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# SIMULATION OF NEAR-EARTH OBJECTS AND RELATED LANDER GUIDANCE SYSTEMS

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## ABSTRACT

ESA and JAXA are currently studying a sample return mission to a Near-Earth Object (NEO). The Marco Polo mission will travel to a primitive NEO, survey it from orbit, approach and land on the surface, retrieve samples, and return them to Earth. The NEO to be visited is thought to be a primitive remnant left over from the formation of the planets.

A controlled landing on a Near-Earth Object (NEO) requires sensors that are able to track the motion of the object and that of the lander approaching it. Computer vision is a strong candidate for this task possibly in conjunction with laser range finders and/or radar ranging devices. One or more cameras may be employed to provide monocular or stereoscopic vision capability. Computer vision is attractive because it uses passive sensors which each sample multiple points on the surface of the target body. The difficulty comes in the algorithms to be used to extract navigation information from the images and in the trade-off between performance, accuracy and robustness. The development, testing and validation of possible computer vision algorithms require a simulation environment that can provide realistic images of NEOs. Shadows need to be dynamic since the NEO may well be tumbling in its orbit and the reflectance properties of the NEO have to be modelled realistically. The lander and its shadow need to be simulated. Simulated images from cameras on the lander have to generated and passed to the image processing system. Ideally the simulation has to operate in a closed loop with the spacecraft model being positioned according to the dynamics of the spacecraft. This has to take into account any control operation initiated by the guidance and navigation control system using information from the processed images.

The PANGU (Planet and Asteroid Natural Scene Generation Utility) is a software tool developed by the University of Dundee for simulating and visualising the surface of various planetary bodies. It has been designed to support the development of planetary landers that use active or passive computer vision to navigate towards the surface.

This paper reports recent work on the PANGU system which is particularly relevant to NEO landing systems. It aims to provide project managers and systems engineers working on NEO rendezvous and landing missions with an overview of the relevant capabilities of PANGU. It will be illustrated by images (and video clips) of highly realistic synthetic NEOs.

## INTRODUCTION

The PANGU (Planet and Asteroid Natural Scene Generation Utility) is a software tool for simulating and visualising the surface of various solid planetary bodies including asteroids. It has been designed to support the development of planetary landers, orbiters and surface rovers that use active or passive computer vision to navigate.

PANGU can be used to generate and visualise surface models representative of the Moon, Mercury, Mars or asteroids based on a combination of real data and artificially generated terrain features. Additional object models such as spacecraft, satellites and rovers can be added to the simulation and manipulated as required.

PANGU includes a custom rendering system which has been designed to give a high degree of realism while operating at near real-time speeds to enable closed loop simulation of complete vision-based navigation systems. This includes simulating cameras, scanning LIDAR and RADAR altimeters. The rendering system includes dynamic shadow casting to enable the realistic rendering of dynamic objects in the simulation.

PANGU surface models are based on an initial digital elevation model that can be imported or generated as fractal terrain. Additional detail can be added through fractal expansion creating a hierarchical multi-resolution module with increasing detail in the central region. Additional surface features such as craters, boulders and dunes can be added with the size, position and other characteristics defined from user defined distributions. The hierarchical surface can be rendered at the appropriate resolution to avoid over rendering and speed up the simulation. The crater model includes the functionality to overlay craters and generate realistic simple craters in the full range of crater degradation from fresh craters with sharp rims to mild depressions. PANGU generates fractal boulder models at user-defined level of detail. The boulder models can be created with multiple levels of detail so that the most appropriate level can be selected for rendering at runtime. A regular icosahedron (which is a 20-sided polyhedron with equal sized equilateral triangle faces) is defined as the base model for boulders. The icosahedron can be doubled in resolution by replacing every triangle with four smaller triangles using triangle-edge subdivision. Realistic boulder shapes are obtained by modifying the position of the initial vertices of the icosahedron and by adding random displacements to new vertices introduced by subdivision.

PANGU was developed by the University of Dundee for ESA and is now being used on several ESA studies and development projects aimed at producing precise, robust planetary lander guidance systems.

Optical imagery provides a powerful means of navigation for spacecraft in the vicinity of Solar system bodies, where the communication delay may be much larger than the dynamical timescales. Recent asteroid rendezvous missions such as NEAR-Shoemaker [1] and Hayabusa [2] have exploited this to enable autonomous descent and landing manoeuvres with unprecedented landing accuracy. PANGU can be used to test and develop the image processing techniques required for such precision operations.

This paper aims to provide project managers and systems engineers working on near Earth objects and related planetary guidance systems with an overview of the capabilities of PANGU. It is illustrated by images of highly realistic synthetic asteroid surfaces, along with discussion of recent work on the use of PANGU in developing vision based guidance systems.

