ENTERN – ENVIRONMENT MODELLING AND NAVIGATION FOR ROBOTIC SPACE-EXPLORATION

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ABSTRACT

Lunar and planetary craters and caves are of special scientific interest and have the potential to provide shelter for human habitats. Robots could provide the means to explore these difficult environments. A number of challenges are involved with the exploration: The robots have to be highly mobile to negotiate the difficult terrain, and need to perform most of their task autonomously, especially in caves lacking radio communication. This paper gives an overview of the Entern project and the associated goals and challenges. This includes the research of technologies for operations, environment representation and navigation. Special emphasis is put into the development of on-board simulation, to improve the reliability and the operational envelope of the robots. Further, a description of evaluation scenarios in relevant earth analogue environments is provided.

Key words: Robots, Exploration, Caves, Lava Tubes, Moon, Mars.

INTRODUCTION

The Entern project[1] is concerned with robotic systems for the use in lunar and planetary exploration missions. Specifically it covers technologies for the robust autonomous exploration of craters and caves in a context of space missions. These types of environments are of special interest to the scientific community and provide potential places for future infrastructures and habitats due to their protected locations [1].

The navigation in these areas puts special requirements onto the methods of navigation and mobile capabilities of the robots. The content of the Entern project is the development of software and hardware to allow semi and fully autonomous navigation of robots in such environments. For this purpose, the project covers the subjects of environment modeling, navigation and operations & control.

Figure 1. Cueva del Viento-Sobrado lava tube, is the biggest lava tube in Europe with significant lava cascades and particular geological interest. Courtesy of Organismo Autónomo de Museos y Centros de Tenerife, photo: Sergio Socorro.

The scenario of the project covers the navigation to geographically interesting sites like caves or craters, based on orbiter or aerial imagery. To negotiate the complex and steep terrain at these locations, detailed physical simulations will be run on environment representations which are generated by the robot. By using a common representation of the environment for simulation and for the navigation of the system, a solution for critical situations can be found either with the help of a remote operator or by autonomous on-board simulations on the system itself.

The development of an environment representation and required software tools as well as the integration with the simulation system to allow on-board simulation are core activities of the project. Additionally, the integration of a control station and connected relevant aspects in relation to the target scenario like communication management and asynchronous mission management for dealing with transmission delays will be covered. Navigation is another important aspect of the project. The project covers the specific difficulties of navigation in craters and caves. The mapping might be optionally supported by artificial landmarks, and the resulting data can be referenced in existing geo information systems (GIS).

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This paper aims to describe the concept mission scenario and key technologies for the mission success. The manuscript will give an overview of each subsystem from a system level perspective and its impact on mission operations. It will discuss current challenges on the design towards future planetary missions in such context. The methods developed along the project will be evaluated on the existing robotic systems Asguard[2] and CREX[3, 4]. These systems will be adapted in hard and software to fit the specific scenario requirements. The mission concept is planned to be evaluated within the project at relevant earth analogue sites in Europe, where underground complex lava tubes are available (see Figure 1).

1. PLANETARY CAVES

Extraterrestrial caves, tunnels and lava tubes exist on both Mars and Moon [5], [6], [7]. There is also evidence of their existence in other planets in the solar system [8], [9].

1.1. Motivations and Explorational Interests

Extraterrestrial caves have the potential to provide shelter for a sustained human presence. Caves and skylights – a lava tube cave which the roof has been collapsed – can reveal a lot about the planet's history and provide crucial information regarding geology, climate and potential biology [9]. Caves on Mars might contain water and biological materials [10]. Subsurface caverns and lava tube on Mars might be the best place to search for extraterrestrial life [11],[12] and [13].

These reasons put exploration of extraterrestrial caves and lava tubes on the astrobiology roadmap of NASA space missions [14]. Despite the detailed information provided by orbiters about the surface of Moon and Mars, the inside of caves and tunnels are yet unknown [9].

