Virtual Validation and Verification of the VaMEx Initative

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***Abstract*— We present an overview of the *Va*lles *M*arineris *Ex*plorer (*VaMEx*) initiative, a DLR-funded project line for the development of required key technologies to enable a future swarm exploration of the Valles Marineris on Mars. The Valles Marineris is a wide canyon range, near the Martian equator. The so far still fictive VaMEx mission scenario compromises a swarm of different robots, including rovers, flying drones and a hominid robot. Here, we present VaMEx-VTB, a virtual testbed (VTB) with a digitalized map of the large and fragmented terrain of the Valles Marineris. The VaMEx-VTB allows an adjustable validation as well as verification of the complex mission design in virtual reality, due to its modular design. It shall also be used in preparation of field tests in the near future for validation of each swarm element's ability for interactive swarm cooperation and collaboration.**

1. INTRODUCTION

The goal of the VaMEx initiative, funded by the German Aerospace Center (DLR) as part of the Explorer Initiatives, is the investigation of new technologies for the exploration of the Valles Marineris on Mars. This Martian region is the largest connected canyon landscape in the solar system with a length of more than 4000 km. In the deep and protected areas of these canyons, it is possible to find valuable resources like water or even signs of extraterrestrial life. However, due to the ragged nature of the canyons, the development of new technologies is required in order to pursue exploration tasks in a robust, reliable and autonomous manner.

The VaMEx initiative proposes to use a swarm of different autonomous robots that complement each other, including UAVs, wheeled ground vehicles and walking robots, supported by a satellite in Mars orbit. In a first phase, we focus on the development of concepts, the hardware but also algorithms, e.g. to allow a flawless cooperation of the individual elements. A key feature for a mission consisting of an heterogeneous and autonomous swarm is a stable real-time communication system.

The validation and verification of such a complex mission, consisting of several interdisciplinary teams with many communication interfaces to exchange different kinds of data, is nontrivial. Real-world field tests for the individual parts are already expensive, time-consuming and not very realistic, because the environments on Earth differ significantly from the environmental conditions on Mars. The logistical effort in performing real-world field tests to evaluate swarm performance is considerable and out of reach in terms of the financial resources.

In order to identify design gaps and inconsistencies at an early stage of mission planning we have developed a *virtual* testbed (VaMEx-VTB) that simulates the communication interfaces, sensor input and important physical properties of the local topography in a virtual environment. This allows the project partners to test the software components of their systems before a real-world field test, diagnose flaws and correct them already at initial research stages. Moreover, our VTB allows to rebuild the Martian environmental conditions and it supports a user-adjustable modification of the terrain.

A main challenge for VaMEx-VTB are the large amounts of data that have to be handled. Actually, we have recreated a 3D model of $40km^2$ of the Martian surface based on digital terrain models (DTMs) provided by HiRise [**?**]. Moreover, we will present the integration of the different communication systems where we guarantee a real-time simulation of the data exchange between the individual VaMEx components. Finally, the VaMEx-VTB is not only a desktop application, but the integration of virtual reality technologies allows the engineers a more natural and immersive interaction with the systems.

