LunaRoo: Designing a Hopping Lunar Science Payload

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Abstract—We describe a hopping science payload solution designed to exploit the Moon’s lower gravity to leap up to 20m above the surface. The entire solar-powered robot is compact enough to fit within a 10cm cube, whilst providing unique observation and mission capabilities by creating imagery during the hop. The LunaRoo concept is a proposed payload to fly onboard a Google Lunar XPrize entry. Its compact form is specifically designed for lunar exploration and science mission within the constraints given by PTScientists. The core features of LunaRoo are its method of locomotion – hopping like a kangaroo - and its imaging system capable of unique over-the-horizon perception. The payload will serve as a proof of concept, highlighting the benefits of alternative mobility solutions, in particular enabling observation and exploration of terrain not traversable by wheeled robots, extending line-of-sight planning and communications for surface assets, and providing data for beyond line-of-sight planning and communications for surface assets, extending overall mission capabilities.

1. INTRODUCTION

Robotic technology will continue to pave humanity’s path to the Moon, to Mars and further out into space. To expedite space exploration, initiatives such as the Google Lunar XPrize (GLXP) are actively engaging privately funded teams to land and drive a robot on the Moon by the end of 2016 whilst sending back images and scientific data. To be part of that great endeavour our LunaRoo concept, shown in Figure 1, is a mechanically hopping robotic system proposed as a secondary payload to PTScientists (PTS), a team vying for the GLXP.

LunaRoo is a true decimetre lunar explorer robot. Its compact form is specifically designed for lunar exploration and science mission within the constraints given by PTScientists. The core attractions of LunaRoo are its method of locomotion – hopping like a kangaroo – and its imaging system capable of unique over-the-horizon perception. The payload will serve as a proof of concept highlighting the benefits of alternative mobility solutions, in particular enabling observation and exploration of terrain not traversable by wheeled robots and providing beyond line-of-sight planning and communications for surface assets, extending overall mission capabilities. The entire robot will be designed into a robust 10cm cube and is designed to weigh less than 1.3kg. We aim for the cube to hop 20m above the lunar surface and while for a successful mission only a single hop is planned we hope to perform repeated hops.

For the PTScientists mission, the hopping LunaRoo provides ‘cool’ and spectacular images from a unique viewpoint that show the lunar rover on the surface of the moon – images that could otherwise not be acquired. The processed images provide useful perspectives for short and long-distance traversability analysis, obstacle detection and beyond-the-horizon planning for rovers. In addition to image collection, at maximum hop height LunaRoo is able to briefly bridge line-of-sight communication gaps between rover and lander, or to be a far-away explorer itself.

In summary LunaRoo is a technology demonstrator. We primarily aim to build a payload to fly with the the GLXP PTScientists team, proving the concept of mechanically propelled lunar hoppers. In addition it will provide a small sized mobile technology platform for developing mission and science relevant technologies, such as, mapping terrain for the main rover. This will also highlight the benefits of extending line-of-sight during hops and employing this type of locomotion to explore otherwise hard to reach places. Hoppers are able to access terrain unavailable to wheeled rovers, e.g. getting in and out of steep-sided craters, or over crevasses. In addition it aims to show the benefits of “being in the air” to provide unique science data, extra mission information and outreach possibilities (“selfie” of the rover from above).

2. THE LunaRoo PAYLOAD & MISSION

The primary mission objective is to deploy and prove the feasibility of hopping robots on the Moon. We will demonstrate how an additional, external sensor platform, in our case focussing on cameras, can provide valuable information to the main mission by collecting data from viewpoints high above the ground that are inaccessible to the rover itself. Our mission will also demonstrate the benefits of such unique viewpoints for terrain modelling, traversability analysis, and obstacle detection in exploration missions. Secondary mission objectives provide additional science and mission relevant information, e.g. to observe the main rover from an external viewpoint and collect imagery of its interactions with the ground as it drives away from the deployment site.

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During this project we follow an iterative design process to create a successful payload. Focussing on the mechanical and the imaging system designs, successive refinements are developed in parallel. To ensure compatibility of the revisions we plan integration tests throughout the project. Close cooperation with PTScientists will allow us to create scenarios for these tests that are aligned with the main GLXP mission. Our design process will allow to deliver a flight-ready payload for the PTScientists on time, which ensures the mission generates valuable results even in case of hopping mechanism malfunction.

