eventually a high cost impact, limiting even more its access to a wider community. Aware of these limitations, the Automation & Robotics Section of ESA has embarked for years on activities for developing space robotics, and in particular planetary rovers, in the scope of conducting research & development of key technologies for real space missions such as ExoMars.

The first goal of this paper is to describe the main challenges and design drivers in the development of laboratory planetary rover prototypes. In this context, the paper highlights how MaRTA, the second generation prototype, benefited from the experience gained and lessons learnt on the design and testing of the early ExoTeR prototype. Secondly, by providing an overview of selected test campaigns, we demonstrate how these platforms supported the actual ExoMars flight rover development. Subsection I-A contains a brief literature research on existing rover platforms developed for R&D purposes. In section II we describe the system architecture and design of the two rover systems, divided in three subsections, one for each of the mechanical, electrical and software subsystems respectively. This section also refers to the main lessons learnt carried from ExoTeR into MaRTA's design. Afterwards, section III focuses on the testing experience describing several test campaigns performed that demonstrate the use cases of these platforms. The paper finishes with a conclusion section where future work is also addressed.

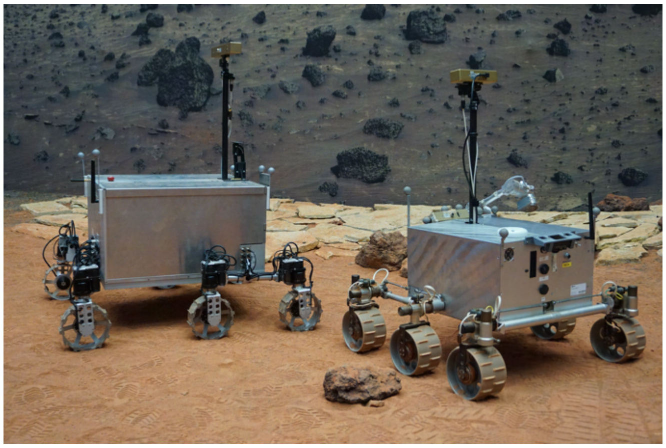

Fig. 1. ExoTeR (right) and MaRTA (left) chassis side by side. Note the parallelogram structure above bogies on ExoTeR that are not present in MaRTA.

M. Azkarate is with University of Malaga and HE Space for the European Space Agency, 2200 AG Noordwijk, The Netherlands. `martin.azkarate@esa.int`

A. Review of existing research rover platforms

In this section, we perform a literature review on existing rover platforms. We focus on those that served as testbeds or early mission prototypes and were used for the research and development of technologies for future missions. Without intending to be exhaustive, these are, to the authors' knowledge, the most relevant ones for our study.

NASA-JPL has led and is performing many successful planetary exploration missions with rovers. This is partially thanks to the development of rover prototypes and testing done on Earth, typically as part of their mission programmes. With the Mars Exploration Rovers (MER) Spirit and Opportunity first, and with the Mars Science Laboratory (MSL) Curiosity rover later on, the same Models Philosophy has ensured the provision of a rover testbed throughout the different phases of development of the mission. These were used to perform analysis of the traverse performance and predict their traversability throughout the mission [1], by mimicking on Earth their apparent flight rover weight on Mars. One to be highlighted is the Scarecrow rover, a vehicle that shares the kinematic configuration of Curiosity and uses commercial off-the-shelf electronics, which has provided for years much useful data for Curiosity's rover operations team [2]. In addition, NASA-JPL continues working on the development of new rover prototypes and platform configurations. Some highlights among these are: the Scarab rover for Lunar exploration [3], the DuAxel rover [4] for exploration in very rough terrain including rappelling motion or the latest developments in the Barefoot Rover [5] instrumented wheel, which focuses on the research of wheel-soil interaction.

The recently baptised Rosalind Franklin rover of the ExoMars mission is the first European rover aiming to land on the red planet. Since its early conception, ESA has been working on the development of breadboard prototypes to analyse different locomotion subsystems and their performance on Mars-like terrain [6], [7]. Later on, in cooperation with European industrial partners, different breadboard rovers were assembled with engineering models of the electronics, software, and locomotion subsystems [8]. In addition to the ExoMars project breadboards, national space agencies around Europe have developed their own testbed rovers for research purposes. It is worth mentioning the Lightweight Rover Unit (LRU) [9] developed by the German Aerospace Centre (DLR), an agile rover prototype used to develop several software components for autonomy. The United Kingdom Space Agency (UKSA) developed the Mars Utah Rover Field Investigation (MURFI) [10], that was used to perform several field tests in collaboration with the Canadian Space Agency (CSA). The French Space Agency (CNES) also developed the testbed rovers IARES (Illustrateur Autonome de Robotique mobile pour l'Exploration Spatiale) and ARTEMIS (Autonomous Rover and Testbench for Exploration MISsions) which were used for years for the development of the Guidance, Navigation and Control (GNC) software that will eventually drive the Rosalind Franklin rover [11]. The German Research Center for Artificial Intelligence (DFKI), developed the SherpaTT [12], a planetary rover testbed equipped with four articulated legs, that participated in international projects conducting field tests in Utah and Morocco among others [13]. Finally, the Lunar Volatiles Mobile Instrument (LUVMI) rover [14] was developed in the framework of the European H2020 project with the same name with the aim to develop a sampling system, capable of extracting volatiles from the moon.

In Asia, two testbed rovers developed by JAXA are worth mentioning: Micro6 and Cuatro [15], both conceived to push the Technology Readiness Level (TRL) of failure tolerant suspension systems and an intelligent navigation system based on novel path planning methods. In China, the few contributions found in the literature refer to a testbed rover developed by the Harbin Institute of Technology. This was used to test a modified active rocker-bogie suspension that demonstrated improvements on tractive performance [16].

II. SYSTEM ARCHITECTURE

In this section, we describe the system architecture and subsystem designs of the two ExoMars-representative laboratory rover prototypes of ESA's Automation & Robotics Section: ExoTeR and MaRTA. The ExoTeR rover concept was designed between 2008 and 2010 whereas MaRTA was developed from 2017 to 2019. While both are conceived as scaled-down models of the ExoMars Rover, ExoTeR is based on an early concept design of ExoMars while MaRTA is more accurate in mimicking its current configuration. ExoTeR has already been extensively used in several test campaigns, while MaRTA is still undergoing software developments and hardware integration to make it ready for testing. This section intends to describe both systems and in particular to highlight the differences in design drivers and choices made, based on the experience gained from testing ExoTeR. This section is divided into three subsections one per main engineering domain of the robotic systems: the mechanical, electrical, and software designs.

A. Mechanical Design

In this section, we describe the mechanical design of the rovers, and in particular, we focus on three of its subsystems: the locomotion, the manipulation, and the mast & pan-tilt unit. It is worth noting that we do not describe other mechanical parts of the rover typically present in space systems, such as the main body structure or Service Module as named in ExoMars, nor the solar array structure and deployment systems. Our lab rover systems are built to only address the pure robotic subsystems of a rover, i.e., the locomotion, manipulation and navigation, without considering other spacecraft subsystems such as power generation and thermal control nor design aspects such as launch loads or radiation tolerance.

1) Locomotion Subsystem: The kinematic chain design on which both ExoTeR and MaRTA rovers' locomotion is based is known as the Triple Bogie. This is the actuation and passive suspension system chosen for the ExoMars Rover's Bogie Electro-Mechanical Actuator (BEMA). Its final design is actually the outcome of a series of prototyping developments that started in the early 2000s at ESA. The Triple Bogie system

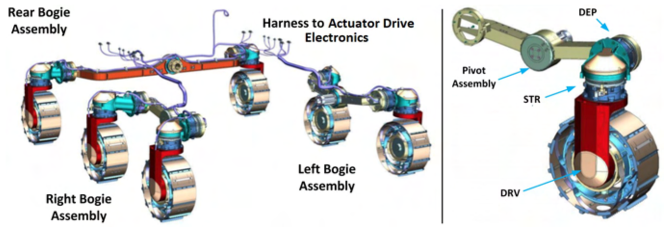

Fig. 2. The BEMA Triple Bogie configuration and right bogie beam with actuator locations [19].

had interesting evolutions in design that iterated over a trade-off between mass, complexity, and traversability performance [17], [18]. Several of these prototypes were built and tested at the Automation & Robotics Section.