Interior spaces of cave and lava tubes might be too hazardous for astronauts and exceedingly risky for exploration robots, therefore exploration of caves requires modeling and simulation of environment in advance [10]

Due to lack of real time communication with station on earth, autonomy of the robots is a crucial issue in such missions. Various different approaches including heterogeneous robots systems have been proposed for such missions in [15], [9], [10] and [16]

1.2. Lava Tubes Formation and Types

In [17], different models, describing the formation of different lava tubes on Mars have been summarized:

Levee bridging in which flow rises create a continuous crust as flow rates diminish [18].

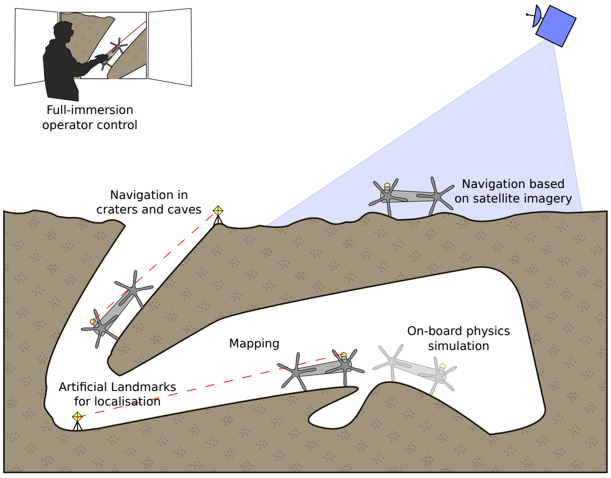

Figure 2. The Entern scenario

Channelized lava after solidifying, makes a dam, which forms an upstream continuous crust. The crust will be overlaid by following flows [19], [20].

Volatile lava beneath the surfaces with holes erupts and spattered. This spattered lava became solid and hard on the levee walls and shapes a continuous crust [19].

1.3. Difficulties and Problems of Exploration

There are several problems regarding the exploration of lava tubes:

1. Any exploration of lava tubes needs high resolution topographic maps which require surface-based exploration of candidate site using surface rovers[1].
2. The next problem is finding a good entrance point for getting into the tube. One trivial solution is getting access through the tube natural entrance which requires a high resolution map of the site in advance. Such an entrance does not guarantee if the inside of the tunnel is structurally sound and safely and easily traversable for the robot [1].
3. In the case of finding a good candidate, it might be not in the vicinity of any other point of interest and valuable site for exploration [1].

2. CONCEPT MISSION SCENARIO

In order to handle the technical aspects of robotic cave exploration, a reference scenario has been developed for the Entern project. See Fig. 2 for an overview of the involved parts. As stated in the previous section, there are a number of difficulties for the exploration of caves. For the scenario the assumption is that an entrance to the cave has been identified using orbiter data. A lander mission has placed a mobile robotic system in the same region. At this part of the mission there will still be communication to the ground station. Localisation of the rover is performed using the orbiter map data. Once the rover has entered the cave, communication will be lost, and all actions have to be performed autonomously. Another problem is that the localisation of the rover may suffer due to the existence of narrow entry points. For this purpose the rover might use artificial landmarks to improve localisation and mapping performance. Caves will likely provide an extreme environment in terms of terrain difficulty. In this defined scenario, the robot has the ability to use the local map data gathered so far of the environment, to perform an on-board physical simulation of the next steps. In this way, a motion plan can be verified prior to execution, improving the safety of the system. Once the required information on the cave has been gathered, the system will exit the cave and transmit the data back to the ground station.

3. EXPLORATION TECHNOLOGIES

This section provides an overview of the key technologies which are used in order to complete the reference mission scenario.

3.1. Closed Loop Planning

To enhance the robustness of the system, we introduce a new technique that we call "Close loop planning". For now, most systems use a motion planner that is completely decoupled from the execution of the motion plan. E.g. the motion plan is generated, and through constrains in the planning phase, it is assumed, that the robot can execute the motion plan. This system fails as soon as the information on which the motion plan was generated is faulty, or if the system model used by the planner does not represent the robot exactly. A good example for a failure would be a robot on loose sand, which is digging itself in, because the planner assumes that the ground is solid. Situations like this are inevitable, as sensor information will most probably never be completely correct. Therefore we add a technique that enables the robot to detect faulty plans, and to recover from such situations.

