Global Space Exploration Conference (GLEX 2021), St Petersburg, Russian Federation, 14-18 June 2021.

Subsurface exploration on Mars and Moon with a robotic swarm

Ban-Sok Shin, Dmitriy Shutin

German Aerospace Center, Institute of Communications and Navigation, Muenchener Strasse 20, 82234 Wessling, Germany, ban-sok.shin@dlr.de, dmitriy.shutin@dlr.de

Abstract

Subsurface exploration has been identified as a key component for understanding planetary evolution and geology, as well as searching of possible life beyond Earth. Both on Mars and Moon subsurface structure remains largely unexplored. Future exploration missions therefore aim for a detailed exploration of the planet's subsurface to prepare landing/base sites, or in case of Mars shed light on the question of life existence. For future exploration missions, we envision the use of multiple mobile robots for subsurface exploration that operate as an intelligent, cooperative swarm. Such a multi-robot system shall perform seismic surveys in a cooperative and autonomous fashion. Each robot is equipped with an active signal source for the seismic experiment, a geophone and communication and navigation units. Robots are then able to communicate with each other in order to decide for the next sampling position and to cooperatively reconstruct the subsurface. Such a swarm of mobile robots enables a larger sensing aperture and therefore a larger acquisition of samples and a faster subsurface reconstruction. Besides, the swarm is resilient against failures of robots since its functionality does not depend on a single entity as in single robot systems. The development of seismic reconstruction algorithms and exploration strategies that function in a distributed fashion within the multi-robot system will play a central role of our research activities. In this paper, we present the basic idea of our exploration concept and show first algorithmic results for subsurface exploration by a multi-robot system.

Keywords: subsurface exploration, robotic seismic survey, full waveform inversion

Acronyms/Abbreviations

Full waveform inversion (FWI), adapt-then-combine full waveform inversion (ATC-FWI)

1. Introduction

The subsurface of Mars and Moon is likely to contain a variety of significant structures or materials such as water, ice, lava tubes or underground caves. Water and ice are indicators for past or present life in the case of Mars. Lava tubes or caves can play a significant role for building future human habitats on Moon. However, both the Martian and Lunar subsurface is largely unexplored. Hence, appropriate exploration systems are required that deliver a detailed view of the interior of those planets. Current exploration missions include systems that shall quantify a planet's subsurface. For instance, missions as ExoMars [1] or Mars2020 [2] plan to equip robots with ground penetrating radar for the exploration of the Martian subsurface to search for ice or water. Moreover, NASA's Dragonfly mission launching in 2026 plans the use of a single drone equipped with a seismometer to measure seismic activity on Titan [3]. However, ground penetrating radar is known to be limited in the resolvable depth and can therefore provide images up to several meters in depth only. Furthermore, single robot systems require long recording times and are limited in their sensing aperture to image deeper structures. However, resolving deeper structures is decisive for planetary subsurface exploration. For instance, lava tubes or underground caves on the surface of Moon or Mars usually lie in areas around 50 – 100m depth.

For future planetary missions, we envision the use of multiple mobile robots for an active seismic survey. In comparison to single robot systems a swarm will enable a faster and more efficient survey. Furthermore, in addition to currently used ground penetrating radar techniques, we propose the use of reflection and refraction exploration techniques that allow for a reconstruction depth up to several 100m. In this paper, we will describe the idea of our envisioned exploration system and show numerical results that demonstrate the feasibility to perform subsurface imaging within a network of multiple agents.

2. Proposed seismic exploration concept

2.1 Overview of concept

We propose the use of multiple mobile robots operating as a swarm for planetary subsurface exploration. Each robot is equipped with a geophone to record seismic traces and with a wireless communication module that allows data exchange among the robots. Thanks to the communication backbone, the robots build a communication network that is essential for an operation as a swarm. Furthermore, the communication backbone allows for in-network processing of the measurement data. Such data processing in combination with imaging algorithms can be used to obtain a subsurface image at each robot in the network by a data exchange among connected robots.

In contrast to passive seismic surveys that rely on natural sources, we propose the use of an active seismic survey by applying an external force to the area of interest. To this end, one or more robots can act as active seismic source by using e.g. a weight-dropping system to inject seismic waves into the subsurface. Active seismic survey for Mars and Moon has been also proposed by [4]. Figure *1* gives an illustration of our proposed seismic exploration concept.

