VAMEX3: AUTONOMOUSLY EXPLORING MARS WITH A HETEROGENEOUS ROBOT SWARM

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ABSTRACT

In the search for past or present extraterrestrial life or a potential habitat for terrestrial life forms, our neighboring planet Mars is the main focus. The research initiative "VaMEx - Valles Marineris Explorer", initiated by the German Space Agency at DLR has the main objective to explore the Valles Marineris on Mars. This rift valley system is particularly exciting because the past and current environmental conditions within the canyon, topographically about 10 km beneath the global Martian surface, show an atmospheric pressure above the triple point of water - thus, physically allowing the presence of liquid water at temperatures above the melting point [9].

The VaMEx3 project phase within this initiative aims to establish a robust and field-tested concept for a potential future space mission to the Valles Marineris performed by a heterogeneous autonomous robot swarm consisting of moving, running, and flying systems. These systems, their sensor suites, and their software stack will be enhanced and validated to enable the swarm to autonomously explore regions of interest. This task includes multi-robot multi-sensor SLAM, autonomous task distribution, and robust and fault-tolerant navigation with sensors that enable a redundant pose solution on the Martian surface.

Key words: swarm exploration, autonomous navigation, life on Mars, virtual twin.

1. INTRODUCTION

This paper introduces the projects involved in VaMEx3 and the general mission design. Subsequently, it describes the swarm participants as well as the developed sensor modules and algorithms. Finally, it briefly outlines the validation through real-time simulation and field tests.

1.1. Motivation

As the most Earth-like planet in our solar system, Mars has been fascinating astronomers, scientists, authors, and society for decades. In almost sixty years of robotic exploration scientists have already gained a lot of insights into the Red Planet. Due to recent speculations of large water deposits [17], past volcanic activity, and shading from UV radiation, the rift valley system of Valles Marineris is particularly exciting because it provides conditions for the potential existence of extraterrestrial life and prospects of human habitation [18, 9].

Most robotic systems in previous planetary explorations used wheeled approaches, which limits their area of exploration to regions with relatively low slopes and few obstacles [25]. Investigations on the lunar far side emphasize that a more powerful locomotion system is required, especially for scientifically interesting areas like craters and caves [7]. Recent planetary analog missions with a team of legged robots concluded that a heterogeneous locomotion approach with drones, rovers, and legged systems could be advantageous [2]. VaMEx3 aims to establish and test such a heterogeneous robot swarm for Mars exploration.

1.2. VaMEx3

Establishing a robust and field-tested concept for a potential future space mission to Valles Marineris is the main objective of the "VaMEx - Valles Marineris Explorer" project line within the DLR Explorer Initiatives [9]. This paper presents the technological topics of the third development phase (VaMEx3) of the VaMEx initiative and our approach to explore a large region of the Martian valley robustly and autonomously with a multi-robot team. Exploration of an environment with such diverse characteristics, e.g. lava tubes, caves, recurrent slope lineae, etc., requires a heterogeneous approach concerning the design of the robotic systems [2, 19]. Moreover, long signal transit times between Mars and Earth make it impossible to directly control the systems. Hence, an exploring robotic swarm must act independently and carry out their mission autonomously. The following paragraphs briefly describe the different projects within VaMEx3 and their focus with respect to the VaMEx initiative.

1.2.1. VaMEx3 Aerial Explorer

The project VaMEx3 Aerial Explorer (VaMEx3-AE) focuses on the development of flying swarm members. Based on the results of former projects like VaMEx-CoSMic [4] and VaMEx-MaHRs [28], first physical components, like rotor blades, and software stacks are built, developed, and tested. The VaMEx3-AE project team is composed of partners from universities and industry to meet the project goals. The Institute of Flight Guidance of the TU Braunschweig develops and implements the navigation stack of the unmanned aerial vehicle, which shall perform an autonomous exploration and mapping of a region of interest without external navigation aids beyond the visual line of sight. Complementary, the Institute of Flight System Dynamics of the TU München develops a suitable flight and trajectory controller for the proposed Mars unmanned aerial vehicle (UAV). The collaboration between the Chair of Helicopter Technology (TU München) and the INVENT GmbH aims at the design, development, manufacturing, and testing of rotor blades for the VaMEx3 Mars UAV. In addition to those tasks a UAV demonstrator, assembled from COTS and equipped with multiple sensor devices like cameras, LIDAR, and IMUs, will be set up for the VaMEx3 field test campaign.