The basic idea of the "Close loop planning" is to provide feedback to the planner about the execution of the motion plan (see Fig. 3). In the terms of the motion planner, every (discretized) motion command corresponds to a edge in the motion plan, that connects a state to a following state. Here the current position and orientation correspond to the initial state in the plan and the goal target position and orientation correspond to the last state in the plan. For every state, there is a set of motion commands available, that moves the robot in a follow-up state. During the planning it is assumed, that the motion command

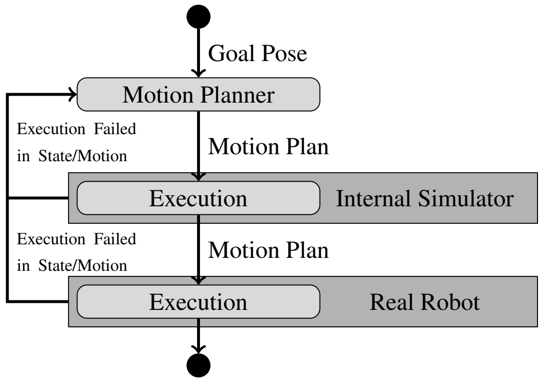

Figure 3. The Closed Loop approach integrates validation from simulation (through the Internal Simulator) and from real execution (through supervision).

can be executed with a given uncertainty. E.g., if we issue a drive forward for 10 cm we assume that the robot moves 10 cm forward with a margin of ± 1 cm. A complete motion plan is a sequence of states connected by motion commands that move the robot from the start state into the goal state. The plan, including the allowed uncertainty in the plan is forwarded to the motion execution. The motion execution part now tries to follow the given plan as close as possible while monitoring if the robot exceeded the given uncertainty boundaries. If the robot does not execute the motion as predicted, the execution is stopped, and the current state in the motion plan, and the failed motion is reported to the planner. The planner now locks the failed edge for the current state and generates a motion plan, were the failed edge is not used. This loop will continue, until either the robot left the current state, or until no motion that would leave the current state is available any more. For the example of the loose sand from above this would mean that the robot would try out to get out of the sand, and in case it does not succeed, it will stop moving at all, which is a wanted and valid behavior in this case.

3.2. Internal Simulation

In space robotics missions the final systems cannot be tested in their target environment before actual deployment. This motivates the research of technologies that will enable the system to better predict its whole behavior and future states when performing certain chain of actions (e.g. [21]). The proposed approach aims to simulate the whole complexity of interactions between the robot and the environment so that the provided plans can be validated or rejected before its real execution.

In the context of this project the main use of the internal simulation will be to validate motion plans (atomic components of a mission plan) and mission plans. In the first case, the so called distance horizon of the simulation is very short and the simulators response must be realtime because the robot might be in a non-stable state. On the other hand, in the case of whole missions validation the process of simulating is in principle allowed to take longer, because the robot will normally be in a idle and safe state.

The simulation system will integrate a resolution control to trade off the simulation speed against the simulation accuracy in terms of the computational capability of the robots and the requirements of the particular validation case. For instance, in cases where the system is subjected to high risks the simulation will run as fast as possible, whereas in the cases where a high accuracy is required, such as a navigation on steep and unknown surfaces, the simulation will execute slowly with higher resolution to improve the success of the action.

A useful internal simulator must provide a realistic emulation of the execution. This requires the integration of the physics dynamics of the world, a realistic simulation of the robot and the execution of the exact same software running on the real execution.

The generation of realistic simulations of the environment based on the environment representation that the robot generated is crucial. Thus, one of the scopes of the project is to highly integrate the simulation engine with the environment representation (e.g. 3D visual map based on the multi-level laser scan data, surface properties, robot kinematics and current status).

The Entern simulation system will provide a heterogeneous dynamics simulation environment where rigid-body dynamics, flexible dynamics, soil contact dynamics, and actuator/sensor dynamics are feasibly integrated together. This simulation system covers detailed physical simulations of the Asguard, CREX robots, and their contact dynamics on rigid and soil surfaces.

