Vision Based Guidance for Exploratory Spacecraft

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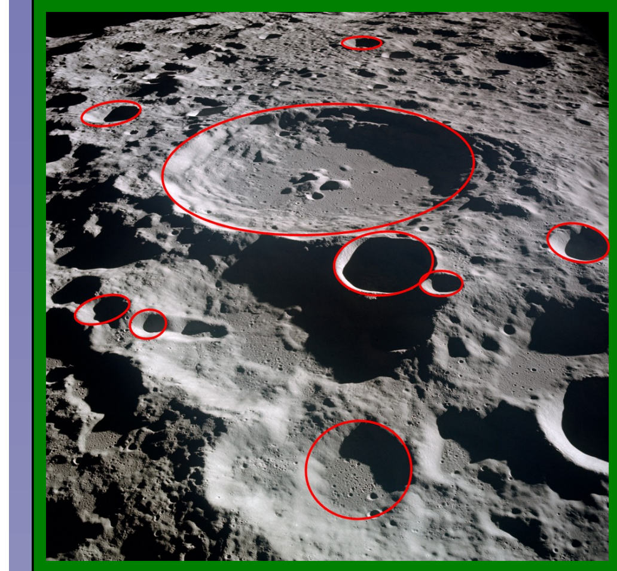
Introduction

With the exception of the Moon, the scientific exploration of remote parts of the Solar system has been conducted entirely by robotic spacecraft. Direct interactive teleoperation of distant spacecraft from Earth is not possible in many cases, due to the time delay in radio signals. The success of such missions therefore depends on the ability of onboard autonomous guidance, navigation and control (GNC) systems to operate the craft safely using available sensors, and make crucial decisions in the absence of human intervention.

Optical navigation using machine vision techniques is a key enabling technology for many future mission scenarios, such as pinpoint landing on asteroids and planets, precision formation flying for multi-satellite missions, and in-orbit rendezvous and docking. The Space Technology Centre at the University of Dundee (UoD) has been involved in several ESA projects to develop virtual test environments for vision guidance systems, and to develop embedded onboard image processing pipelines to aid GNC systems for planetary and asteroid lander missions.

Optical Navigation Principles

There is a wide variety of methods for extracting navigation information from images. These can be roughly divided into two classes: *Absolute Navigation*, where the instantaneous location of the craft is tied to some known external reference frame, and *Relative Navigation*, where the motion of the craft is propagated from a known starting point using image and inertial measurements.

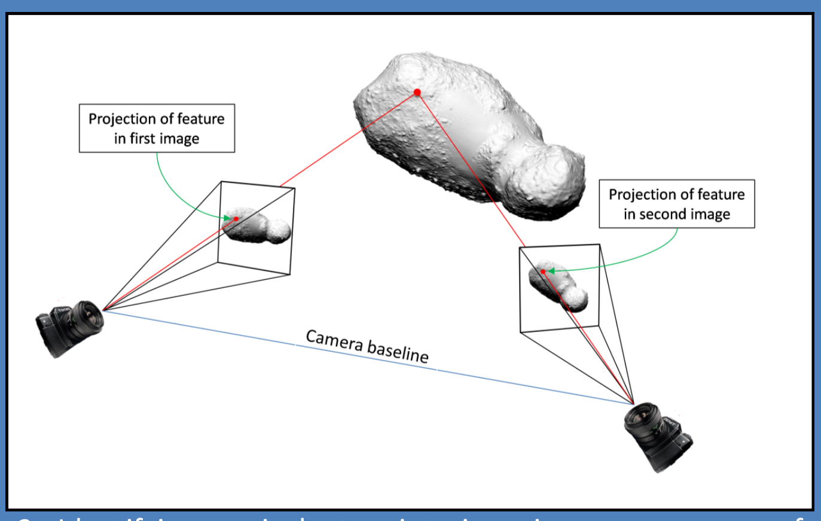

1a. Craters provide prominent navigation landmarks on many Solar system bodies...