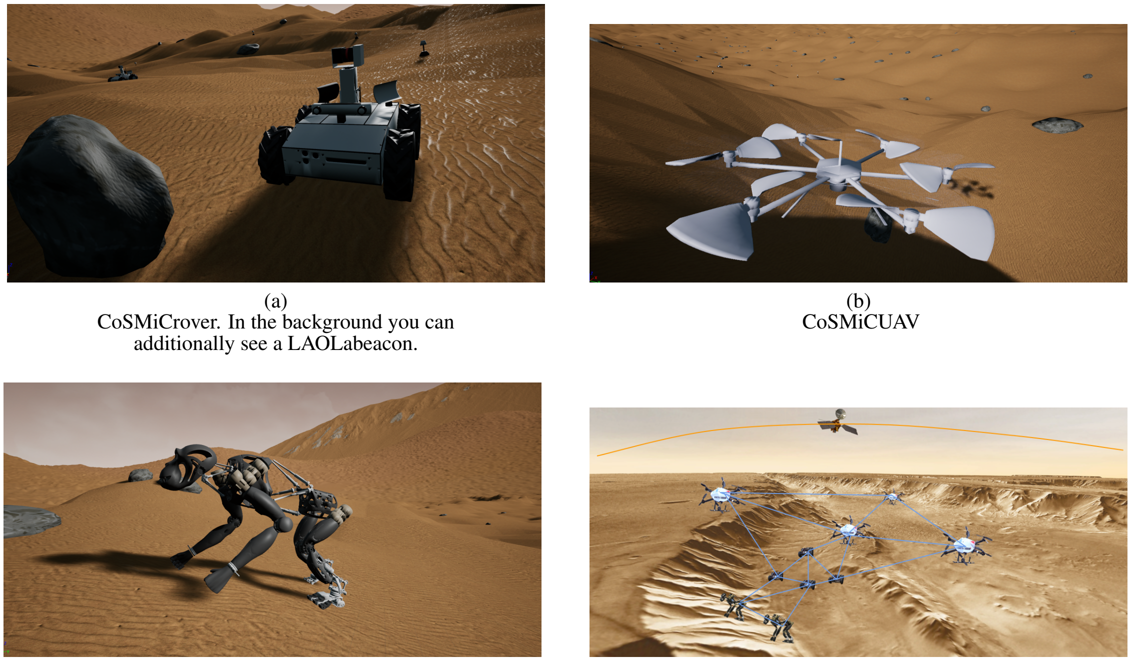
In the presented manuscript, we will give a brief overview on the individual parts of the VaMEx initiative and then focus on our novel verification and validation platform, VaMEx-VTB.

2. VAMEX OVERVIEW

The VaMEx initiative consists mainly of four parts to explore the unknown terrain of the Valles Marineris: a swarm of unmanned aerial vehicles (UAVs) and wheeled rover that can cover large distances (VaMEx-CoSMiC), a hominid robot platform to explore also hardly reachable places like caves (VaMEx-VIPE), a ground-based localization and navigation network (VaMEx-LAOLa) and orbital support for global localization and communication (VaMEx-NavComNet).

VaMEx-CoSMiC

The VaMEx *Co*operative *S*warm Navigation, *Mi*ssion and *C*ontrol (VaMEx-CoSMiC) project focuses on the swarm exploration using autonomous rovers and UAVs (see Fig. 1). The main goals are the development of efficient algorithms for surveying large areas without human supervision. The different vehicles are equipped with different sensor types, such as inertial sensors and monoscopic and stereoscopic cameras. Swarm communication is used for the distributed simultaneous localization and mapping (SLAM). Beyond the goal of using the sensor output for the navigation of the VaMEx-CoSMiC vehicles, it is used to create a map of the explored terrain and made available to other members of the VaMEx swarm.



(a)
CoSMiCrover. In the background you can additionally see a LAOLabeacon.

(b)
CoSMiCUAV

(c)
VIPECharlie

(d)
Complete VaMEx swarm including the NavComNet orbiter

Figure 1: Models of the VaMEx swarm members in VaMEx-VTB.

VaMEx-VIPE

For an extensive exploration of the Valles Marineris, a robotic platform that can move within the fissured rock formations and navigate in caves and crevices that are unreachable by the rovers of VaMEx-CoSMiC is desired as part of the heterogeneous team. The hominid robot Charlie [**?**], developed by DFKI, closes the remaining gap in the swarm (see Fig. 1).

To put the project into practice efficiently and cost-effectively, expertise and hardware built in previous projects from different areas, such as deep-sea robotics [**?**], [**?**], [**?**], was used. Charlie, a four-legged walking robot, is well suited to overcome difficult terrain due to its light and highly integrated construction and agility. In addition, the tactile sensors are powerful tools in many applications [**?**]. In order to keep the weight of the robot platform low (important for the agility and transport costs of the system), only light sensors were used.

Visual navigation is a very suitable technology based on light, passive sensors, which allows a reliable position determination due to the high redundancy but usually requires a robust semantic representation of environmental objects and features like described in [**?**]. In contrast to radio-based positioning, no (visual) connection to other swarm participants is necessary. The position determination based on continuous visual odometry using a stereo camera, as it is used for the rovers and flight systems, can only be applied to a limited extent to Charlie. Especially in areas with low brightness, the exposure times would be too long or would require a continuous, and thus resource-intensive, illumination.

