PRELIMINARY INVESTIGATION ON INTEGRATION OF DATA ACQUIRED FROM MARTIAN SURFACE EXPLORATION

Shih-Yuan Lin[1], Jung-Rack Kim[2], and Chi-Pei Wang[3]

[1]Asssistant Professor, Department of Land Economics, National Chengchi University
64, Sec. 2, Zhinan Rd., Wenshan Dist., Taipei 11605, Taiwan; Tel; +886-2-29393091#51651;
E-mail: syl@nccu.edu.tw

[2]Research Professor, Department of Geo-Informatics, University of Seoul,
Seoulsiripdaero 163, Dongdaemun-gu, Seoul 130-743, Korea;
E-mail: kjrr001@gmail.com

[3]Undergraduate student, Department of Land Economics, National Chengchi University,
64, Sec. 2, Zhinan Rd., Wenshan Dist., Taipei 11605, Taiwan;
E-mail: 97207410@nccu.edu.tw

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ABSTRACT: In order to search for and characterize a wide range of rocks and soils that hold clues to past water activity on Mars, NASA launched two rovers towards Mars in the Mars Exploration Rover Mission in 2003. The rovers named Opportunity and Spirit landed on Mars in 2004 and have been performing the geological exploration since then. Up to the present, many close-range images were taken by various camera systems installed onboard the rovers and were archived in NASA's Planetary Data System. Moreover, for recording and displaying positions of the rovers, traverse maps are updated nearly daily on MER mission's official website. As these data are all available to public domain, there will be additional benefits if the archived image data and the traverse map can be demonstrated and accessed in an integrated environment. To achieve this, a 3D virtual reality environment is constructed. In which the digital terrain model produced from stereo images acquired by High Resolution Imaging Science Experiment (HiRISE) instrument onboard Mars Reconnaissance Orbiter is employed as the 3D terrain base. Daily positions of the rovers are then located in the HiRISE DTM and the 3D traverse map is obtained subsequently. In this paper, the area covering the traverse route of Spirit is taken as an example to demonstrate the 3D traverse mapping in the public-accessible virtual reality environment. In further research, the exterior orientation recorded in the archived images are extracted and connected to the corresponding rovers' locations in the system. As a result, the archived image data and the traverse map can be demonstrated in an integrated environment. The developed system is expected to facilitate MER data demonstration and accessibility for users who are of interests.

1 INTRODUCTION

In order to search for and characterize a wide range of rocks and soils that hold clues to past water activity on Mars, NASA launched two rovers towards Mars in the Mars Exploration Rover Mission in 2003. The two rovers named Opportunity and Spirit landed on Mars in 2004 and have been performing the geological exploration since then. Although the communication with Spirit was ended in May 2011 due to the rover's batteries lost, Opportunity is still working at the present. The close-range images taken by various camera systems installed onboard the rovers are continuously acquired and archived in NASA's Planetary Data System (PDS). The data are accessible in public domain. Moreover, to keep track of the positions of rovers and geological environment on Mars, rovers' locations are updated nearly daily by Mapping and GIS Lab at Ohio State University (OSU). Together with the coordinate values of each rover site, traverse maps showing sequential rover traverses are produced and released on MER mission's official website for public use.

The data acquired from the Martian surface exploration and the locations collecting these data are all available for public usage. The data accessibility provides great value to scientists for diverse Mars explorations. Nevertheless, inefficiency may be found when observing the image data and corresponding rover locations as these data are stored in two different systems. To address the issue, a system integrating data introduced above is proposed. Furthermore, high-resolution 3D Martian digital terrain model (DTM) will be introduced as the reference terrain in the system. Within the 3D virtual reality (VR) environment, additional benefits, e.g. 3D visualisation, 3D rover traverse mapping, human-machine reaction, etc., can be achieved.

This paper reports the preliminary investigation of the system construction. As Spirit's task was completed and the rover locations were well adjusted, the data of Spirit rover were applied in the system. The Martian DTM employed in the system, the integration of rover traverse sites and the DTM, and the technique for establishing the overall system, will be introduced respectively in the following sections. The summary of the current progress and the future works are reported at the end of the paper.

2 REFERENCE FRAME

As described in the previous section, the coordinates of each rover site were determined. Also, the DTM treated as the reference surface was applied in the system. Although the data were accessible, it was noted that the rover locations and the DTM were defined in different coordinate systems. Therefore a conversion was required before the implementation of integrating rover location and DTM. To this end, a number of global and local coordinate systems involved in the conversion, including Mars body-fixed (MBF) reference system, landing site cartographic (LSC) frame and rover motion counter (RMC), were following introduced.

