Mars Visual Simulation for ExoMars Navigation Algorithm Validation

M. McCrum*, S. Parkes*, I. Martin*, M. Dunstan*
*Space Technology Centre, University of Dundee, Scotland, UK
e-mail: {markmccrum|sparkes|imartin|mdunstan}@computing.dundee.ac.uk

Abstract

The ExoMars rover will make heavy use of machine vision algorithms for autonomous navigation. To support the validation of these algorithms, a visual simulation capable of generating realistic simulated images of a Mars-like virtual environment has been developed. This is an enhancement of the University of Dundee’s PANGU planet surface simulation tool. The simulation is based on data from the planetary science literature and validated using images from the Mars Exploration Rovers. It includes models of rocks, surface reflectance, atmospheric dust, a rover vehicle and dynamically computed shadows. It provides a straightforward way for autonomy researchers to generate high-quality images for testing, and has potential to be used as a more general rover simulation visualisation tool.

1 Introduction

Since the large distance between Earth and Mars makes teleoperation of a rover impractical, the ExoMars rover needs to be able to navigate autonomously, travelling on average 100m per Sol [1]. To do this it will make use of stereo cameras, both to create terrain maps for path planning and also to track robustly the movement of the rover in the presence of wheel slip [2].

The robust operation of the navigation algorithms is critical to the success of the mission and therefore it is imperative that they are thoroughly tested. Knowledge of the environment in which the rover will operate is very uncertain, so a large number of tests are needed to ensure robustness over the range of possible environments. For instance, it will be necessary to test performance under different rock distributions. Much of this testing will be carried out using software simulation. The use of simulation offers a number of important benefits:

Repeatability: Tests can be repeated exactly. This is important for debugging and for comparing the performance of different configurations.

Flexibility: Since the test environment is virtual, it can be configured easily to exercise all control paths in an algorithm.

Speed: Tests can be set up very quickly. For instance the distribution of rocks or the shape of the terrain can be changed instantly. The tests themselves may often be carried out faster than real time, which is particularly important given the large number of tests that must be carried out, and the slow speed of rovers. Being able to carry out tests quickly allows for a more iterative approach to development.

Availability: Hardware testing requires access to prototype hardware and a suitable ‘Mars Yard’ or natural analogue environment. Access to these limited resources will be highly constrained, and suitable hardware may not exist at all in the earlier stages of development.

Software simulation is complimentary to testing with real hardware, which in any case is needed to validate the simulation models. A good example of this synergy is provided by the testing approach to the MER lander DlMES [3] vision system, which combined software testing using the MOC2DIMES software [4] with hardware testing using a helicopter test bed [5].

As ExoMars rover prime, Astrium Ltd. is developing rover test benches to support the validation of the rover navigation system. As part of this activity we are developing an enhanced version of the University of Dundee Planet and Asteroid Natural Scene Generation Utility (PANGU) software which will generate synthetic images of a Mars-like virtual environment that may be used as inputs to the vision-based navigation algorithms. PANGU [6] was originally developed to provide simulated sensor data for planetary landers, including camera images, RADAR and LiDAR data. It has been used on various European Space Agency projects to simulate the Moon, Mercury, Mars, asteroids, and more recently spacecraft for in-orbit rendezvous simulation. As part of a recent project, the feasibility of using PANGU for rover simulation was also demonstrated [7]. The work described here is a continuation of those efforts.