The ExoMars final BEMA [19] comprises three independent bogies, connected to the main body structure at the front-left, front-right, and at the rear. In contrast to the Rocker Bogie solution seen in all NASA rover missions to Mars, the Triple Bogie provides platform stability through its three points of attachment without the need for a differential bar across the body structure. The three attachment interfaces allow for passive rotation around the axes perpendicular to the body structure planes at those points. Each bogie extends two horizontal levers, and at their ends the wheel modules are connected. Each module consists of the following three actuators (in the order of the kinematic chain): the deployment (DEP), the steering (STR), and the wheel drives (DRV). Typically this locomotion system is referred to as a 6×6×6+6 formula, as it contains a total of six wheels out of which all are driven and all are steerable, and additionally, each of them has a deployment actuator that permits the system to be stowed. This is achieved by putting the wheels upwards to optimise for volume accommodation, particularly during the launch and cruise phases. Deployment actuators can be further exploited during the surface mission, permitting the implementation of a locomotion mode referred to as Wheel Walking (see subsection III-A for more details on this mode). Figure 2 shows the ExoMars BEMA system where kinematic chain details are reflected.

The locomotion systems of ExoTeR and MaRTA were built as half-scaled versions that mimicked the ExoMars design each at their current times. As such, MaRTA's configuration is equal to the final one adopted for ExoMars' BEMA, while ExoTeR corresponds to an earlier version of the Triple Bogie prototypes. The main difference with the current BEMA design is found at the parallelogram structure that ExoTeR presents at the bogies kinematic chain with passive linkages. This constrains the wheel motion to a straight line translation, perpendicular to the rover chassis plane, when the bogies rotate. Despite its slightly superior tractive performances, the bogie parallelogram was eventually removed from the ExoMars BEMA design to increase the static stability limits of the rover and at the same time reduce even further the mass and complexity of the suspension system. Additionally, ExoTeR has only 4 wheel steering capability, instead of the 6 wheel steering of the latest BEMA design, which brings the crab motion capability that is relevant for some approach manoeuvres during scientific tasks. These two changes, together with some adaptations to the bogie lever dimensions to accommodate the wheels in the stowed position, resulted to the final ExoMars Triple Bogie design that MaRTA features in scale. In Figure 1, both rovers are shown side by side.

The realisation of these platform designs was accomplished by an analysis of the required forces and torques to be exerted by the rover locomotion system at any possible configuration which leads to the selection of components for the motor drive units. In the case of ExoTeR, this resulted in DC electric Maxon brushed motor drives, assembled with an incremental encoder at the motor back and a gearbox at the output shaft. This is followed by a harmonic drive stage to further reduce the nominal speed and increase the torque capability of the system, and in the case of steering and deployment joints an additional potentiometer at the output end for absolute position sensing. Similar potentiometer sensors are installed at the three passive bogie joints attached to the base platform. ExoTeR's platform system mass is $14\,\mathrm{kg}$ with a target payload capacity of approximately $8\,\mathrm{kg}$ to embark all avionics including the battery, actuation control electronics and sensors.

When MaRTA was designed, a few modifications were introduced with respect to ExoTeR based on the experience gained conducting several research activities. Motor drive components were upgraded to increase the speed and torque capabilities of the locomotion system, and therefore enlarge the payload capacity of the platform. From the $22\,\mathrm{kg}$ of ExoTeR's system mass, the total mass budget was increased to $32\,\mathrm{kg}$ in MaRTA. In terms of components, brushless motors were selected for MaRTA and absolute position sensors were upgraded from the original wire-wound potentiometers (SP5-21A) to optical sensors (LIR-DA219A) with 12-bit resolution. Each motor unit in MaRTA has integrated a temperature sensor in its housing, which is used for thermal monitoring and Fault Detection, Isolation, and Recovery (FDIR) functions that prevent the motors from overheating and potentially damaging the windings. A more modular design approach was taken in MaRTA, enabling each drive module to be removed and maintained individually if needed. This includes the motor drive harness which is externally routed and has a connector to an interface plate at the rover body. Additionally, the steering and deployment actuators are identical and interchangeable. The steering operational range is increased to ±95° (compared to the ±70° of ExoTeR), which together with steering units added to the middle wheels enables full crabbing motion as in the ExoMars BEMA. The MaRTA wheels were designed proportionally slimmer to match the Effective Ground Pressure of the ExoMars Rover flight system on Mars, for the sake of traction performance representativeness. Finally, each of MaRTA's wheel modules is equipped with a force-torque sensor that provides data for future research activities, such as performance characterisation of different locomotion modes or the development of traction control algorithms.

2) Manipulator Subsystem: Although the ExoMars mission does not embark a manipulator system, it was decided that developing a robotic arm fitting the rover constraints would allow for performing relevant research in the field of robotic

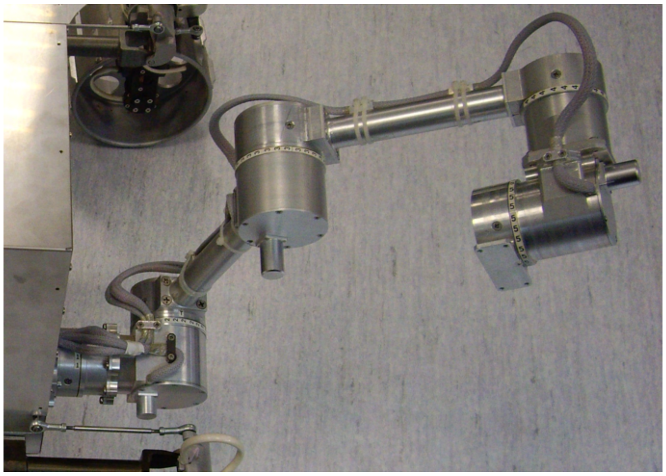

Fig. 3. Photo of ExoTeR manipulator attached to the front body wall.

manipulation for future planetary exploration. This scenario has become has become relevant with the upcoming joint NASA-ESA Mars Sample Return campaign where ESA will be developing the Sample Fetch Rover. The manipulator system in Figure 3 was developed to be integrated into ExoTeR. It has five degrees of freedom, 528 mm of operational reach and a total mass of 2.4 kg with a payload capacity of 2.0 kg. Its development follows the same design drivers as the locomotion system. Low mass and power budgets (around 10 W of nominal operation) with a high payload to mass ratio which implies high reduction ratios to provide enough torque at the expense of speed. The motor drive design comprises a small brushed motor, several reduction stages of planetary gear, a custom spur gear and harmonic drive, with an incremental encoder at the motor end, and an absolute position sensor at the output shaft, i.e., a wire-wound type of potentiometer (SP5-21A). The high reduction ratio of the joints (83200:1) and stiffness of its parts, makes the arm practically non-backdriveable, eliminating the need for any motor brakes to hold position when powered off, but also significantly slow (0.5 °/s), following the approach of a potential space operation.

In 2020 it was decided to develop a new robotic arm to be integrated in the MaRTA rover and would take into consideration the lessons learnt from ExoTeR's arm. The new design targets 6 DoF, allowing full unconstrained operation in 3D space, and a joint rotational speed of 8 °/s. A more compact joint design is targeted with a flat motor, fewer reduction stages and no spur gear resulting in a cylinder-shaped block design. A total mass budget of 3.0 kg with 0.5 kg of payload capacity and an operational reach of 700 mm. The power budget is also increased to approximately 20 W in nominal operation. According to load analysis, motor brakes will not be needed to hold position of joints when these are powered off. A mechanical bracket interface is being designed where the arm can rest while parked in stowed position. An upgrade in the sensors is also foreseen with absolute position contactless electric encoders replacing the much less reliable and less accurate potentiometer sensors. All in all, it is expected to have this robotic arm integrated in MaRTA by end of 2021 and be of relevant use for the lab in the research activities of autonomous fetching of sample tubes.