1.2.2. VaMEx3 Absolute Position- and Orientation

The goal of the VaMEx3 Absolute Position- and Orientation (VaMEx3-APO) project is to develop a failsafe system that can precisely determine an object's pose on Mars. To achieve this goal, multiple sensors are developed: ultra-wideband (UWB) radio navigation, a sun sensor, and camera SLAM. These are then combined with inertial sensors and LIDAR simultaneous localization and mapping (SLAM), ensuring the individual sensor solutions are consistent and reliable. For the UWB radio navigation, the beacons must first be deployed by one of the rovers to cover the region of interest. This project also includes a simulated orbiter pass for any tests on Earth using a UAV to capture images and determine the locations of the lander and swarm entities on the surface. VaMEx3-APO is a collaboration between ANavS GmbH, the University of Würzburg, and the German Research Center for Artificial Intelligence.

1.2.3. VaMEx3 Robust Ground Exploration

A central element of the robot swarm comprises ground-based units in the form of wheeled robots and crawlers. These units and their algorithms are developed in the project VaMEx3 Robust Ground Exploration (VaMEx3-RGE) by four university institutes. The Cognitive Neuroinformatics Institute of the University of Bremen is in charge of implementing an overarching multi-robot multi-sensor navigation solution. The German Research Center for Artificial Intelligence provides and enhances ground-based swarm entities (Section 3.1 and Section 3.2). The High-Performance Visualization Institute develops an interactive software application for mission control based on CosmoScout VR [22]. The Institute of Microwave and Photonics develops a RADAR-based navigation solution. The project addresses algorithms for autonomous navigation that facilitate the cooperative behavior of diverse units, including multi-robot multi-sensor fusion, distributed high-level planning, and cooperative decision-making. Different algorithms such as radio navigation (Section 4.3), RADAR-SLAM (Section 5.5), and multi-sensor multi-robot SLAM (Section 5.7) enable the robust and multi-modal exploration of the environment. The interaction between the swarm entities is governed by mission control (Section 5.1). VaMEx3-RGE enables the ground-based entities to traverse toward regions of interest (ROI) and perform various tasks at the destination.

1.2.4. VaMEx3 Validated Robust Navigation Payload

A cornerstone of the VaMEx3 Validated Robust Navigation Payload (VaMEx3-VRN) project involves the comprehensive planning and design of a viable Mars mission concept, wherein the deployed swarm members function in a cooperative manner. This aspect is jointly orchestrated by the Institutes of Space Technology (LRT9.1) and Satellite Navigation (LRT9.2) at the Universität der Bundeswehr München (UniBw M). To facilitate a holistic evaluation of the mission from the development phase itself, a Virtual Testbed (VTB) is being developed based on previous work [26] and validated. This VTB will accurately emulate the topographical features of Valles Marineris and will simulate the behavior of deployed robots along with their designated sensor arrays. The VTB is under development by the Visual Computing Lab (CGVR) at the University of Bremen and will be validated by institutes affiliated with UniBw M. Another pivotal objective within the VaMEx3-VRN project is the modification of the existing Terrain Relative Navigation (TRN) system to make it compatible with hardware that meets the qualifications for Martian expeditions. This task is being undertaken by DSI Aerospace Technologie GmbH in Bremen.

2. MISSION

The VaMEx initiative is an interdisciplinary research program funded by the German Space Agency at DLR aimed at developing new concepts, algorithms, and hardware for swarm exploration of the Valles Marineris on Mars. As such it is centered around the advancement of engineering and technological capabilities that would enable more ambitious scientific goals such as discovery, mapping, and large-scale extraction of water deposits in the long run. One of the main goals of VaMEx3 is the study of collaborative navigation. The mission concept highlights the complementary nature of the heterogeneous team of driving, walking, and flying robots. A large team of robotic explorers requires a high degree of autonomy. Manual interventions should be reduced to the lowest degree possible.