The remainder of this paper is structured as follows: In section 2, we examine related work in rover simulation. In section 3 we describe the development of requirements for the extended PANGU. Section 4 is a discussion of our approach to modelling the Mars environment, while sections 5-9 describe the new models implemented. In Section 10 we discuss the steps taken to validate the new models, and in Section 11 the results of this process. We suggest possible future work in Section 12, and finally present our conclusions.
2 Related work

Several existing simulation tools have been used to test rover navigation systems. NASA’s ROAMS is a comprehensive end-to-end real time rover simulation system developed by the Jet Propulsion Laboratory [8]. It is used to support the development and testing of rover software and hardware, and may also be used to provide simulation facilities in support of mission operations [9]. In addition to providing models of rover subsystems such as mechanical, electrical and control, ROAMS aims to generate images which are realistic enough to test vision based algorithms. The image generation capabilities focus on camera model, texture, and accurate shadows, because these are the features that most affect the stereo matching employed by many JPL algorithms [10]. ROAMS is built on the JPL DARTS/Dshell multi-mission spacecraft simulation toolkit, and uses the DSPACE visualisation tool to generate 3D imagery [11]. Terrain data is provided by the Simscape terrain modelling software [12]. ROAMS is an internal NASA tool, that does not appear to be available to outside users.

The French Space agency CNES have developed the EDRES rover simulator for testing rover autonomous navigation software during development [13]. It has been used to support autonomy algorithm development for the ExoMars rover [2, 14]. Since the main focus of the tool is autonomous navigation, other aspects of the simulation such as terrain interaction are simplified, and the various elements of the simulation appear to be quite tightly coupled.

Most recently, ESA has funded the development of a rover end-to-end simulation tool called 3DROV [15, 16]. It is intended to fulfil a similar role to the NASA ROAMS tool as a virtual simulation test bed to support rover development. Like ROAMS, it contains models of rover subsystems, including mechanical, power, thermal, sensor, actuators and scientific instruments, as well as an environment model. 3DROV has the potential to be useful in a wide range of scenarios from rover development through to operation. Its modular architecture is a key strength, permitting new capabilities to be integrated relatively easily by adding new components or replacing existing ones. The current graphical capabilities seem to be more oriented towards presenting simulation visualisations to users than to providing synthetic input to vision-based guidance algorithms, and it is not clear that they would be adequate for this task.

Each of the tools described above are much broader in scope than the PANGU tool, since they offer a simulation of the complete rover, whereas the focus of PANGU is purely on image generation, leaving simulation of other aspects of the rover to other tools. The advantage of decoupling the visual simulation element from the rest of the simulation in this way is that it allows the same tool to be reused easily to provide realistic image generation capabilities to autonomy researchers without requiring them to implement one from scratch. This is similar in philosophy to another NASA rover tool, the Mission Simulation Facility [17], which aims to allow autonomy researchers to test their algorithms in a realistic simulation environment without having to develop their own custom test bed.

3 Requirements

The primary aim of this work was to provide the visual simulation component for use by Astrium, however, PANGU has the potential to be used more broadly in rover simulation, both for camera image simulation, and for more general visualisation of simulations. For this reason, we also analysed the features provided by other rover simulation tools, as these provide examples of functionality that has already been found to be useful. From this, a comprehensive set of requirements have been developed which can serve to guide the future development of the tool.

4 Modelling the Mars environment

Before a realistic visual simulation could be created it was necessary to characterise the Mars visual environment at rover scale. This was accomplished by synthesising information from several sources. The planetary science literature provided useful qualitative and quantitative descriptions of important features such as rocks, and also mathematical models which could be implemented where possible. The second important source of data was images of the Mars surface. These were mostly images from the Mars Exploration Rovers. Initially, images from the planetary photojournal [18] were used. These provided a useful overview and could be searched by feature, but have limited coverage and the disadvantage that images may have undergone significant post-processing before publication. Later, further raw imagery was acquired using the MER analyst’s notebook [19]. This allowed access to radiometrically corrected and linearized images.

5 Rock models

Rocks are a very common feature of the surface of Mars. Large rocks represent an important navigational hazard, and rocks of all sizes are an important visual feature of many Martian landscapes. There are two aspects to rock modelling in PANGU; the appearance of rocks, and their size distribution.
5.1 Appearance

Rocks seen on Mars are not of uniform type, but vary greatly in texture and shape, for instance a great diversity was found by Spirit on the Columbia hills [20]. From an engineering perspective, rock shapes have been characterised as round, square or triangular [21]. A variety of surface textures are seen, the main terms used to describe these textures in the literature are ‘pitted’, ‘vesicular’, ‘fluted’, ‘knobby’, ‘smooth’, ‘bumpy’ and ‘lineated’ e.g. [22-24].