3) Mast & Pan-Tilt Unit: The Mast & Pan-Tilt Unit (PTU) is an element present in many (if not all) planetary rover systems. The perspective view provided by sensors mounted at the top of it is not only valued by scientist, but also sometimes necessary for accomplishing mission or engineering objectives. For the case of our lab rover prototypes it became necessary to integrate such a system and mount camera sensors that allowed us to conduct research in the area of autonomous navigation. In 2014, we developed and integrated a lightweight mast and PTU system in ExoTeR. The total system mass is below 0.4 kg while the maximum payload capacity is 0.8 kg. The two motor drive units have almost identical design for both axes with a linear assembly of motor, gearbox, harmonic drive, and conductive plastic potentiometer sensor (PL130). The operational range of the PTU is 300° of rotation in pan axis and 180° in the tilt. See Figure 4 for an overview of the PTU design elements.

Two identical PTU sets were built and delivered that could be mounted at two different height adjustments (mast lengths), which conveniently allowed us to integrate a set in MaRTA as soon as the rover platform was delivered, thanks to both rover having the same mechanical interface. This subsystem has enabled significant R&D activities in the area of perception, localisation, and navigation. The system is fast and easily backdrivable. Care must be taken so the tilt motor does not "fall down" when powered off, especially if more than one sensor is mounted on its top, which also offsets the COM of the PTU payload further away than what it was designed for. This lead to a frequent miscalibration of the axis. In 2019, we decided to produce an upgraded version of this subsystem with a higher payload capacity and a stiffer and more robust design. Apart from the more capable motor and gears assembly, we also opted to upgrade the absolute position sensor, using an optical 12-bit sensor (LIR-DA219A), which provides a higher positioning accuracy than 0.1°. The new system has doubled its mass, but also its payload capacity, and has increased its

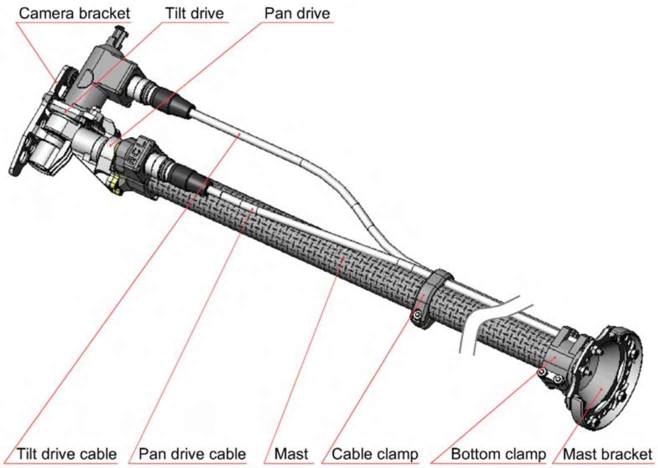

Fig. 4. Schematic rendered view of the PTU design.

motion range allowing a full 360° rotation in the pan axis and 180° in the tilt. This permits pointing the cameras in any direction around the rover.

B. *Electrical Design*

This section describes the electrical design of the rover, and focuses on the main elements of the rover avionics, such as, motion control, power conditioning and distribution electronics, Onboard Computer (OBC), and the sensor suite integration. It is worth noting that we do not select space-grade electronics or components. Our design does neither include radiation-hardened avionics nor components that are tested under the harsh space environment conditions of temperature, vacuum and launch vibrations. We usually select Commercial Off-the-Shelf (COTS) components for embedded systems and add specific custom Printed Circuit Board (PCB) designs for the final accommodation and integration of those. This gives us a good balance between cost of manufacturing, design flexibility, and system engineering budgets. Further details on this process are given in the subsections below.

1) Motion Control Electronics (MCE): As seen in the previous section, all the mechanical subsystem elements can add up to more than twenty active joints. Considering the high amount of motors to control for locomotion, manipulation and PTU commanding, it was soon understood that a centralised approach would be hardly feasible from the I/O signalling and harness considerations point of view. Instead, a better approach is to delegate the whole joint control task to dedicated micro-controllers, i.e., servo drives, which can all then be "daisy-chained" to the main OBC through a single bus line. Therefore, the motion control electronics follow a distributed (non-centralised) design approach with a network of motion control drives connected through a Fieldbus. Besides, this is in line with the design of ExoMars. In such an approach, the OBC is only in charge of defining and sending the command signals for all the servo drives. These are thus responsible for translating these commands into actual power provided to each motor and control the flow of current to achieve the commanded set point. As for the Fieldbus protocol, several options exist from the classics Modbus, Profibus or CAN to the more recent ones based on Real-Time Ethernet. We decided to follow the choice made for ExoMars, i.e. CAN, which is a widely used protocol for motion control applications and that offered us the required features in terms of communication bit rate or number of slaves. Regarding the joint micro-controllers, several manufacturers exists in the market. Even the Maxon motor supplier that we have opted for in our mechanical design offers their own motor control drives (Maxon EPOS). After a market study, we concluded that the servo drives by Elmo Motion Control provide a compact and power dense choice for embedded applications, both with brushed or brushless motors, with a wide-range of control and feedback options that fit our design approach.

For ExoTeR, we chose the Elmo Whistle SimplIQ line of drives that implement the CANOpen Application Standard. In particular they fulfil the DS301 communication specification and the DS402 motor drive specification, which are standards defined by the CAN in Automation Organisation. Each Elmo Whistle, similar to a matchbox in size, can control a motor with a bus voltage range of 12 to 60 Volts and a maximum current of 1 to 20 Amperes. Motor feedback control can be achieved via incremental or absolute encoders, Halls-effect sensors, resolvers or potentiometers with specific feedback ports or generic I/O digital and analogue inputs. The Whistles can be PCB-mounted to facilitate access to all pin-outs. All these features allow us to control the full range of active joints present in our platforms. In ExoTeR, a total of 23 drives had to be mounted: 16 for locomotion, 2 for the pan-tilt unit, and 5 for the manipulator. A custom PCB was designed and manufactured that could hold up to four Elmo Whistles. Several samples of this PCB were printed to integrate the avionics for locomotion and PTU control. Additionally, a dedicated PCB for the manipulator with a capacity to host 5 Whistles was manufactured. The split of the MCE in PCBs and modules aimed at modulatity (such as being able to connect/disconnect the arm) and maintainability (swap out MCE cards easily in case of failures). The resulting accommodation of the avionics architecture including the Motion Control Electronics (MCE) is shown in Figure 5.

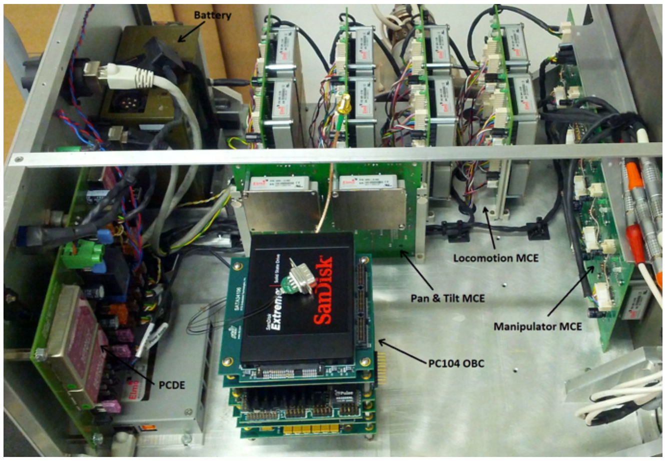

Fig. 5. Photo of ExoTeR's avionics integrated in the rover body chassis

For MaRTA, we decided to upgrade the motor drives and opted for the Gold line of Elmo. In particular, we chose the Twitter family of drives, which was the latest product released by Elmo in 2018. This choice meant an even smaller footprint, more efficient and power-dense drives, reduced Electromagnetic Interference (EMI), and a faster communication protocol based on EtherCAT. The experience with ExoTeR showed that certain control tasks could reach the CANBus maximum bit rate of $1\,\mathrm{Mbit/s}$ and required a higher bandwidth to perform. Hence, the need for faster control of the rover platform joints pushed our MaRTA design to move to this newer communication standard, which has a maximum bit rate of $100\,\mathrm{Mbit/s}$. In addition, the force-torque sensors installed in each of the wheel modules of MaRTA provide an interface to EtherCAT as well and can be therefore connected to the main OBC through the same EtherCAT bus. The Elmo Gold Twitter also implements the CANOpen over EtherCAT application standard and provide the same flexibility of IO and feedback control options as the Whistles in ExoTeR. All these synergies were positively considered for MaRTA's system integration.