Our main mechanical design is based on the fact that the Moon’s gravity is about a sixth of Earth’s [1], making alternative modes of mobility interesting. This can be seen in the astronauts trying a variety of gaits on the lunar surface [2]. The video footage of the Apollo astronauts “kangaroo hopping” [3], [4] lead us to our overall design idea: a hopping mechanism that would propel a cube 10cm tall to several meters above ground. The LunaRoo hopper is capable of leaping up to 20m from the lunar surface (see Figure 1), collecting images and providing extended communications support to rovers and landers. It is designed to withstand the impact at touchdown, which will be a similar force as generated during lift-off due to the limited lunar atmosphere (see Sec. 5). Due to higher altitude above the ground compared to the rover the visible horizon (under optimal conditions) can be greatly improved. At 1m altitude the visible horizon is about 1.8km away, at 20m it is more than 8.2km (more information in Sec. 5). By accommodating a camera system inside the cube (Figure 2), LunaRoo can provide long-range terrain maps for the rover.

The mechanical structure will be designed to extend the mission to as many hops and touchdowns as feasible, extending the mission duration, range, and success. However, the hopping spring will be pre-loaded so that the point of failure for the initial hop from the lunar surface is limited to the latching mechanism (see Sec. 5). Reducing the complexity and dependencies allows us to reduce the chance of failures that would stop us from achieving the primary mission objectives.

The other focus for the LunaRoo is on the camera and imaging subsystem designed to create unique data from its quite different viewpoint, metres above the ground during the hop. By accommodating a camera system inside the cube, pictures providing information about the terrain (Figure 3), soil characteristics and valuable mission information about obstacles and traversability (Figure 4). A proof-of-concept image registration (stitching) algorithm demonstrates that well-established and computationally efficient methods are applicable to imagery collected from a hopping lunar robot. The method closely parallels that employed in the panoramic image stitching found on most modern mobile phones and cameras. It extracts certain features and matches them in image pairs, creating a projective transformation. To reduce the reconstruction errors, iterations are run over the computed images. The result from our first experimental test can be seen in Figure 3.

Using the stitched images and structure from motion, a digital elevation map (DEM) with visual information of the terrain surrounding the rover and the LunaRoo will be generated. This DEM will then be used to compute a traversability map, which indicates to the rover which areas of the terrain are safe to drive through, as well as the estimated difficulty to traverse (e.g. in terms of risk for the platform and/or energy required). Thanks to the extended field of view obtained during the hop, this traversability map will enable the rover to anticipate hazardous areas at much greater distances than it can with its onboard sensors, and with a much greater level of detail than an orbital image system can provide. In addition, the unique point of view will significantly reduce the occurrence of occlusions in the map, which is a common problem for vehicles on the ground (i.e. the rover cannot observe what is hidden behind rocks).

3. GLXP/PTS Mission Objectives and Criteria for Success

The project is driven by the mission objectives (MO). These primary and secondary mission objectives, together with their respective measures of success, are providing guidance for the whole project, and in particular for the iterative design process, i.e. the next phases of development, testing and integration. The following hard constraint (CO) is required before the mission objectives can be considered:

[CO 0] LunaRoo is deployed on the lunar surface

[0a] LunaRoo survives the journey from Earth to Moon, including launch and landing on lunar surface

SUCCESS if LunaRoo is deployed upright by the main rover

[0b] Communication with the payload is possible

SUCCESS if LunaRoo communication is established via PTScientists

Once this hard constraint is satisfied, the following list of the primary mission objectives and success criteria for each step becomes relevant:

- [MO 1] (primary mechanisms objective): Demonstration of a hopping robot on the Moon
  1a Pre-charged spring is released and the LunaRoo is propelled several metres above the surface
  SUCCESS IF an altitude > 3m above the surface is reached
  AND IF the angular derivation from vertical is 20°
  1b LunaRoo survives the impact on the surface after the hop
  SUCCESS IF structural integrity upon touchdown
  1c Collected data & images are transmitted back to mission control
Figure 2. Considerations for the mechanical design, including the hopping mechanism and an integrated camera. On the right: some sketches showing the design evolution.