PANGU provides the ability to create a library of rock types. When generating a surface model, rocks are selected at random according to a user-defined probability distribution. To increase the rock variety, each rock model added to the surface is randomly stretched, rotated and buried, again according to user-defined probability distributions. Each rock model may be stored at several levels of detail, with distant rocks being rendered at lower resolution in order to improve rendering performance.

PANGU rocks are parameterised polygonal models generated using fractal techniques. User-controlled parameters allow rocks with a variety of shapes, colours and surface roughness to be defined. Figure 1 shows PANGU rock models of various shapes. Using this system we were able to generate a library of rocks that appeared to be broadly representative of some of the types of rock that have been seen on Mars. Since there is no way directly to control the shape of the rocks, a large amount of trial-and-error is involved. This situation could be improved in future by allowing the basic shape of each rock (for example triangular, round, square) to be specified explicitly.

Figure 1: PANGU Rock shape variation.

The texture of each rock is represented implicitly in the rock geometry. Rocks with varying degrees of fractal surface roughness can be created as illustrated in Figure 2, but it is not generally possible to recreate specific detailed rock textures. For very detailed textures a large number of polygons are required, which can result in higher rendering times. One way to improve the handling of rock textures would be to use a texture map or displacement map rather than representing the texture in the rock polygon mesh. In addition to improving performance, this would also have the benefit of allowing a more realistic variety of surface textures.

5.2 Distribution

The rock size distribution models of Golombek and Rapp [25] are commonly used in engineering models of the Martian surface. The cumulative fractional area distribution function:

\[ F_k(D) = k e^{-qD} \]  

\[ q(k) = (1.79 + 0.152/k) \]

Figure 2: PANGU Rock texture variation.

Given a target \(k\) value, PANGU can generate an appropriate distribution of rocks. To do this, the surface area of each rock is approximated by an ellipse, and thus the rocks are assumed to be ellipsoidal. To ensure that the resulting rock fields are accurate it is important to ensure that the randomly placed rocks do not overlap; otherwise the apparent distribution will be altered. Efficient testing for overlaps is achieved by storing the list of generated rocks in a quad tree data structure. Further adjustment may also be made to compensate for any apparent reduction in size caused by the partial burial of a rock. Figure 3 shows the actual distribution of a PANGU rock field, compared with the theoretical distribution from which it was generated.

Figure 3: PANGU rock distribution.
6 Surface reflectance model

The way in which a surface reflects light defines its Bidirectional Reflectance Distribution Function (BRDF) [26]. Using the reflectance geometry illustrated in Figure 4, and assuming an isotropic reflector, this has the form

\[ f_r(\theta_i, \theta_r, g) = \frac{dL_r}{dE_i} \] (3)

\[ \text{Figure 4: Reflectance geometry.} \]

and gives the ratio of the radiance of light reflected toward the camera, \( L_r \), to the irradiance of light incident on the surface \( E_i \). The reflectance function used to render a surface has a large effect on its appearance. PANGU offers three different reflectance models. The simplest of these is the Lambertian reflectance model widely used in computer graphics. This seems to be an appropriate model for many Mars surface materials, for instance Bell et al [23] found that most surfaces at Meridiani Planum were ‘approximately Lambertian’. Also widely used in computer graphics is the Phong model, which adds to the Lambertian model a simple model of specular reflection. Specular reflection has been observed under certain lighting conditions by a number of surface materials [24, 27, 28].