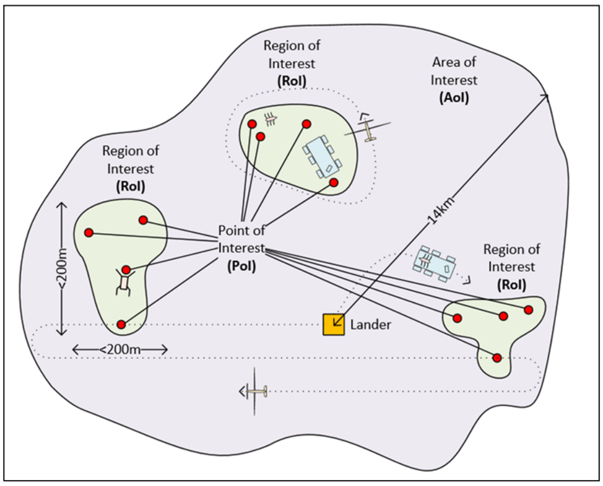

Figure 1. The robotic exploration team will act in an area of interest with a radius of 14 km. Rovers and crawlers are expected to collaborate within regions of interest with a diameter of around 200 m. [19]

A typical scenario within the mission concept looks like the following (see Figure 1): Assuming a successful entry, descent and landing (EDL) operation, the robot team is assembled around a lander that serves as a central communication and computing hub. The rovers setup a local network of radio beacons. The precise geoposition of the lander and the radio beacons will be determined from ground control with help of orbiter imagery. This is the only situation where a manual intervention is intended. Then a scouting UAV will use the local radio network and its onboard sensors to initialize its mapping system and explore a target area that shall be investigated later by the rover. It collects sensor data that is geotagged via Terrain Relative Navigation and multi-sensor SLAM. Once the UAV returns, the sensor data is deposited on the lander, which will create a high resolution 3D map. This map is used by a global path planner to create a safe route for the rovers to the target destination and is used by the rovers periodically as a reference map for geolocalization.

At the target location, the rovers will setup a local navigation network for high precision collaborative navigation with cm accuracy. If necessary, the crawlers will be released by the rovers for exploring inaccessible terrain in the local vicinity. In the meantime, the UAVs can be called for assistance for mapping tasks or as communication relays to establish data transfer from the target area to the lander.

3. HETEROGENEOUS ROBOT SWARM

The robot swarm entities used in the VaMEx3 field tests are described in this section. They are characterized by different mobility capabilities and are equipped with various sensor suites.

3.1. Crawler CREX

CREX (CRater EXplorer) is a biologically inspired six-legged walking system (Figure 2), based on its predecessor SpaceClimber [3]. It has been developed in the RIMRES project as a scout system for the exploration of deep lunar polar craters, where water ice, and other volatiles are suspected [24]. This makes the system ideal for the challenging terrain that is to be expected in the Valles Marineris. As the only legged member of the heterogeneous swarm, it will be able to explore unconsolidated, inclined, and rugged terrain that is not traversable for any of the other ground-based systems [6]. In past projects, the system was upgraded with a second computer and a VLP16 Velodyne LIDAR. Since the body is blocking the field of view of the rotating laser scanner right in front of the system, it is equipped with two depth sensing time-of-flight cameras (PicoFlexx). In the scope of VaMEx3, the current sensor suite is upgraded. For visual SLAM, a stereo camera will be mounted on the front. Furthermore, the sun sensor (Section 4.2) and a stationary ultra wideband (UWB) radio beacon (Section 4.1), both developed in the scope of VaMEx-APO (Section 1.2.2), will be mounted. The crawler has the dimensions 82 x 10 x 22 cm and weighs 27 kg.