Particularly when overcoming a rugged terrain, it is crucial to place the legs of the walking robot precisely on stable surfaces [**?**]. In order to make this possible, a proprioceptive approach was researched that uses tactile sensors to record body position and movement in space and converts them into position information. This is a prerequisite for motion planning and reactive motion control, which makes it possible to overcome obstacles. By merging tactile data with visually-perceived surface structures such as edges and gaps, these two technologies complement each other to form a very promising approach for reliably pursuing exploration tasks in topographically-challenging areas.

The reactive motion control in Charlie was extended by further behavior modules, so that a safe locomotion over leveled and uneven ground as well as the overcoming of obstacles with the robot could be shown. In addition, an algorithm for optimal foot placement was developed. This adaptive foot-placement algorithm makes it possible to find an optimal foot contact point for each leg either between or including various obstacles with the help of a local map. It has to be mentioned that this is not a purely planning-based control of the robot. The reactive walk control is maintained, the planning level is only allowed to write offsets on the respective walking pattern of the different legs. This procedure takes place in real time and extends the robot's mobility in that it is not necessary to stop on uneven ground or in front of obstacles in order to plan the next steps. Even if the ground does not behave as expected (e.g. due to the flexibility of an obstacle, where a contact between foot and obstacle has been planned into the step cycle), the robot is able to continue its locomotion stably due to the permanently active reactive control level.

VaMEx-LAOLa

The goal of the VaMEx-LAOLa (*L*okales *A*d-hoc *O*rtungs- und *La*ndesystem[2]) project is to provide systems for the communication between the individual members of the swarm, as well as enabling a localization to determine their positions relative to other swarm members. The local position is important for the coordination of the swarm members and to find the way back to the lander. The accuracy of

[2]German for: local ad-hoc localization and landing system

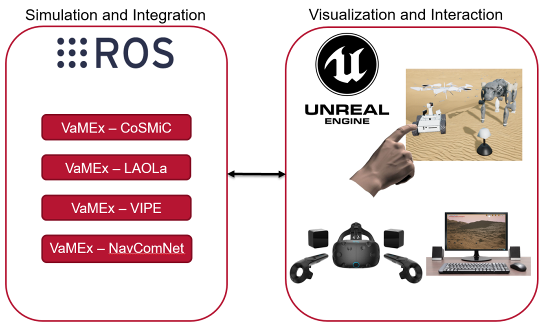


Figure 2: High-level overview of VaMEx-VTB structure.

the local reference frame is higher than that of the global reference frame. The system is based on a set of beacons that are equipped with Frequency Modulated Continuous Wave (FMCW) secondary radar. For the communication, the beacons contain additionally a 2.4 GHz module.

VaMEx-NavComNet

The VaMEx-NavComNet (*Nav*igation and *Com*munication *Net*work) has the concrete aim of serving as as a science data, telemetry and telecommand relay between Earth and the in-situ users, as well as a cross-communication relay between users, but also providing a near real-time positioning system for surface, aerial and (potential future) space-based users. An ideal solution would consist of four satellites dispersed at different altitudes [**?**], ranging between 800 and 1200 km, and orbital inclinations up to 35 degrees, allowing for data exchange volumes of up to 300 Mbits per Sol (or Martian day). We are currently investigating more cost-efficient solutions consisting of a single satellite or nano satellites.

3. VAMEX-VTB

Virtual testbeds are already successfully used in fields like autonomous automotive development [**?**], physically-based automotive control [**?**], supply chain planning [**?**] but also planetary exploration [**?**], [**?**]. In general, virtual testbeds are software solutions that enable the validation and verification of arbitrary simulation models in user-definable virtual environments. They mainly help to reduce the need to build expensive physical prototypes by moving, especially early testing, into a pure virtual simulation environment. Consequently, VTBs reduce development time and cost significantly. Moreover, VTBs can be used as a common development and evaluation platform [**?**].

The main goals of VaMEx-VTB are:

- to serve as a common validation and verification platform for the VaMEx initiative,
- to simulate all relevant environmental aspects, including sensor synthesis, distribution of resources, collision detection,
- to deliver immersive natural interaction with the system and to provide a highly detailed graphical feedback,
- and to allow extensions and exchangeability of the individual parts of the system.

