A GIS-based spatial data structure for integrating multi-resolution terrain data from lunar orbiter and rover: Application to Lunar Rover Path Planning and Operation

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Abstract: The discovery of rare resources and water-ice has led to a surge in rover-centric lunar exploration missions. While GIS-based spatial data structures have been widely used to support lunar missions, they have limitations in integrating global low-resolution terrain data from lunar orbiters with local high-precision 3D data from rovers. This study proposes a new network model that integrates a quadtree with an 8-direction network. The network model supports unmanned rover exploration by integrating terrain data and generating a high-resolution DEM of the exploration area. The proposed model was validated on a simulated lunar terrain, confirming its ability to generate a safe driving path and a high-resolution DEM.

Keywords: GIS, spatial data structure, path planning

1. Introduction

Following the discovery of rare resources and water-ice in lunar permanently shadowed regions (PSRs), a scientific breakthrough has emerged, indicating the potential for space exploration and human habitation. Major space agencies worldwide are planning and executing lunar missions with the goal of in-situ resource utilization (ISRU) and constructing moonbases. The lunar's lack of an atmosphere subjects it to extreme temperature variations and cosmic radiation, making it a harsh environment. Unmanned rovers can operate stably for extended periods in extreme conditions and are capable of exploring high-risk areas. This capability makes rover-centric lunar exploration a prevalent approach. Rovers need path planning to autonomously navigate uncertain environments. However, existing terrain images and DEMs from orbiters have low-resolution, making detailed path planning impossible. On the other hand, lunar exploration rovers can acquire high-precision 3D data. Therefore, to ensure rover safety and enhance mission efficiency, path planning need to integrate global lunar terrain data from orbiters with high-precision terrain data acquired by the rover. Representing the entire terrain with a regular grid, a representative data structure for exploration rovers, has limitations in expressing fine terrain changes and small obstacles and consumes a large amount of memory (Nagy, 2022). Data structures that use an adaptive grid and multi-layers have been developed to express detailed terrain changes based on terrain complexity and systematically manage various terrain information like altitude and slope (Rekleitis et al., 2013; Sánchez-Ibánez et al., 2019). However, as the accuracy of terrain representation increases, so does the memory requirement, and there are limitations to efficiently integrating terrain data from lunar orbiters and rovers. Therefore, this study developed a GIS-based spatial data structure that integrates low-resolution lunar orbiter data with high-precision lunar rover data to perform detailed path planning and visualize 3D terrain data.

2. Methodology

The quadtree-based 8-direction network model aims to support rover path finding and driving, as well as to construct a high-precision DEM of the exploration area. Figure 1 illustrates the three main functions of the proposed model.

First, the Create Network function creates a quadtree network of the exploration area based on the resolution of the input DEM. Then generates a hierarchical 8-direction network by connecting the center of each pixel to the centers of its neighboring pixels. The network's nodes store altitude, while its links store slope and the distance between nodes. A quadtree offers efficient memory usage and fast search speeds due to its hierarchical structure. The generated network is then used for path planning and 3D visualization.

Second, the Path Planning function applies the A* algorithm on the 8-direction grid. It considers distance and slope cost functions to perform path planning that accounts for the terrain's undulations. The initial network has low-resolution, making it difficult to identify small obstacles. Therefore, a global path is generated based on low-resolution terrain data from a lunar orbiter, and this path is subsequently refined using high-precision 3D terrain data from the exploration rover.

Finally, the 3D Visualization function converts the terrain and the rover's driving path into a mesh. The mesh is constructed from the nodes, and grayscale color variations are applied based on altitude values to intuitively represent changes in terrain height. In addition, the planned path is visualized in 3D along with the network by sequentially connecting the nodes.

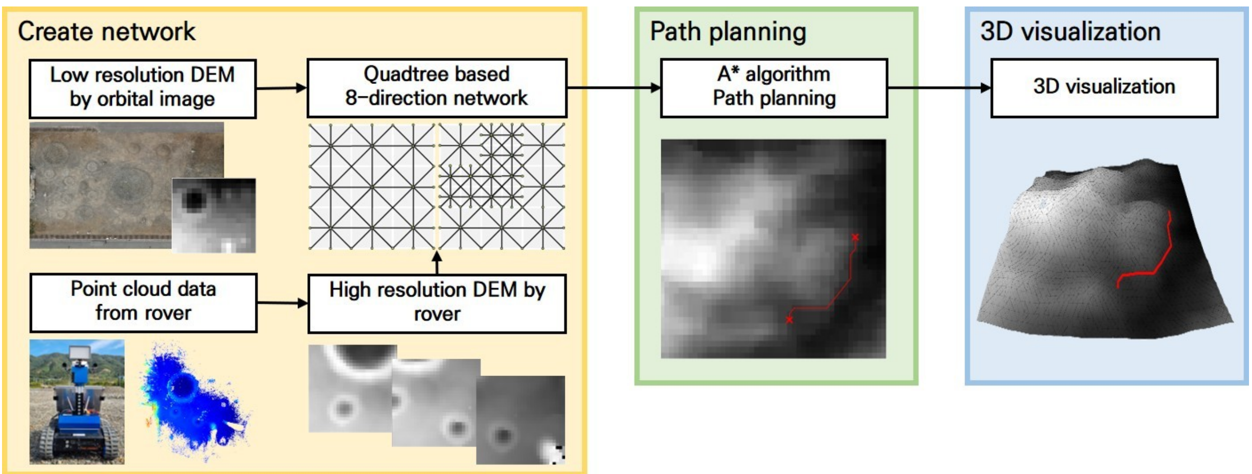

Figure 1: Overview of a Quadtree-based 8-direction network model.