The internal simulation (on-board simulation) has the same capabilities as the simulation used for the mission control station for the operator.

3.3. Mission Control Station

The Mission Control station integrates telemetry data visualisation and robot control in a single, combined 3D visualisation. For example, the robot model is displayed within a 3D map of the environment generated by the on-board sensors and is also controlled from this view. This gives the operator the opportunity to use several view points in the environment to control the robot, also those which are normally impossible, like a birds eye view.

Remote controlling robots without a direct line of sight is a challenging task. Especially on planetary missions, high command transmission delays is rendering direct remote control impossible. Robots are controlled by either sending trajectories, command sequences or goal positions [22].

Entern wants to create these trajectories by aid of a simulation within the Mission Control Station. Therefor a simulation environment is generated based on the robots telemetry. Afterwards the software state of the robot is requested and duplicated in the ground station, were only the components for sensors and actuators are replaced by simulated ones. Through this system it is possible, to generate a very accurate prediction of how the robot would react to given commands. The system also allows to revert simulation / software states thus allowing the evaluation of multiple possible commands without harm to the robot itself. The telemetry from the simulation is directly fed to the visualisation of the environment. After selecting a solution, it is sent to the robot and the visualisation is switched back to the live telemetry. This means the operator can switch to the simulation mode at any time, and switch back to remote control after a decent solution within the situation is found.

The generated trajectories sent to the robot are re-checked and monitored by the internal simulator of the robot on location. In this way, the robot can react to situations where its updated environment model does not fit the environment model used to create the trajectory any more. The robot can either use its internal simulation and planning to find a new solution or await a new trajectory from the operator.

3.4. Environment representation

Environment perception is a key functionality for the robot to navigate across unknown environments. State-of-the-Art representations of such environments are suitable for the robot to navigate and construct the environment while driving (e.g.: SLAM). However the interchange of such information among robotic subsystems is mostly limited or some cases impossible. The robot collects and generates rich amount of perceptive data while driving across the terrain. When performing isolated or complicated tasks like localization and mapping the same environment representation might be used with almost zero cost. Conversely, when robots perform complex mission scenarios other subsystems (i.e.: perception, planning, internal simulation, telemetry, etc.) have the requirements to actively inter- and exchange information in an effective manner.

Environment Representation (EnviRe) technologies are meant to close the gap and provide techniques to store, operate and interchange information within a robotic system. The application of EnviRe mainly focus to support navigation, simulation and operations and simplify the interchange of algorithms among software components.

3.5. Fail-Safe Strategies

For autonomous systems that operate inaccessible in an unknown environment, the robustness of the whole system is a crucial aspect. Various hardware and software components of a robotic system (e.g., drivers, planner) may fail caused by different reasons like hardware faults or misconfiguration. Such errors can be recovered by reinitializing or reconfiguring components with default settings.

We therefore propose a supervision module that continuously monitors dedicated states of the components and that, in case of the occurrence of predefined error states, executes emergency strategies to counteract these failures. For this purpose possible error states are defined per component and one or more possible solutions to recover into a normal state are stored alongside these error states. When an error state is detected, the related emergency strategy is executed. The success of an emergency strategy is monitored and in case the normal state could not be recovered by this strategy the next assigned strategy is executed.

4. EVALUATION SCENARIOS

The validation of the implemented technologies will be performed in scenarios where hard challenges similar to those of a robotics autonomous mission on an extraterrestrial planet are present (e.g. robust cave exploration).

One main evaluation point is the navigation capabilities enhancement achieved with the simulation integration, the close-loop planning approach and the fail-safe strategies. Another important goal is to evaluate the approach for the control of operations from a station distant to the deployed system. Though still on earth, communication related challenges will arise due to bandwidth specificities and the connection breaks in certain areas (e.g. inside lava tube). Finally, the environment representation models will be evaluated by planning and navigating in complex structures like caves with steep and irregular surfaces.