2.1 Mars Body-Fixed Reference Systems

The Mars global reference systems include the Mars inertial reference system and the Mars body-fixed reference system (Li et al., 2004). The former system is mainly used for navigation of orbital spacecraft while the latter is used for mapping ground features observed from orbiting spacecraft (Li et al., 2006). The Mars body-fixed reference system uses the center of mass of Mars as its origin and a specified orientation that matches Mars rotation and pole position. In Figure 1, $+Z_{MBF}$ is in the direction of the north pole, $+X_{MBF}$ is in the direction of the intersection of the Prime Meridian and the equatorial plane, and $+Y_{MBF}$ lies in the Mars equatorial plane and completes a right handed coordinate system (Maki, 2003).

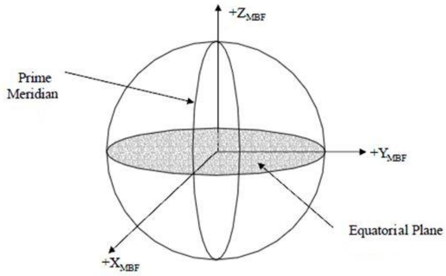

Figure 1: MBF Coordinate System.

Two types of MBF systems are defined by the International Astronomical Union/International Association of Geodesy (IAU/IAG) Working Group, including (1) a spherical coordinate system using planetocentric latitude and longitude measured toward the east, and (2) an ellipsoidal coordinate system using planetographic latitude and longitude measured toward the west. Originally the planetographic latitude and west longitude were most often used in making maps of Mars. However, since the Mars Orbiter Laser Altimeter (MOLA) Science Team adopted the use of planetocentric latitude and east longitude for their operational work and products, the spherical coordinate system has been widely used. The MER also adopted the spherical system (Li et al., 2004).

2.2 Landing Site Cartographic and Other Local Reference Systems

One of the important local coordinate system is Landing Site Cartographic (LSC) reference system. Once the rover landed on the Martian surface, a LSC reference system was established. The LSC system is an east-north-up (X-Y-Z) right-handed local system with its origin fixed to the lander within the landing site. Rover locations and landing site cartographic products are calculated and generated in the LSC reference system (Li et al., 2006). Other local reference systems include surface fixed reference system (S frame) and site reference system (site frame). The former is a north-east-down (X-Y-Z) right-handed local system with its origin at the lander. The latter system is defined locally within an area to locate each rover location and surrounding ground features. A new site frame is defined as the rover moves a significant distance (e.g. over 50 m), and the number of the new site frame is accumulated accordingly.

From the perspective of multiple data integration, it is worth to note that although ground data are collected in the site frames, derived rover locations and topographic mapping products released on the MER's official website are all presented in the LSC frame for consistent referencing and regional context (Li et al., 2006). Therefore a transformation is required when integrating data acquired or computed from different site frames. Based on the knowledge of the initial site frame is identical to the S frame, and the S frame and LSC frame shares the same origin, the transformations between site frames and the LSC frame can be achieved through the translations and orientations between the site frames and the S frame.

2.3 Rover Motion Counter

Rover Motion Counter (RMC) is a set of compact notation for referencing the rover position during a traverse or activity (Maki, 2003). It is placed in the headers of data products acquired by the imaging instruments installed onboard the rovers (such as navigation camera (Navcam), panoramic camera (Pancam), etc.). As the RMC values will increase when the rover moves around on the surface, the location of collected data can be determined using the RMC. Such information is critical when performing integration of instrument data and other topographic data in the proposed 3D VR system.

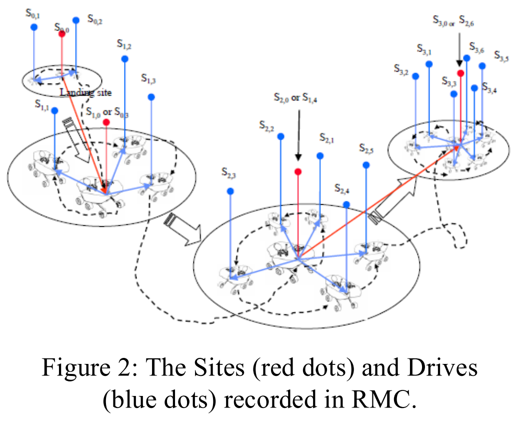

Figure 2: The Sites (red dots) and Drives (blue dots) recorded in RMC.