3. Application and Results

The network model proposed in this study was evaluated on the simulated lunar terrain at the Yeoncheon SOC Demonstration and Research Center of the Korea Institute of Civil Engineering and Building Technology (KICT). The simulated lunar terrain, which measures 21m by 23m, is composed of craters, rocks, and mounds (Figure 2).

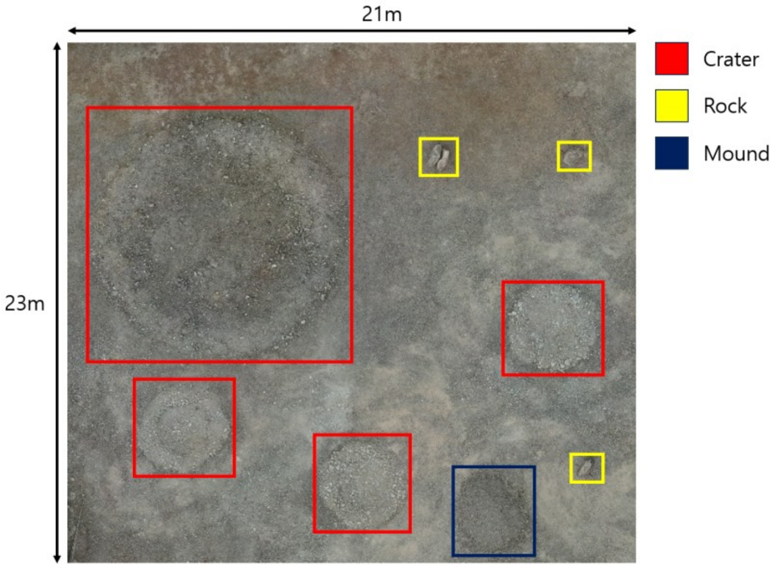

Figure 2: Simulated lunar terrain.

In the field test, a 1.5m-resolution DEM was used for a simulated lunar DEM. To acquire simulated rover observation data, a four-wheeled platform equipped with a stereo camera system was used (Figure 3). 3D terrain data was acquired from the rover's stereo images to generate a 0.375m-resolution DEM of the area around the driving path.

Figure 3: Rover hardware.

In Figure 4, the initial path was set by designating the upper-left corner of the simulated terrain as the starting point and the lower-right corner as the destination point. As the rover traversed the terrain following the path, it performed six updates to the DEM, network, and path. The final path was refined to a safe driving route that successfully avoided even small obstacles, while a high-resolution DEM was generated along the entire route.

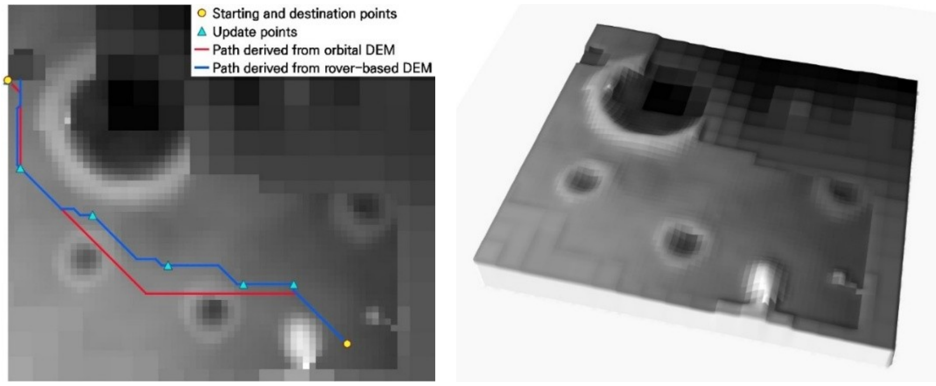

Figure 4: Path planning results and 3D visualization of the updated DEM.

4. Conclusion

This study proposed a quadtree-based 8-direction network model for lunar rover path planning, which can efficiently integrate terrain data from lunar orbiters and exploration rovers. The proposed model improved the efficiency of data integration and updating and enabled 3D visualization by converting terrain data and the rover's driving path into a mesh. Additionally, the model can store and manage observation data such as temperature and resource distribution. This capability is expected to optimize rover driving paths and enhance data utilization in future lunar exploration missions.

Acknowledgements

This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korea government (MSIT) (No. 2022R1F1A1064577), and in part by "Development of spatial data model for associating and utilizing observation data from rovers and orbiters" funded by the Korea Institute of Civil Engineering and Building Technology.

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