1b. ...but some interesting targets show no craters at all! *- Image courtesy of JAXA*

Absolute navigation relies on being able to identify known reference points (*landmarks*) in the image, which allow the position and orientation of the craft to be deduced using photogrammetry and statistical techniques. Identifying landmarks in images and linking them to a known database autonomously is not a trivial task. Craters provide navigation landmarks on many Solar system bodies, but not all targets have prominent features (Fig 1).

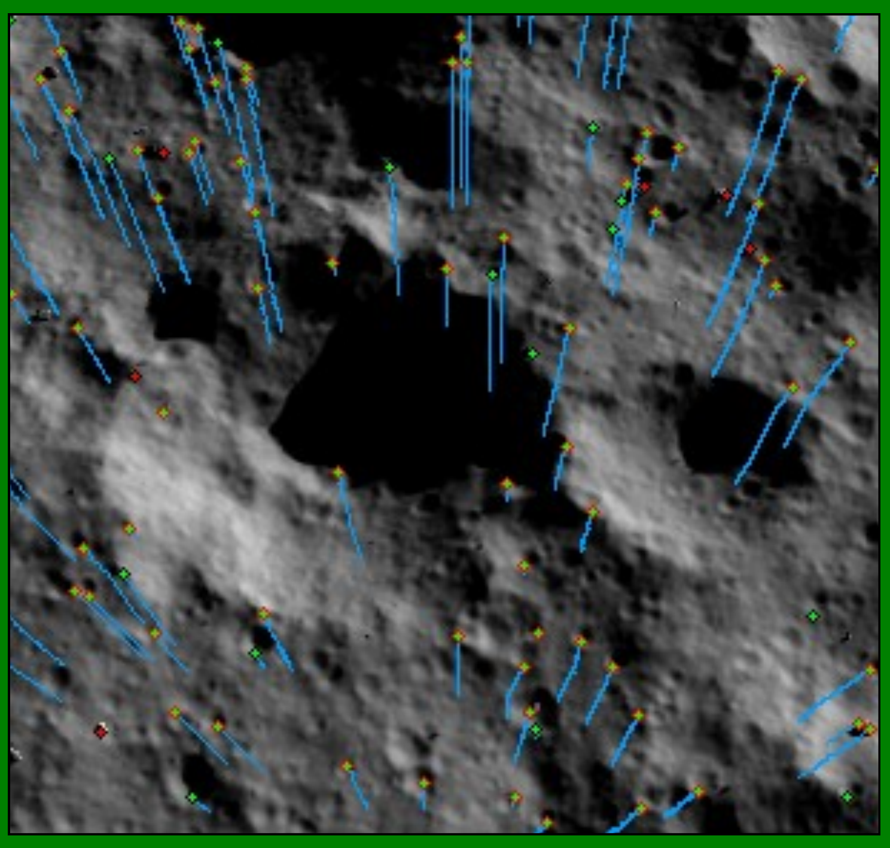
Relative navigation works by tracking surface features from one image to the next (Fig 2). The intrinsic geometry of pairs and sequences of images allows the camera motion to be constrained from the tracks that the features follow in the image plane.

These image measurements are processed by the *navigation filter*, which combines noisy image data with existing knowledge to produce a statistically optimal estimate of the spacecraft *State Vector*—the vector of all navigation variables.