Figure 2. The six-legged walking system CREX on an artificial lunar crater. (Credit: DFKI, Annemarie Popp)

3.2. Rover Artemis

The Artemis rover (Figure 3) was developed and built for the national robotics competition DLR SpaceBot Cup by the University of Bremen and the DFKI [16, 23]. It was specifically designed for navigation in unknown and unstructured terrain. Due to its passive suspension chassis and custom-made rubber tweels, it achieves excellent mobility. The ability to turn all of the six wheels allows the system to move sideways and execute point turns. Furthermore it is possible to switch controllers at runtime, which enables the system to dynamically adapt its behaviour to task requirements or changing environmental conditions [27]. The robot is already equipped with a powerful Velodyne HDL-32E. In order to cover the area in front of the system in more detail, a new Velodyne VelArray M1600 is added. For redundancy in the Multi-Sensor-SLAM, an additional stereo camera is acquired for visual SLAM. Similar to other swarm members, the systems sensor suite is enhanced by the sun sensor (Section 4.2) and a stationary UWB radio beacon (Section 4.1), both developed in the scope of VaMEx-APO (Section 1.2.2). Additionally, Artemis will be equipped with a mechanism to deploy several UWB beacons. In order to account for the space application scenario, the rubber tweels are replaced by metal tweels with similar locomotion properties. The rover has a size of 120 x 80 x 107 cm and a weight of 75 kg.

Figure 3. The six-wheeled rover Artemis. (Credit: DFKI, Thomas Frank)

3.3. Rover Summit-XL

The Summit-XL (Figure 4) is an off-the-shelf rover produced by Robotnik. It has four rubber wheels, each of which is driven by one electrical motor. The wheels are mounted on a passive suspension system. In contrast to Artemis (see Section 3.2), the wheels cannot be turned, and thus, skid steering is used. Up to six Summit-XL are used in VaMEx3, each of which is equipped with a custom sensor setup. All of them have wheel encoders as well as an IMU. Furthermore, it is planned to mount the DLR radio navigation system (Section 4.3) on all six rovers, which allows for estimating the distance between the rovers as well as to fixed beacons. At least two rovers are equipped with a Velodyne VLP16, which is used for multi-robot multi-sensor SLAM (Section 5.7) and obstacle avoidance. One of those rovers will also be fitted with two to four RADAR sensors utilized for RADAR SLAM (Section 5.5). A camera will be mounted on some of the rovers, which is not used for navigation but for documentation purposes. Finally, the rovers are equipped with a GNSS RTK reference system, which is also not used for navigation but for validating the developed algorithms. The rovers have a size of 72 x 61 x 80 cm and a weight of 75 – 100 kg, depending on the exact setup.

Figure 4. A Summit-XL with a preliminary sensor setup. (Photo by C. Rachuy.)

3.4. Unmanned Aerial Vehicle

Among other previous VaMEx projects, VaMEx MaHRS [28] focused on a vertical take off and landing (VTOL) aircraft design for a beyond visual line of sight scout mission. The winning VTOL design is quite similar to those of NASA's Mars helicopter *Ingenuity*, but larger in size, i.e., a rotor diameter of about 3.04 m and a maximum take-off weight of 21.5 kg. The scientific payload is restricted to a maximum of 2.2 kg. Based on the outcome of the Mars mission study SKAD [19] and VaMEx-MaHRS [28], an experimental sensor payload has been assembled. To proof the concept of the navigation and communication stack during the field test campaign, an off-the-shelf UAV with six rotors has been selected to carry the sensor suite and communication devices. The set of sensors for navigation purposes consists of an SBG Systems Ellipse-N IMU, a rotating HOKUYO UTM-30LX LIDAR, and two downward facing cameras. To fulfill the mapping task, a high resolution of 12.3 megapixel (MPx) camera with a maximum frame rate of 9 FPS and a focal length of 8 mm has been procured. To perform tracking for the visual SLAM, the IDS UI-5149CP camera, that provides images at a lower resolution of 1.31 MPx and at a frame rate of 88 FPS, has been added to the camera bundle. In addition to both cameras a rotating LIDAR is installed to provide distance measurements and data for LIDAR SLAM. The LIDAR shall be used while executing tasks in close proximity to swarm members, and a 360° perception of the surrounding is beneficial for safe operations. The navigation stack is completed by the NVIDIA Jetson AGX Orin 32 GB processing unit that computes the inertial navigation system (INS) state estimate, performs SLAM, and additionally handles the high level and communication tasks of the aerial swarm member. To control the UAV, an off-the-shelf Pixhawk autopilot is used. The autopilot receives high level tasks and the computed pose estimate from the equipped companion computer. Like other swarm members, the aerial swarm member is equipped with a Ubiquity Bullet AC to establish a communication link to the swarm and lander. With 3 kg of navigation and communication equipment and a 6S LiPo battery of 2.5 kg, the maximum take-off weight is estimated to be around 10 kg. The total flight time is estimated to be around 15 minutes, which is suitable for the VaMEx field test scenario.