Figure 3. A stitched image, demonstrating our algorithm for fusing images from a falling Cubesat into a single map (see more information in Sec. 6). The shadow of the Cubesat has been left in place (lower-right), but simple masking techniques can be employed to remove shadow artifacts. Insets show a single input image (bottom) and intermediary results in the registration process showing misaligned (center) and a correctly registered image (top).
SUCCESS IF images and data are received at mission control

- [MO 2] (primary science objective): Demo of visual terrain modelling
  2a Camera captures data during the hop
  SUCCESS IF at least 3 images per second are captured & stored
  2b Image registration during one hop
  SUCCESS IF captured images are registered into one large image
  2c Terrain modelling
  SUCCESS IF using structure from motion methods, the LunaRoo constructs a 3D terrain model, deemed useful by mission control and/or experts
  2d Traversability estimation using the registered images and the terrain model
  SUCCESS IF a “danger map” for traversability is created
  2e (optional) Transmission of map to main rover
  SUCCESS IF the danger map is communicated to the rover

Identified Risks and Mitigation—the LunaRoo may come to rest on its side after a hop, after tipping or rolling on landing due to surface irregularities. If reaction wheels are included and are able to right the robot, the mission can continue as planned. If the LunaRoo cannot self-right (the current design based on the tight time frame aims to be simple and therefore might lack this capability) but is on its side the hopping mechanism may still engage with the lunar surface and be able to push the LunaRoo horizontally, which would allow limited continuation of Objectives 2b, 2d, 3a, 3b.

The interaction with the electrostatically charged lunar soil might lead to problems with the imaging system. We plan to mitigate this fact by having a mechanical lid for the cameras. In addition we are planning to test the use of a small electromagnetic field to repel all the dust before opening the lid.

4. PRIOR RESEARCH

Currently deployed and planned planetary robotics platforms rely on wheeled locomotion to cover long distances on extraterrestrial bodies. While early-stage concepts for aerial platforms exist (e.g. blimps on Venus), little research focuses on hopping mechanisms, although they offer a range of unique possibilities. The Apollo missions provided a real-world experimental platform for Lunar mobility, and astronauts preferred jumping gaits over walking and running both for covering long distances and for speed. While hopping would certainly not serve as the means of locomotion for the primary mission robot, smaller external sensor platforms can provide sensor data from high above the ground such as images or atmospheric measurements, or glimpse above obstacles like boulders or crater rims. Controlling the hopping mechanism could enable the platform to even explore terrain not reachable by the main rover (e.g. inside craters with steep or very slippery crater walls).

Hopping for Lunar mobility has a long history, including the Hopping Transporters for Lunar Exploration (“Lunar Leaper”) proposal by Kaplan and Seifert in 1969 [6], [7]. The experiences from the aforementioned Apollo missions, provide valuable information about lunar hopping. The loping gait favoured by the Apollo astronauts is not feasible within the size constraints of this payload though, but hopping was shown to be stable on the Apollo 11 mission and stable and useful on Apollo 17 [2]. Even before the Apollo astronauts landed the “Lunar Leaper” design was published. It proposed...
for the purpose of motion planning. Traditional techniques traversable by the robot or not, or its degree of difficulty, onboard exteroceptive sensors (e.g. stereo cameras) is traversability estimation seeks to determine whether information is produced. Estimation process, a geometrically consistent map with scale adjustment [19]. In these methods the 3D structure of the scene is jointly estimated along with the camera's motion. By fusing information from an IMU and compass into the approach, this will significantly reduce the size of such occluded areas. The remaining ones should then be interpreted accurately by the state-of-the-art technique of the authors. Deformable terrain is another significant challenge for terrain traversability prediction. As the rover traverses over loose soil or unstable rocky terrain, its weight can cause terrain deformation, which affects the actual traversability. In the worst cases, as a result of such deformation, the rover might get stuck in loose soil or by rocks around it, or even tip-over, both of which are mission-ending failures without the presence of humans. Recent work presented a method capable of predicting some terrain deformation occurrences by learning from experience [32]. It would be interesting to extend this research to the case of a hopping robot, by trying to predict the impact of the robot upon landing from a hop.

The LunaRoo may tip over after or during a hop: if it is able to avoid this and self-right, it will be able to execute multiple hops and extend its mission. Options for improving stability and self-righting will be investigated thoroughly during the development and testing process. An option is to include reaction wheels both for after a hop and to stabilise during hops to achieve an upright landing (Objective 1b). The Cubli [11] and M-Blocks [12] systems have demonstrated flipping and balancing cubical robots in Earth gravity using reaction wheels, and the SandFlea [13] uses gyro stabilisation during hops. Reaction wheels are internal systems protected from dust and radiation and have a long history in satellite attitude control systems. They have been proposed for internally-actuated micro-gravity rover missions [14], [15].