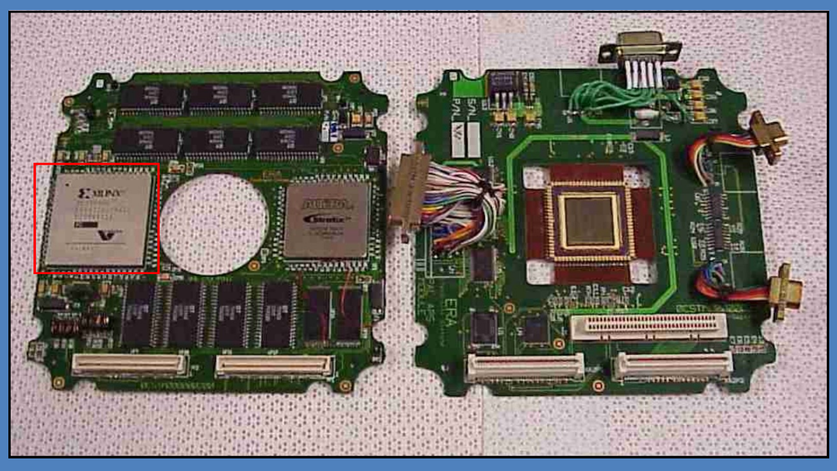
2. Identifying equivalent points in pairs or sequences of images is the foundation of many optical navigation algorithms. The instrinsic geometry of pairs of images—the *Epipolar Geometry* [1] - places constraints on the camera motion and 3D structure of the scene.

Embedded Image Processing


3. Feature tracking algorithm [2] operating on a sequence of simulated Lunar surface images.

Optical feature tracking methods developed by our group [2] use the Harris corner detector to select prominent image points that have a large 2D spatial intensity gradient in all directions. These features are tracked by extracting a small 7×7 pixel patch surrounding the feature, and correlating this with the next image in the sequence. The point of strongest correlation marks the new location of the feature—see Fig 3.

Feature tracking is a computationally demanding task, but like many image processing algorithms it can be solved using highly parallel processing. For rapid, parallel onboard image processing, Field Programmable Gate Arrays (FPGAs) may be used to offload the calculations from the central navigation computer. Fig 4 shows the *Navigation for Planetary Approach and Landing* (NPAL) camera [3]. This combines a camera and image processing FPGA (designed by the UoD) into a single unit. This modular design allows a much lower data rate between sensors and the GNC computer, with much of the processing delegated to dedicated subsystems.



4a. Interior view of the NPAL navigation camera showing the image processing chip (red box).

4b. Exterior view of NPAL navigation camera.

Mission Analysis and Simulation



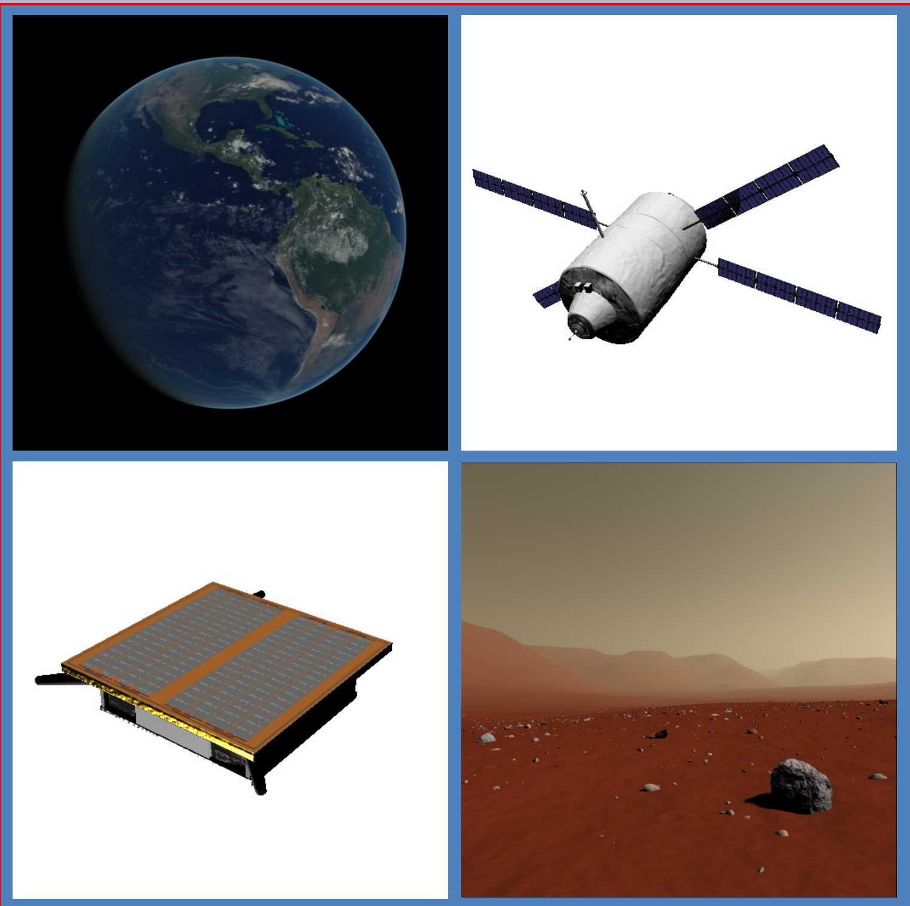
5a. Dynamical simulation facility for satellite rendezvous and docking tests. *- GMV @ INTA*

