3D surface visualization of planetary data using Indian remote sensing datasets on a specialized multiprojector system

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This article describes the software (SW) implementation work to generate and visualize 3D surface models over the Earth, Moon and Mars using high-resolution satellite datasets from Indian remote sensing satellites over a specialized multiprojector system. Varied resolution datasets from Indian satellites like Cartosat series, ResourceSat, Mars Orbiter Mission and Chandrayaan-1, and digital elevation model (DEM) from CartoDEM were used for surface modelling and visualization. The generated high-resolution 3D surface model over the Earth is useful for strategy, urban planning, infrastructural planning, disaster management and educational purposes. It is also important to visualize the 3D surface of planets other than the Earth to visualize potential rover landing sites navigating to prominent features of the planet and validating future imaging sites.

An indigenous SW package has been developed to model and visualize the 3D surface over multiprojector system, utilizing image processing techniques of data interpolation, image mosaicking, image registration, triangulation and texture mapping. Geographical information system layers representing places, roads and waterways have been integrated and overlaid on the terrain models for information.

Keywords: Multiprojector system, planetary data, satellite datasets, three-dimensional surface.

WITH the availability of high-resolution image datasets globally, many new computer-based visual analysis techniques and tools have been developed. It also becomes important to model the three-dimensional (3D) surface of any given area over the Earth for applications in strategy, urban planning, infrastructural planning, disaster management and educational purposes. The 3D surface modelling of planetary data helps in the visual analysis of potential rover landing sites to understand the geography of the planets, as a navigational aid to different features of the planets and to validate imaging sites for future missions to the Moon, Mars and other planets.

Here, we describe a software (SW) implementation work carried out to visualize 3D surface models over the Earth, Mars and Moon using inputs such as digital elevation models (DEM) of different resolutions (1 to 400 m), the corresponding imagery of various resolutions (0.5 to 300 m) and geographical information system (GIS) information of planets in the form of vector shape files. The work consists of 3D surface visualization using fine/coarse resolution data from the Indian remote sensing satellites and other global satellite missions. We have implemented 3D visualization of high-resolution terrains over the Earth using datasets of Cartosat, ResourceSat missions, surface modelling of full disk over Mars using National Aeronautics and Space Administration (NASA's) Vikings and India's Mars Orbiter Mission (MOM)-1 data, as well as surface modelling over the Moon using NASA's Lunar Orbiter Laser Altimeter (LOLA) and India's Chandrayaan-1 (CH-1) data.

Computer-generated terrain was used in the movie Alien for the first time in 1979 (ref. 1). Perlin[2] proposed a coherent noise function which is used in almost every movie/video game nowadays; it is known as Perlin noise. The continuous improvement in the graphics performance of computers made it possible to develop applications like NASA world wind[3], Google Earth[4], Google Moon[5] and Google Mars[6] explorers. Several commercial companies and many start-ups are developing SW solutions to visualize of 3D surface models over the Earth and other planets using satellite and aerial datasets.

DEM is primarily required for surface modelling of any area of interest (AOI). It is generated using techniques like stereo photogrammetry, radargrammetry, etc. Cartosat-1 is the first Indian mission which acquired in-orbit stereo data. A team of scientists and engineers at the Space Applications Centre (SAC), ISRO, Ahmedabad, had initially developed DEM over Indian region using Cartosat-1 datasets; it is available on the National Remote Sensing Centre (NRSC) website[7]. CartoDEM v3 has been updated and refined over time and it has a vertical accuracy of ~10 m. DEM with better accuracy from high-resolution multi-view was proposed by Krishna *et al.*[8] in 2008 using Cartosat multi-view data. Krishna *et al.*[9] also generated initial DEM from CH-1 payload.

