Spatial Analysis of Terrain in Virtual Reality

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ABSTRACT

We extend an existing virtual reality terrain visualization framework to support spatial analysis tasks for geoscientific purposes. We demonstrate both interactive measurement of height profiles as well as volume measurement within polygonal footprints. In this application, virtual reality technology enables superior perception of the placement of these lines with respect to terrain features.

Index Terms: J.2 [Physical sciences and Engineering]: Earth and atmospheric sciences—; I.3.6 [Computer Graphics]: Methodology and Techniques—Graphics data structures and data types; I.3.7 [Computer Graphics]: Three-dimensional graphics and Realism—Virtual reality;

1 INTRODUCTION

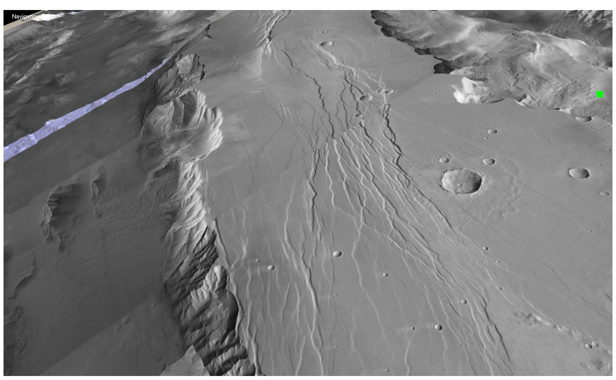

Figure 1: Fault network on Mars next to Valles Marineris

Measuring the geometric properties of topographic features is an important sub-task in cartography. Due to the widespread availability of remote sensing data such as Digital Terrain Models (DTMs), these measurements are nowadays almost exclusively carried out in a desktop environment using Geographic Information Systems (GIS). Most GIS are limited to a top-down perspective which can lead to ambiguities in interpreting topography. Domain experts have reported, for example, that certain features like crater rims or mountain foothills covered by sediment can be difficult to locate accurately in traditional systems, but are more readily identifiable when using 3D visualization.

We present a virtual reality (VR) system for the spatial analysis of Digital Terrain Models (DTMs) based on an existing terrain rendering framework [7]. We demonstrate that the hierarchical level-of-detail data structure used for rendering does support efficient implementation of analysis operators. As an example, we implemented virtual tools for measuring height profiles and the volume of surface features such as mountains or craters.

Height profiles are an important geoscientific tool to help understand the morphology of predominantly linear surface features such as canyons, river beds or seismic faults (see Figure 1). A height profile is a cross-sectional representation of topography produced by sampling elevation along a given profile line. A common approach to analyze surface features is to place multiple profile lines at different significant points along a feature and to compare them within a single 2D plot.

The volume of surface features is an important quantity used in geoscientific reasoning, for example when trying to account for the volume of rock ejected from a crater during impact. Volume computation requires the definition of the 2D integration domain as well as a zero level surface. The signed volume (positive for mountains, negative for craters) is then computed by integrating the height difference between the elevation model and the zero level surface within the 2D footprint.

Using stereoscopic rendering and head tracking, our system improves depth perception of the measurement footprint lines with respect to the terrain, allowing for accurate placement. The system was applied to the surface of Mars using a DTM composed of Mars Orbiter Laser Altimeter (MOLA) [6] data by NASA as well as High Resolution Stereo Camera (HRSC) [3] data by German Aerospace Center (DLR).

1.1 Data set

As a reference data set we used the high-resolution HRSC data set which provides a DTM of Mars with a resolution of about 50m per pixel. As the data capture and processing is still ongoing, only approximately 30% of the planetary surface is currently covered by HRSC. To provide a global model, the gaps in the HRSC model were filled by using the older MOLA data set by NASA, which provides a resolution of about 500m per pixel. The resulting composite multi-resolution data set is augmented by high resolution black and white imagery provided by the HRSC mission (12.5m per pixel). Note that the additional imagery is not considered by the spatial analysis operators but is used to provide visual cues for the user in identifying features.