2) Power Conditioning and Distribution Electronics (PCDE): As the name suggests, the Power Conditioning and Distribution Electronics (PCDE) shall distribute the power coming from a source and this needs to be conditioned prior to reaching the different avionics components. The design of this subsystem starts with a system power budget analysis that allows us to dimension the system and identify the different levels of voltage and current needed. During this step, it is important to identify the normal operational power usage of the various components as well as their maximum input power ratings. This also permits to size first the power source, i.e., the battery capacity and discharge parameters, and finally select a proper battery that will allow for sufficient time of continuous operation. The PCDE can also run the system from a standard laboratory power supply and implements other functionalities, such as current measurements, and input power selection.

The first function of the PCDE is therefore to decide which input source to use, battery or external power supply. A diode placed in series with each power source implements this function. When both sources are connected, only the one with the highest voltage delivers current to the rover. This also provides the option to hot-swap a battery by connecting an external power supply while interchanging batteries, since the system is kept powered externally during this operation. The next stage is to convert and regulate the input power into the different voltage lines needed by the system avionics, typically ranging between $24\,\mathrm{V}$, $12\,\mathrm{V}$, $5\,\mathrm{V}$ and $3.3\,\mathrm{V}$. We selected TRACO Power DC/DC converters for the different stages because they are efficient and reliable components that we are familiar with. They can be PCB mounted and also provide galvanic insulation between primary and secondary lines. The current deliverable by each DC/DC is sized according to the power budget and the output is further protected with fuses.

In the case of ExoTeR, the PCDE is a rather simple design with little intelligence on-board and limited to the functions just described. In MaRTA, we decided to add a microcontroller within the PCDE board to control certain additional functionalities and provide more useful data. The battery status is displayed on an LCD screen at the back of the rover. Similarly, the consumption of several power lines is monitored, including the total power currently running the rover. The current measurements of the PCDE can be helpful to find potential issues and degradation in the electronics. A coloured LED alerts the operator when the battery is low and needs to be replaced. An emergency stop function is also implemented within the PCDE that can accept emergency signals coming from three sources: a physical push button at the deck of the rover, a similar remote emergency switch that communicates with the rover PCDE through a radio link, or a specific telecommand message sent from the rover OBC to the PCDE. Regardless of the source, an incoming emergency signal effects cutting the power to all motors in the platform and stopping any active motion, yet the rest of avionics and the logic power to the MCE is maintained in order to allow for potential recovery actions and proceed with any test execution.

3) OBC and Sensor Integration: Here we address the topic of integrating the elements that are most relevant to our actual robotics field. These are the OBC and the sensors used by rover that are the source of data needed for implementing many important functionalities. Sensors can be classified as proprioceptive or exteroceptive, depending on whether they provide information about the inner-self or the outer environment respectively. Relevant examples of the first type would be accelerometers, gyroscopes or full 3-axes IMUs. Also worth mentioning within this group are the motor encoders and other sensors that belong to the control of the mobility system and that have been properly addressed in subsection II-A. A proprioceptive sensor present in all our lab rover prototypes is the Sensonor STIM-300 IMU, a small footprint sensor with 3-axes gyros and accelerometers that uses MEMS technology to provide 3D orientation data. Other sensors we have opted to mount on MaRTA are: the Level Developments SOLAR Dual-axis inclinometer or the KVH DSP1760 Fiber Optic Gyroscope.

As for the exteroceptive sensors, the most widely used ones would be cameras, and within this type certainly the optical sensor cameras (RGB or monochrome) are the most relevant ones, due to their low cost, miniature size, ease of integration and heritage, and also in terms of algorithms available for image data processing. Two camera sensors can be combined to compose a stereo camera rig that once properly calibrated can additionally provide depth information. Depth data is essential for any navigation application since it forms the basis for two key functionalities, localisation and mapping. The relevance of stereo cameras is highlighted in space robotics applications, given the existence of space-grade sensors of this kind. This is why both ExoTeR and MaRTA are equipped with several stereo cameras (FLIR Bumblebee BB2 and XB3), typically one dedicated to localisation mounted at the rover body rim pointing downwards and close to the ground, and another one for mapping and navigation mounted on top of a mast with pan-tilt pointing capability from a higher perspective viewpoint. Within the exteroceptive group, we could also mention the Depth cameras (RGB-D cameras), Time-of-Flight (ToF) cameras and laser sensors or LiDARs. While we have available in our lab a few of the popular models of this kind, such as the Intel Realsense Depth camera, MESA SR 4000/4500 ToF camera or Velodyne LiDAR, we do try to limit their use in our applications and research activities, due to the lack of existing space qualified sensors of this type. Finally, RaDAR sensors, that are very popular within the automotive industry and the increasing market of self-driving cars, are rarely seen on space robotics applications due to the slow dynamics and speeds of the rover system and RaDAR are best known for providing accurate relative speed information of nearby moving targets.

While we try to be representative in the type of sensors we use, it is important to note that we do not use space-grade or qualified components in this regards, which would make our research non-affordable. Similarly, when it comes to choosing the OBC, we opt for embedded computers used in a wide range of robotics applications that potentially embark powerful processors and the latest technologies in computing architecture. The first computer in ExoTeR was selected from the PC104 form factor, due to their flexibility and modularity, being able to customise the computer stack and interface ports by selecting and adding specific layers, such as FireWire, CAN Bus or WiFi modules. However, the stack soon became quite bulky, similar to a 2U cubesat in dimensions and the availability of processors was limited to slightly old and low power units. Therefore, at the point of selecting the OBC for MaRTA we decided to unify and upgrade the OBCs in both rovers with embedded systems from the Pico-ITX form factor. At the moment both rovers have almost identical OBCs, which is obviously a convenience, embarking relatively new and powerful Intel processors within a 64 bit x86 system architecture with several GBs of RAM and plenty of fast accessing Solid-State-Drive storage.

Communications between processing modules in space is typically done through point-to-point SpaceWire interface links. And wireless communications use UHF antennas and implement protocols for satellite communications. In our case, these are replaced by Ethernet and WiFi standard communications for convenience of use in lab environment.

4) HMI, Thermal, and EMI Considerations: The electrical design of the rover cannot be completed without taking into consideration other aspects at system level. One important consideration is related to grounding and harness routing in order to minimise the EMI as much as possible. Twisting power lines and separating them from data sensitive lines or using common ground planes and short current return path that avoid current loops are recommended practices. Encapsulating noisy components and properly shielding cables at both ends is also important, especially when high frequency radio signals are present and mixed such as GPS, WiFi or other radio links. Many lessons learnt were taken out of the experience gained from ExoTeR, when during tests it suffered drops in the communication link or sudden blackouts of detected GNSS satellites. We discovered that FireWire cables tend to badly interfere with the GNSS signal and in order to avoid building a separate dedicated mast for the GPS antenna, in MaRTA we have opted to use Ethernet cameras (GigE), instead of inheriting the FLIR Bumblebee stereo cameras mounted on ExoTeR. We also took the aforementioned EMI suppression design practices thoroughly into account when designing the PCDE of MaRTA and integrating the rest of the avionics components, e.g. the rover chassis was used a common ground plane.