The final demo scenarios presented are different in their morphology but the missions themselves share a common agenda: First, the robot sends its state and this is received in the ground control station. Second, the operator selects the mission to achieve. The operator will have the possibility to evaluate or modify the mission and how it will be performed. Then, the mission is sent. Once received, it is internally simulated by the robot and if it is validated then it will be executed.

Each evaluation mission is divided in motion plans which will be always simulated before its execution. If no communication is available, then the robot will select the motion plan based on the planner's policy and the results from the internal simulation. If communications are available, then operator can manually modify these motion plans. If a motion plan fails on its execution phase and no alternative motion is possible, or if some unexpected error occurs, then the error handling and the fail-safe strategies will attempt to recover from the failure.

Figure 4 depicts the sequence of activities common to all evaluation scenarios.

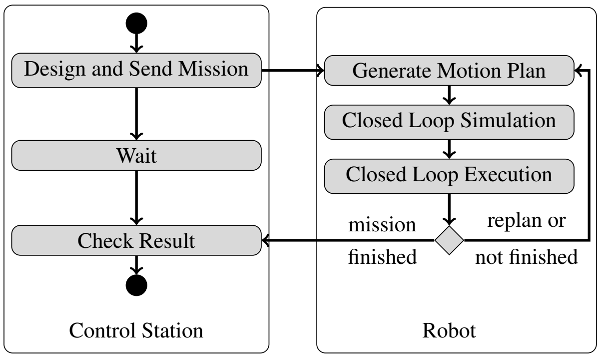

Figure 4. Activity diagram of the final validation scenarios.

Figure 5. The Bunker Valentin share some common features with caves and space exploration scenarios: Unstructured terrain, narrow corridors, complex morphology and areas where communication is impossible. This picture was taken in one of the areas where the robots will be deployed for evaluation.

The first evaluation scenario is an abandoned submarine bunker close to Bremen (Germany) [23]. This site was chosen because it is semistructured and has several cave-like features like narrow corridors and multiple levels (see Fig. 5).

The roof is partially destroyed and because of the rubble some of corridors offer surfaces similar to those in lava tubes or craters. The generation of a map of this environment will be challenging and similar to some extent to the case of the cave: with different levels that have to be represented.

Thus, the most challenging issues of this scenario are expected to be those related with the environment representation and navigation.

Another interesting feature of this scenario is that the communication constraints resembles the case of a cave or a lava tube due to the thickness of its walls.

The second evaluation site is a lava tube located in the

Figure 7. Entrance to the cave. The system will find and access the cave autonomously. Courtesy of Organismo Autónomo de Museos y Centros de Tenerife, photo: Sergio Socorro

foothills of Mount Teide (in Tenerife, Canary Islands). The *Cueva del Viento-Sobrado*[24] is the largest lava tube in the European Union. It contains a large variety of geological structures (e.g. lava stalactites). The selected area to explore is named *Breveritas* and has a total length of 259 m. The average slope is $9.2°$ having two maximum inclination of $23.6°$ and $16°$. Those locations correspond to lava cascades which have particular geological interest (see Figure 6).

The mission will start with the robot deployed with a distance of around 30 m from the entrance of the cave. The geo-referential localization of the robot along with its state (including environment representation) will be sent to the Control Station. From the Station the mission to find and enter the cave will be designed and sent. The robot will use its geo-referential knowledge and its self localization algorithm to find the cave entrance. Then it will access it (Figure 7 shows the entrance). Then, a first cave exploration of about 100 m will be performed. The robot will traverse the planned distance, get back outside and send the produced environment representation of the cave. This representation the environment, once received by the operator will be used to plan a second mission. In this mission the robot will perform a directed exploration, constrained by its limitations. The system decides based on its internal simulation, and the details of the exploration, taking into account different constraints (e.g. get back outside before the battery level is low).

The mission control will be performed from Germany. The Operations Control Station will be particularly stressed in this demonstration scenario as well as the robustness of the communication software. Inside the cave no communication will be possible with the station and outside it the bandwidth will be limited and cuts may take place. The autonomous safe navigation inside and in the entrance of the cave, along with the generation of a precise 3D map of the cave are also hard challenges of this mission.