ERDAS Imagine[10] and Worldviz[11] SW solutions are primarily utilized for 3D surface visualization using satellite data. These SW solutions are expensive and have limited capabilities to render large-scale data on the multi-projector system. It was challenging to develop a low-cost/zero-cost

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Table 1. Data over the Earth/Moon/Mars acquired using various sensors

Sensor/satellite information	Product type	Resolution	Source
ResourceSat Series	Imagery	5.6–52 m	Bhuvan website[12]
Cartosat Series	Imagery	0.6–2 m	Bhuvan website[12]
Mars Orbiter Mission	Imagery	0.6–2 km	ISSDC website[13]
Chandrayaan-1	Imagery	10–100 m	ISSDC website[13]
Viking's data over Mars	Imagery	Colourized global mosaic 232 m v2	USGS website[14]
LRO mission	Imagery	Moon LRO WAC global mosaic 100 m v3	USGS website[14]
CartoDEM	DEM	10 m	Bhuvan website[12]
LRO mission	LRO LOLA DEM	118 m	USGS website[14]
Viking's mission	MFS MOLA DEM	463 m v2	USGS website[14]

SW solution that can render high-volume satellite data in 3D over a multiprojector system. Over time, we worked on this challenging problem and developed an in-house SW package to render 3D surfaces on a specialized visualization system. The 'Planet3D' SW was developed in-house using open-source libraries without incurring any expenses and has been granted copyright by the Government of India. The SW can render 3D surface models at the planet scale using high-resolution datasets. The SW takes inputs of satellite images, DEMs and vector shape files to generate informative surface models. Vector shape files are used for displaying important geographical information over different places. There were obvious challenges to rendering such a high volume of satellite data on this multiprojector system, which have been addressed later in the text. In this work, high-resolution image data refer to spatial resolution of coarser than 2 m and very high-resolution data to specify a spatial resolution better than 2 m. In the case of DEM, very high-resolution DEM refers to a resolution better than 5 m and high-resolution DEM means a grid interval of 5–30 m.

Study site and dataset details

The developed SW requires raster image data, DEM and OpenStreetMap (OSM) data (vector layers) over a given place as input for generating the 3D surface of the given AOI. As described below, data from various Indian and contemporary international missions have been used here.

ResourceSat is a series of remote sensing satellites for resource monitoring. It contains three different payloads with a swath range 23–70 km. The sensors can capture data in infrared and visible bands with a spatial resolution of 5–50 m.

Cartosat-1 is the first Indian remote-sensing satellite capable of providing in-orbit stereo images. The images have been used for cartographic applications meeting global requirements. The cameras of this satellite have a resolution of 2.5 m. CartoDEM is the DEM generated from the Cartosat-1 mission.

Cartosat-2 contains a series of sophisticated and rugged remote sensing satellites that can provide scene-specific spot imagery. It carries a panchromatic camera (PAN). The spatial resolution of this camera is better than 1 m and it has a swath of 9.6 km.

Mars Orbiter Mission-1 is India's first interplanetary mission to Mars with an orbiter craft designed to follow an elliptical orbit around the planet. The Mission has been configured to carry out observations of the physical features of Mars and for a limited study of the Martian atmosphere with five payloads. Mars Color Camera (MCC) is one of the payloads, which has captured data of varied resolution over the Martian surface.

Chandrayaan-1, India's first mission to the Moon, was launched successfully on 22 October 2008. The orbit of the spacecraft was at a height of 100 km from the lunar surface for chemical, mineralogical and photo-geologic mapping of the Moon. Terrain Mapping Camera (TMC) was used to capture data of varied resolution over the Moon's surface. TMC sensor data are also useful in generating DEM over the lunar surface. Table 1 lists the datasets used as inputs in this study[12–14].

Besides imagery and elevation models, vector datasets over the Earth, Mars and Moon were also used as follows.

GIS data over the Earth: Over time, OSM has collected important data from all countries across the globe. Different vector layers are available for information about 2D buildings, important landmarks, road networks, waterways and administrative boundaries. OSM data over the Earth (~5 m spatial resolution) were downloaded from the GeoFabrik website[15].

GIS data over Moon and Mars: Vector shape files containing information about various features on the planets were obtained from the International Astronomical Union (IAU) website[16].

Methodology

The developed SW uses satellite imagery, DEM and OSM data (vector format) as inputs for the generation and rendering of the 3D surface model. We have used high-resolution datasets from the Cartosat series and CartoDEM, full disk (~100 m resolution imagery and ~150 m grid interval DEM) of the Moon, ~256 m resolution imagery and ~460 m grid interval DEM of Mars, CH-1 (~10 m data), and Mars Orbiter Mission (MCC, ~600 m resolution) datasets for surface modelling and visualization.