Another important aspect consists of the operational thermal limits of the devices, in particular the high temperatures reached by the power-dense motion control electronics. In MaRTA, MCE are mounted against the front and rear metallic walls of the rover (side and top walls are removable covers), essentially turning them to heat sink radiators. Additionally, both ExoTeR and MaRTA feature small fans that provide cooling by flowing external cold air to the warm components inside and extracting warm air towards the outside.

A final consideration is given to the Human-Machine Interface (HMI) and the accessibility and maintainability of components. For example, providing external access to internal ports such as Ethernet, USB or graphics, or easing the access to the other avionics ports and cables to debug or replace efficiently, especially for time-constrained operational conditions. Similarly, enclosures are optimised for easy removal to access internal components and later readjustment without the need for any tools.

C. Software Design

The already mentioned balance towards space representativeness in our system architecture is similarly applied to the software design. ExoTeR and MaRTA are lab rover prototypes allowing for quick iteration and demonstration of technologies where space qualification cannot and does not have to be achieved. Consequently, the focus of our software developments is on the algorithms and not so much on the optimisation and qualification aspects of the software engineering that would be needed to run in space hardware. And while we keep ourselves aware of the computational complexity of developed algorithms we do not invest in system integration optimisations. Further details on this are given in the sections below where the selection of the running OS and the use of well-known robotic frameworks is discussed. These considerations support a modular approach to the developments conducted by our research lab that includes many short stay members. Finally, we elaborate on some activities that ESA has conducted to reduce the gap between lab developments and flight software implementations.

1) Operating System: For years now, the OS in use in all our lab rover platforms is Ubuntu, a free and open-source operating system. This popular Linux distribution based on Debian is continuously improved and maintained by the open-source community, offering a bi-yearly Long Term Support (LTS) release with Standard Support guaranteed for at least five years. The main reason for this selection is the stability of the system and the vast adoption of this Linux distribution around the world. Any newcomer to our lab group has certainly had some previous Ubuntu experience. Similarly, many of the developments done in research labs and institutes in the world are carried out on Ubuntu and software libraries are often released with step-by-step installation instructions for Ubuntu systems. This is also the case for the Robotics Frameworks that we discuss in the coming section.

The main drawback with Ubuntu is the lack of real-time applications support. Indeed, the Ubuntu vanilla kernel does not guarantee the real-time execution of a given application, as it is based on a best-effort approach. Consequently, Ubuntu could decide to delay an execution if another higher priority task needs attention. If real-time execution is a concern on a developed application, Ubuntu will not satisfy the needs. The standard Linux kernel of Ubuntu releases does not provide the preemption capabilities that a developer would need to alter the scheduling rules of processes to guarantee its real-time execution. Whereas real-time could potentially improve the rover control based on kinematic and dynamic computations, the generally slow dynamics of our system make this feature less noticeable in reality and therefore we usually do not impose hard real-time requirements on our lab rover developments. Eventually, the gap for the lacking feature could be overcome for example with the installation of the PREEMPT_RT kernel patch or of Xenomai, a real-time development framework cooperating with the Linux kernel and which has been continuously supported on Ubuntu LTS releases.

An alternative and space representative option would be RTEMS, a real-time operating system used in most ESA missions nowadays [20]. However, this would hinder many developments of our fast-paced research activities by introducing issues with system configurations and hidden dependencies. Additionally, it would prevent us from using any of the general-purpose open-source robotics frameworks available to the community which play an integral part in all our applications' software development approach.

2) Use of Robotics Frameworks: Robotics frameworks have become increasingly popular in the last two decades with the Robot Operating System (ROS) becoming a default framework in almost every robotics lab. There are a handful of robotics frameworks available, most of them providing useful tools for data visualisation, logging and debugging along with a plethora of implemented software packages that range from low-level drivers to full robot navigation solutions. Yet, the most important aspect that these frameworks brought, is the change in paradigm with respect to developing applications. As it is explained hereafter, these made applications inherently highly modular.

Originally, these frameworks were developed for providing a communication middleware between independent components. The middleware is a common language, with standard defined interfaces that any *component* can use to talk to another. A component defines interfaces to communicate and receive data and fulfil a specific task or function that it is meant for. A developer can focus on a library to implement a specific function and easily embed this within the framework to transmit or receive data. The modularity of this development approach is inherently implied, allowing the ease of replacement or switching between components with the same interface and to have a standardised way of component configuration. Additionally, the deployment of a modular system can be such that a crashed component does not bring down the entire system and FDIR can be more efficient.

When our time to make a decision on which framework to use arrived (early 2010s), the shortlisted finalists were ROS, RoCK, and GenoM. Eventually, the RoCK framework developed by DFKI ranked at the top due to the more formal and structured approach in software engineering. Based on ORoCoS Real-Time Toolkit (RTT), RoCK includes real-time logging capabilities, modular deployment and component introspection and a state machine implemented at component level that allows for the control of its life-cycle. Despite the larger ROS community, the fact of having a direct line of contact with the RoCK developers at DFKI turned out to be a significant advantage. During these years, we have also used ROS for some developments and testing, but the core software stack of our lab rovers is developed in the RoCK framework. In the last year, we have started migrating some components to ROS2 and are currently considering a full migration to the second generation of the popular framework.

Without detailing the entirety of our software architecture stack, Figure 6 shows a setup of some components that has been of interest for some project support activities and test campaigns that are detailed later on in section III. This configuration was used for the assessment of operational aspects, mainly utilising, switching between, and potentially blending various operation modes. From left to right the figure visualises the remote interfaces for human interaction down to the drivers to access the different hardware elements. 3DROCS represents the rover Monitoring and Control Station (MCS), which is the base development from which the flight MCS for the ExoMars mission has been derived [21]. The TM/TC component running onboard the rover takes care of implementing the communication protocol with 3DROCS by translating and passing the telecommands further down to the lower level components and by gathering all relevant data from different sources to generate the telemetry packets. The operators can also use a joystick to control the rover and an arbiter makes sure that the mutually exclusive access by either of the components is guaranteed to avoid conflicts. The rover can be controlled by direct body level motion commands or using higher-level navigation functions following waypoints. The perception chain models the environment and increases the awareness of the rover surroundings both onboard and at the remote station by forwarding the generated maps. The localisation estimate is computed by the odometry component that fuses the data from different sensors. Further details about the implementation and theoretical principles behind several of the components shown in Figure 6 can be found in the references given throughout the subsections of section III.

3) Bridging the Gap to Space: As already stated in this section's introduction, we do not seek space qualification nor is our objective to produce or develop flight software. The operating system and robotics framework on our lab rovers facilitate fast developments and functional algorithmic demonstrations and this creates a gap for a potential path-to-flight. That is where the Reliability, Availability, Maintainability and Safety (RAMS) requirements applied to the software development and testing become relevant.

ESA has developments where RAMS requirements for software development are taken into consideration at their foundations. The most relevant reference in this regard is the TASTE[1] framework. In constant development for over a decade, TASTE is a development environment composed of a set of tools where software components can be developed and automatically deployed in specific target platforms which include space-grade boards and OS. It provides a graphical and textual development environment for the definition and implementation of functions and interfaces and an automated process for the generation of glue code to run them on the selected target system. It also facilitates the validation and verification of software by analytical and statistical tools.

The development of TASTE started with the aim to build functional blocks for satellite missions. However, the approach to robotics, and particularly for the planetary exploration missions, is quite different to the orbital counterparts, and

---

[1] TASTE: https://taste.tools/

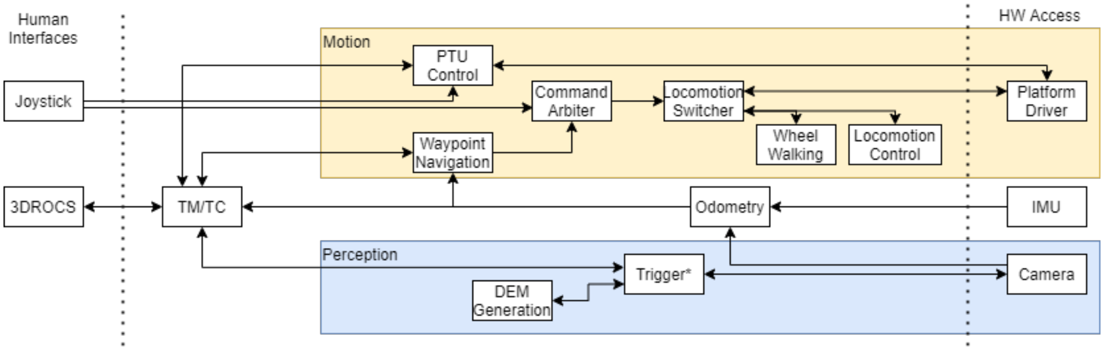

Fig. 6. Simplified overview over ExoTeR's principal telemetry/telecommand components.