5b. Image generation hardware for Lunar landing, using gantry-mounted camera and model of the Lunar surface.

Modern spacecraft GNC systems are thoroughly tested in simulations during the design process. The test procedure involves integrating the motion of the spacecraft within a detailed dynamics and environment model, and generating synthetic navigation sensor data for the GNC system to process. Control signals determined by the GNC are fed back in to the motion of the craft in a closed loop. Monte Carlo methods are used to assess the sensitivity of the GNC performance and mission outcome to a wide range of factors.

In the context of vision based GNC, such test environments require a means to simulate realistic navigation imagery during flight. One method to do this is to use dedicated hardware platforms such as scale models of the Lunar surface or target satellite, combined with high precision moveable camera rigs (Fig 5).

An alternative approach is to use computer generated imagery (CGI) techniques to produce fully synthetic images. These have the benefit of being much cheaper and faster to produce, and have the advantage that the ground truth motion is known precisely. Over the last ten years, the Space Technology Centre has developed an image simulation tool that generates navigation images for testing spacecraft vision-based GNC systems (Fig 6). The *Planet and Asteroid Natural scene Generation Utility* (PANGU) is presently being used in a variety of ESA design studies and mission simulators.

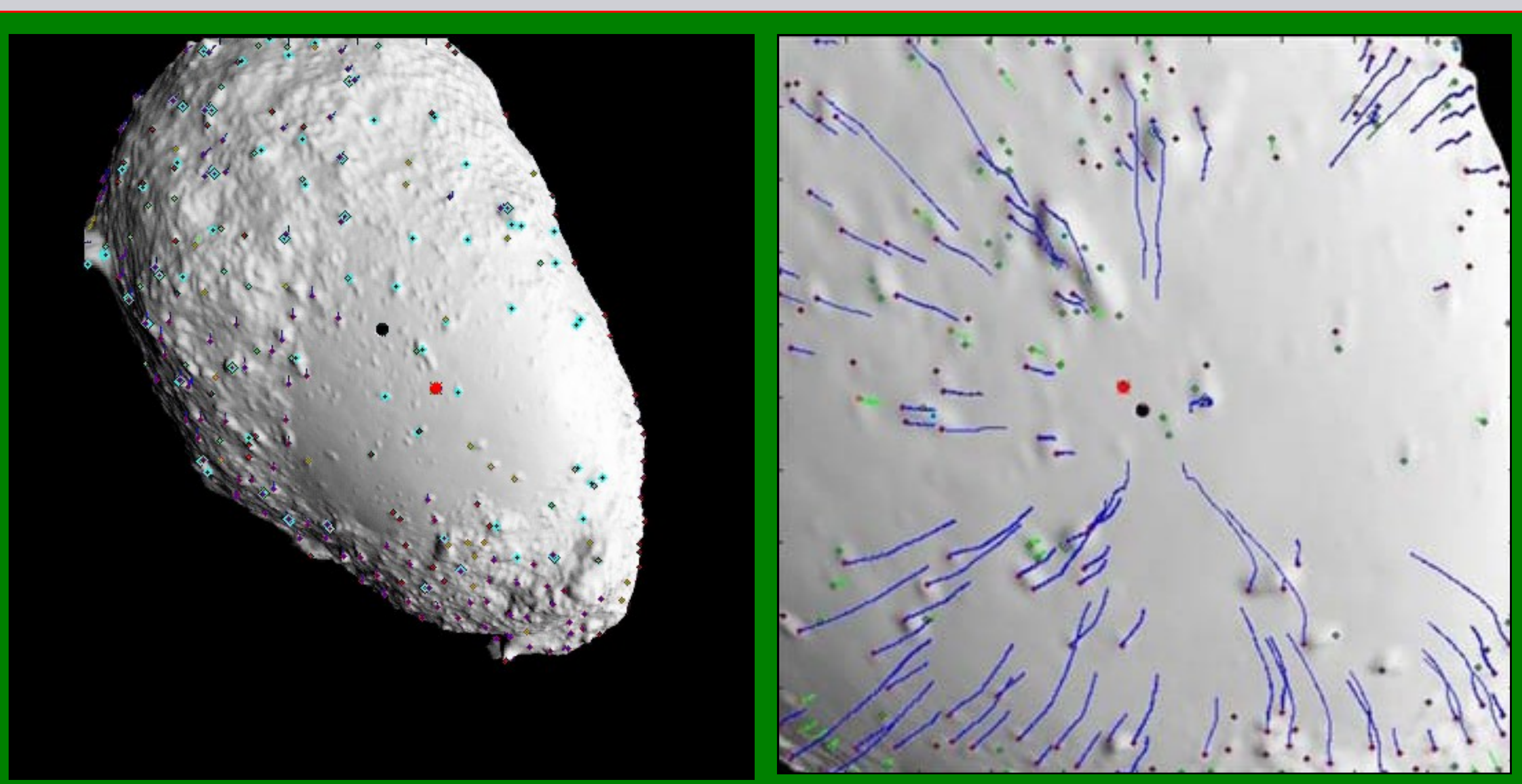

6. Simulated images using PANGU tool. Clockwise from top left: Earth, ATV, Mars (West Candor region) with atmosphere & aerial perspective, PRISMA-TANGO vision guidance test satellite.

Case Study: NEOGNC