Image processing has provided user and mission-friendly data from low-level camera acquisitions. Lunar image stitching, for example, has much in common with previously-well-explored methods for stitching on Mars [16], and indeed in terrestrial applications [17]. Prior work has addressed image stitching, compression, and delivery in the context of image delivery for Mars rover science planning [18]. The latter work explores state-of-the-art image stitching methods, and an adaptive level-of-detail tile-based delivery methodology to compress and distribute the resulting mosaics. Future refinements will consider more sophisticated methods drawn from the closely related fields of structure from motion, simultaneous localisation and mapping (SLAM) and bundle adjustment [19]. In these methods the 3D structure of the scene is jointly estimated along with the camera’s motion. By fusing information from an IMU and compass into the estimation process, a geometrically consistent map with scale information is produced. Terrain traversability estimation seeks to determine whether a given patch of terrain, usually observed by the rover’s onboard exteroceptive sensors (e.g. stereo cameras) is traversable by the robot or not, or its degree of difficulty, for the purpose of motion planning. Traditional techniques evaluate the “roughness” of the terrain by computing characteristics of terrain geometry locally [20]. This can be improved by augmenting the traversability map with additional information such as platform stability (to minimise the risk of tip-over) [21], [22] and slip [23], [24]. Slip is a measure of the lack of mobility or progress of a rover on the terrain; existing approaches that predict slip involve visual odometry [23], stereo vision [25], motion profile [26], current draw [27], wheel odometry [28], or wheel trace [29]. More information can be found in a recent survey of traversability [30].

Recent research considered the challenges of incomplete terrain data [31], and deformable terrain [32]. Terrain representations used by rovers to predict terrain traversability are often incomplete due to occlusions. Even if the cameras observing the terrain are mounted on top of a mast, areas behind rocks are hidden from the rover’s view. However, recent research has shown that it was possible to make accurate estimates (with uncertainty) of the traversability of such areas using machine learning techniques such as Gaussian processes [31], as long as the occluded areas remain relatively small. Since the LunaRoo will be observing the terrain from an elevated point, this will significantly reduce the size of such occluded areas. The remaining ones should then be interpreted accurately by the state-of-the-art technique of the authors. Deformable terrain is another significant challenge for terrain traversability prediction. As the rover traverses over loose soil or unstable rocky terrain, its weight can cause terrain deformation, which affects the actual traversability. In the worst cases, as a result of such deformation, the rover might get stuck in loose soil or by rocks around it, or even tip-over, both of which are mission-ending failures without the presence of humans. Recent work presented a method capable of predicting some terrain deformation occurrences by learning from experience [32]. It would be interesting to extend this research to the case of a hopping robot, by trying to predict the impact of the robot upon landing from a hop.

Related research concerns mobility prediction, which is the problem of anticipating the likely outcomes of actions that the rover may take (e.g. going straight or turning on the spot), for the purpose of path planning and guidance [33], [34]. Prior work has studied this problem and demonstrated the benefits on a wheeled rover [35]. The method consists in learning a stochastic mobility prediction model and using it in a planning strategy that accounts for control uncertainty. A hopping robot proposes an interesting variant, especially due to the difficulty to predict the position, attitude (pitch and roll) and orientation (yaw) of the robot once it has landed back on the surface of the Moon. Predicting the position would be critical, in order to make sure that the integrity of the robot would not be compromised. In addition, anticipating the likely attitude of the LunaRoo would be essential to maximize the chances to perform further hops (the pitch and roll angles would need to remain small to allow for an effective hop).

Automatically classifying terrain such as rocks, sand and gravel from images, is useful to improve the autonomous operations of rovers on planetary bodies. It can also help with the classification of potential science goals [36] (Figure 6). Images acquired by rovers have been vital for scientists looking for past signs of life, e.g. astrobiologists looking for stromatolites, i.e. rock structures that were formed by a biogenic process. Prior work has investigated the use of computer vision techniques to provide a planetary rover with the ability to autonomously detect stromatolites [37]. Although stromatolites are not expected to be found on the Moon, similar strategies may be used to find other rock formations of particular scientific interest.

Figure 5. Left: a hopper design at JPL by Fiorini et al. [8] Right: the QUT kangaroo leg [9].

