Probabilistic Approach toward Seismic Exploration with Autonomous Robotic Swarms

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This research introduces a novel approach to seismic exploration on the Moon and Mars, employing autonomous robotic swarms equipped with seismic sensing and processing hardware. By relying on probabilistic inference methods, we aim to survey large surface areas to both autonomously identify and map subsurface features such as lava tubes and ice deposits. These are crucial for future human habitats and potential in-situ resource utilization.

This endeavor presents unique challenges due to the communication limitations and uncertainties inherent in remote, autonomous operations. To address these challenges, we adopt a distributed approach with robotic swarms, where each rover processes seismic data and shares the results with other rovers in its vicinity, contending with imperfect communication links. Thus, the swarm is used as a distributed computing network. The decisions made within the network are based on probabilistic modeling of the underlying seismic inference problem. A key innovation in this respect is the use of factor graphs to integrate uncertainties and manage inter-rover communications. This framework enables each rover to generate a localized subsurface map and autonomously decide on strategic changes in the seismic network topology, either exploring new areas or repositioning to enhance measurement accuracy of targeted underground regions.

The vision is to implement this approach on a distributed factor graph, allowing for a coordinated, probabilistic analysis of seismic data across the swarm. This strategy represents a significant departure from traditional static seismic sensor arrays, offering a dynamic and adaptable solution for planetary exploration. The first step towards realizing this vision involves implementing a Kalman filter for the one-dimensional linear heterogeneous wave equation. This has been achieved by reformulating finite difference schemes for wave propagation simulation into a state-space description. The resulting linear continuous n-th order system can be explicitly solved and rewritten into a discrete state space model that can be used in the standard Kalman filter recursion. However, the standard Kalman filter is limited due to its assumption that both model and process noise are Gaussian. With factor graphs, this limitation can be overcome, enabling a more robust and versatile analysis. Several simulation results will be shown to demonstrate the performance of these approaches.

We intend to extend the approach to higher-dimensional problems, implementing distributed versions of the Kalman filter and factor graph with simulated, non-perfect communication links. Eventually, the seismic inverse problems will be solved in these frameworks. Successfully achieving these objectives could greatly enhance our capabilities in extraterrestrial exploration, paving the way for more informed and efficient future space missions.