NEAR-SURFACE SEISMIC EXPLORATION OF PLANETARY BODYS WITH ADAPTIVE NETWORKS

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Brief Presenter Biography: Ban-Sok Shin received his Doctoral degree in electrical engineering/information technology (with distinction) from the University of Bremen, Bremen, Germany, in 2020. From 2013 until 2019 he was a Doctoral candidate with the Department of Communications Engineering, University of Bremen, where he worked on distributed nonlinear estimation schemes. Since 2019 he is a postdoctoral researcher in the Swarm Exploration Group at the Institute of Communications and Navigation of the German Aerospace Center, where he is currently working on seismic subsurface exploration using a multi-agent network. His research interests include seismic imaging, distributed inference/estimation, machine learning, and their application to sensor and multi-agent networks. Dr. Shin received the OHB Award for the best Doctoral thesis in the faculty of Electrical Engineering of the University of Bremen in 2021.

Introduction: Ground motion observations on planetary objects (planetary seismology) are a prerequisite for a detailed understanding of their interior structure and evolution. On all Apollo missions from 1969 to 1972 seismometers were installed on the moon and led to important discoveries of Moon's deep earthquakes, its internal structure, as well as its near surface material properties. Several attempts to build on these early missions and deploy seismic sensors on other planets failed until in November 2018 the INSIGHT mission landed successfully on Mars deploying a single site setup with a 3-component broadband and a 3-component short-period sensor that both operate ever since. Despite the relatively moderate seismic activity a number of revolutionary new discoveries could be made [1], [2, and special issues].

In the past few years the dramatic progress of commercially operated spacecraft (e.g. SpaceX), the success with reusable rocket engines, as well as the international competition (USA, Europe, India, China) to explore space, has led to a substantial acceleration of activities in the design and preparation of ambitious future space mission. It is likely that following unmanned exploratory missions to Moon and Mars manned outposts will follow. Half a century after the Apollo missions, several lunar missions are planned including the Commercial Lunar Payload Services (CLPS), the Lunar Geophysical Network (LGN), and the Artemis Program. Spacecraft technology is evolving such that in the near future payload restrictions are likely to further decrease. To prepare for future manned and unmanned observatories, potential sites will be explored with geophysical means. This may involve gravity, electro-magnetic, and seismic observations.

Active seismic experiments are ideal to image the near surface structure of planetary objects. The imaging of the near surface structure - in particular on the moon - has strong practical implications. First, the race is on to detect ice-bearing rocks near the surface from which water could be extracted and used as a resource for manned missions [3], [4]. Second, due to the substantial bombardment of the lunar surface with meteorites due to the lack of an atmosphere, observatories or habitats may have to be build underground. It has been proposed that cavities from ancient lava flows exist below the lunar surface that could be used as natural cavities in which to place infrastructure [5].

The current mission plans with geophysical exploration focus on static seismic sensor (arrays) that would be restricted in the area they can explore. This abstract shortly summarizes the proposal of German Aerospace Center, Ludwig-Maximilians University Munich and Technical University Munich to go beyond these restrictions and develop concepts for mobile seismic arrays that work in an autonomous way using robot technology.

The focus of the proposed project is on aspects of experimental design and optimization of the seismic sensing topology as well as on automated data processing and analysis, rather than robotic aspects. The scientific challenges include the **understanding of wavefield effects** of icy rocks and caves in a strongly scattering environment, the provision of **optimal source-receiver configurations** to detect them, as well as an **integrated data-processing work flow** from observation to subsurface image including the **quantification of uncertainties**. The outcome will be detailed technical specifications that can support the hard/soft implementation of the entire system in future missions.

In the following we will outline two main aspects of the proposed project in more details. First, it is investigations related to planetary seismology as one of the planetary exploration tools; second, it is the realisation of this tool on multi-robot system, which allows to introduce adaptivity into a seismic sensing.

Planetary seismology: Seismology is one of the most important tools for near surface imaging not only on our planet Earth but also on extraterrestrial bodies like the Moon and Mars. During the Apollo lunar missions five seismometers were deployed on the near side of the Moon between 1969 and 1972 [6], [7], four of them operating continuously until 1977. Despite the sparsity of this lunar seismic network, important conclusions on the internal structure and seismic sources could be drawn [8]: deep moonquakes [9], [10], the periodicity of seismic activity due to tides [11], [12], [10], as well as extremely strong scattering and low attenuation near the surface for wavefields generated by impacts [9]. However, precise data analysis was hampered by a lack of sensitivity of the deployed seismometers as well as by unstable time synchronization of recording systems [13].