TASTE lacked the tools to address this at its origins. In 2016, an ESA activity named Space Automation & Robotics General cONtroller (SARGON) took the first steps to extend the capabilities of TASTE to build robotics applications. ExoTeR was used as the target platform to deploy the application built for the final demonstration of SARGON. These efforts were continued within ESROCOS (European Space Robotics Control and Operating System) [22], an activity that is part of the European Commission's Horizon 2020 programme. Since the completion of ESROCOS, several activities of the Space Robotics Cluster of Horizon 2020 have used TASTE as their development and deployment framework for planetary robotics applications with field test demonstrations [23].

These activities are bridging the existing gap between laboratory developments and critical space software. TASTE can deploy components on machines running Ubuntu and use bridge tools to communicate with ROS and RoCK applications. Eventually, it could fully replace these frameworks for our lab developments and reduce the gap to space.

III. TEST CAMPAIGNS

In this section, we provide a brief description of the main test campaigns performed with ExoTeR that have driven our lab research activities for the last five years. These are chronologically introduced and references to previous publications are provided for further details. While MaRTA is now at a ready state for testing activities, there have not been any relevant test campaigns that we considered for reporting yet.

A. Wheel Walking – ESTEC 2014 & DLR 2015

Wheel Walking refers to a rover locomotion mode that synchronises the motion of the wheel driving motor with another motor that is connected through a lever or *leg* that can be used to swing the wheel back and forth following a pattern that increases traction on soft soils. In the case of ExoMars, this second motor is referred to as deployment motor, since it is used to stow and deploy the wheels for an efficient accommodation during the spacecraft cruise phase. The Triple Bogie locomotion system has a total of 6 deployment motors, one for each wheel (see subsection II-A).

Motivated by the difficulties that MER rovers had traversing the Martian surface, even getting stuck in loose soil several times, and inspired by the peristaltic motion demonstrated on Lavochkin's planetary rover prototypes [24], a project was started to implement and evaluate the Wheel Walking locomotion pattern on ExoTeR. The expected outcome was an improved tractive performance in challenging conditions, such as sandy terrains or high slopes, where the nominal roving motion was subject to high slip ratios. The improved locomotion capabilities were validated in a comprehensive set of tests, showing the reduced slip ratios of Wheel Walking compared to the standard mode.

A first test campaign was conducted in ESTEC at the end of 2014, and the encouraging results motivated a second test campaign at DLR's Robotics and Mechatronics Center (RMC) facilities in Munich in early 2015 (see Figure 7), making use of a significantly larger test bed and different soil types available there, allowing us to validate our results in a wider set of test conditions. Further details on this can be found in [25]. These campaigns were instrumental to demonstrate the need of this capability for the ExoMars mission, and motivated further research [26] that eventually led to Wheel Walking being implemented as a locomotion mode on the ExoMars rover.

Fig. 7. ExoTeR at DLR performing a Wheel Walking test.

B. Remote Rover Operations – CNES 2015 & 2016

The objective of the remote rover operation campaigns was to assess the readiness level and adequacy of the procedures and decision making processes established for the future

ExoMars Rover Operations Control Centre (ROCC). Two campaigns in consecutive years took the ExoTeR rover to CNES facilities in Toulouse. In parallel, a rover operations centre was temporarily arranged at ESTEC, emulating the conditions of the ROCC.

In 2015, the campaign focused on the Egress phase of the mission. The objective was to validate whether the telemetry data coming from the rover together with the tools available at the control centre were sufficient to evaluate the potential hazards and decide on the egress direction in full situational awareness to minimise the risk of failure. Our team in the SEROM (*Site d'Essai pour les Rovers Mobiles*) field in Toulouse orchestrated up to five Egress scenarios adding several hazards and hidden traps for the operations team in ESTEC. The campaign was a success, demonstrating that the operations team was capable of identifying any potential risk and managed to verify the procedural telecommands and telemetry checks to guarantee the safe egress of the rover.

Fig. 8. ExoTeR ready for Remote Operations tests at SEROM (CNES).

In 2016, the focus was set on demonstrating post-Egress operations with the commissioning activities involving the rover and lander platform and a subsequent traverse towards the first scientific target and experiment cycle. Yet the campaign started with another rehearse of the Egress operations, which was considered adequate due to the confidence gained in the previous campaign. While the egress itself was successful, it did condition the rest of the operations considerably by setting the rover in a challenging situation for the upcoming activities, eventually failing to accomplish them.

Despite the unaccomplished objectives on the latter, both campaigns provided many important lessons for the ExoMars mission rover operations team and served to validate numerous rover and control centre functionalities. More details on these campaigns can be found in [27].

C. GNC algorithms development – ESTEC 2017

Previous campaigns identified the need to embark additional navigation functionalities onboard the rover systems. This would allow performing more complex operations including longer traverses. First, a trajectory control algorithm was designed and implemented in ExoTeR. Instead of following the classic control theory approach with a PID-type control, our controller uses geometrical relations, making it much more intuitive to the operator and easy to tune. Thus, the controller parameters are defined using rover dimensions and mechanical constraints of the locomotion system. Moreover, the provided path as input comprises any finite amount of waypoints, without a fixed distance between them. The controller takes care of smoothly transitioning between waypoints and finding the directional vector to steer the rover towards at any point in time. The algorithm was experimentally validated at the Planetary Robotics Lab (PRL) in ESTEC in early 2017. More details on the algorithm implementation and testing results can be found in [28].

In parallel, a path planning algorithm was developed that could dynamically re-plan the path of the rover along the traverse when needed. The planner uses a novel technique based on the Fast-Marching Method to significantly reduce the computational time while maintaining the features of other grid-based planners such as optimality and smoothness (no angle restrictions) of the generated paths. The planner was extended with the capability to also plan global paths at the beginning of a traverse. These two capabilities were finally combined, making the planner able to reason in a multi-layer approach, with lower resolution grids in the global frame and higher resolution grids in the local frame and connecting both outputs as a single planned path. The algorithm was experimentally validated at the PRL in summer 2017, making use of the aforementioned trajectory control algorithm to follow the planned paths.

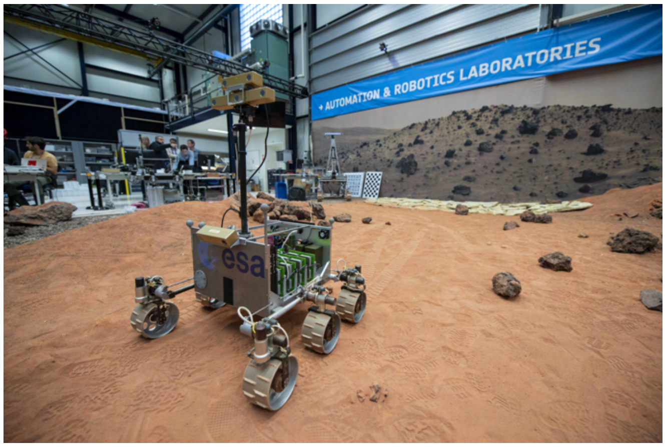

Fig. 9. ExoTeR during algorithm validation tests at the PRL.

Finally, the experiments were taken outdoors for a longer traverse in a planetary analogue terrain located in the vicinity of ESTEC. These experiments demonstrated the functionality and robustness of both algorithms in a Mars representative scenario completing a trajectory of approximately $100\,\mathrm{m}$. More details about the algorithm implementation and testing results can be found in [29].