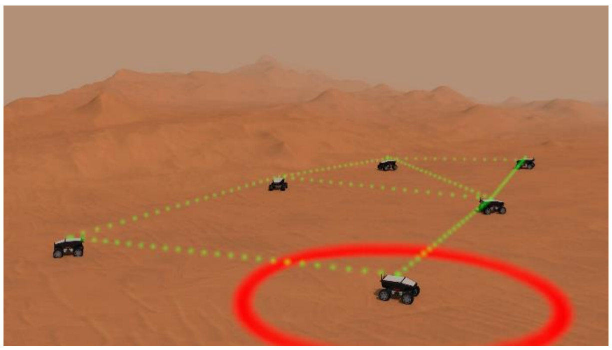

Figure 1: Illustration of concept for seismic exploration by a multi-agent system.

2.2 Swarm localization and topology adaptation

To process the seismic data adequately for an imaging, measurement locations need to be known, i.e., each robot needs to know the positions of the other robots in the network. This can be achieved by distributed swarm localization algorithms [5] that operate in environments where no GPS data is available such as on Mars or Moon. The localization procedure is realized using wireless communication techniques in combination with particle filters that provide the locations of the robots. Positioning of the robots is also important for an optimization of the survey. Using a swarm of mobile robots allows us to adapt the sensing topology depending on the subsurface to be explored. Hence, movement strategies can be developed that assign optimal sampling positions to the robots in order to improve the imaging result or specific regions of the image. With a reconstructed subsurface image available at each agent, such a movement strategy can be realized using e.g. concepts from optimal experiment design [6].

2.3 Subsurface imaging methods

To obtain an image of the subsurface using the seismic measurements in the network, imaging methods are required. In general, seismic imaging can be separated based on two methodologies. The first methodology is travel time tomography [7]. This technique exploits the arrival times of the reflected and refracted waves at the geophones. Based on an initial model of the subsurface, synthesized arrival times of seismic waves are computed for each geophone position. These synthesized arrival times are compared to the actual measured travel times and a residual error is evaluated. By minimizing this residual error with respect to a subsurface parameter such as velocity, the initial model can be iteratively refined until a satisfying image is achieved. Travel time tomography usually relies on the Eikonal equation to determine travel times and iterative methods exist that solve the equation efficiently [8].

The second methodology is known as full waveform inversion (FWI) [9]. Here, instead of travel times the full measured seismic traces are exploited. Using an initial subsurface model and the elastic or acoustic wave equation seismic measurements at the geophone positions are computed and compared to the actual measurement data. Again, a residual error is evaluated between synthesized and measured seismic traces. Iterative minimization of this error is then used to adapt the initial subsurface model to resemble the true subsurface model. Compared to travel time tomography, full waveform inversion achieves higher resolution images of a subsurface but is sensitive in its iterative optimization due to strong non-convexity and high non-linearities. On the other hand, travel time tomography is less prone to getting stuck at a local minimum, but can only resolve structures that are larger than the first Fresnel zone [10].

3. Numerical results

In the following, we show numerical results from a distributed processing procedure that is combined with FWI. The corresponding algorithm is the so-called adapt-then-combine full waveform inversion (ATC-FWI) that has been proposed by the authors in [11]. It employs the FWI imaging method and diffusion-based information exchange [12] as distributed procedure to obtain a subsurface image at each robot. It is therefore essential for an autonomous seismic survey by a robotic swarm.

Figure 2 depicts the simulation setup with 20 static receivers and seven sources placed on the surface of the considered area. The receivers are placed in a line array to obtain a 2D image of the subsurface. Figure 2-a shows the ground truth distribution of the P-wave velocity in the subsurface with a rectangular anomaly in its centre. Figure 2-b depicts the starting model which is assumed to be known to each receiver. Figure *3* shows the imaging results using ATC-FWI for three receivers in the line array. The result of the centralized FWI in Figure *3*-d assumes that all seismic measurements are available at one entity and that FWI is performed on all measurements at once. It therefore represents the benchmark performance for the ATC-FWI results. As we can observe, the imaging results at different receivers highly resemble the centralized imaging result. In particular, receiver no. 10 achieves an image where no differences to the centralized result are observable. This is due to the fact, that receiver no. 10 is placed in the centre of the line array and therefore has more connected neighbouring receivers than receiver no. 1 and no. 20.