From the late 1970s it took more than 40 years until another milestone in planetary seismology was reached: In November 2018 the NASA's InSight (Interior exploration using Seismic Investigations, Geodesy, and Heat Transport) mission deployed a set of geophysical instruments on the surface of Mars. The InSight scientific payload includes the Seismic Experiment for Interior Structure (SEIS; [14], [1]) that records seismic activity on Mars. This single-point setup has allowed a large range of interesting seismic observations from the thermal effects on the lander, local to regional marsquakes, dust storms, as well as wavefields generated actively by the (eventually failed) attempts to push the heat probe into the Mars surface [15], [1], [2], [14]. The processing of the InSight data enabled the location of marsquakes, and the determination of some internal boundaries from travel-time inversion, as well as receiver function analysis [16]. The InSight observations have also highlighted the strong impact of rotational motions (e.g., induced by atmospheric effects or lander vibrations (Philippe Lognonné, personal communication) motivating the future inclusion of rotational motion sensing in mission concepts, as envisaged in the EU-funded PIONEERS project [17].

The ongoing race to explore the moon as a first human outpost on the way to Mars leads to a number of preparatory measures that are planned using unmanned missions. These include identification of appropriate landing sites, the search for water (ice) in the near-surface rockmass, and the identification of possible subsurface cavities that may allow lowering manned observatories and protecting them from impacts. To achieve these goals imaging methods need to be devised that lead to experimental setups that are realizable in the next decades. From a physical point of view, gravitational, electromagnetic, and seismic wavefields provide observables that may allow constraining the desired types of structural heterogeneities. It is expected that ground-penetrating radar and active seismic imaging have similar resolution power of the near-surface. In our proposal we focus on the seismic wavefield imaging, further exploring recent progress in including wavefield gradient observations that improve the resolution of near-receiver subsurface structure [18], [19].

It is well-known that seismic wavefields on the Moon have a very different character compared to Earth: due to the lack of any water molecules in the rock mass, the intrinsic attenuation of the seismic wavefield is dramatically reduced [20], [21], [22]. On the other hand, due to the bombardment with interplanetary objects and the lack of atmosphere and weathering phenomena, the top part of the lunar crust is highly shattered (regolith) and characterized by extreme scattering. This poses a tremendous challenge for seismic imaging problems, that we aim to explore in this project. On the other hand, the strong scattering offers the opportunity to make use of coda interferometric methods, that allow the estimation of impulse functions between station pairs of seismic networks [23], [24], [25] that can be used to image subsurface structure. Applications on lunar seismograms have been reported by [26], [27]. We further aim at breaking new ground with exploring the potential of direct gradient observations (strain, rotations) in this interferometry-based imaging workflow with the specific application to lunar seismic experiments.

Data science technologies (in particular supervised deep-learning approaches) are entering the field of seismic inverse problems in particular with the opportunity to dramatically reduce the computational requirements and speed up the time-to-image at the expense of a previously well-trained neural network. This tool set will be explored in the project when optimizing imaging [28] and experimental design [29] procedures towards a potential implementation in an autonomous, mobile robotic array setting. It is clear that a lunar active seismic experiments will have to minimize data size and computational requirements with compressive sensing concepts [30].

To test these concepts, high-end wave simulation technologies are required. To this end, parallel solvers that are implemented on a local cluster (including GPU technology) as well as SuperMUC-NG, the supercomputer at the Leibniz Rechenzentrum Munich) will be used. Random seismic wavefield calculations in 3D are computationally expensive, have only recently been possible, and they themselves constitute an active research field. However, it is straight forward to initialize lunar models with random heterogeneities of appropriate statistical properties [22] and access to large-scale supercomputers enables the calculation of synthetic wavefields in realistic frequency ranges. The problem of imaging in such scattering media is substantially less well developed.

In summary, this leads to the following *seismological* research questions with specific applications to lunar seismology:

- What is the most efficient way to model near-surface wave propagation through strongly scattering media (regolith)?
- What are characteristic observables of ice-bearing rocks, cavities, and other relevant objects in strongly scattering media (regolith)?
- What are optimal observables, experimental and inversion strategies to image subsurface structures under such conditions?
- What criteria can be defined that can steer an autonomous mobile seismic array towards exploring relevant structures?