4. SENSOR & NAVIGATION MODULES

For the VaMEx field tests, several off-the-shelf sensors like LIDAR, RADAR, IMU, and camera are employed. Additionally, new sensor systems are developed, which are briefly described in this section.

4.1. Ultra Wideband Radio Navigation

The UWB radio navigation is comprised of two parts. First, there are the UWB transceivers mounted on the swarm entities, whose position should be determined. Second, stationary beacons are deployed in the ROI to construct a coordinate system. The UWB system relies on distance measurements between the individual nodes in the network. Through the use of two-way ranging, no time synchronization is required for the distance measurements. After the Artemis rover deploys the beacons, all distances between them are measured, if there is a line of sight. Multidimensional scaling is used to construct a 3D coordinate system based on the distance measurements. In this stationary coordinate system, the mobile explorers can determine their position by measuring only the distances to the beacons. A major challenge in this system is the position of all beacons and rovers on the ground for optimal signal coverage. This limits the vertical difference between each node, resulting in a high vertical dilution of precision.

4.2. Sun Sensor

The sun sensor determines the absolute heading by measuring the position of the sun. Since Mars lacks a global magnetic field, a magnetic compass can not be used for absolute heading determination as it is usually done on Earth. To determine the heading, both a rough estimate of the absolute position on Mars as well as the current time are needed. With this information, the position of the sun can be predicted using orbital mechanics. Comparing the prediction to a local measurement of the sun's position, the absolute heading is determined. The tilt of the vehicle affects the local sun measurement, therefore it must be compensated by utilizing the other sensors on the vehicle.

4.3. Combined Radio Communication & Localization

On closer examination, the radio navigation is just one of three parts of the combined communication and localization system. The general concept allows not only communication, but also a relative localization and time synchronization in a network of agents. The experimental setup is based on orthogonal frequency-division multiplexing (OFDM). For an interference-free channel access, a time division multiple access (TDMA) without a central coordinator is utilized. This means that swarm members can synchronize themselves relatively to the time slots of neighboring agents and readjust the broadcast timing of their OFDM symbols additionally. Thus, a robust multi-channel access without a single-point-of-failure (SPOF) can be obtained. The length of the time slots and the signal bandwidth are adjustable in a flexible manner to suit different applications or scenarios, i.e., to a small number of swarm members. In the earlier project VaMEx-CoSMic the system was tuned and assessed for a swarm size of 20 agents, whereas the OFDM signal bandwidth was set to 25 MHz with 1024 subcarriers to enable all agents a channel access within 10 milliseconds.

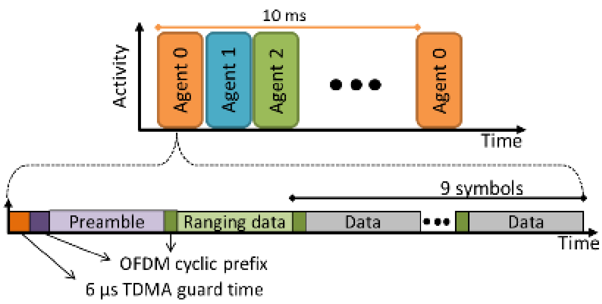

Figure 5. TDMA schema and OFDM symbols per slot for a combined communication and localization system [4].

Figure 5 shows an example of the TDMA schema with OFDM symbols. A time slot consists of 11 OFDM symbols. The first symbol is a frame preamble, which is required for an initial channel guess, the frame and time synchronization, and the identification of the agent. Packet number, transmission time stamp, and response data for distance estimation are encoded in the 2nd OFDM symbol. The subsequent 9 symbols are unallocated and thus can be used for communication purposes. For distance measuring, software-defined-radios (SDR) are used to fulfill the task of data samplers for transmitting and receiving data on arbitrary high frequencies (HF). The distance estimate between two swarm members is based on Two-Way-Ranging. To parallelize distance estimation, the response has been adapted to contain not only the successfully decoded time stamp of one, but all agents. Hence, all distances inside the swarm network can be estimated. To compensate for skew, additionally a Kalman filter is implemented that estimates skew by evaluating the data packet's transmission time stamp and the time stamp at reception.