Small near-Earth asteroids represent a fossil record of the formation of the Solar system, and a successful sample return mission allowing laboratory analysis of asteroid material has become a priority for ESA. The ESA-funded project NEOGNC (*Guidance, Navigation and Control systems for Near-Earth Object missions*) was carried out by an industrial consortium headed by GMV and including the UoD [5].

Landing on a small asteroid presents significant problems to traditional GNC techniques, due to the low gravity, irregular shape and small landing area. During the NEOGNC project, the PANGU tool was integrated with a High Fidelity Simulator and vision-based GNC system designed by GMV [4], with feature tracking and known landmark recognition performed using algorithms developed by the University of Dundee [2].

Monte Carlo tests (Fig 7) verified that in nominal conditions, a landing accuracy of 65±35cm is achieved with a horizontal velocity at touchdown of 0.7±0.4cm·s^{-1}, well within the requirements set out in the mission analysis.


7. Two processed navigation images from the NEOGNC High Fidelity Simulator [4] during descent and landing tests onto the asteroid Itokawa. The lines show the motion of tracked feature points. The turquoise diamonds mark the location of known landmarks, which are used to determine the absolute position and orientation of the spacecraft. The red circle indicates the landing site, and the black circle the centre of brightness—another useful vision-based navigation measurement.

References
[1] Hartley & Zisserman (2003) *Multiple View Geometry in Computer Vision,* Cambridge University Press
[2] Rowell, Parkes, Dunstan (2012) *Image processing for Near-Earth Object optical guidance systems,* IEEE Transactions (in press)
[3] Flandin et al. (2010) *Vision Based Navigation for Autonomous Space Exploration,* NASA/ESA conference on Adaptive Hardware and Systems
[4] Gil-Fernández et al. (2012) *Autonomous GNC System to Enhance Science of Asteroid Missions,* Proceedings of the IAC 2012
[5] Contract number 23048/09/NL/AF