Level of details (LOD) technique for data visualization was implemented in the SW for better performance. Using

LOD-specific details are provided to the viewer according to his/her position. For example, if the viewer is at an altitude of 10,000 km, a coarser view is furnished, whereas viewing from an altitude of a few metres provides a detailed and finer view of the surface.

The following steps were performed for the generation and rendering of 3D surface models.

(i) Data mosaicking and interpolation

Due to imageries of varied resolution and DEM, there is a need to perform resampling of data to match the resolution of input image and DEM. Image mosaicking of the overlapped regions was performed for a seamless scene visualization using gdal_merge module[17]. According to the literature, nearest neighbour resampling, bilinear resampling, cubic resampling, and cubic spline resampling are popular resampling algorithms[18]. The cubic resampling algorithm outperformed other resampling techniques in terms of results. So, it was implemented to resample the datasets in this study.

(ii) Registration

There is a basic requirement to register satellite imagery with DEM data. There are various image registration techniques available like fast Fourier transform (FFT)-based registration, contour-based registration and wavelet-based registration[19]. Although most of the input datasets were well registered, the FFT-based registration was used wherever needed. The Fourier shift approach proved too robust to identify the linearly shifted features. DEM and image data were co-registered using the Fourier shift approach.

(iii) Implementation of mesh of triangles

Triangulation is the process of generating a network of triangles based on the height from DEM. For the generation of a mesh of triangles, the Delaunay triangulation algorithm was implemented because of its advantages over other algorithms: The triangles were as equiangular as possible, thus reducing potential numerical precision problems created by long skinny triangles; this ensures that any point on the surface is as close as possible to a node and triangulation is independent of the order in which the points are processed.

(iv) Texture mapping

This is used to improve the visual realism of images synthesized by rendering. The basic idea is to add image-based information to the rendered primitives. The digital image data could be obtained from satellite images or photographs or generated using mathematical functions[20]. As the data are in a discrete raster format, before texture mapping, a continuous texture function $f(X, Y)$ in the texture space (X, Y) has to be established using these discrete data. To map from the texture space to the 3D terrain, interpolated and registered data were used to establish one-to-one relationship between the 2D image and 3D mesh.

(v) Overlaying of vector shape files

For the nomenclature of 3D surface GIS information of planets, location-specific shape files are available from OSM. Respective shape files in vector format were downloaded and overlaid as a layer over the surface model. The computer-generated 3D surface was overlaid with several OSM layers for complete information (road network, rail network, water bodies, buildings, etc.) about specific locations over the Earth. GIS information about important features such as mountains, valleys and craters was overlaid on the Moon and Mars terrain models for a better understanding.

(vi) Memory management and efficient rendering

It is challenging to store a voluminous dataset in the main memory of the computer and render a 3D terrain model containing millions of polygons and tiles using computer graphics hardware. There are various memory management techniques available in the literature to manage the memory and represent terrain data in a polygon mesh using triangulated irregular network (TIN) and regular height field streaming mesh and hybrid approach[21].

The streaming mesh algorithm, which utilizes advanced features of computer graphics hardware such as displacement mapping, and geometry caching was implemented[22]. This involves a light pre-processing stage, in which the algorithm generates hierarchies of elevation maps and colour textures and stores them in the main memory. Using OSG's paged level of details (LOD)[23], the rendering mechanism was implemented in which coarser tiles were replaced by four sub-tiles as the viewer was near enough, and rendering high-resolution data. Further, these patches were stitched together to provide a seamless view. Data used in this study were in terabytes; it may increase to petabytes in the future. Thus an efficient rendering mechanism has been designed, keeping the system memory and graphics card memory constraints in mind. Figure 1 shows the basic structure of a quad-tree LOD in terrain rendering.

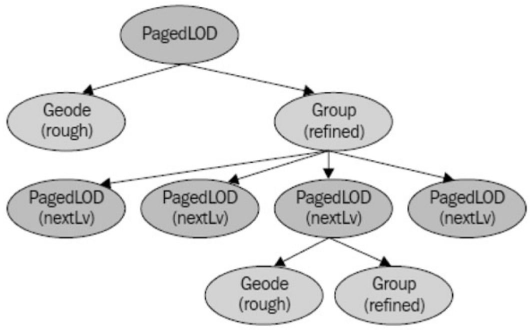

Figure 1. OpenSceneGraph (OSG) rendering mechanism.

