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.

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 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.

Mission Analysis and Simulation

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 into 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 6).

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.

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, well within the requirements set out in the mission analysis.