Multi-Agent Seismic Exploration: Ever since the successful landing of the Sojourner rover on Mars in 1997 robotic platforms have been indispensable for planetary exploration missions. However, only recent missions such as InSight [14], [1], ROSETTA [31] or the Mars2020 Perseverance have included instruments that acquire seismic or electro-magnetic data either passively or actively (e.g. ground penetrating radar, active seismics). For further planetary missions such as ExoMars or Dragonfly seismic data instruments build an essential part of the platforms.

The aforementioned missions employ a single robotic platform. However, for future planetary missions we envision the use of multiple robotic platforms that are specifically designed to image a planet's subsurface in a cooperative and autonomous manner. Such a multi-agent concept for seismic exploration has been e.g. proposed by the Planetary Science Institute (PSI), USA, that will act as a scientific partner in this proposal. The proposed Autonomous Roving Exploration System (ARES) consists of multiple small rovers that are able to autonomously conduct a seismic survey with an active source on the Moon (or other object) to image the near-surface structure [32]. The concept foresees one large stationary lander that acts as a seismic source and multiple small mobile rovers equipped with geophones. Independent of PSI, the authors from DLR have proposed a similar concept but with a higher degree of autonomy [33], [34], [35]. Our concept envisions a fully distributed multi-agent network where one mobile rover is equipped with a seismic source that can be relocated. Hence, there is no central station necessary such that a higher flexibility in the seismic survey can be achieved. Furthermore, thanks to the network aspect of this concept we are able to design movement strategies that position the rovers at optimal sampling positions to capture certain features in the subsurface. This will allow to the implement adaptive sensing strategies. To realize such a system it is required to i) formulate the requirements and design communication, timing and localization components for multi-agent networks, and ii) provide a suitable numerical method to enable an autonomous subsurface imaging over a network of drones.

Distributed multi-agent exploration plays a central role in the proposed system. Such exploration relies on cooperative collection and processing of data within a network known as "in-network processing" [36]. A distributed estimation is done such that each agent makes "local" computations and shares intermediate results with its neighboring agents. The key to these computations is a decomposition of a network-global cost function into "local" sub-objectives. Such algorithms can be dichotomized into *consensus-based algorithms* [37], [38] and *diffusion-based algorithms* [39], [34]. Within recent years distributed inference techniques slowly found their way into subsurface imaging, e.g. for seismic sensor networks. The main goal of such an approach is to achieve an image of the subsurface at each sensor without a central entity that collects all seismic data from the network but based on sensor-to-sensor data exchange. A few works dealt with the problem of distributed subsurface imaging in the past. For instance, in [40] a decentralized form of the full waveform inversion is presented. However, for certain update steps a central node is still required which does not enable a fully distributed implementation. Authors in [41], [42] propose distributed approaches for travel time tomography and ambient noise tomography in seismic networks using randomized gossip and consensus-based techniques. In [34] the authors from DLR propose a distributed implementation of the full waveform inversion using above mentioned diffusion-based techniques. Reconstructed images at each sensor are close or same as traditionally achieved images using a central node. Yet all mentioned approaches have not been investigated within the scope of a mobile multi-agent system and scattering subsurface media.

Within the project in the context of general inverse PDE problems present in seismic inversion methods, a special focus will be placed on Bayesian learning techniques. Bayesian methods have been used for these purposes in the past [43], [44]. In [44], a distributed exploration of a gas field is addressed by using a factor graph representation for the reconstruction. However, these approaches do not cover the case of inverse problems for seismic exploration. The advantage of using a Bayesian, probabilistic framework consists of obtaining uncertainty measures of the reconstructed physical parameters. Such measures can then be exploited to design a movement strategy that identifies optimal sampling positions of the agents for an improved parameter estimation. For instance, based on inferred model parameters intelligent path planning schemes can be designed [45], [46]. The methods rely on optimal experiment design techniques to identify sampling locations that reduce parameter uncertainty. Closely related information-driven approaches [47] use information-theoretic metrics to guide agents to more informative locations. We note that such techniques have not yet been investigated in the context of seismic imaging to improve estimation of subsurface parameters.

Based on the above described state-of-the-art for multi-agent exploration the following research questions are identified:

- What is an efficient method to adapt a seismic imaging method suitable for scattering media to distributed data processing for a multi-agent network?
- What is the optimal movement strategy in conjunction with the imaging method that positions the agents at sampling points such that relevant subsurface features are resolved?

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