In addition to these simple models, a version of the Hapke Bidirectional Reflectance Distribution Function [29] has also been implemented using the programmable Graphics Processing Unit provided by modern graphics cards. Hapke functions are commonly used in photometric studies of the Martian surface, e.g. [30], so it would be possible to use fits of the Hapke model based on real Martian surfaces. The Hapke model is capable of modelling a variety of reflectance behaviours that have been observed on Mars including backscattering, forward scattering and the zero-phase opposition surge. The Hapke function is used with a variety of ‘phase functions’ which model the single scattering behaviour of individual surface grains. Our current implementation uses a simple backscattering phase function originally intended to model lunar surface materials. During validation it was realised that for Mars, a more flexible phase function such as the Henyey Greenstein function [31] would be more appropriate, since the lunar phase function is highly backscattering compared to the Martian surface.

Figure 5 shows on the left the ‘opposition effect’ in a Mars Exploration Rover image, visible as a faint ‘halo’ around the shadow of the mast head. The right hand PANGU image was generated using the Hapke reflectance model, and shows an equivalent highlight. The brightening of the hills in the background is partly due to the lunar-like phase function.

\[ \text{Figure 5: The opposition effect. MER (left), PANGU (right).} \]

7 Atmosphere model

Numerous authors have reported evidence for a permanent ‘dust haze’ in the atmosphere e.g. [32-34]. The light-attenuating effect of this dust haze is measured by the atmospheric optical depth. Viking measured background optical depths ranging from a few tenths to more than 1.0, but generally around 0.5 [33]. Subsequent measurements by Pathfinder [35] and the Mars Exploration Rovers [36] have supported this result.

In the run up to a dust storm, optical depth increases considerably. During a series of dust storms, the Mars Exploration rovers recorded maximum optical depths of 1–1.5 for 1–7 sols with a 0.6–0.9 inter-storm optical depth [36]. The highest optical depth recorded by the Viking Landers during a dust storm was 6 [37].

Dust particles in the atmosphere both absorb and scatter light in a wavelength-dependent way. The combination of scattering and absorption results in light being attenuated according to the Beer-Lambert law:

\[ \frac{I}{I_0} = e^{-\tau} \] (4)

where \( \tau \) is the optical depth of the path over which the light is attenuated.
The scattering behaviour of dust particles is given by its phase function. We model this using the Henyey Greenstein phase function:

\[ F_m(\theta) = \frac{1 - g^2}{4\pi (1 + g^2 + 2g \cdot \cos(\theta))^{3/2}} \] (5)

where \( \theta \) is the scattering angle and \( g \) controls the asymmetry of the phase function.

In each case it is necessary to consider the approximately exponential reduction in dust density with height. Thus, the dust density of the atmosphere at height \( h \) is:

\[ \alpha(h) = \alpha_0 e^{-h/H_0} \] (6)

where \( H_0 \) is the atmospheric scale height, which is approximately 11km for Mars [34] and \( \alpha_0 \) is the density at the datum.

7.1 Implementation

PANGU models several important effects of atmospheric dust. The first of these is ‘aerial perspective’. This is the loss of contrast of distance terrain caused by the attenuation of the light reflected by the terrain and the in-scatter of sunlight towards the camera. To improve the rendering performance for rover simulation, where the camera will always be close to the ground, we make the reasonable simplification, suggested in [38], of assuming that the atmosphere between the terrain and the camera has constant density.

The second effect is sky colour modelling. For this it is necessary to account for the exponential atmosphere density profile and the curvature of the atmosphere. A GPU shader program is used to numerically integrate the light scattering equations from [39] for every pixel of the sky. This process is accelerated by precomputing part of the integral into a lookup table as suggested in [40].

The final effect is the attenuation of the sunlight which directly illuminates a surface.

In addition to a diffuse dust haze, dust devils are quite common on Mars, and have been observed by the Mars Exploration Rovers [36]. PANGU incorporates a dust devil model (Figure 6). This is useful in establishing the sensitivity of navigation algorithms to dust devils, and might also be useful for testing dust devil detection algorithms.