Gas compressed jumping transporters for explorers on the Moon. A lot of research has focused on lunar lander and hopper designs based on chemical propulsion and thrusters. Fiorini et al. [8] designed and tested an egg-shaped mechanical hopper robot for space exploration. They also proposed to include a camera in their design (Figure 5). An on-going project is to build an energy efficient outdoor terrain robot. A prototyped, innovative joint enabling hopping motion exists at QUT. The next step is to progressively build a complete hopping robot kangaroo [9]. Only last year Festo showed a bionic kangaroo built for their annual showcase [10]. The LunaRoo may tip over after or during a hop: if it is able to avoid this and self-right, it will be able to execute multiple hops and extend its mission. Options for improving stability and self-righting will be investigated thoroughly during the development and testing process. An option is to include reaction wheels both for after a hop and to stabilise during hops to achieve an upright landing (Objective 1b). The Cubli [11] and M-Blocks [12] systems have demonstrated flipping and balancing cubical robots in Earth gravity using reaction wheels, and the SandFlea [13] uses gyro stabilisation during hops. Reaction wheels are internal systems protected from dust and radiation and have a long history in satellite attitude control systems. They have been proposed for internally-actuated micro-gravity rover missions [14], [15].
5. Design Considerations

The LunaRoo mission consists of a self-contained cube of 10 cm side. It will be attached to the PTScientists’ rover and stay in hibernation until deployed on the Moon.

The current design is based on a communication link to the rover and/or lander by PTScientists, the details of which will be discussed after payload selection. We plan to have a single hop on the Moon and provide the data products to mission control. Therefore, the main goal is not longevity of the payload, which reduces thermal considerations (assuming a landing during the Lunar day). The LunaRoo design will be developed and tested iteratively.

Solar Energy Considerations—Given solar panels covering the whole top of the cube we get a 0.1 x 0.1 m area. Assuming a conservative estimate of the energy received from the Sun on the Moon of about 1000 W/m² and an efficiency of about 20%, one can expect 2 W output. During 24 h 172800 J would be generated.

Mechanical Considerations—The structural mechanics of LunaRoo are designed around the following functional requirements:

- Surviving launch & landing on the moon,
- Hopping & subsequent impact after,
- Image collection and on-board processing,
- Generating and storing solar energy.

In order to minimize weight to below the maximum allowable of 1.33 kg, the preliminary design calls for titanium with small amounts of stainless steel for latches and the ball-screw. However, the primary structural materials are still under investigation. Inside the cube, there is a lattice-like framing to maximize rigidity and minimize vibration during launch from Earth and hopping on the Moon (see Sec. 5). This internal structure also provides support for electronics, imaging and power systems.

Core to the structural design is a light-weight yet powerful spring and compression system. The spring compression is achieved by a small, highly-geared DC electric motor and ball-screw. The supporting structure is required to contain the high-spring forces and as such is optimized axially, reducing bending moments and overall weight.

To maximize solar power generation, we consider covering the top and each side face of the cube with thin-film solar panels. Using conservative Earth-based energy conversion calculations, each face could theoretically generate 2 W. However, in practice due to shadowing, at best 3 faces would be receiving solar power. Therefore, our power budget calculations are based on the conservative estimate of 2 W continuous power (assuming landing during lunar day).

To protect the camera lens from regolith dust a simple lens cap has been devised. This cap is mechanically coupled to the hopping leg whereby when it extends, it opens the cap, revealing the lens. When LunaRoo is landing, the leg is in an extended. As the leg is passively compressed during landing, the lens cap closes to facilitate protection from dust kicked up during landing.

Internally, the space in the LunaRoo is optimised to fit the cameras, computing equipment, battery and power management, communications and hopping mechanisms and, as other parts of the payload, it is going through iterative design updates. Optimal attachment points and coupling for stress testing and thermal protection of all systems are still under investigation.

Hopping Considerations—The LunaRoo has been designed to withstand the stress of a maximum hop height of 20 m. During the Moon mission, the hop height will be incrementally increased from 5 m to validate systems and assess lunar regolith compression during launch and landing, as well as, image capture and reconstruction quality. The primary hopping system consists of a mechanically compressed spring attached to a bumper-plate-like “foot” that is released to transfer stored elastic energy into kinetic energy. The spring is compressed using a small, highly-geared DC electric motor driving a ball screw mechanism to a latching point, which disengages the ball-screw from the spring. A solenoid is used to unLatch the spring and drive the foot down into the regolith, with the reaction force launching the robot upward.

The physics for lunar hopping are simplified by the effective lack of atmosphere (see details in Lunar Sourcebook, p. 40 [1]), rendering any drag forces during flight negligible. To estimate hopping height $h$ based on the velocity $v$ at launch, Newton’s equations of motion for constant acceleration are used: $h = \frac{v^2}{2g_L}$.

We assume lunar gravitational attraction to be $g_L = 1.622 m/s^2$ on the surface of the Moon. To conservatively estimate hopping height, the absolute maximum payload mass of 1.33 kg is assumed. Figure 7 shows the ideal maximum hopping height with launch velocity as well as the time-of-flight during the hop. This shows that a launch velocity of approximately $8 m/s$ is required to achieve a maximum height of 20 m.