2 RELATED WORK

Related literature includes the work by Kreylos et al. [5], which examines the efficacy of performing scientific analyses within VR environments. Cartography is given as an example, and from preliminary results, the authors conclude that mapping performance in their VR environment is higher compared to performing the same task within in a desktop GIS. Navigation within the terrain data set is performed by grabbing and manipulating the terrain using a 6DOF manipulator.

In the work presented here we use a different navigation approach by moving the camera instead. This allows for a higher degree of immersion, as it is more similar to the user actually being present at the target site.

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Not all data structures used by spherical terrain rendering systems are capable of supporting efficient spatial analysis queries. For example, the Crusta system by Bernardin et al. [1] and the Planetary Scale Composition approach by Kooima et al. [4] use implicitly defined coordinate systems. A random point query against these data structures would require testing the boundary of each traversed node within the subdivision hierarchy for intersection with the given point.

Our software extends our previous work on terrain visualization [7], which used a data structure based on the HEALPix coordinate system by Górski et al. to provide spherical rendering while avoiding artifacts due to coordinate singularities. At the same time, this data structure is well suited for interactive spatial analysis, as it provides a closed projection formula relating geographic points to parametric (database) coordinates.

3 Interaction

For interaction, a flystick is used to control a virtual pick-ray. Similar to the mapping system by Kreylos et al. [5], we use separate navigation and analysis modes, between which the user can switch using a button on the flystick.

For navigation we provide both a trackball and a free flight metaphor. At planetary scales, the trackball metaphor was found to be an intuitive method for quickly navigating to sites of interest by grabbing a point on the planet and rotating it to a new position. Flying, on the other hand, is an immersive navigation metaphor useful to examine mostly linear features such as canyons or fault lines. The travel direction is determined by the orientation of the pick-ray. Additionally, a small analog joystick integrated in the flystick ("coolie hat") is used to provide pitch and yaw control.

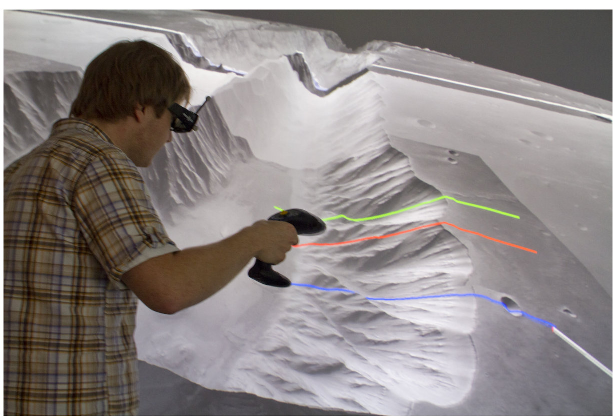

Figure 2: Accurate placement of profile lines in VR

Using the pick-ray, profile lines can be drawn directly onto the surface. Figure 2 shows the interactive placement of fault lines as the user manipulates the end point using the pick ray. As the profile line is swept across the topography it is updated in real time. The resulting 2D plots can be visualized within the system (Figure 3) or exported in standard formats for further analysis, e.g. using spreadsheet software.

To measure the volume of a surface feature, the user defines its footprint by drawing a polygon (Figure 5). The average surface height along the polygon defines the zero level for the subsequent integration, which executes concurrently with rendering in order to maintain interactivity.

The benefit of using Virtual Reality in this application is the accurate placement of height profiles and feature footprint polygons with respect to topography, enabled by stereoscopic rendering and head tracking.

