Institution: University of Dundee		
Unit of Assessment: UoA 11 Computer Science and Informatics		
Title of case study: PANGU (Planet and Asteroid Natural scene Generation Utility)		
Period when the underpinning research was undertaken: 2002-2020		
Details of staff conducting the underpinning research from the submitting unit:		
Name(s):	**Role(s) (e.g. job title):**	**Period(s) employed by submitting HEI:**
Iain M. Martin Martin N. Dunstan Stephen M. Parkes	Senior Lecturer (Computing) Post-doctoral researcher Prof. of Space Technology	2002 - current 2000 – current 1995 – March 2019
Period when the claimed impact occurred: 2013 – 2020		
Is this case study continued from a case study submitted in 2014? N		

1. Summary of the impact

PANGU is a software package that generates realistic, synthetic images of planetary surfaces, asteroids, spacecraft and surface rovers to test and develop autonomous navigation, guidance, approach and landing technologies. PANGU was developed with European Space Agency (ESA) funding and is an essential, officially validated tool for core work performed in the Guidance Navigation and Control Section of ESA for current and future space missions. PANGU has enabled the validation and benchmarking of new technical solutions for autonomous guidance systems through simulating new and complex scenarios that are difficult or impossible to simulate in other ways. PANGU is a cost-effective tool widely used by space agencies and industry in Europe, Asia, and the USA as a flexible software alternative to physical generation of test images with expensive laboratory robotic camera systems or flight tests on Earth.

2. Underpinning research

PANGU was conceived in 2002 as a tool to generate realistic, simulated images of rocky, airless, planetary bodies such as the Moon or Mercury to test vision-based spacecraft as an alternative to expensive and less-flexible physical mock-ups. The most significant research concepts underpinning PANGU are a novel age-degraded, overlapping crater model **[R1]**, novel techniques developed to generate asteroid models **[R2]** and a comprehensive camera model implemented in a Graphics Processor Unit (GPU) **[R3, R4]**.

The novel crater model simulates the geological process of impact cratering over time and has been demonstrated to enable the simulation of airless, rocky, planetary surfaces like the Moon or Mercury with sufficient realism to test and evaluate image processing and vision algorithms for spacecraft navigation, guidance and hazard avoidance. The initial research concepts were implemented in PANGU and extended to enhance the resolution of existing Digital Elevation Models (DEMs) of planetary surfaces to create hybrid real/synthetic multi-resolution models. This extension enabled PANGU to generate simulated images of spacecraft landers from the start of the landing phase to touchdown on the surface **[R1]** at sufficiently fast frame rates to support real-time testing, with image resolution requirements varying from kilometres at the start of the descent to centimetres at touchdown.

The impact of the original PANGU tool led to further funding from ESA to research and develop an extended range of mission scenarios on different solar bodies. This included synthetic asteroids for spacecraft navigation and approach simulations **[R2]**, LIDAR images to simulate laser ranging sensors, Mars surface models with dunes and multi-resolution boulders to simulate Mars exploration and surface rover missions, atmosphere models, spacecraft, satellite and surface rover CAD models, stars, whole planet models, and a client-server interface to enable PANGU to be integrated with other simulation environments.

The importance of PANGU to ESA was shown with the ESA-funded, €600k PANGU v4 contract (2014 to 2017) to enhance the core features of PANGU to support the challenging simulation demands for future ESA missions. These included asteroid approach and landings **[R2]**, multiple high-resolution landing sites, combining whole planet and enhanced elevation surface models to simulate full descent sequences from orbit to landing **[R3]**. They also included a novel Graphics Processing Unit (GPU)-based camera model **[R4]** which enables real-world camera noise and distortion effects to be applied to the simulations at high speeds to generate and render large models (>80GB) in closed loop simulations in real-time to match the image processing capabilities of space-qualified computing systems (currently around 10 images per second). PANGU outputs were verified for realism through image analysis comparisons with real images and by independent planetary scientists who verified the realism of PANGU images of the Moon, Mars and asteroids **[R5]**.

PANGU is continuing to be enhanced with a recent, further €400k funding from ESA which has supported research into improved realism of asteroids and boulders for testing missions to unknown small-bodies, a web-portal (https://pangu.software/), and new research into realistically simulating infra-red cameras for spacecraft landers and orbital rendezvous. PANGU has been supported by approximately €1.5M total funding.