The RMC contains five index values, including Site, Drive, IDD, PMA and HGA. In which the Site and Drive are the two values most relevant to describe the rover positions. The Site is an

integer ranging from 0 to 65535. The Site index increments when the rover drives to the next significant position or for a specific distance (Figure 2) (Li et al., 2006). As the Site index is incremented, the rest four indexes will be reset to zero. The Site index recorded in the RMC indicates the number of site frame introduced in the previous section. To connect those different sites (from S_0 to S_n), the relation between every site and the Landing site (S_0) can be defined using the positional vectors are archived in MER Analyst's Notebook (PDS Geoscience Node, 2011).
The Drive is an integer ranging from 0 to 65535 and indicates rover positions in each site. The Drive index will be increased after the rover moves or turns from one position to the next one. That is, it is allowed to have more than one Drive in each Site. The two indexes are considered as the tags of the positions of collected image data. The information is applied when integrating rover location and instrument data with any topographic data.

3 METHODOLOGY

As described in Section 1, a 3D virtual reality system employing high-resolution Mars DTM was proposed to integrate data acquired in the Martian surface exploration mission. Critical issues involved in the system, including the creation of high-resolution DTM, the localisation of the rover in the DTM, and the technique for constructing the 3D virtual reality environment, are introduced respectively in the following sections.

3.1 Creation of HiRISE DTM

Martian imagery and topographic data produced by stereo processing comprise an essential basis for the establishment of virtual reality. The first accurate systematic topographic measurements were the Mars Orbiter Laser Altimeter (MOLA) experimenters of Mars Global Surveyor (MGS) launched on the 7th of November 1996 (Smith et al., 2001). As the vertical accuracy of the MOLA DTM is better than l m with respect to Mars' center of mass (Neumann et al., 2001), it is considered as the most consistent Mars DTM and treated as a "base topography" (Heipke et al., 2007; Kim and Muller, 2008).
In addition to the MOLA, stereo imagery captured by spaceborne imaging systems has also been successfully applied to produce Mars DTM. In late 2006, the successful deployment of the NASA Mars Reconnaissance Orbiter with the CTX and HiRISE instruments began to provide repeat-pass stereo image pairs. The spatial resolution of acquired imagery was further upgraded to 6 m and 25 cm respectively, thereby providing an opportunity to produce very high resolution DTMs (McEwen et al., 2007). Through the developed algorithms, Kim and Muller (2009) produced CTX DTMs with grid spacing of 12-20 meters. For stereo HiRISE data processing, Kirk et al. (2008) and Kim and Muller (2009) demonstrated that the resolution of processed HiRISE DTM was up to one meter or even sub-meter level.
Due to the advantage of the highest resolution, HiRISE data were selected as the image source for generating base DTM for the 3D VR environment. For HiRISE processing, the full non-rigorous sensor model was introduced. This approach has been used for the commercial satellite imagery for decades and now possesses accuracy comparable to that of the conventional physical sensor model, as demonstrated in many photogrammetric applications (Dowman and Dolloff, 2000; Fraser et al., 2006). Regarding the Martian data, Kim et al. (2007) have examined the availability of a non-rigorous model for the Martian imagery and showed that a 'few pixels' level positioning error could be achieved. Therefore the non-rigorous sensor modeling was applied to HiRISE image data.

3.2 Localisation of Spirit Rover

Soon after the lander landed on the Martian surface, the Mapping and GIS Lab at OSU regularly computed the rover's positions in LSC reference system and published on the MER Analyst's Notebook website (PDS Geoscience Node, 2011). The positions were indicated by Site index, Position index (i.e. Drive index) and the positional vectors (X, Y, Z). In which the Site and Position indexes were treated as tags of rover's position (refer to Section 2.3), while the positional vectors revealed the specific intercept values against its origin fixed to the lander within the landing site.
It was realised that the location of the Spirit rover and the HiRISE products were produced in different coordinate systems. In order to visualise the traverse of the Spirit rover on the created HiRISE topographic products, a map transformation was performed to convert the HiRISE topographic data to the LSC reference system. Then the traverse of the rover could be determined in the transformed HiRISE DTM.