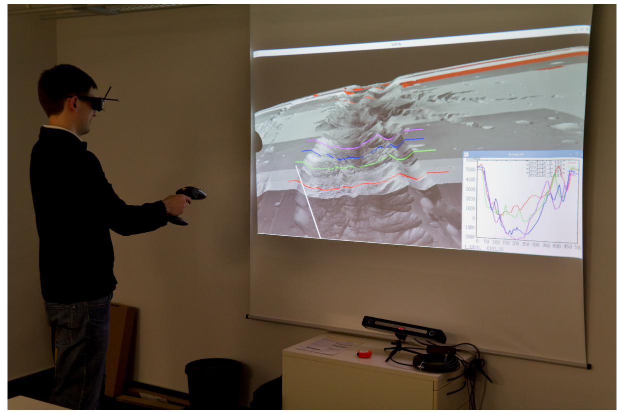

Figure 3: Simultaneous display of profile graph

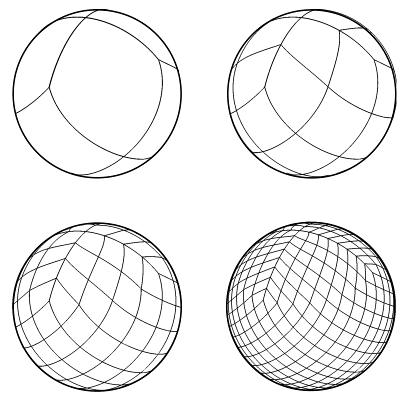

Figure 4: The HEALPix hierachical sphere tessellation

4 Data structure

As described in [7], the data structure used is based on the HEALPix [2] tessellation (Figure 4), which decomposes the sphere into 12 curvilinear patches. Our terrain rendering framework represents a digital terrain model using one quad tree for each of these patches. Tree nodes contain tiles of 255×255 height samples to allow for triangle batching in rendering.

The HEALPix coordinate system has two properties which make it particularly useful for spatial analysis: The equal-area property guarantees that all samples on a given resolution level (tree depth) represent the same physical area on the surface, which simplifies integration. Furthermore, it has a closed projection formula relating geographic and parametric coordinates. Compared to systems which use implicitly defined coordinates, for example by hierarchical subdivision of a platonic solid, HEALPix allows for more efficient point queries against the database.

5 Algorithms

The analysis algorithms which are presented in the following share the same level-of-detail database which is used by the underlying terrain renderer. Height profile and volume measurements are implemented using point and region queries against a quad tree, respectively. In both cases, selection of surface points is realized by using CPU based ray-casting to test the pick-ray against the visible subset of the hierarchical DTM.

5.1 Height profile

To compute a height profile, we sample the DTM equidistantly along a line segment between two given geographic points. At planetary scales, where curvature becomes significant, the notion of a line segment as the shortest path between a pair of points has to be generalized to great circle segments, which are the shortest paths between two points on a spherical surface. A parametrization of the great circle segment connecting two points is given by spherical interpolation.

Note that while the end points of the profile line are specified in geographic coordinates, spherical interpolation uses three-dimensional euclidean coordinates. The intermediate sample positions are converted back to geographic coordinates.

To generate the height profile, each sample position is then converted to parametric HEALPix space. The quad tree selected by the coordinate is then traversed recursively to determine the leaf node containing the query point. Note that in the current implementation, this traversal is limited to the visible set, which is the sub-tree currently available in memory according to the level-of-letail metric employed by the terrain renderer.

The height value at the query point is then obtained by sampling the tile of height samples stored with the leaf node using bilinear interpolation.

As a profile line is being manipulated, the topography is sampled at 200 equidistant points along the line in each frame to provide an interactive feedback of the height profile. Once the user accepts the position of the profile line, the system samples the topography again at a higher resolution (1000 samples) to improve the accuracy of the final result.

5.2 Volume measurement

For volume measurement, the given footprint polygon is first converted to parametric HEALPix space. A region query is then executed against the quad tree, recursively visiting all tree nodes which intersect the polygon.

When encountering a leaf node, the tile of 255×255 samples is tested against the polygon and those samples which intersect the polygon are integrated. This process is accelerated by using a scan line algorithm which considers each row of samples in turn. The footprint of a single row, which is a line segment in HEALPix space, is intersected with the polygon to obtain a set of intervals which are located within the polygon. The difference between each height sample and the zero level is computed and scaled by the surface area covered by the sample to obtain a volume contribution. This is simplified by the fact that due to the equal-area property of the HEALPix parametrization, the surface area represented by a given sample depends only on the depth within the tree and is independent of the geographic location.

Note that in our volume integration tool, unlike in height profile sampling, the tree traversal does not stop at the currently visible set of nodes. Instead, the on-disk database is traversed down to the finest level of resolution available to provide maximum accuracy.