Achieving a desired launch velocity requires conversion of stored electrical energy into kinetic energy. Using ideal spring equations, with a 50 mm compression, it is calculated that a launch velocity of $6 m/s$ would require $23.9 J$ of stored energy (equating to 958 N in the spring). To achieve $8 m/s$
would require $43J$ of stored energy (equating to $1702N$ in the spring). These spring forces, whilst significant, can be managed through the use of carbon fibre and/or titanium tension members within the cube structure. The lack of a thick atmosphere landing, which increases the maximum achievable height, also means that the robot will land at the same speed as it was launched. Therefore, the basic robot structure is internally latticed to increase rigidity for surviving landing. Additionally, the “foot” once fully extended during launch passively engages a light friction pad against the internal structure of the hopping mechanism. This is designed to provide a damping force to reduce the maximum impact loads during landing. Note that during recompression of the spring, the friction pad is disengaged from the hopper mechanism to reduce losses during the next hop launch.

A consideration for maximum launch velocity, and hence hop height is the energy loss from regolith compression by the foot when the spring is released. This is difficult to model due to the reduced gravity and low mass of the robot. Therefore, the surface area of the foot is made as large as possible to reduce compression. Earth-based assessment of this phenomena with evaluating different soil characteristics is planned. A consideration for maximum launch velocity, and hence hop height is the energy loss from regolith compression by the foot when the spring is released. This is difficult to model due to the reduced gravity and low mass of the robot. Therefore, the surface area of the foot is made as large as possible to reduce compression. Earth-based assessment of this phenomena with evaluating different soil characteristics is planned.

Based on our previous experience [9], it seems the amount of energy required to compress the spring is easily achievable by using efficient DC motor and ball screw in connection with the on-board solar panels. The bulk of the energy is required for the computing and vision system, while the remaining energy budget should be more than enough for 5 hops per 24 hrs.

Due to surface irregularities on take-off, the robot is unlikely to be perfectly level during flight, which will allow it to traverse the surface but will also contribute to instability on landing. While it will increase complexity, consideration will be given to embedding two very small DC motors attached to light-weight reaction wheels within the robot structure. These reaction wheels would be spun-up just before launch and help control attitude during flight and landing gyroscopically, and may apply small attitude corrections using feedback from images or an IMU.

Control Considerations—The control software is designed for the following functional requirements in support of the mission objectives:

- Safe interaction with the Main Rover,
- Power and thermal management,
- Communication management,
- Hopping,
- Image collection, on-board processing and storage, and transmission,
- Handling fault conditions for mission continuation.

The control system is tightly coupled with the electronic and physical design, and will be developed and validated iteratively alongside the electronic and physical design and testing process. Adversarial analysis and testing will produce a system that is as capable and robust as possible.

Electronics and Computing System Design

A small-form-factor processor board will be responsible for high-level management of the various on-board resources, including sensor, power, communications and motor control subsystems. The main processor will also carry out image processing, including pre-filtering, fusing, and compression.

Launch hardware will be built around a custom-designed main processor board. Its design will borrow heavily from the rich variety of commercially available ARM processor boards, with the Beagleboard XM paired with a ViFFF-024 camera representing a typical configuration. This board features an ARM Cortex A8 processor running at 1GHz, with 4 GB MDDR SDRAM and 512 MB of low-power DDR RAM, and extensive I/O including a camera connector, USB and ethernet

3http://beagleboard.org/beagleboard-xm
filters, and supports a frame rate up to 60 fps.

Customisation of the design will include a reduction in form factor, primarily by removing unnecessary peripherals and connectors, mechanical stabilisation for launch survivability, and probably the introduction of a radiation-hardened main processor. This will occur iteratively, with initial prototypes employing commercial-off-the-shelf (COTS) hardware, followed by a succession of custom boards moving towards a more specialised, compact and robust design.

Power consumption for the computing system is estimated to peak at 12 W, though peak consumption will only occur while simultaneously capturing, processing and storing imagery. Average active power consumption is in the 3-5 W range, with a fast-starting standby mode consuming less than 0.1 W.

Imaging System Design

We will collect “aerial” imagery from the onboard camera during each hop of the LunaRoo. Two main processing steps will be performed with the captured image data: First, all images captured during one hop will be registered and merged into one image using structure from motion techniques. Second, a traversability analysis will be performed on the resulting terrain model, including the identification of potentially hazardous objects for the main rover.