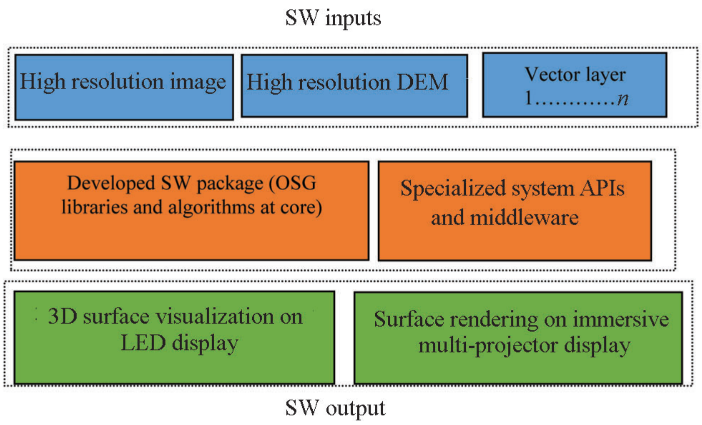

Figure 2. Software (SW) processing diagram.

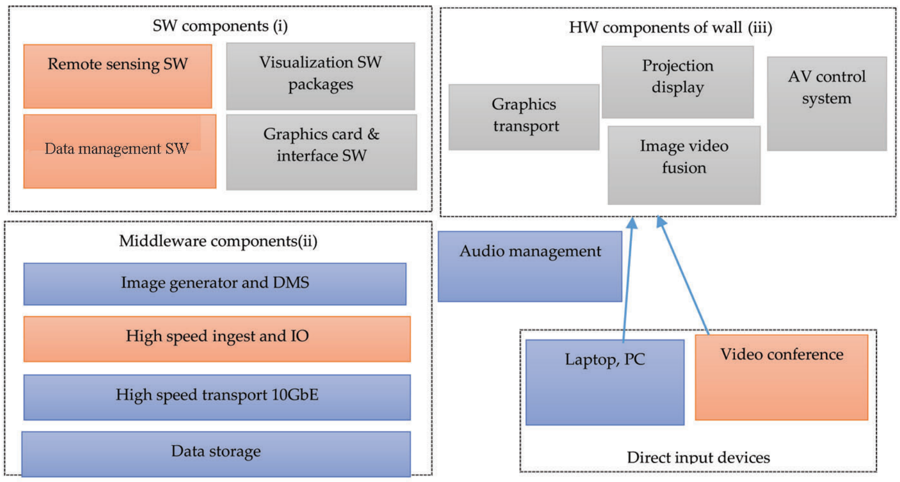

Figure 3. Components of multiprojector immersive system.

Software and system architecture

The developed SW is a desktop application which works equally well on Windows and Linux operating systems. It displays data correctly on a single screen or multiple projectors and specialized projection systems. Figure 2 describes the basic diagram of SW processing. The SW design and development involves OpenSceneGraph (OSG) libraries[24], GDAL libraries and C++ language.

OSG packages and classes used

The OSG library contains all classes related to the scene graph node the osgDB library contains classes and methods to create and render 3D databases. The osgViewer library contains classes that manage views into the scene. The osgUtil library contains classes and functions for operating on a scene graph and its contents, gathering statistics and optimizing a scene graph, and creating the render graph. We have inherited all the relevant classes for our custom development.

Specialized multiprojector visualization system architecture

A specialized multi-projector system is a customized system with a display size of 12,000 × 3,000 pixels (36 mega pixels). It has a LED-based active stereo projection (state-of-the-art) system installed at our premises. The system is mainly used for immersive visualization of stereo data, their analysis, rendering of 3D models and 3D surface visualization of planetary data.

Figure 3 shows the main components of the system:

(i) SW components: Layer 1 has content generation packages such as remote sensing SW, visualization SW packages, data management SW and graphics interface SW. These SW components are mainly used to generate 3D content for rendering and visualization purposes.

(ii) Middleware components: These are a set of image generation (IG) systems – high-end engineering workstations, Spyder system and Techviz middleware SW[25] to drive the entire projection system, storage system, high-speed network and display management system. This layer is used to seamlessly integrate, optimize and render the contents to a multi-projector wall.