## ASTEROID SIMULATION

PANGU can also generate and render asteroid models. Base asteroid models are defined in polar coordinates and are generated using an extended Poisson faulting algorithm which provides control over the roughness of the resulting surface [3]. The standard PANGU crater model is used but modified to impact craters onto a three dimensional model in polar coordinates. Craters and boulders can be distributed evenly around an asteroid model. Crater diameter and age distributions can be defined specifically for asteroid models. Boulder size and depth distributions can be defined similarly. Figure 1 shows an artificially generated PANGU asteroid model with small craters distributed across the model.

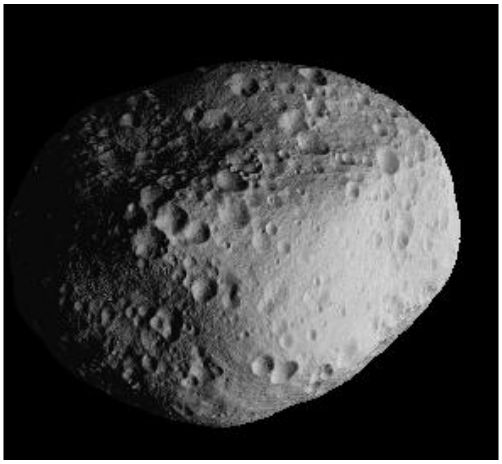

Figure 1: PANGU simulated asteroid.

The surface reflectance of airless rocky bodies such as asteroids is not well modelled by the Lambertian reflectance model commonly used in computer graphics. PANGU provides an implementation of the Hapke bidirectional-reflectance function [4], which is widely used in the study of rocky planetary surfaces. The Hapke function effectively models important reflectance phenomena such as the zero-phase opposition surge that has been observed in images of asteroid Itokawa.

For NEO applications, it is important that accurate shadows are computed dynamically, since the asteroid may well be tumbling. It is also important that the lander shadow be correctly displayed as this is a potential source of confusion for vision-based algorithms. PANGU incorporates a dynamic shadow-mapping system based on the Parallel-Split Shadow Maps technique [5] that computes both asteroid self-shadowing and shadows cast by a 3D model of the lander.

The importance of spacecraft shadows and the asteroid surface reflectance model can be seen in Figure 2, which is an image of asteroid Itokawa captured by the Hayabusa spacecraft. A bright opposition highlight is clearly visible in the middle of which the shadow of Hayabusa may be seen. Figure 3 demonstrates a similar scene created using PANGU.

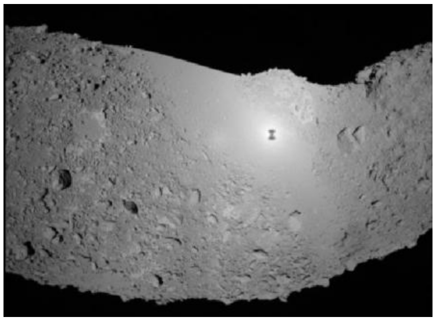

Figure 2: Asteroid Itokawa

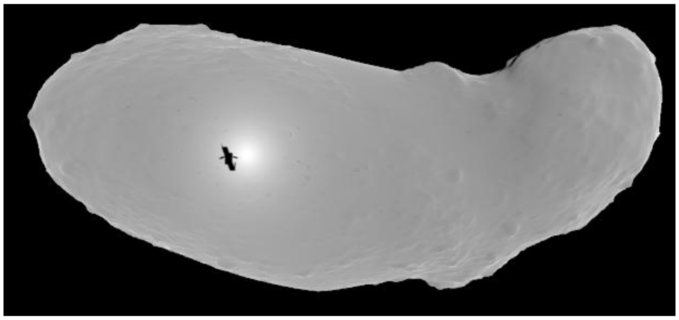

Figure 3: PANGU simulation including spacecraft shadow and Hapke reflectance model.

## OPEN AND CLOSED LOOP TESTING

Given the combined position and attitude of a spacecraft, the PANGU viewer can generate synthetic images, RADAR and LIDAR responses of the target PANGU model. Many relevant properties of the system can be controlled interactively via the viewer, such as Sun position, asteroid rotation, parameters of the camera and other sensory instruments. The dynamical information and simulated data can be exchanged in a number of ways, enabling a variety of possible test environments for developing applications, such as guidance systems, that fuse information from a range of sensors.