D. ExoMars ROCC – ALTEC 2018 & 2019

Following the validation of the algorithms described in subsection III-C, the rover was ready to execute more complex navigation tasks. This included the nominal traverse mode of ExoMars at the time, used for following a path provided from the Ground Control Station. In 2018, ExoMars was getting ready for its launch foreseen for summer 2020, yet the Ground Test Model (GTM) rover model to be delivered to the ExoMars ROCC at Aerospace Logistics Technology Engineering Company SpA. (ALTEC) Turin was not yet fully assembled due to ongoing subsystem qualification activities. Given the previous experience with ExoTeR in the Remote Rover Operations campaigns and the more complex capabilities integrated into the system, it was decided to temporarily use it at the ROCC instead of the GTM, so the infrastructure facilities and tools could be tested and prepared. The rover commanding interface was enhanced and adapted to work with the 3DROCS software tool, i.e., the rover control, operations planning and monitoring station used in ExoMars. It also implemented the same telecommands protocol specified for the commanding of Rosalind Franklin. The first campaign of ExoTeR in ALTEC was performed during summer 2018, and served to validate tools, interfaces and operational procedures, including the training of the staff operators in ALTEC.

ExoTeR returned to ESTEC at the time when the ExoMars mission finally confirmed the inclusion of the Autonomous Navigation (AutoNav) functionality onboard the rover. Therefore, it was decided to integrate this functionality on ExoTeR as well. Thanks to the support of our colleagues of CNES, who provided us with their AutoNav implementation for ExoMars, we were able to quickly integrate and demonstrate the capability. In early 2019, ExoTeR was sent again to ALTEC and several tests were executed making use of the newly added AutoNav functionality. This campaign culminated with the ExoMars ROCC inauguration event on 30 May 2019 [30].

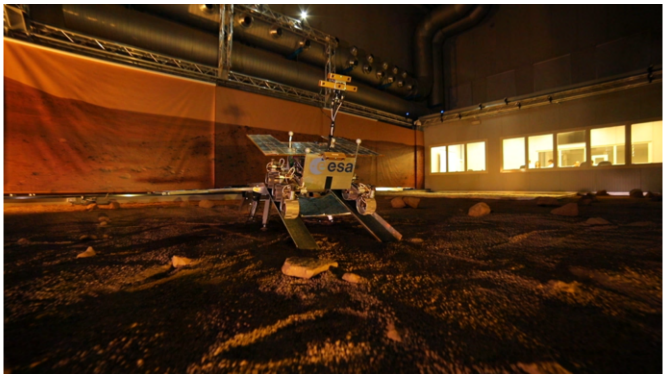

Fig. 10. ExoTeR at the ROCC inauguration event.

E. Sample Fetch Tests – ESTEC 2019

With the imminent foreseen launch of ExoMars, our lab started to put the focus on the next ESA rover mission to Mars, the Sample Fetch Rover (SFR). As already mentioned in subsection II-A, a robotic arm was developed that can be integrated at the front panel of ExoTeR's chassis. This enabled the possibility to work on this highly relevant phase of the SFR mission, i.e., the sample fetching part. Coupled with the path planning algorithm development work described in subsection III-C the planner was further extended to not only plan the motion of the rover platform towards the sample location but to also include the trajectory planning of the robotic arm. The same Fast-Marching Method was used to find the optimal arm trajectory and to synchronise it with the rover platform motion while avoiding any collision of the arm with the rover or the environment. In the first experimental campaign [31] the actual grasping of the samples was not performed due to the missing gripper development. However, at the moment the lab is working towards integrating such a mechanism together with the perception means to detect the sample and estimate precisely its full pose, and perform a complete demonstration of the sample fetching scenario.

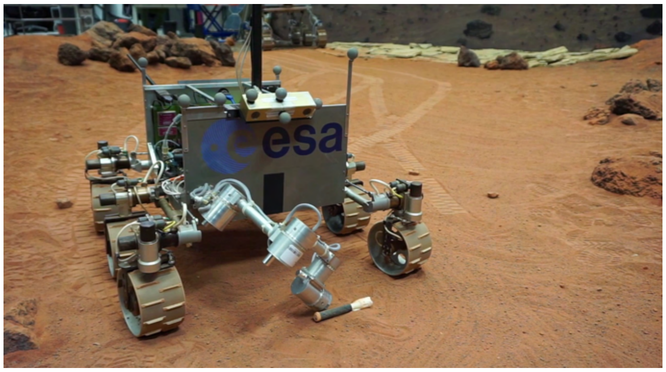

Fig. 11. ExoTeR performing a sample fetching test at the PRL.

F. Visual Odometry Tests – ESTEC 2020

Following the investigations for the SFR mission, the lastest test campaign performed with ExoTeR aimed at characterising the performance of the Visual Odometry (VO) component on conditions representative to those of SFR compared to the more benign conditions given for the ExoMars mission. The SFR rover is designed to traverse six times faster than the ExoMars rover [32]. This identified the risk of a potential impact on the performance of VO. Motion blur, coupled with a higher optical depth in the Martian atmosphere than for the ExoMars mission were the first parameters evaluated. This was done by running several experiments at different rover speeds and with varying lighting conditions. In addition, the lack of sufficient matching features between consecutive stereo pairs was considered which was directly proportional to the rover speed and VO running frequency. Finally, the effect of terrain characteristics, i.e., loose sand versus rocky or fractured terrain, and camera location, i.e., fixed at the rover rim versus mounted on a PTU at the top of a mast, were studied. The tests carried out during this campaign allowed us to identify the conditions in which the performance of VO was degraded compared to its nominal (ideal) scenario conditions and provided significant insight as to what measures or strategies could be adopted to mitigate or reduce the impact of those in the SFR mission. All details and results of these tests were recently presented at [33].

IV. CONCLUSION

Two lab rover platforms, ExoTeR and MaRTA, built as scaled-down prototypes of the ExoMars rover design have been introduced. Their robotic subsystems have been thoroughly described with focus on the mechanical, electrical, and software design aspects. These testbeds have been of great use to provide project support to ExoMars and other R&D activities of the Automation & Robotics Section of ESA in order to increase the TRL of different robotics building blocks. The test campaigns described demonstrate how the ExoMars mission has used the ExoTeR platform in numerous occasions to get qualitative results in short time. This served as derisking actions to flexibly identify potential solutions outside of the tight project schedule and contractual constraints. As the ExoMars mission is approaching its launch date, these platforms will provide support to the following SFR mission, with specific campaigns on the field of autonomous sample fetching. In parallel they will continue to contribute to the conception, demonstration and maturation of identified key technologies of future robotics missions.

ACKNOWLEDGMENT

Authors would like to thank the members of the Automation & Robotics Section who for years have contributed to the design and work of these rover platforms and for their guidance and comments in the elaboration of this paper, namely, Michel Van Winnendael, Gianfranco Visentin and Luc Joudrier.

REFERENCES

[1] M. Heverly, J. Matthews, J. Lin, D. Fuller, M. Maimone, J. Biesiadecki, and J. Leichty, "Traverse performance characterization for the mars science laboratory rover," *Journal of Field Robotics*, vol. 30, no. 6, pp. 835–846, 2013.

[2] E. Graser, S. McGill, A. Rankin, and A. Bielawiec, "Rimmed wheel performance on the mars science laboratory scarecrow rover," in *2020 IEEE Aerospace Conference*, pp. 1–12, 2020.

[3] P. Bartlett, D. Wettergreen, and W. R. L. Whittaker, "Design of the scarab rover for mobility and drilling in the lunar cold traps," in *Proceedings of International Symposium on Artificial Intelligence, Robotics, and Automation in Space (iSAIRAS '08)*, 2008.

[4] I. A. Nesnas, J. B. Matthews, P. Abad-Manterola, J. W. Burdick, J. A. Edlund, J. C. Morrison, R. D. Peters, M. M. Tanner, R. N. Miyake, B. S. Solish, *et al.*, "Axel and duaxel rovers for the sustainable exploration of extreme terrains," *Journal of Field Robotics*, vol. 29, no. 4, pp. 663–685, 2012.