3.3 Google O3D

O3D is an open-source JavaScript Application Programming Interface (API) provided by Google (Google, 2011). One of the key features of O3D is its capability of developing interactive 3D applications that run in a browser window. As the code is free sharing and the results can be available to the public, Google O3D was selected as the main technique for constructing the 3D virtual reality environment.
It was noted that data structure and format compatible in O3D were specified. Therefore a number of software (e.g. ArcGIS, SketchUp, COLLADA converter) was applied on the constructed HiRISE DTM to obtain the required data. Also, as the image size acceptable in Google O3D was limited, a workaround was adopted for displaying the whole area in the 3D environment. Detailed methods were described in Section 4.

4 VR ENVIRONMENT OF 3D ROVER TRAVERSE MAPPING

4.1 Creation of Base Terrain Model in VR System

Topographic data of area covering Spirit rover traversing route were produced using stereo HiRISE images. For image pre-processing, the Integrated Software for Imagers and Spectrometers (ISIS) software (Gaddis et al., 1997) developed by United States Geological Survey was employed. The processed images were then input to the in-house software for producing DTM and ortho-image based on sinusoidal projection. Details of implementation of non-rigorous sensor modeling, geodetic control and stereo image matching were described in Kim and Muller (2009). The resultant DTM with 1 m grid spacing and ortho-image with 50 cm resolution are shown in Figure 3.

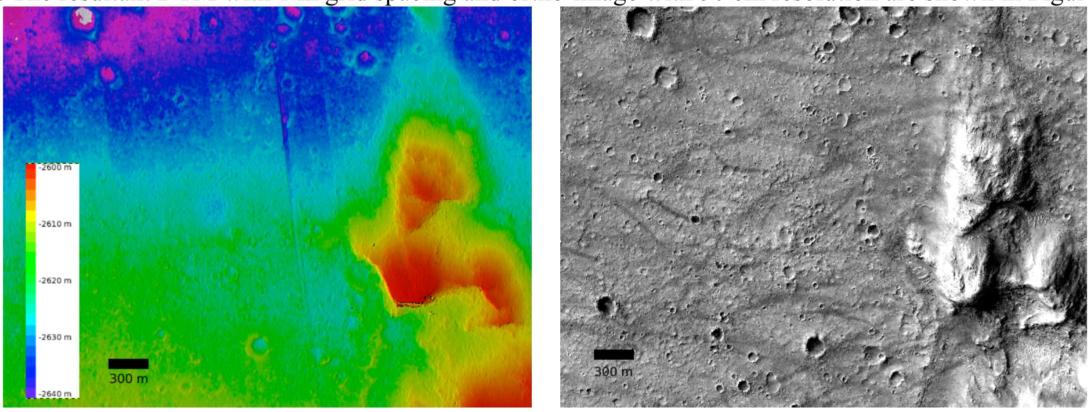

Figure 3: Resultant DTM (left) and ortho-image (right) covering Spirit traversing route.

Due to the reason described in Section 3.2, a transformation of the HiRISE products created in this paper was performed. To this end, a 2D conformal transformation was applied and the HiRISE ortho-image in LSC frame provided on the MER Analyst's Notebook website was used as the reference map. A total of 11 objects identical in the two HiRISE images were selected and used to carry out the transformation.

In order to import the transformed topographic products to Google O3D, the DTM was saved as the TIN structure. In addition, considering the data size limited in O3D, the DTM and the ortho-image were cut into six parts. Then Google SketchUp Pro 6 GIS Plugin was used to convert the TIN model into .skp file format. Once the ortho-images were textured on each TIN model in SketchUp software, the comprehensive 3D textured DTM was obtained and employed as the base model in the 3D VR system (Figure 4).

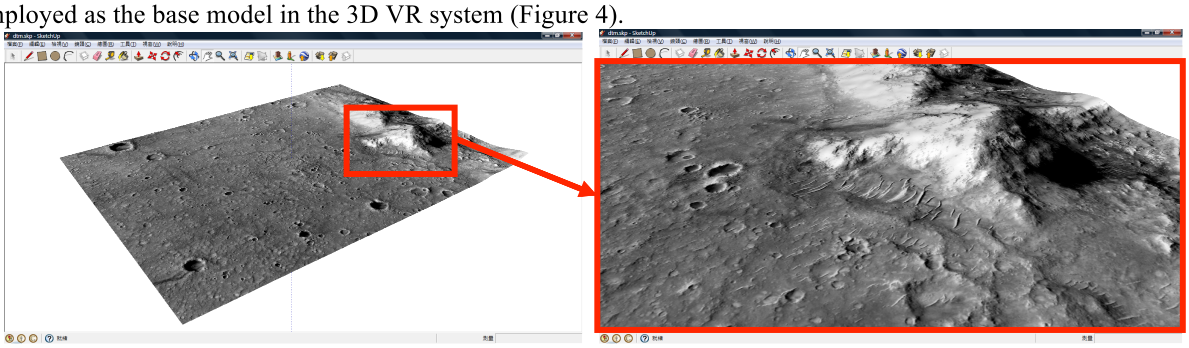

Figure 4: Perspective view of textured HiRISE DTM displayed in SketchUp software.