In the following we will briefly sketch some design details and discuss the features of VaMEx-VTB with respect to the requirements defined above.

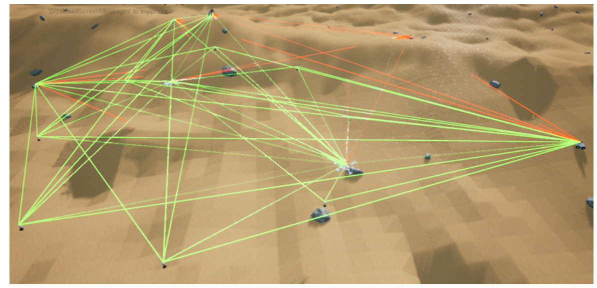


Figure 3: The line-of-sights connecting the VaMEx-LAOLa beacons.

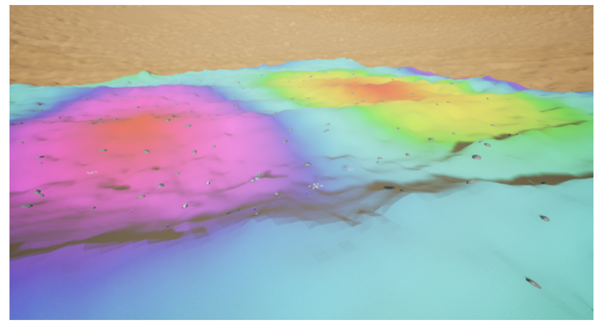


Figure 4: Visualization of the process to be measured by the swarm in VaMEx-VTB.

General Design

Figure. 2 provides a broad overview on the design of our virtual testbed. One core element of our VaMEx-VTB is a high-end visualization in combination with the possibility of virtual reality (VR) interaction. We decided to use a state-of-the-art game engine, the Unreal 4 Engine, that supports the most modern visualization effects and has an integration for a large amount of VR hardware devices.

Moreover, we have manually created a $40km^2$ terrain of the Valles Marineris based on data available from the NASA. However, the accuracy of the data is limited, hence we included the possibility to easily add surface details. For instance, our systems supports simply painting the specific terrain type (e.g. sandy, rocky, etc) directly on the surface. This includes also different texturing and even different physical properties for the simulation depending on the terrain type.

In order to connect the individual VaMEx components, which are predominantly implemented in the widely used robot operating system (ROS) [**?**], to the VTB we integrated and extended an interface to ROS. More specifically, the VTB establishes a connection to a ROSbridge server [**?**] via a websocket to which the components can register to receive and send data. This fast ROS interface allows a simple modular design of practical relevance while maintaining real-time capability of our VTB.

VaMEx-VTB Features

A main feature of our VaMEx-VTB is the synthesization of sensor input that can be delivered to the specific modules via the ROS connections. This includes images of RGB(D) cameras, the odometry and the generation of LIDAR data via ray tracing. The same technique is used to compute the line-of-sights between the LAOLa beacons and the swarm units (see Fig. 3). All this data is generated in real time.

The simulation in our VTB is based on detailed models of the individual swarm members, including working vehicle wheel physics for the VaMEx-CoSMiC rovers, working rotors of the VaMEx-CoSMiC UAVs and a skeletal model with physically-based movement of the VaMEx-VIPE robot. Obviously, the number of vehicles, beacons and hominid robots is user-definable. The VaMEx-NavComNet satellites fly in a realistic orbit as calculated by SPICE kernels, providing position updates in a Mars-centered absolute reference frame.

Our interactive data visualization includes ellipsoidal uncertainty visualizations based on covariance matrices, ghost models to display the differences between real and expected positions of the vehicles, the planned paths of the swarm units and a visualization of the process that is being measured by the swarm, both ground-truth and currently measured (see Fig. 4).

4. Conclusions and Future Works

We have presented a brief overview on the VaMEx initiative for the swarm-based exploration of the Valles Marineris on Mars. Moreover, we have introduced VaMEx-VTB, a virtual testbed for the verification and validation of complex planetary surveying missions.

We are confident that the modular and future-proof design of our VaMEx-VTB qualifies it to serve as a testing platform for other space projects, especially for planetary surface exploration scenarios. Additionally, the navigation and communication technologies researched within the VaMEx initiative are of interest for future missions.

Acknowledgments

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