7.2 Limitations

To keep the computations manageable in real time, the effects of multiple scattering are ignored. This may be significant for low Sun angles where the optical path lengths will be longer. A method for approximating real time multiple scattering has been suggested in [41]. However, it was not deemed practical to use at this stage due to its complexity and heavy resource requirements.

A further effect of atmospheric dust is to provide a significant diffuse illumination of the surface [42]. PANGU supports a simple global ambient illumination source, but this is currently user controlled rather than being computed using the atmosphere model.

![Figure 6: Dust devil model.](image)

8 Rover model

The simulation includes an articulated model of the ExoMars rover. This was derived from CAD data provided by Astrium Ltd. A large amount of manual processing of this data using the NuGraf [43] 3D model processing Blender [44] 3D authoring packages was required in order to produce a simplified model for fast rendering. In many cases it was necessary to recreate components from scratch using the originals as templates. In addition to the model of the rover geometry, the kinematic structure of the rover and the position of the rover cameras are defined using a separate XML file.

9 Dynamic shadowing system

Shadows are vital for realistic image generation. In a rover simulation, since both the Sun and the rover may move significantly over the course of a simulation, it is necessary that these shadows can be recomputed efficiently. To this end, we have implemented a dynamic shadow system based on the Parallel Split Shadow Maps technique [45]. This includes shadows cast by the terrain and by the rover (Figure 7).
10 Validation

In order to assess how realistic the images generated by PANGU are, we have made qualitative comparisons to images from the Spirit Mars Exploration Rover obtained from the MER Analyst’s Notebook [19]. These comparisons can be carried out most effectively if the terrain geometry is similar in both images. To achieve this, we use a Digital Elevation Model (DEM) of the Columbia Hills produced from HiRISE data by the USGS [46], with surface albedo variation from the same HiRISE image. The rover images include an extensive label describing how the image was produced. From the time the image was acquired we look up the position of the rover. From the rover camera model parameters and rover frame definitions we are able then to determine approximate camera position and pointing. Using this approach we are able to create images with very similar terrain geometry to the original (Figure 8). Discrepancies between the images are most likely due to uncertainties in the DEM and the rover position.

Once we have the appropriate camera settings, we can then add the feature we want to assess. For instance, Figure 9 shows an image generated to help validate the rock model. The distribution of rocks was generated from equation 1, except that several of the larger rocks were manually placed to match those in the real image.

11 Results

The enhancements described above have improved the realism of the images that the PANGU tool can generate from a rover perspective, and should be sufficient for use in the ExoMars navigation algorithm testing. The most obvious discrepancy is that PANGU images do not exhibit the variety of detailed rock and surface textures found in the real images, instead being restricted to a rather homogenous fractal roughness. This would be a useful area for future development, either using textures derived from real images, or more complex procedural texture models.

12 Future work

Several ways in which the realism of the tool could be further enhanced have already been described above. In addition, there is scope to develop PANGU’s capabilities as a visualisation tool for rover simulation. This would involve adding the ability to include ‘visualisation objects’ to annotate a scene such as waypoints, traverse paths, and overlays with traversability maps. These would allow a greater insight into the state of the rover during a simulation. Finally, it would be useful to improve the performance of the system so that tests can be carried out more quickly.

13 Conclusion

The work describe in this paper represents progress toward the creation of a visual simulation of the Mars environment for rover applications, which is based on the available scientific data on Mars and validated against images from real Mars rovers. While our initial focus is on ExoMars navigation algorithm validation, by decoupling this element from other parts of the
simulation, our tool provides a simple way for other autonomy researchers to generate high quality test data to support their development and testing. Future development will improve the realism and performance of the system, and enhance the scope for use as a more general visualisation tool.

14 Acknowledgements

The work described here has been funded in part by Astrium Ltd, and also by the European Space Agency under contract 20858/07/NL/EK.

References