4.2 Co-registration of Spirit Rover Sites

Since the Spirit's traverse and the textured HiRISE DTM were in the LSC coordinate system, the locations of the Spirit were illustrated in the terrain model accordingly (Figure 5).

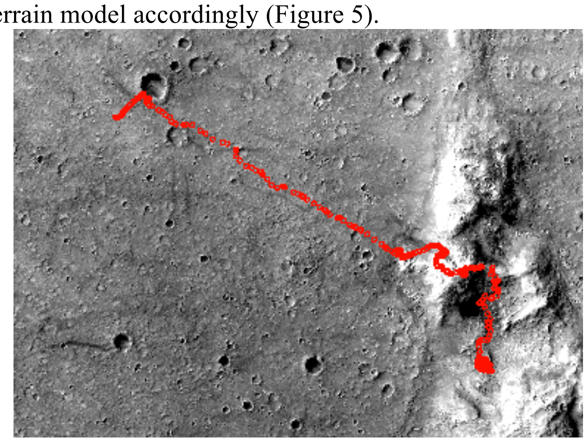

Figure 5: Spirit traversing route (red circles) with background of transformed HiRISE ortho-image.

4.3 Construction of Web 3D Virtual Reality

The textured HiRISE DTM obtained in Section 4.1 was saved as the format of Collaborative Design Activity (COLLADA) through the COLLADA converter and then loaded into Google O3D. This data was treated as the base terrain of the VR system. As for the display of the Spirit rover, the rover model was downloaded from the Google 3D warehouse (Google, 2011). As the rover's locations were solved in the previous section, the rover model could be located in the HiRISE DTM in the web virtual reality (Figure 6). Through the control of the assigned keys on computer keyboard, the manipulation of the DTM and the movement of the rover were achieved respectively.

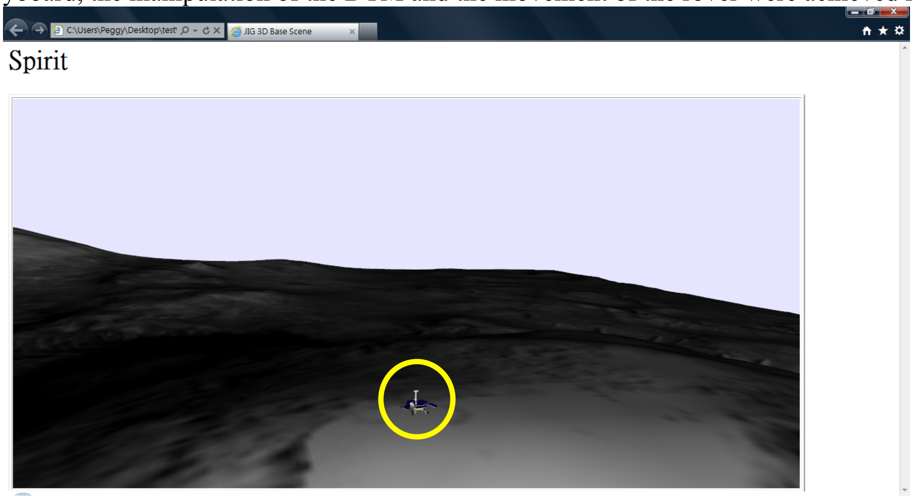

Figure 6: The demonstration of the DTM and the Spirit rover (marked in a yellow circle) in a browser window.

5 CONCLUDING REMARKS

The experiments described in this paper have shown that the web 3D VR system provides a practical tool for exploring the Martian surface. The integration of traverse of the Spirit rover and the HiRISE 3D topographic products has been implemented in the system. As the system is constructed based on an interactive 3D applications that run in any browser window, public of interest can access the system and manipulate on the local machines. Although further investigations, such as improved user interface, approximate data resolution, and manipulation speed, are required to improve the overall performance, the preliminary experiment presented herein still demonstrates that this system is feasible and has the potential to integrate Martian surface PDS data into the system.

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