(iii) Hardware components: Projector array of 26 active stereos (3D) solid-state projectors with solid-state LED illumination is available for the projection of high-definition contents on the display screen. This screen is the output console that displays high-resolution data with 12,000 × 3,000 pixel resolution.

(iv) Control system: Multi-touch table, tabletop 12″ colour touch panel is available for controlling the graphics and applications.

(v) Integrated audio system, fly box and active stereo 3D shutter glasses are integrated with the system to enhance user experience.

(vi) Calibration system: This system is used for adjustment of radiometric and geometric quality of the projector array.

Results of 3D surface modelling over the Earth

As described earlier, datasets were taken from the Indian remote sensing satellite series of ResourceSat and Cartosat-2, which provide imageries of 0.6 m (pan) – 1.6 m (mx) resolution. The stereo images provided by Cartosat-1 were used for generating DEMs employing the satellite photogrammetry technique. The indigenously developed SW solution has the potential to handle voluminous data, generate a 3D surface mesh and render the data over a specialized system. In this study data volume of more than 800 GB and projections such as World Geographic System (WGS), North American Datum (NAD) coordinate system containing data all over the world are handled smoothly using in-house developed SW. Details of a raster and elevation dataset are given below.

Input (raster) data description: multiview ortho data of Muscat acquired using Cartosat

File name: mviewc2e_ortho_geog_muscat1
Image dimension: width – 12,324, height – 11,254
Coordinate reference system: WGS 84 (EPSG:4326) Geographic
Extents: 58.3362,23.518535, 58.4485,23.6211
Units: Degrees
Pixel resolution: 0.6 m.

Input (elevation) data description of Muscat DEM using Cartosat

File name: mviewc2e_dem_geog_muscat1
Dimensions: width – 12,366, height – 11,257
Coordinate reference system: EPSG:4326 – WGS 84 – Geographic
Extents: 58.3361,23.5185, 58.4489,23.6211
Units: Degrees
Grid interval = 1 m
Datum: WGS84 ellipsoid.

3D surface visualization results over different parts of the Earth

Now we present the 3D terrain visualization results of various sites over the Earth. Perspective views of 3D surfaces can be seen in Figure 4 *a–d* using the in-house developed SW package. In Figure 4 *a*, the hilly area near the Himalayan region is seen at a very high-resolution, whereas in Figure 4 *b*, the 3D surface of the city area is rendered. Figure 4 *c* depicts Jammu and Kashmir in 3D at sub-metre resolution and Figure 4 *d* presents the perspective view of a city area.

Results of terrain modelling over Mars

In this study, data from the USGS website as well as from the Indian MOM were used. Data volume of ~100 GB and projections according to the Martian coordinate systems have been handled. A description of NASA's Vikings datasets is given below.

Input (raster) data description of Mars colorized Viking mosaic

File name: mars_big.tif
Dimensions: width – 92,160, height – 46,080
Map projection: Simple cylindrical
Scale (pixel/degree): 256
Origin = (–180.000, 90.000000)
Pixel resolution = 231.54 m.

Input (elevation) data description of Mars MGS MOLA DEM

File name: mola.tif
Dimensions: width – 46,080, height – 23,040
Map projection: Simple cylindrical Mars 2000
Scale (pixel/degree): 128
Pixel resolution = 463.08 m
Datum: Mars_2000 sphere.

Figure 4. Perspective view of (***a***) the Himalayan valley, (***b***) urban city area at sub-metre resolution, (***c***) Jammu and Kashmir at sub-metre resolution, and (***d***) city site.