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REFERENCES

[1] Andrew Daga, Carlton Allen, Melissa M. Battler, James D. Burke, Ian A. Crawford, Richard J. Léveillé, Steven B. Simon, and Lin Tze Tan. Lunar and Martian Lava Tube Exploration as Part of an Overall Scientific Survey. 2009.

[2] Markus Eich, Felix Grimminger, Stefan Bosse, Dirk Spenneberg, and Frank Kirchner. Asguard: a hybrid legged wheel security and sar-robot using bio-inspired locomotion for rough terrain. In *IARP/EURON Workshop on Robotics for Risky Interventions and Enviromental Surveillance*, 2008.

[3] Sebastian Bartsch, Timo Birnschein, Malte Römmermann, Jens Hilljegerdes, Daniel Kühn, and Frank Kirchner. Development of the sixlegged walking and climbing robot SpaceClimber. *Journal of Field Robotics*, 29(October 2008):506–532, 2012.

[4] TM Roehr, F Cordes, and F Kirchner. Reconfigurable Integrated Multirobot Exploration System (RIMRES): Heterogeneous Modular Reconfigurable Robots for Space Exploration. *Journal of Field Robotics*, 2014.

[5] GE Cushing, TN Titus, and E Maclennan. Orbital observations of martian cave-entrance candidates. *LPI Contributions*, 1640:12, 2011.

[6] JW Ashley, MS Robinson, BR Hawke, AK Boyd, RV Wagner, EJ Speyerer, H Hiesinger, and CH van der Bogert. Lunar caves in mare deposits imaged by the lroc narrow angle cameras. *LPI Contributions*, 1640:2, 2011.

[7] Andrew W Daga, MM Battler, JD Burke, IA Crawford, RJ Léveillé, SB Simon, and LT Tan. Lunar and martian lava tube exploration as part of an overall scientific survey. 2009.

[8] JW Ashley, AK Boyd, H Hiesinger, MS Robinson, T Tran, CH van der Bogert, RV Wagner, et al. Lunar pits: sublunarean voids and the nature of mare emplacement. In *Lunar and Planetary Science Conference*, volume 42, page 2771, 2011.

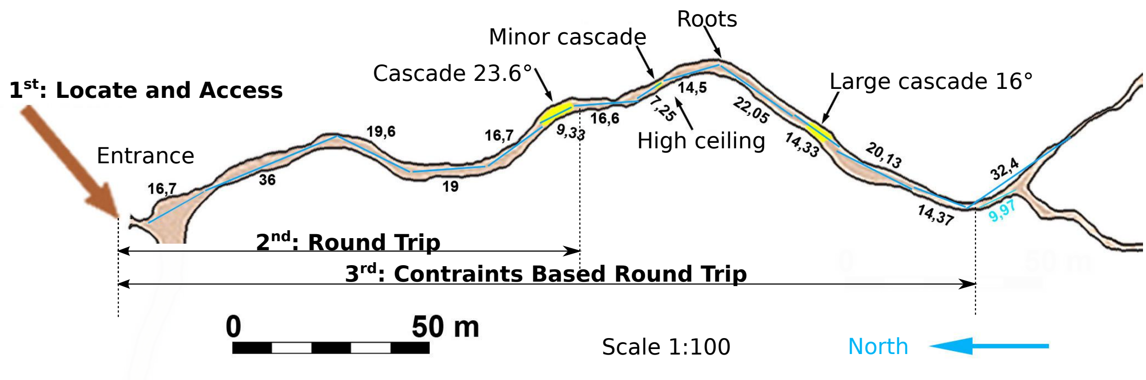

Figure 6. Traversal view of the lava tube in which the system will perform exploration and 3D mapping in three phases: Find and Access (1), Position Based Exploration (2) and Constraints Based Exploration (3). The numbers are distances (in meters) taken with a measuring tape inside the cave. Original map Courtesy of Organismo Autónomo de Museos y Centros de Tenerife, map: Sergio Socorro

[9] Ammar Husain, Heather Jones, Balajee Kannan, Uland Wong, Tiago Pimentel, Sarah Tang, Shreyansh Daftry, Steven Huber, and William L Whittaker. Mapping planetary caves with an autonomous, heterogeneous robot team. In *Aerospace Conference, 2013 IEEE*, pages 1–13. IEEE, 2013.