5. SOFTWARE MODULES

In this section, we describe the software systems developed for the autonomous, swarm-based exploration. All of those run on Linux. Most algorithms are implemented with the Robot Operating System 2 (ROS2), which is also used for inter-robot communication. In general, the software pipeline will fuse the sensor information on each system with different SLAM approaches. Afterwards, the multi-robot multi-sensor SLAM (Section 5.7) will generate a map and pose solution, which is then used for trajectory planning (Section 5.3) and execution. The autonomous swarm will negotiate the task distribution autonomously through the multi-robot coordination module (Section 5.4). The following subsections describe these modules in more detail.

5.1. Mission Control

The mission control tool provides a 3D display of the mission area and the mission output within a three-dimensional, interactive solar system as well as the ability to assign high-level tasks to the swarm and a visualization of the swarm's state. For depicting the target area, level-of-detail terrain rendering techniques are used based on CosmoScout [22], allowing for a smooth and centimeter-precise representation of several square kilometers. Users can display multi-spectral data over orthophotos and on the 2.5D terrain model. For this, they can select and connect different spectral bands in a data flow editor. Using this data, they can identify a region of interest (ROI) and mark it with a polygon on the virtual terrain.

5.2. Simulated Orbiter Pass

In a hypothetical Mars mission, an orbiter would fly over the landing site to capture images of the lander and other vehicles, enabling the determination of an initial absolute position for all of them. To simulate this process in VaMEx3 on Earth, a camera-equipped UAV flies over the test area. The flight path and camera orientation are designed to mimic a satellite pass, but of course at a much lower altitude. The resolution and field of view of the camera are adjusted accordingly. After the absolute positioning on the planet's surface of the vehicles in the image, it can be used as a starting point for navigation systems as well as a coordinate system transformation from the local UWB radio navigation frame to an absolute Martian frame.

5.3. Local Trajectory Planning

In order to minimize the development efforts and establish a common navigation behavior throughout the ground-based swarm, it is foreseen to use a common navigation stack. Due to the heterogeneous locomotion approaches through the swarm members, a navigation stack is required that supports skid drive as well as Ackermann and sideways motion. A navigation stack developed at DFKI based on the ROCK framework [21] provides all of those capabilities. The utilized planner for unmanned ground vehicle navigation, called *ugv_nav4d*, is based on SBPL (`www.sbpl.net`) and uses the SBPL ARA* planner to plan in a custom environment. A traversable, robot motion constraint compliant 3D trajectory is generated by combining valid motion primitives of neighboring grid cells. In order to bridge communication into the common ROS2 network, a light-weight and framework independent library is used [5]. The entire navigation stack with required ROS2 interfaces will be deployed as a ready-to-go docker image on each system.

5.4. Multi-Robot Planning and Coordination

The multi-robot planning and coordination has the goal of distributing the tasks among the swarm entities. Exemplary tasks are traversing to a POI, mapping a certain region, or collecting soil samples. The module becomes active whenever new ROIs, POIs, or other tasks are registered by the mission control. Each ground-based unit computes its individual utility and execution cost of performing a certain task and exchanges the results with the others. By means of an auctioning system, a rover claims a task, when offering the best reward (i.e., a combination of utility and cost). Tasks can be aborted by a rover due to various reasons, in which case the task is auctioned again with updated information. One example would be the necessity to climb a steep slope, which was not known in advance and for which only a crawler might be suited.

Besides the auctioning of tasks, the multi-robot planning and coordination calculates a rough path consisting of several way-points to reach the goal. The path serves as an estimate for the expected costs as well as a guideline for traversing towards the goal position. It is computed based on map information provided by the SLAM algorithm (Section 5.7), which is triangulation using growing neural gas [8] in order to compute the shortest path using A* [12]. The final control commands are calculated by the local trajectory planning (Section 5.3).