The spacecraft trajectory and all relevant information may be supplied to the viewer in a data file, which consists of simple one-line commands that update the position and attitude and other simulation parameters from frame to frame. The viewer may write all synthetic images and sensory data to disk for each camera position specified in the data file. This enables post-flight processing of sensory data to evaluate, e.g. the performance of navigation systems against the known trajectory parameters. Figure 4 displays an example trajectory rendered with a PANGU asteroid simulation using the viewer. The trajectory was calculated externally by numerically integrating the equations of motion in the gravitational potential of the asteroid.

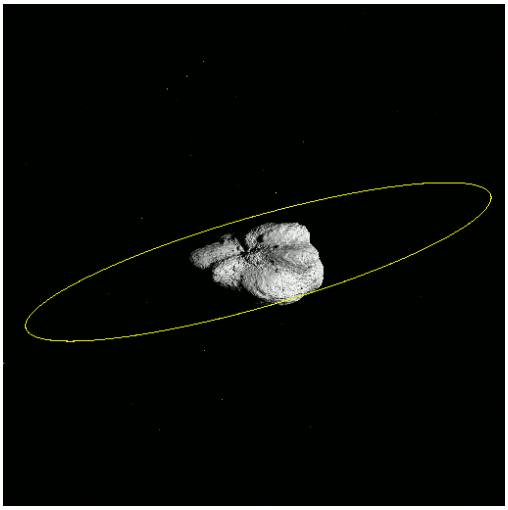

Figure 4: Rendering of a trajectory data file for a flight around a PANGU asteroid model.

The viewer is also equipped with a TCP/IP server, allowing images and sensory data to be obtained on-the-fly and delivered directly to programs in near real time. For example, a Java client is available that controls the PANGU simulation via the TCP interface, requesting images and issuing commands to update the camera position and attitude with appropriate function calls. This could be incorporated into a Simulink model using a Matlab S-Function that in turn calls the appropriate Java methods. Closed-loop testing in this manner allows full GNC systems to be simulated and tested, with the spacecraft control systems operated in response to the frame-by-frame data received from the PANGU server.

## VISION BASED GUIDANCE SYSTEMS: PROTOTYPING AND DEVELOPMENT USING PANGU

The University of Dundee has developed an image processing chip capable of carrying out the rapid feature extraction and tracking necessary to support GNC systems during descent and landing onto large planetary bodies, where the approach speed is high and the processing must be done quickly. The Feature Extraction Integrated Circuit (FEIC) is implemented in FPGA technology, and is capable of processing images at a rate of 20Hz. The image processing algorithm identifies and tracks surface features through the sequence of images, feeding these to the onboard computer to assist in navigation. Suitable features are identified by applying the Harris corner detector to each new image; regions with a large response indicate features with a high intensity gradient in all directions. Such features are by definition easily distinguishable from their surroundings, and are capable of being tracked from one frame to the next. The tracking of features is based on the correlation of intensity between a search region in the later images and a small template region surrounding the feature and extracted from the original image in which the feature was first identified. The search gate is restricted to a square region surrounding the last tracked position; this restricts false matches while allowing considerable motion between frames, depending on the size of the search gate chosen.

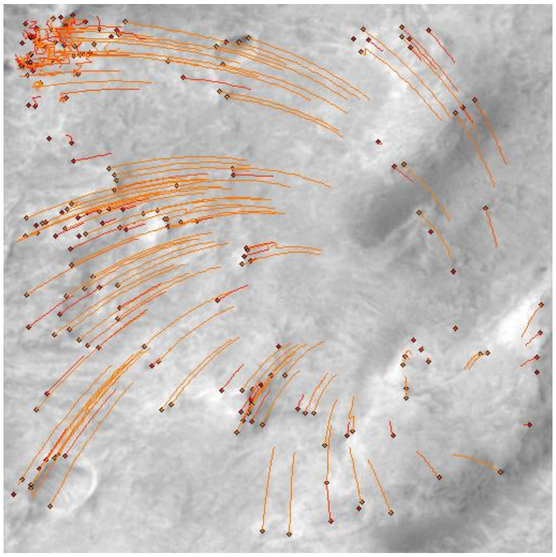

Figure 5: Feature tracks from a Martian descent and landing scenario with considerable transverse velocity and camera rotation.

Figure 5 shows the results of a simulation carried out to test the application of the FEIC to a Martian descent and landing scenario, where the feature tracks are used to calculate the transverse velocity and rotation of the camera during descent. The elimination of these is crucial for a safe landing. Most features move on smooth tracks during the descent, however some are seen to jump abruptly from one frame to the next, and a large group of features in the top left have failed to track altogether. This is likely due to the features moving out of the field of view between frames, and the basic correlation tracking algorithm getting confused with similar features nearby. The onboard computer is expected to identify tracks such as these that have diverged from their original feature, for example by using a Kalman filter to verify the consistency of individual feature tracks prior to inclusion in the state propagation.