[10] Samuel B Kesner, Jean-Sébastien Plante, Penelope J Boston, Tibor Fabian, and Steven Dubowsky. Mobility and power feasibility of a microbot team system for extraterrestrial cave exploration. In *Robotics and Automation, 2007 IEEE International Conference on*, pages 4893–4898. IEEE, 2007.

[11] Jim C Werker, SM Welch, SL Thompson, Barbara Sprungman, Val Hildreth-Werker, RD Frederick, and Penelope J Boston. Extraterrestrial caves: Science, habitat, and resources (a niac phase i study). 2003.

[12] Richard J Léveillé and Saugata Datta. Lava tubes and basaltic caves as astrobiological targets on earth and mars: a review. *Planetary and Space Science*, 58(4):592–598, 2010.

[13] P. J. Boston, R. D. Frederick, S. M. Welch, J. Werker, T. R. Meyer, B. Sprungman, V. Hildreth-Werker, and S. L. Thompson. Extraterrestrial Subsurface Technology Test Bed: Human Use and Scientific Value of Martian Caves. In M. S. El-Genk, editor, *Space Technology and Applications*, volume 699 of *American Institute of Physics Conference Series*, pages 1007–1018, February 2004.

[14] David J Des Marais, Joseph A Nuth III, Louis J Allamandola, Alan P Boss, Jack D Farmer, Tori M Hoehler, Bruce M Jakosky, Victoria S Meadows, Andrew Pohorille, Bruce Runnegar, et al. The nasa astrobiology roadmap. *Astrobiology*, 8(4):715–730, 2008.

[15] KM Peterson, HL Jones, and WL Whittaker. Mission design for combined lander-rover modeling of a skylight. *LPI Contributions*, 1640:29, 2011.

[16] I. Siles and I.D. Walker. Design, construction, and testing of a new class of mobile robots for cave exploration. In *Mechatronics, 2009. ICM 2009. IEEE International Conference on*, pages 1–6, April 2009.

[17] Jonathan A Meyer. *New methods for the discovery and characterization of lunar lava tubes using Lunar Reconnaissance Orbiter data*. The University of Texas at El Paso, 2012.

[18] Ronald Greeley. Lava tubes and channels in the lunar marius hills. *The Moon*, 3(3):289–314, 1971.

[19] DP Cruikshank and CA Wood. Lunar rilles and hawaiian volcanic features: Possible analogues. *The Moon*, 3(4):412–447, 1972.

[20] Cassandra R Coombs and Bray Hawke. A search for intact lava tubes on the moon: Possible lunar base habitats. In *Lunar Bases and Space Activities of the 21st Century*, volume 1, pages 219–229, 1992.

[21] Jürgen Roßmann, Eric Guiffo Kaigom, Linus Atorf, Malte Rast, Georgij Grinshpun, and Christian Schlette. Mental Models for Intelligent Systems: eRobotics Enables New Approaches to Simulation-Based AI. *KI - Künstliche Intelligenz*, 28(2):101–110, March 2014.

[22] Jeffrey J Biesiadecki, Eric T Baumgartner, Robert G Bonitz, Brian K Cooper, Frank R Hartman, P Chris Leger, Mark W Maimone, Scott A Maxwell, Ashitey Trebi-Ollenu, Edward W Tunstel, et al. Mars exploration rover surface operations: Driving opportunity at meridiani planum. In *Systems, Man and Cybernetics, 2005 IEEE International Conference on*, volume 2, pages 1823–1830. IEEE, 2005.

[23] Bunker Valentin Memorial Homepage. http://www.denkort-bunker-valentin.de, 2015.

[24] Cueva del Viento-Sobrado Homepage. http://www.cuevadelviento.net, 2015.