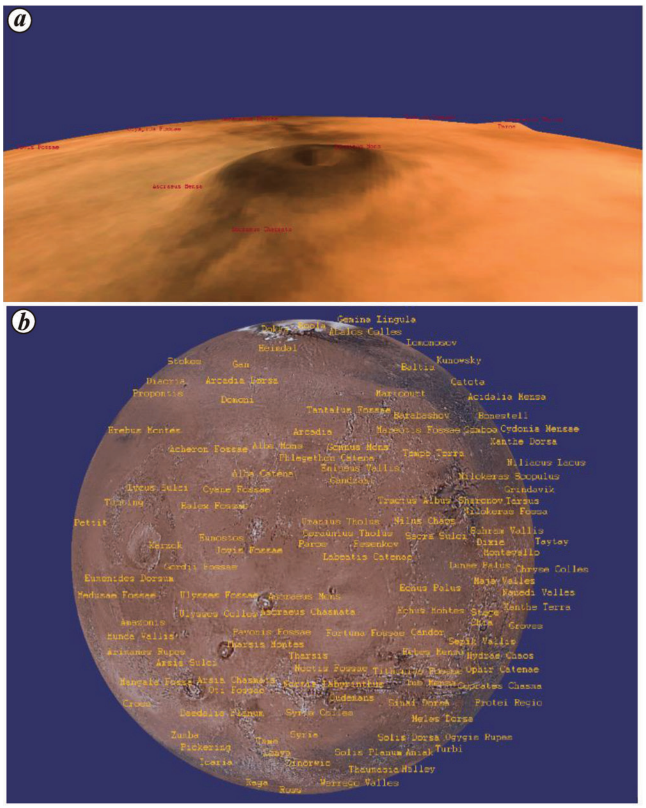

Figure 5. ***a***, Perspective view of Ascraeus Mons volcano using MCC data. ***b***, MARS full disk using Vikings data with marking of Olympus Mons.

3D surface visualization results over MARS using input datasets

Full disk imagery and DEM over Mars were downloaded from the USGS site. The MOM imagery was taken from the ISSDC website. Using the given information, important features of the Martian surface were rendered in 3D. Figure 5 *a* shows terrain visualization of Ascraeus Mons, while Figure 5 *b* gives a glimpse of the complete disk of Mars with annotations using Vikings data. Figure 6 *a* provides a 3D view of Mount Olympus, while parts of the Marnier valley are seen in Figure 6 *b* using MCC datasets.

Results of 3D surface modelling over the Moon

In this study, data from the USGS website as well as from the Indian Chandryaan-1 and Chandrayaan-2 missions available at the ISSDC website were used. Here, a data volume of ~500 GB and map projections according to the Moon coordinate system have been handled. A description of NASA's LRO datasets is given below.

Input (raster) data description of Lunar Reconnaissance Orbiter Camera (LROC) Wide Angle Camera (WAC) global mosaic

File: Lunar_LRO_LROCWAC_
Mosaic_global_100m_June20131.tif

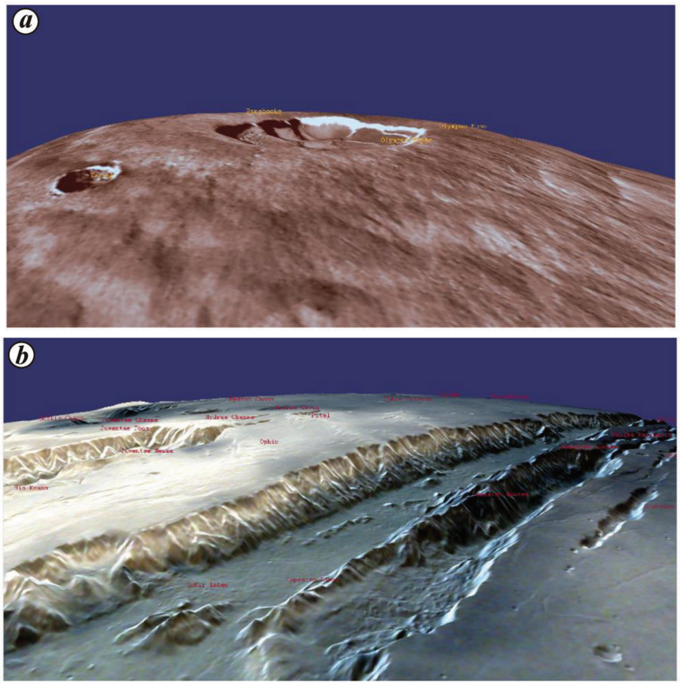

Figure 6. ***a***, Enlarged perspective view of Mount Olympus (26 km high – Vikings data). ***b***, Perspective view of Marnier valley at 600 m using MCC data.