5.5. RADAR SLAM

Using RADAR SLAM, a robot can sense and map the environment using RADAR sensors [20], all while simultaneously estimating its own position within that environment. RADAR sensors measure the distance, direction and relative radial velocity of objects or features within their field of view. The features and objects extracted from the raw RADAR data are typically represented as a point cloud. The ego-motion of either the RADAR sensor or the robot can be estimated using various methods, including preceding and stand-alone approaches for ego-motion estimation [13], scan matching of point clouds, or analysis of the Doppler shift in the raw RADAR data. A map of the environment is then constructed step by step using a SLAM algorithm. If necessary, odometry data from an IMU or navigation system can be incorporated to enhance the accuracy of the robot's estimated pose.

One of the primary advantages of RADAR over LIDAR or camera-based SLAM systems in dynamic environments is its ability to directly measure velocity features while remaining independent of weather and lighting conditions. Depending on the RADAR parameters used, it is also possible to penetrate the surface beneath the robot [10]. Consequently, additional features can be detected underneath the surface, which can lead to an improvement in the SLAM results.

5.6. Multi-Sensor SLAM (UAV)

Based on the current UAV mission, we can make use of either a visual- or a LIDAR-based SLAM approach to obtain a pose estimate, which shall be fused with the state estimate of an inertial navigation system (INS). Which of both SLAM approaches is favored heavily depends on the flight altitude. During the mapping and exploration task of a region of interest at flight altitudes of more than 100 meters above the ground, the visual SLAM is going to be deployed since the equipped LIDAR's range is limited to 30 meters. In situations or tasks at lower altitudes, i.e., at take-off, landing, or near ground operations, which involve precise perception of the environment, the LIDAR SLAM, processing 360° point clouds, might be more suitable and thus favored over the visual SLAM. Both SLAM techniques incorporate inertial measurements and INS state estimates to speed up data processing. Furthermore, they are graph-based and make use of the GPU and CPU of the companion computer. The LIDAR SLAM implementation rests upon the work of Koide et al. [15]. Additionally, to evaluate the impact on robustness of the position estimation, under favorable environmental conditions both SLAM algorithms shall be engaged at the same time and fused all together with the INS state estimate by making use of covariance intersection.

5.7. Multi-Robot Multi-Sensor SLAM

A decentralized SLAM algorithm is developed for navigating and mapping the environment for the ground-based swarm. A graph-based approach [11] is chosen due to its intrinsic adaptability for supplementary sensor measurements. The foundation of this framework is given by a single-robot SLAM algorithm [15] based on LIDAR. The functionality is extended for multi-robot multi-sensor scenarios.

The general algorithm follows the well-known LIDAR-based graph SLAM scheme. Each node corresponds to the pose of the rover at different points in time and is associated with the point cloud perceived at this pose. The nodes are connected by odometry edges, which are determined using LIDAR or inertial odometry or a combination of both. Furthermore, loop closures are determined using scan matching, which also results in edges between corresponding nodes. Finally, the poses of the nodes are optimized with respect to the constraints induced by the edges under consideration of the corresponding uncertainty.

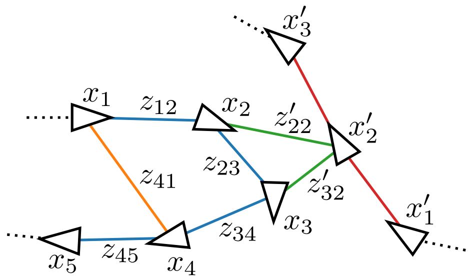

Figure 6. Multi-robot graph SLAM: x and z denote the nodes and edges of the first rover, x' denotes the nodes of the second rover, and z' denotes loop closure edges between nodes of both rovers. The edges $z_{i,j}$ with $j = i + 1$ correspond to odometry edges (blue), while z_{41} corresponds to a loop closure edge (orange). The odometry edges of the second rover (red) are not named, but z'_{22} and z'_{32} are the loop closure edges between both rovers (green).