[5] Y. Marchetti, J. Lightholder, E. Junkins, M. Cross, L. Mandrake, and A. Fraeman, "Barefoot rover: a sensor-embedded rover wheel demonstrating in-situ engineering and science extractions using machine learning," in *2020 IEEE International Conference on Robotics and Automation (ICRA)*, pp. 6000–6006, IEEE, 2020.

[6] M. Hoepflinger, A. Krebs, C. Pradalier, C. Lee, R. Obstei, and R. Siegwart, "Description of the locomotion control architecture on the exomars rover breadboard," in *Proc. of The 10th ESA Workshop on Advanced Space Technologies for Robotics and Automation (ASTRA)*, Eidgenössische Technische Hochschule Zürich, Autonomous Systems Lab, 2008.

[7] M. Apfelbeck, S. Kuß, B. Rebele, S. Michaud, C. Boesch, R. Krpoun, and B. Schäfer, "Exomars phase b2 breadboard locomotion subsystem test campaign," *Proceedings of Advanced Space Technologies for Robotics and Automation (ASTRA'11)*, 2011.

[8] M. Winter, C. Barcaly, V. Pereira, R. Lancaster, M. Caceres, N. McManamon, N. Silva, D. Lachat, and M. Campana, "Exomars rover vehicle: detailed description of the gnc system," *Astra*, 2015.

[9] M. J. Schuster, S. G. Brunner, K. Bussmann, S. Büttner, A. Dömel, M. Hellerer, H. Lehner, P. Lehner, O. Porges, J. Reill, *et al.*, "Towards autonomous planetary exploration," *Journal of Intelligent & Robotic Systems*, vol. 93, no. 3-4, pp. 461–494, 2019.

[10] M. Balme, M. Curtis-Rouse, S. Banham, D. Barnes, R. Barnes, A. Bauer, C. Bedford, J. Bridges, F. Butcher, P. Caballo-Perucha, *et al.*, "The 2016 uk space agency mars utah rover field investigation (murfi)," *Planetary and Space Science*, vol. 165, pp. 31–56, 2019.

[11] A. Torres, M. Maurette, S. Moreno, L. Rastel, X. Rave, E. Remetean, and A. Robert, "Robotic planetary exploration: autonomous navigation in cluttered unknown environments," in *42nd International Conference on Environmental Systems*, p. 3619, 2012.

[12] F. Cordes and A. Babu, "Sherpatt: A versatile hybrid wheeled-leg rover," in *Proceedings of the 13th International Symposium on Artificial Intelligence, Robotics and Automation in Space (iSAIRAS 2016)*, 2016.

[13] R. Sonsalla, F. Cordes, L. Christensen, T. M. Roehr, T. Stark, S. Planthaber, M. Maurus, M. Mallwitz, and E. A. Kirchner, "Field testing of a cooperative multi-robot sample return mission in mars analogue environment," in *Proceedings of the 14th symposium on advanced space technologies in robotics and automation (ASTRA)*, 2017.

[14] J. Gancet, D. Urbina, K. Kullack, P. Reiss, J. Biswas, S. Sheridan, S. Barber, N. Murray, J. Rushton, L. Richter, *et al.*, "Luvmi: A concept of low footprint lunar volatiles mobile instrumentation," in *Proceedings ASTRA-14th Symposium on Advanced Space Technologies in Robotics and Automation*, pp. 1–8, The European Space Agency (ESA), 2017.

[15] T. Kubota, "An overview of jaxa space robotics activities," in *Proceedings i-SAIRAS - International Symposium on Artificial Intelligence, Robotics and Automation in Space*, pp. 1–6, The European Space Agency (ESA), 2016.

[16] J. Zheng, H. Gao, B. Yuan, Z. Liu, H. Yu, L. Ding, and Z. Deng, "Design and terramechanics analysis of a mars rover utilising active suspension," *Mechanism and Machine Theory*, vol. 128, pp. 125–149, 2018.

[17] V. Kucherenco, A. Bogatchev, and M. Winnendael, "Chasis concepts for the exomars rover," in *Proceedings of the 7th symposium on advanced space technologies in robotics and automation (ASTRA)*, 2004.

[18] N. Patel, R. Slade, and J. Clemmet, "The exomars rover locomotion subsystem," *Journal of Terramechanics*, vol. 47, no. 4, pp. 227–242, 2010.

[19] P. Poulakis *et al.*, "Overview and development status of the exomars rover mobility subsystem," in *Proceedings of the 13th symposium on advanced space technologies in robotics and automation (ASTRA)*, 2015.

[20] F. Nicodemos, O. Saotome, and G. Lima, "Rtems core analysis for space applications," in *2013 III Brazilian Symposium on Computing Systems Engineering*, pp. 125–130, 2013.

[21] K. Kapellos, K. Wormnes, and L. Joudrier, "3D Rover Operations Control System: application to the ExoMars mission," in *Proceedings of International Symposium on Artificial Intelligence, Robotics, and Automation in Space (iSAIRAS 2014)*, 2014.

[22] E. Commission, "ESROCOS." https://www.h2020-esrocos.eu/, 2021.

[23] J. Ocon *et al.*, "Using the ergo framework for space robotics in a planetary and an orbital scenario," in *Proceedings of the 14th International Symposium on Artificial Intelligence, Robotics and Automation in Space (i-SAIRAS)*, 2018.

[24] P. Ehrenfreund, C. Krafft, H. Kochan, and V. Pirronello, *Laboratory astrophysics and space research*, vol. 80. Springer Science & Business Media, 1998.

[25] M. Azkarate, M. Zwick, J. Hidalgo-Carrio, R. Nelen, T. Wiese, P. Poulakis, L. Joudrier, and G. Visentin, "First experimental investigations on wheel walking for improving triple-bogie rover locomotion performances," in *2015 Advanced Space Technologies for Robotics and Automation (ASTRA)*, 2015.

[26] T. Wiese, *3D Kinematic Modeling and Evaluation of Rough-Terrain Locomotion Modes for an ExoMars-like Mobility Subsystem*. PhD thesis, Technische Universität München, 2017.

[27] M. Azkarate, K. Kapellos, R. A. Hewitt, E. Boukas, L. Joudrier, P. Poulakis, D. Bussi, E. Ferentino, and G. Visentin, "Remote rover operations: Testing the exomars egress case," in *2016 International Symposium on Artificial Intelligence, Robotics and Automation in Space (iSairas)*, 2016.

[28] J. Filip, M. Azkarate, *et al.*, "Trajectory control for autonomous planetary rovers," in *14th Symposium on Advanced Space Technologies in Robotics and Automation (ASTRA)*, June 2017.

[29] C. J. Pérez-del Pulgar, J. R. Sánchez-Ibáñez, M. Azkarate, A. Sánchez, and G. Visentin, "Path planning with reconfigurable rovers for planetary exploration," in *14th Symposium on Advanced Space Technologies in Robotics and Automation (ASTRA)*, June 2017.

[30] ALTEC, "Inauguration of the ExoMars ROCC with ExoMars-like lab rover prototype." https://www.altecspace.it/en/may-30-2019-rocc-inauguration-event, 2019. Last accessed: April 2021.

[31] J. R. Sánchez-Ibáñez, G. J. Paz-Delgado, P. Romeo-Manrique, C. J. Pérez-del Pulgar, and M. Azkarate, "Coupled path and motion planning for a rover-manipulator system," in *15th Symposium on Advanced Space Technologies in Robotics and Automation (ASTRA)*, May 2019.

[32] L. Duvet *et al.*, "Mars exploration at esa (plenary keynote at astra symposium)," in *15th Symposium on Advanced Space Technologies in Robotics and Automation (ASTRA)*, May 2019.

[33] M. De Benedetti, M. Azkarate, and M. Innocenti, "Parametric performance characterization of visual odometry for the sample fetch rover," in *Proceedings of the 15th International Symposium on Artificial Intelligence, Robotics and Automation in Space (iSAIRAS)*, 2020.