As can be seen, the ATC-FWI enables a distributed imaging of subsurface in a network of seismic receivers. It marks a first step towards an autonomous seismic survey by a robotic swarm.

4. Conclusion

In this paper, we proposed a concept for future planetary subsurface exploration on Mars or Moon by a robotic swarm. Using a swarm of robots that performs an active seismic survey in a cooperative manner provides higher efficiency and flexibility for subsurface imaging. However, to cooperatively obtain an image at each robot in the network, current imaging methods need to be adapted to include distributed computation techniques. We showed numerical results for a full waveform inversion in combination with distributed computation techniques to achieve a global image of the subsurface at each robot.

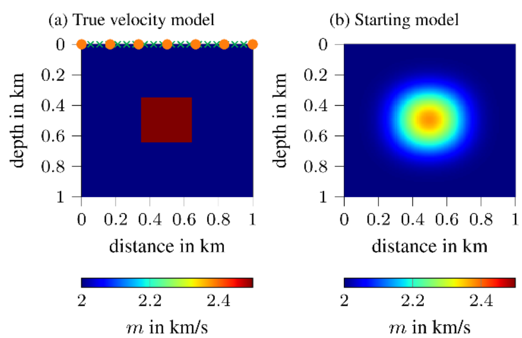

Figure 2: (a) Ground truth P-wave velocity model. Crosses indicate geophone positions, circles indicate source positions. (b) Starting P-wave velocity model for each receiver.

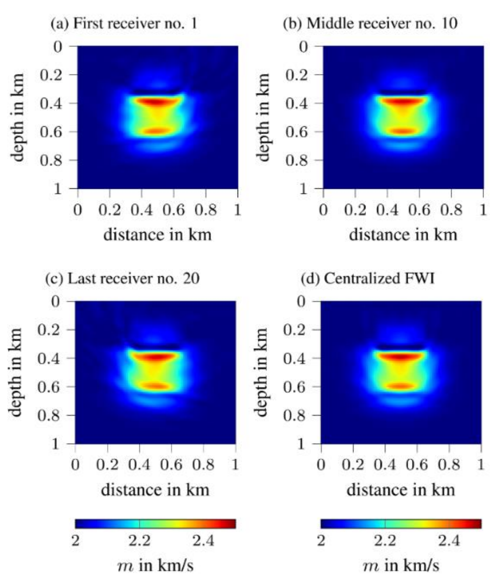

Figure 3: (a)-(c) Imaging results of ATC-FWI and (d) of centralized FWI.

References

[1] ESA. Esa exomars rover. https://exploration.esa.int/s/WLdR7oW

[2] NASA. Radar imager for mars' subsurface exploration (RIMFAX). https://mars.nasa.gov/mars2020/mission/instruments/rimfax/

[3] NASA. Dragonfly mission. https://dragonfly.jhuapl.edu/index.php

[4] S. W. Courville et al., ARES: The autonomous roving exploration system for active source seismology on the Moon and Mars. *In 51st Lunar and Planetary Science Conference, 2020.*

[5] E. Staudinger et al., Swarm technologies for future space exploration missions. *In 14th International Symposium on Artificial Intelligence, Robotics and Automation in Space, June 2018*

[6] V. Fedorov, *Theory of optimal experiments.* Academic Press, 1972.

[7] D. White, Two-Dimensional Seismic Refraction Tomography. *Geophysical Journal International, 97(2), 223–245, 1989.*

[8] E. Treister, E. Haber. A fast marching algorithm for the factored eikonal equation. *Journal of Computational Physics, 324, 210–225, 2016*.

[9] A. Tarantola. Inversion of seismic reflection data in the acoustic approximation. *Geophysics, 49(8):1259–1266, 1984.*

[10] L. Guasch et. al. Full-waveform inversion imaging of the human brain. *Npj Digital Medicine, 2020.*

[11] B.-S. Shin and D. Shutin. Adapt-then combine full waveform inversion for distributed subsurface imaging in seismic networks. *IEEE International Conference on Acoustics, Speech and Signal Processing, June 2021*.

[12] A. H. Sayed. Adaptive networks. *Proceedings of the IEEE, 102(4):460–497, Ap*