Whenever the robots are in close proximity to each other or when cooperation is required, they exchange graph-related information and integrate it into their own graph. More precisely, all nodes and edges that are not known by the other rover are transferred. After that, the rovers perform loop closure detection using the newly received parts, which connects the individual graphs with each other (see Figure 6). Finally, the subsequent optimization relaxes the graph and both rovers have a consistent representation of the environment explored so far. With this approach, robots can traverse long distances away from the base station without the need for a functional communication to it. At the same time, they can utilize information collected by other rovers when needed. Furthermore, the decentralized architecture distributes the computational load on all rovers and avoids a single point of failure.

We plan to incorporate additional sensor modalities described in the previous sections to the SLAM framework. In particular, the radio navigation systems hold (Section 4.1 & Section 4.3) the potential to improve the localization performance and minimize the inherent drift. The corresponding measurements can be added to a graph in form of edges constraining the distance between two nodes. Furthermore, the fusion of RADAR SLAM data with existing LIDAR information presents a possibility for augmenting the robustness and fidelity of the environmental modeling. Finally, we aim for incorporating the map information provided by the UAV as well. While it is less detailed compared to information collected by ground units, it can provide a drift-free reference within the ROI. However, matching point clouds recorded from completely different points of view as well as with different resolutions is a challenging task.

6. VALIDATION

The results of VaMEx3 are continuously validated through the virtual testbed (Section 6.1) and will be demonstrated in a final field test (Section 6.2).

6.1. Virtual Testbed

To enable a comprehensive evaluation of the entire Mars mission, a Virtual Testbed (VTB) is developed, serving as a testing environment for both the algorithms and systems that underlie the mission. This testbed simulates robotic agents along with their sensors and actuators in a digitally reconstructed terrain of Valles Marineris (see Figure 7). The VTB utilizes cutting-edge rendering and simulation technologies from Unreal Engine 5 to enable high-fidelity simulations of sensor modalities, including but not limited to RGB cameras, LIDAR systems (see Figure 8), and IMU. Additionally, the VTB offers interfaces via ROS2, which are identical to the interfaces of real-world sensors. This ensures seamless integration of existing algorithms, such as the developed multi-robot multi-sensor SLAM, for evaluation in the context of our Mars mission. Given the high computational demands of real-time sensor simulation, the VTB is designed as a distributed system. This allows the computational workload to be distributed among multiple computers throughout Germany. Furthermore, the VTB includes a virtual reality component for the direct observation and interaction with the robotic agents. The VTB will also be capable of simulating environmental factors such as sandstorms and lens contamination due to sand. Finally, a validation phase for the VTB is planned, where the behavior of robots operating with real sensor data will be compared to those operating within the VTB environment. This will serve as an indicator for the accuracy of the simulation and its approximation to real-world conditions.

6.2. Field Tests

Bilateral tests to evaluate swarm communication and localization are performed throughout the project. Separate field tests with subsets of the swarm are planned to take place towards the 2nd half of the project. VaMEx3 will conclude with field trials in 2025/26, where all the aforementioned swarm elements as well as software and navigation modules will be evaluated under challenging real world conditions. The exact location has yet to be determined.

Figure 7. Real-time rendering in Virtual Testbed (VTB).

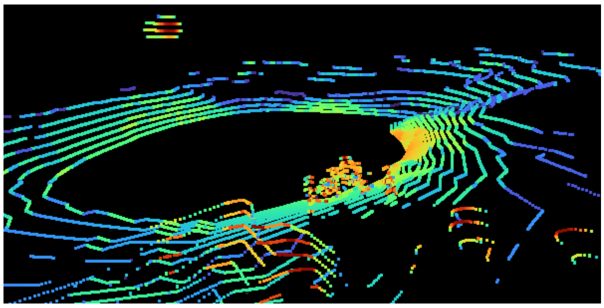

Figure 8. Visualization of LIDAR output.

7. OUTLOOK

The goal of the VaMEx3 development phase is to make the VaMEx swarm available for a field test campaign (VaMEx4) that is designed to last several weeks/months. This long-term demonstration mission shall demonstrate the VaMEx swarm's ability to autonomously and cooperatively explore a terrestrial analog environment. Successful field trials could enable VaMEx to be considered as payload for future robotic space flights to Mars [1, 14].

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