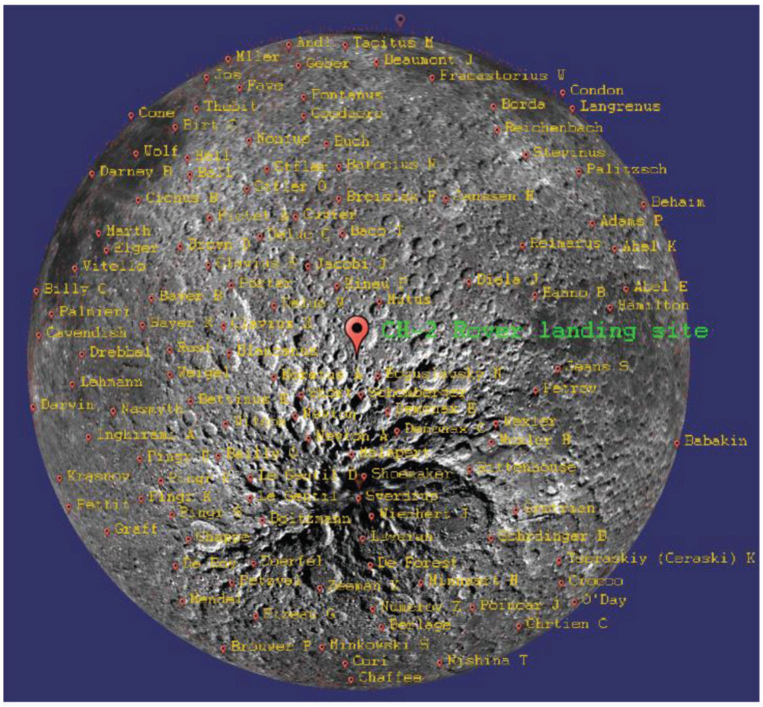

Figure 7. Moon full disk using LROC data.

Dimensions: width – 109,164, height – 54,582
Map projections: Simple cylindrical
Scale (pixel/degree): 303.233
Origin: (–5458203.076346, 2729101.538173)
Pixel resolution = ~100 m.