To maintain interactivity, the integration was implemented to execute in parallel with the main render loop. A breadth-first traversal is used in which an active set of tree nodes to be loaded is maintained in memory. This set initially only contains the root node. Once a node has been loaded, the four child nodes are tested against the boundary polygon. Those child nodes which are found to intersect the polygon are added to the active set and scheduled to be loaded by the I/O thread. Leaf nodes which do not have any children are integrated into the total volume as described above. The volume computation is finished once the active set is empty.

To further improve interactivity, the number of nodes which are visited per frame can be limited. We found that expanding 4 nodes per frame is sufficient to maintain good interactivity while still providing results within an acceptable time frame (multiple seconds) even for large integration domains (e.g. Olympus Mons).

6 Results

The system was benchmarked on a workstation equipped with an Intel Xeon E5520 quad-core CPU, 24 GiB of RAM and a NVIDIA Quadro 6000 GPU. All examples were rendered at full-screen resolution of 1920×1200 pixels. In a full-screen view of Valles Marineris an idle frame rate of 68 fps was achieved for terrain rendering alone. While dragging profile lines across the canyon the system maintained interactivity at 38 fps.

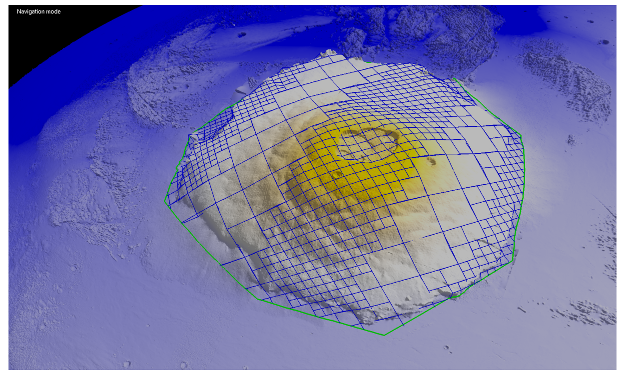

Figure 5: Measuring the volume of Olympus Mons

Figure 5 shows a view of Olympus Mons which was rendered at 69 fps. During volume computation, which took 10 seconds, performance dropped to still interactive levels at 40 fps. For illustration purposes, the visited leaf nodes of the terrain database are outlined in blue. The difference in sizes between these nodes is explained by the fact that Olympus Mons is represented by mixed resolution data (MOLA and HRSC). A total of 1106 leaf nodes were integrated which required loading 274 MiB of data. A volume of $2.67 \times 10^6\ km^3$ was measured which is in close agreement with literature [8].

7 Conclusion

We have described a system for spatial analysis of digital terrain models in virtual reality environments. Using a large digital terrain model of Mars, we have demonstrated that existing level-of-detail data structures which are designed for terrain visualization can be used to sample height profiles interactively and perform volume measurements of very large surface features in a short amount of time while maintaining interactive navigation. The benefit of using virtual reality technology for these tasks was the superior perception of the location of measurements with respect to the topography being examined.

8 Future work

In future work, we want to further improve immersion by simulating a walk on the surface of Mars and providing more intuitive tools to enable virtual land surveying. One challenge we identified is that even high-resolution HRSC imagery does not sufficiently resolve features on the scale of a human, which implies that the ground below and in the close vicinity of the user would appear very blurry due to excessive magnification of the available imagery. This situation could be improved by introducing artifical detail, for example using normal maps based on procedurally generated noise. Care must be taken in this approach, however, to avoid distorting the actual data content.

We also want to examine whether haptic feedback can improve perception of topography. A desktop-based Phantom Omni device, for example, could be used for probing small to medium sized linear features such as the fault networks shown in Figure 1. Using the device for point selection in spatial analysis could be beneficial, as the perception of height and slope discontinuities might improve identification of the natural boundary of a surface feature such as the rim of a crater. From a technical point of view it would be straightforward to provide contact information for a single point using a point query against the database. Haptic feedback, however, requires a much higher update rate than interactive rendering which might pose additional challenges.

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