Image Registration—With each jump lasting between five and ten seconds, we expect to capture on the order of 500 images of the lunar surface for each jump. This imagery will be massively redundant, and so we will employ well-established structure-from-motion techniques, fusing information from the onboard compass (if feasible with the weak magnetic field on the Moon) and IMU, to produce a single, fused map for each hop. The resulting imagery will cover large areas at very low cost compared with rover-based exploration. Future work might consider extension to fusing multiple maps. We expect the fused maps to be invaluable in beyond-the-horizon planning, obstacle avoidance, and rover inspection, as well as in lunar mapping and outreach activities.

Providing External Image Footage of the Main Rover—As a secondary mission objective we want to gather images of the main rover at its deployment site. An external “aerial” view of the rover will be hopefully picked up by the media since it allows the interested audience on Earth to witness the events on the Moon from an observer’s perspective. External TV cameras have been part of the Apollo missions since Apollo 12 for this reason. External footage can also provide scientific and technical insights when the interactions between the rover’s wheels and the lunar surface are observed from close-by.

Localisation—The LunaRoo’s initial position is known for the first hop, allowing the traversability and obstacle map to be translated into the rover’s coordinate frame. The LunaRoo may slip over the surface during a landing so re-localisation may be necessary after each hop. The IMU will supply odometry, and visual localisation can be achieved with the help of secondary cameras, which can supply landmarks (including the Sun and Earth if above the horizon), or by matching features in ground-facing images during the next hop.

6. Testing

An important part of this project is to make sure that our payload works. For this we have planned several stages of testing. In March 2015 we performed first drop tests of a cube manufactured with 3D-printing techniques in Kioloa, NSW. In addition a vision dataset was collected from a GoPro camera mounted inside the cube. We will continue testing the vision system on Earth in close to real environments, with known ground truth, to confirm a low reconstruction error.

Camera and Image Subsystem Test

To check the feasibility of both our early mechanical designs and our image stitching software we performed drop tests with a GoPro camera mounted. We dropped the structures from various heights between 3 – 7 m. To compare the impact forces to those on the Moon, we slowed down the payload with a parachute for most of the tests. The structure did stay intact throughout the multiple day test and the camera survived repeatedly being dropped on hard and soft surfaces (gravel and beach sand).

A demonstration of the map-building process was performed using data collected from a falling cubesat-sized mockup. The experiment was run over a sandy surface in Kioloa, New South Wales, standing in for the similarly textured lunar surface. The proof-of-concept image stitching algorithm demonstrates that well-established and computationally efficient methods are applicable to imagery collected from a hopping lunar robot. It begins by identifying and matching keypoints between pairs of images, in this case using computationally efficient SURF features. The resulting feature matches are used to estimate a projective transformation between image pairs, under the assumption of a planar scene. The chain of transformations are then applied to co-register the images into a common map. Edge blending is performed to smooth transitions between images. Error accumulates over the chain of pairwise image transformations, and so once a map estimate has been constructed a second-pass refinement is employed in which each image is re-registered to an incrementally refined map. This is best performed by applying an inverse transform to the incremental map to bring it into registration with each untransformed input image. The additional projective transformation required to bring each image into a final, aligned registration with the map is then estimated. The result is a self-consistent map produced at very low computational cost.

The results of the fusion, which was completed without the benefit of compass or IMU, are shown in Figure 3. Note that the effective resolution of the smaller patch, collected closer to the sand’s surface, is much higher than the larger patch, and this is reflected in the full-resolution data product. To visualise we overlaid a white grid representing the resolution of the first (seen on the bottom left) and last image (top middle).

Testing Strategy

Further tests will be performed throughout the project. Tests we are planning to do, and for which facilities in the region exists, are:

- Drop/landing tests: to test the structural integrity of the main LunaRoo frame, from the forces during launch on Earth to the repeatedly hopping on the Moon
- Thermal-vacuum tests: to demonstrate that the integrated
payload can withstand the anticipated thermal environment in the near-vacuum of the Moon

- Shaker-stress tests: to ensure the components can withstand the loads during launch and touch-down on the Moon, and no components are knocked loose

We are also considering electromagnetic radiation testing, both for reducing interference with other payloads and ensuring safe operations, also for the possible use of EM to repel Lunar dust. On top of this we aim to have integration tests at regular intervals, to ensure that the various subsystems work together. All these performed and proposed tests are aiming at a qualification procedure of the LunaRoo robot. It will be based on the freely available ESA standards for space qualification ECSS, namely on the engineering standards E-ST-E10 to E-ST-E70, where applicable.