Input (elevation) data description of the Moon LROC WAC DTM

File: Lunar_LRO_WAC_GLD100_DTM.tif
Dimensions: width – 109,165, height – 47,912

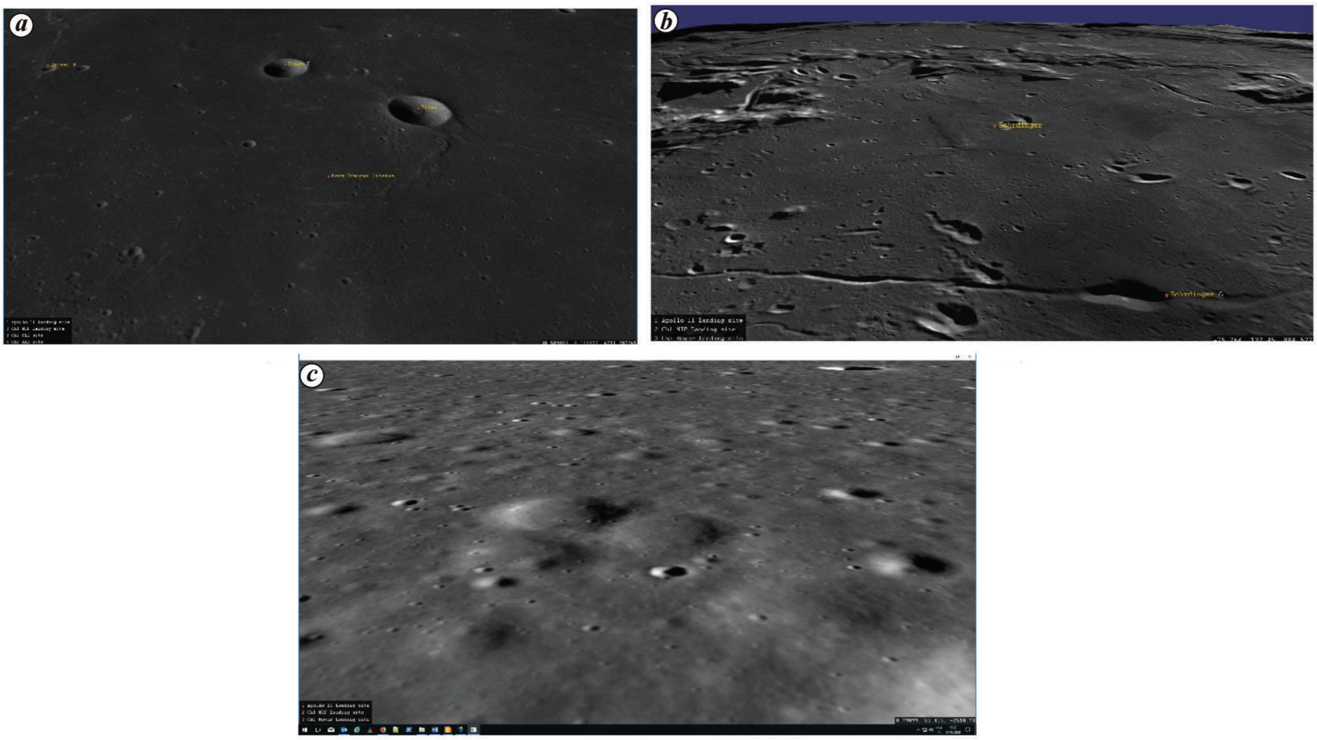

Figure 8. Perspective view of (***a***) Apollo-11 landing site using LOLA at 100 m, (***b***) Schrödinger crater using CH-1 TMC payload at 10 m and (***c***) 3D surface rendering using Indian Planetary data.

Map projection: Equi-rectangular
Scale (pixel/degree): 356
Pixel resolution: 118.5 m
Datum: Moon_spheriod, Ellipsoid.

3D surface visualization results over the Moon using input datasets

Complete disk of the Moon (imagery and DEM) was downloaded from the USGS website. CH-1 and Chandrayaan-2 (CH-2) ortho-rectified imageries and DEM were collected from the ISSDC website. Figure 7 shows the 3D surface results over the Moon using USGS data. Figure 8 *a* shows the proposed rover landing site for CH-2, while Figure 8 *b* depicts 3D terrain visualization of Schrödinger crater using 10 m data from CH-1. Figure 8 *c* shows 3D surface rendering over parts of the Moon using high-resolution data obtained from the CH-2 mission.

Challenges

A specialized multiprojector system with 26 active stereo projectors and a curved screen is available on our premises. As discussed above, ERDAS Imagine and Worldviz SW solutions were primarily utilized for 3D surface modelling using satellite data. These COTS SW solutions have limited capabilities to render large-scale data on the multiprojector visualization system. So, there is a need to develop a low-cost/zero-cost SW solution which can render high-volume satellite data in 3D over multiprojector system.

It is challenging to understand the system design and middleware components associated with the system for developing indigenous SW solutions on this platform. We must overcome technical hurdles like specialized interfaces, system-dependent APIs, projection transforms like aspect ratio of screen, field of view, far-culling and near-culling effects to correctly project 3D surface models on such a large-scale screen. Middleware SW (Techviz), which is a prime interface for application developers to render the contents on a curved screen supports certain commercial off-the-shelf tools and also provides interfaces for applications written in native languages such as OSG. Also, OSG support was the prime reason for choosing C++ and OSG as programming interfaces for SW development.

However, there were limitations in support for rendering 2D texts and for handling voluminous datasets. By gaining insights into the system architecture, middleware and system drivers, we have customized our SW design based on the system-level projection transforms (aspect ratio, field of view, zfar and znear values) to address the seamless rendering. With SW design level changes, we can visualize scenes like 3D surface modelling of full disk of planetary data, city models, imagery on a specialized system better than the solutions offered by commercial tools in terms of memory efficiency and performance.

Conclusion

ArcGIS and ERDAS Imagine SW solutions are popular for the visualization of 3D surface models. There are limitations of large data volume and real-time rendering speed on multiprojector system using COTS packages. To overcome them, an in-house scalable SW was developed. Using this SW, 3D surfaces over the Earth, Mars and Moon using data of varied resolution was generated and visualized efficiently with the specialized system. Important vector layer information on these surface models was overlaid to identify various features. The indigenously developed SW has capabilities to visualize 3D surface at planet scale using satellite data. Applications of this SW include strategy disaster management, urban planning, change detection and infrastructure management. Visualization information of various planetary 3D surfaces will be useful for future planetary missions to Mars and Moon, as visualization will help identify potential rover landing sites, navigation to different planet features and validation of future imaging sites.

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