3. References to the research

[R1] Martin, I, Parkes, S, & Dunstan, M. (2014). Modeling cratered surfaces with real and synthetic terrain for testing planetary landers, *IEEE Transactions on Aerospace and Electronic Systems*. Vol. 50, No. 4. pp. 2916-2928. DOI: 10.1109/TAES.2014.120282

[R2] Martin, I, Parkes, S, Dunstan, M & Rowell, N. (2014). Asteroid modeling for testing spacecraft approach and landing, *IEEE Computer Graphics and Applications*, Vol. 34, No. 4. pp. 52-62. DOI: 10.1109/MCG.2014.22

[R3] Martin, I, Dunstan, M, Parkes, S, Gestido, MS & Ortega, G. (2017). Simulating planetary approach and landing to test and verify autonomous navigation and guidance systems, *10th International ESA Conference on Guidance, Navigation & Control Systems (ESA GNC 2017)*, Salzburg, Austria.https://discovery.dundee.ac.uk/en/publications/simulating-planetary-approach-and-landing-to-test-and-verify-auto

[R4] Martin, I, Dunstan, M, Parkes, S & Gestido, MS. (2018). Testing Vision-based Guidance and Navigation Systems for Entry Descent and Landing Operations, 2018, *IAC 2018 Conference Proceedings*, IAC-18, D1,3,4,x42780, International Astronautical Federation, pp. 1-9, 69th International Astronautical Congress, Bremen, Germany. Available at: https://iafastro.directory/iac/archive/browse/IAC-18/D1/3/42780/ [Accessed 19 March 2021].

[R5] Martin, I, Dunstan, M. (2017). TR3: Independent Validation of PANGU Realism By Planetary Scientists, UoD-PANGU-4-TR3-PS, July 2017. Technical document for PANGU v4 study which will be made available to the REF panel.

Funding awards:
Funding within this REF period includes:

A. PANGU v6 (2019-2020) ESA €200k
B. PANGU v5 (2018-2019) ESA €200k
C. PANGU 4 (2014-2017) ESA €600k
D. PANGU Enhancement (2006-2008) ESA €200k
E. PANGU Extension III (2006) ESA £27,000
F. PANGU Clouds Extension (2005) ESA £6,700

G. Asteroid and Whole Planet Simulation (2004) ESA £34,000
H. Planet and Asteroid Scene Generation Utility (2001-2002) ESA €200k

4. Details of the impact

PANGU supports the testing and benchmarking of guidance systems for space exploration by providing a real-time, virtual test environment for spacecraft lander navigation and guidance that is cost-effective and flexible **[E1]**.

Major missions

ESA have provided a letter of support **[E2]** that highlights recent and current major space missions and projects where PANGU is being used. For example, ExoMars is a major ESA/Roscosmos space programme with an initial budget of over €1.3 billion. PANGU was used by Airbus Defence and Space (UK) to test the critical ExoMars rover perception system with simulated PANGU images and corresponding disparity maps, enabling the accuracy of the perception system to be quantified **[E3]**.

PANGU is cited by a senior ESA Engineer as "…, *an instrumental tool in robotic exploration for ESA, being used in different areas such as object recognition to perform early analysis in Mars Sample Return*" **[E4]**.

ESA highlighted the impact of PANGU in April 2018, by selecting PANGU as one of the technologies that are "Shaping the Future", promoting the most successful and interesting activities within the ESA Technology Research and General Support Technology programmes **[E5]**. This is further corroborated by the section head of the ESA Guidance Navigation and Control Section at ESTEC (TEC-SAG), "*PANGU has been an essential tool throughout the years for a number of tasks at the core of the work performed in the Guidance Navigation and Control Section of ESA. Both in developing new technologies in the area of vision-based navigation and in supporting project developments relying on this technology (notable examples in the last few years are ExoMars, Mars Sample Return, Hera, PILOT, Heracles/EL3, the CleanSpace initiative), the image rendering capability of PANGU has been used to design, develop and test the image processing algorithms enabling vision-based navigation application." **[E6]**.*

Cost-effective solution

PANGU can simulate a wider variety of scenarios and terrain types than is possible with alternative physical testing such as laboratory cameras mounted on robotic arms taking images of physical mock-ups, or drone/helicopter flight-testing (which is limited to Earth terrain, lighting and atmospheric conditions). By increasing the range of possible testing scenarios to verify navigation and landing technologies required for future space missions, PANGU significantly reduces the cost of generating test images and can be integrated with other spacecraft test systems. According to the ESTEC TEC-SAG section head "*Space images of celestial objects, especially those with the right resolution and radiometric properties to allow their use in spacecraft navigation and those of little-known objects, are a rare resource, hence the flexibility of PANGU to artificially generate high-fidelity images provides a key benefit in reducing the cost of generating test images and enabling rapid prototyping of vision-based navigation solutions in real-time closed-loop test facilities*." **[E6]**.

Benchmarking and validation

PANGU is an officially validated tool (by ESA) and is being used to benchmark and validate new technical solutions for autonomous guidance "*The availability of a validated tool such as PANGU allowed, on one hand, ESA contractors to focus their efforts on algorithm development, rather than on image generation, and, on the other hand, allowed ESA to have common benchmark to evaluate and compare technical solutions developed by different contractors"* **[E6]**.

According to a senior ESA engineer on the ESA Lunar Resource Lander Team (HRE-PL): "*PANGU is used extensively in the frame of the PILOT project (Precise and Intelligent Landing using Onboard Technologies)… PANGU is used for the generation of realistic landing images* *and 3D models, which are used, in simulation and in test on representative HW, to validate the PILOT functions*" **[E7]**.