**Stability and self-righting testing**—Testing mechanical stability for hopping, in-flight, and landing phases will be incorporated in the test cycles, particularly in the mechanical and electronic iterative cycles as these will alter the dynamic mechanisms and the centre of mass. Adversarial testing will be used to identify the range of poses and motions in which the LunaRoo becomes unstable and tips onto one side, or rolls onto its top. Testing will then identify opportunities to design for improved stability, and mechanisms for partial or whole recovery from tipping or rolling.

The LunaRoo will not change its centre of mass during hops, and there will be no atmospheric effects, so instability will occur at take-off or landing, or while the foot is retracting in preparation for the next hop. Retracting the foot brings the centre of mass closer to the lunar surface, so this phase is less likely to result in instability. Likely causes of stability failure are:

- Instability on landing due to surface gradients such as slopes, or irregularities such as rocks,
- Instability on landing, take-off, or foot retraction due to compaction or slip of the regolith – either dust or rocks,
- Instability on landing due to landing angle compounding the above factors.

Stability can be determined from the static poses or dynamic motion measured by the IMU, compass, and camera input. If the LunaRoo can accommodate reaction wheels, active stability design and testing will develop control algorithms and priorities for X-Y attitude in the flight and landing phases, and for self-righting by flipping the LunaRoo from its side onto its base if enough momentum is available.

If the design cannot accommodate reaction wheels the LunaRoo prototypes and testbeds can be repurposed - after mission - for further research on self-righting and dynamic stabilisation using reaction wheels.

**Integration Tests**—For at least one of the integration tests we plan to partner with the local Electrical Engineering Student Society at QUT. They launched a scientific instrument package to 30km altitude on a weather balloon in February 2015. LunaRoo integration testing can leverage this experience – in regulatory clearance and high-altitude packaging, tracking, and retrieval – for LunaRoo system testing in vacuum/low-pressure, high radiance, and high radiation regimes. We believe it would be a great opportunity to test the functioning of all subsystems during one of their flights.

Traversability Analysis and Obstacle Detection—One of the primary mission goals of our LunaRoo is to aid the main rover’s navigation by providing a traversability and obstacle map. Both types of information can be communicated in the form of a danger map as illustrated in Figure 4. Each grid cell is assigned a traversability value that ranges from 0 (safely passable, flat terrain) to 1 (impossible obstacle). Terrain roughness, terrain slope, and step height determine the value for each cell, depending on the rover’s capabilities. The terrain roughness, slope, and step sizes will be estimated from the images captured during the hop by applying Structure from Motion techniques. Using this danger map, the main rover will be able to find safe paths through the environment.

**7. Future Work**

As described earlier, the imagery taken by the LunaRoo during the hop is meant to be exploited for the safe navigation of the main rover. In future work, additional information acquired by the hopping robot could also contribute to this terrain analysis. In particular, the impact of the cube upon landing from a hop could be measured and used to better identify the type of terrain underneath. For example, the landing will push sand particles in the air, which is a function of how sandy or compressed the lunar soil is. The depth of the footprint of the robot on the ground could also inform on the characteristics of the soft material layer. Another interesting avenue of future work is terrain traversability analysis for a hopping robot, especially considering that most of the existing research on terrain traversability estimation techniques has focused on wheeled robots. For hopping robots the problem will present different challenges:

1. to predict where the robot might land after a considered hop, accounting for uncertainty,
2. to anticipate the reaction and potential bounces of the robot on the ground, and the subsequent final position and orientation,
3. to evaluate the corresponding risk for the platform’s integrity.

Multi Robot Cooperation—As another future research topic we plan to investigate cooperative interactions between multiple robots for space exploration [38], [39], such as the interaction between a rover system and a lightweight scout system, like our proposed LunaRoo. Issues that have to be addressed in this field are, for example, robust communication [40] and sensor fusion in a shared world model, i.e. the fusion between internal map and pose representation of the rover and the scout system [41]. The scout system could be used to visually explore an area which is inaccessible for the rover system. Coordinated mission planning and task execution by heterogeneous multi-robot teams is another area of active research [42]. A mission plan can be generated that involves several agents (in this case two different robots) which have different roles and different abilities. The action planning has to take the roles, abilities and internal states of the two robots into account. Another research question deriving from coordinated planning is the plan execution monitoring if several systems are involved. As an example for a suitable mission scenario, the lightweight LunaRoo can be used to explore traversability of the lunar surface, leading to a higher reliability of the whole system.
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REFERENCES


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