We also find that changes in the viewing and illumination angles during tracking slowly degrade the strength of the correlation with the original feature template. This is due in the first case to the evolving projection of the surface feature onto the image plane, and in the second case to changes in the shadow structure. With the default correlation threshold of 0.8 for an acceptable identification, we find that feature tracks are generally robust over changes in illumination and/or view angle of around ten degrees. This has implications for NEO vision based navigation, where the rotation periods may be short and result in the loss of prominent features on short timescales.

## NEO Applications

For vision based guidance in the vicinity of NEOs, the requirement of low image processing latency can be relaxed due to the longer dynamical timescales associated with the weaker gravitational potential. This allows extra processing blocks to be implemented that aim to improve on the basic algorithm. We have investigated several improvements to the basic FEIC algorithm so that the feature tracks used for navigation are of the highest quality, by increasing the robustness of tracking to changes in the illumination and viewing angles and eliminating features that wander from their correct location.

### Eliminating wandering features

Discontinuous feature tracks and those that linger after the original feature has left the field of view are a result of false-positive identifications during correlation tracking. The location of maximum correlation within the search window is adopted as the new position of each feature, as long as the correlation strength is above the default threshold of 0.8. The existence of secondary maxima above the correlation threshold indicates sources of possible confusion that may lead to incorrect matches if, for example, noise causes a secondary feature to produce a stronger correlation than the original in some image. This is especially pertinent to NEO image processing, because the horizon is often in the field of view and forms a prominent edge along which many similar features may lie. Alternatively, once the correct feature has moved out of the field of view or disappeared over the horizon the strongest secondary maximum would then be identified as the new location of the feature. This is the case in the top left corner of Figure 5. We have investigated the effect on feature tracking when all features with strong secondary correlation maxima are purged. We used a descent and landing trajectory onto a PANGU surface model to generate the image sequence, and extracted and tracked features using both the original FEIC algorithm and the new approach.

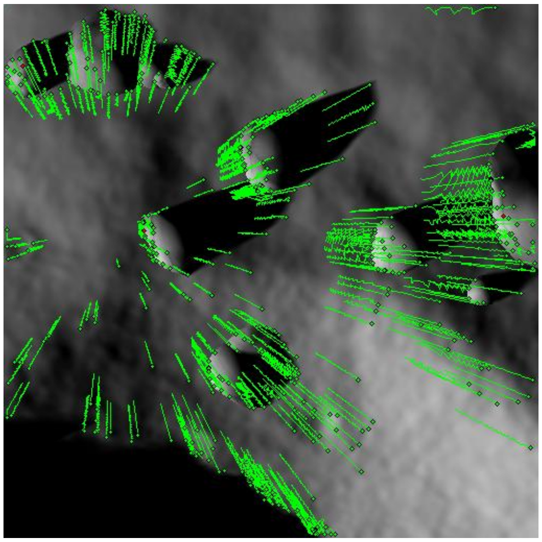

Figure 6: Descent and landing sequence onto a PANGU surface model, with no checks for secondary correlation maxima.

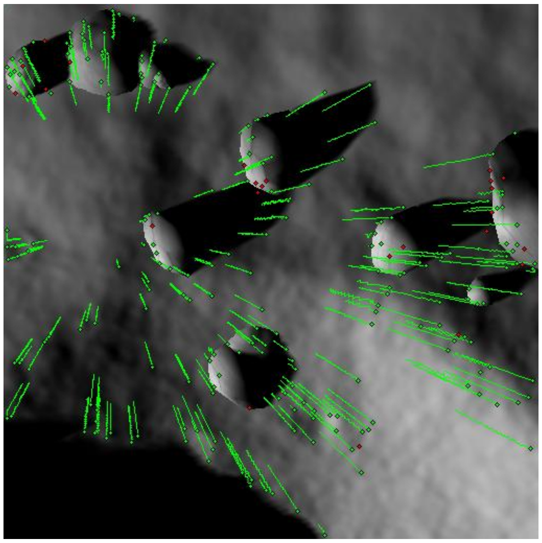

Figure 7: The same descent and landing sequence, with features rejected if secondary maxima appear in the correlation search gate.

Figure 6 shows a still image captured 56 frames into the decent sequence, using the default tracking algorithm. Tracked features are indicated with green diamonds and associated tracks; red diamonds are new features identified in this frame. Many wandering features are apparent, in particular along the strong edges of boulders on the right of the frame. Several orphaned features also linger around the image boundaries. Figure 7 is taken at the same point in the descent sequence. This time, features with strong secondary correlation maxima in the search gate have been purged during tracking. The most obvious difference is in the number of tracks – most features have been rejected by this extra level of constraint. However, the remaining features show almost no signs of wandering, and provide superior tracks for navigation purposes.