PANGU is also being used to prove test and develop guidance systems. A unique, resolution-enhanced model of Phobos, a moon of Mars, was created with PANGU to support the ESA Phootprint activity (Phobos Sample Return) to prove the technologies for a Phobos sample-return mission by generating higher resolution, representative images of Phobos than would otherwise be possible. GMV Innovating Solutions (a large, private, international technology company) then used PANGU with this model to generate simulated images of Phobos for their high-fidelity simulator to validate their feature tracking navigation algorithms by emulating the behaviour of the spacecraft sensors **[E8]**.

Proving and validating future space technology
PANGU is having significant impact in developing and verifying future generic space navigation technologies. For example, GMV (UK) have also integrated PANGU within their Harwell Robotics and Autonomy Facility (HRAF), which supports the integration, validation, and verification of autonomy components for Entry, Descent and Landing Systems (EDLS) and surface rover mission scenarios. According to a Space Segment & Robotics Engineer from GMV (UK): "*In the UK, PANGU is being used in the frame of an ambitious ESA activity called Harwell Robotics and Autonomy Facility (HRAF). In HRAF, PANGU is an integral component in the architecture of a large, multi-site distributed simulation environment which includes multiple GMV and ESA sites." and "PANGU is a core component in HRAF which provides synthetic images of the given scenario to the simulator. … in the context of Verification & Validation of the complex autonomy and GNC systems required in ambitious Space Missions, such as Mars Sample Return and HERA*" **[E9]**.

International Impact
PANGU is freely available to any institution working on ESA-funded projects, thus benefitting companies and institutions involved in the development and evaluation of ESA missions. It is also having an increasing impact outside Europe though PANGU licenses sold by STAR-Dundee Ltd for non-ESA missions.

STAR-Dundee is a University of Dundee spin-out company that specialises in spacecraft on-board data-handling and processing technologies. [text removed for publication].

MathWorks (a USA corporation specialising in mathematical software) recently developed a MATLAB workshop to showcase their powerful MATLAB Vision and Deep-learning Toolboxes by running MATLAB algorithms on a PANGU image sequence of descent to the challenging lunar South Pole region. PANGU was attractive for MathWorks because PANGU "*provided realistic simulated images of simulated descent on challenging terrain that would otherwise be difficult for us to obtain*" and "*we see growing interest from our customers to use MATLAB and Simulink together with PANGU to develop and validate space navigation algorithms."* This is corroborated by a letter of support **[E12]**.

5. Sources to corroborate the impact

[E1] I. Martin, M. Dunstan, S. Parkes, "PANGU v4 Software: Planet and Natural scene Generation Utility", 2014 - 2018 (many incremental releases), Available at: https://pangu.software/wp-content/pangu_uploads/pdfs/PANGU_v5_Brochure_2019aug26.pdf [Accessed 19 March 2021].

[E2] Letter of corroboration from ESA project manager, ESA Technical Officer confirming major ESA mission programmes using PANGU, 19/11/2018.

[E3] McManamon, K, Lancaster, R, & Silva, N. (2013). ExoMars Rover Vehicle Perception System Architecture and Test Results. *Proceedings of the 12th Symposium on Advanced Space*

Technologies in Automation and Robotics (ASTRA), Noordwijk, 15-17 May. Available at: http://robotics.estec.esa.int/ASTRA/Astra2013/Papers/Mcmanamon_2811324.pdf [Accessed 19 March 2021].

[E4] Email correspondence: ESA Senior Robotics and Autonomy System Engineer working on the Mars Sample Return mission, 02/12/2019.

[E5] European Space Agency (2018) *Planet and Asteroid Natural Scene Generation Utility (PANGU) Tool Enhancement*. Available at: https://www.esa.int/Our_Activities/Space_Engineering_Technology/Shaping_the_Future/Planet_and_Asteroid_Natural_Scene_Generation_Utility_PANGU_Tool_Enhancement [Accessed 19 March 2021]

[E6] Email correspondence: Head of ESA's Guidance Navigation & Control Section (TEC-SAG), ESTEC, 28/04/2020.

[E7] Email correspondence: senior ESA engineer on the ESA Lunar Resource Lander Team (HRE-PL), 19/12/2019.

[E8] Bidauz-Sokolowski, A, Lisowski, J, Kicman, P, Dubois-Matra, O & Voirin, T. (2017), GNC Design for Pinpoint Landing on Phobos. *10th International ESA Conference on Guidance, Navigation and Control Systems*, (GNC 2017), Salzburg, 29 May – 2 June. Available at: https://www.researchgate.net/publication/319154160_GNC_DESIGN_FOR_PINPOINT_LANDING_ON_PHOBOS [Accessed 19 March 2021].

[E9] Email correspondence: Space Segment & Robotics Engineer from GMV (UK), 20/12/2019.

[E10] [Text removed for publication]

[E11] [Text removed for publication]

[E12] Letter of corroboration from Mathworks, 30/04/2020.