Updating feature templates

In order to reduce the number of feature tracks lost due to the changing illumination and viewing angles during tracking, we have developed a scheme by which the image template used to locate the feature by correlation can be updated over time. This counters the slow decline in correlation and can allow features to persist for far longer. Simply switching the original template with one extracted from the new image each time a feature is successfully tracked is somewhat catastrophic; the tracks tend to wander gradually or even remain stationary while the surface features all move past. We have tested an alternative system that involves extracting a new template every few frames, and, rather than immediately swapping it with the original template, tracking the two templates in parallel for several frames to check that the new template does not cause the track to diverge from it's original path. If the new template passes this validation stage, it replaces the original template, which is discarded. We refer to this process as the 'cloning' of feature points. To test this technique we have extracted and tracked features through a descent and landing sequence onto a PANGU surface, with a rotating camera to enhance the effects of declining correlation strength.

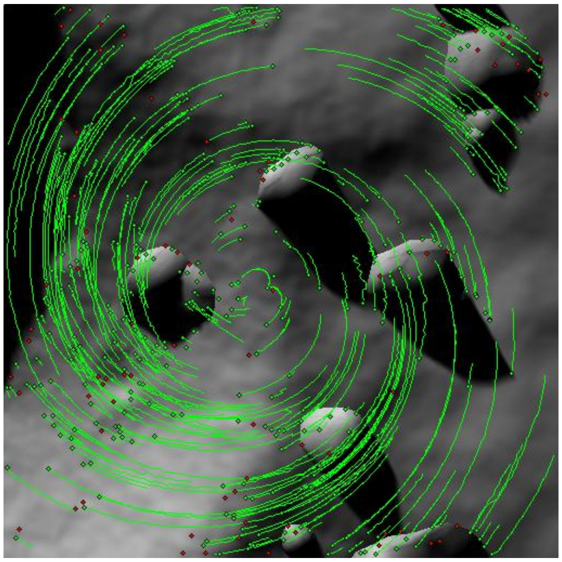

Figure 8: Descent and landing sequence with a rotating camera, without feature 'cloning' to reduce the loss of tracks.

Figure 8 depicts a still image from the sequence after eighty frames of tracking. The colours of the tracks and features are the same as before. Compare this to Figure 9, which is taken at the same point in the sequence but uses cloning to update feature templates every four frames. Green diamonds with red borders indicate features that have been cloned at least once during tracking. Many tracks correspond to the same feature – a case in point is the track originating from the peak of the boulder shadow on the lower right of the image. It is clear that when cloning is used, tracks are often significantly longer. We find that prominent features are frequently lost and recovered in the absence of cloning, whereas cloning allows these features to persist. There is also no noticeable wandering of tracks that occurs when templates are simply updated every frame without the validation stage.

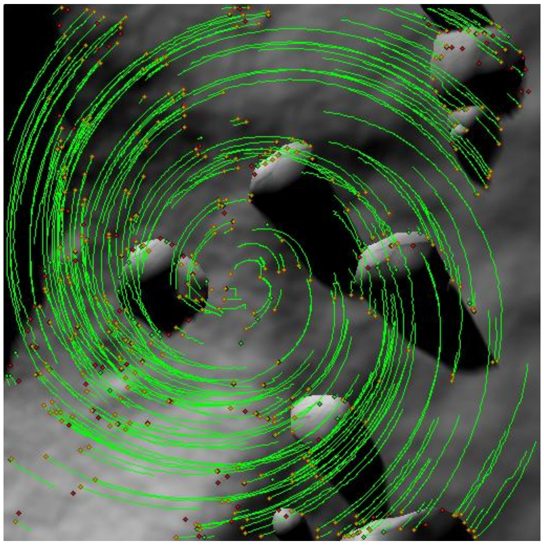

Figure 9: The same descent and landing sequence, this time with feature 'cloning'. There is an obvious tendency for features to be tracked for longer.

## CONCLUSIONS

The PANGU can simulate a range of types of Solar system body, and provide synthetic observations in the form of images, RADAR and LIDAR measurements given a particular vantage point. It can be used in both open and closed loop testing to develop and validate image processing algorithms to assist in guidance, navigation and control systems design. Example algorithms of particular relevance to NEO missions have been discussed, with reference to systems already developed at the University of Dundee.

## ACKNOWLEDGEMENTS

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