Development and Field Testing of Moonraker: a Four-Wheel Rover in Minimal Design

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Abstract

A light-weight, four-wheel rover was developed as a research test platform for a low cost lunar exploration that could be conducted commercially near future. The name of the platform is MoonRaker, The purpose of the MoonRaker development is investigate control techniques and physical performance for a lunar rover with minimal size, such as less than 10 kg. In this paper, the authors describe the design, development and field testing results of the MoonRaker project.

1 Introduction

In the Space Robotics Laboratory, Tohoku University, Japan, we developed a light-weight, four-wheel rover as a research test platform for a low cost lunar exploration that could be conducted commercially near future. As a case study, the requirements for the Google Lunar X-Prize (GLXP) is considered. In the GLXP, more-than-500 m of traverse across the surface of the Moon and transmission of high quality video images to the Earth are set as the minimum requirements [1].

As a technical partner of Team Hakuto, an official team of the GLXP challenge in Japan, the Space Robotics Laboratory has been working on the development of mobile robots (rovers) for wheel-based traverse on the lunar surface. As minimal-size design options, we developed a two-wheel rover with less-than-2 kg, code-named Tetris, and a four-wheel rover with less-than-10 kg, code-named MoonRaker. Both rovers can conduct the traverse mission just by one, but if the two are combined, more complicated exploration mission can be challenged.

In this paper, a possible science mission scenario for such rovers is discussed first, then some technical details of MoonRaker and its performance evaluation are elaborated.

2 Possible Landing Site and Exploration Target

There are many underexplored aspects of the lunar surface and potential for commercialization, such as mining for water ice or Helium-3, But one of the most exciting targets for lunar exploration is potential caves on the surface of the moon.

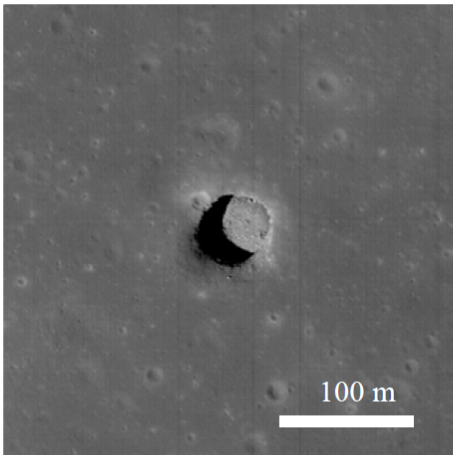

Figure 1. An image of a lava tube skylight, Marius Hills Hole acquired by Lunar Reconnaissance Orbiter Narrow Angle Camera (M122584310LE).

In recent years, researchers have speculated that underground tubes or caves, similar to those found on Earth in volcanic areas, may exist on the moon. In 2009, Haruyama et al. discovered evidence of collapsed lava tube skylights from JAXA's SELENE (KAGUYA) images of the surface of the moon [2]. Since then, many potential skylights have been discovered from various imagery taken by NASA's Lunar Reconnaissance Orbiter (LRO) [3]. See Figure 1 as an example image. These Lunar lava tubes are a potentially important location for a future lunar base, whether for local exploration and development, or as an outpost to serve exploration beyond.

Examination of a potential skylight from its edge or rim would provide valuable information, and descent into such a feature is desired to maximize the value of the mission. From the visual data, we will be able to further the knowledge of potential skylights on the lunar surface to help understand on a detailed size and characteristics of the hole, how the hole was formed, and how to use the hole for future human exploration or lunar development.

Leading teams of the GLXP challenge are developing the lander technology with precision landing capability with typically 100 m (3σ) accuracy to the target point. If such a precision landing is possible, the rovers that have 500 m travel capability can easily approach to the edge of the hole.

Down-into-the-hole exploration is, however, not an easy mission. One promising approach is rappelling using an anchor and tether. The concept of robotic rappelling have been studied and tested by CMU's Dante II rover [4] and NASA/JPL's Axel rover [5], for example.

Figure 2 and 3 show our concept of cooperative mission by a pair of heterogeneous rovers, MoonRaker (4-wheel) and Tetris (2-wheel). For the approach from the landing point to the edge of the hole, two rovers travel tandemly, as show in Figure 2. After arriving at the edge, MoonRaker stays on a flat and safe position as an anchor, then Tetris uses tether to go down into the hole, as illustrated in Figure 3.

In the following sections, technical details of the MoonRaker and its performance evaluation are elaborated.

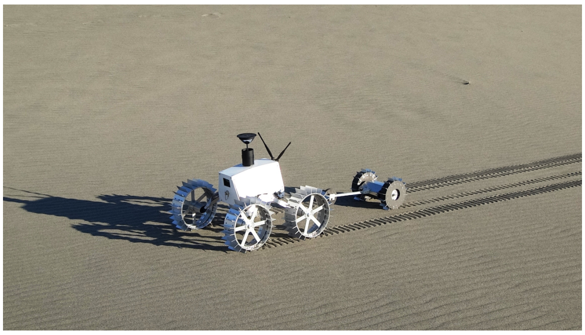

Figure 2. Tandem locomotion by a tethered four-wheel rover (MoonRaker) and a two-wheel rover (Tetris)

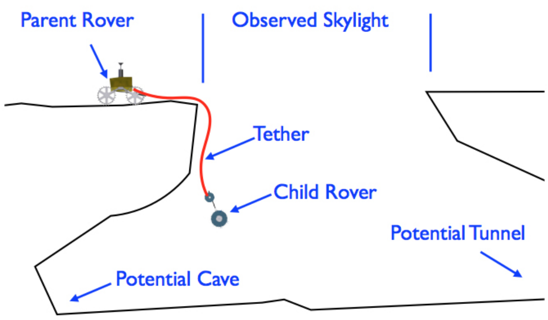

Figure 3. Concept of cave exploration by tethered rovers.

3 MoonRaker Rover Design

Based on the case study mission and requirements, a micro rover prototype Moonraker was constructed for Earth-based testing and validation. In order to meet a limited size-mass constraints, non-essential actuation points were removed where possible to minimize mass, power consumption, and the total number of failure modes. The resulting system is unique among similar micro-rover missions, such as the 1997 Mars Pathfinder rover component Sojourner, particularly due to the large wheel-size to system-size ratio.

Figure 3 shows the exterior and interior design of the Moonraker, which has four active wheels. A 12 W electric motor is built in each wheel axis and independently controlled. But there is no other motor installed in order to minimize the actuation components. It uses skid-steering and a passive differential suspension system to cope with rough terrain. The size is about 550 mm (length) x 450 mm (width) x 500 mm (height). In order to maximize the locomotion performance, we tried to have a larger wheel diameter. In addition, to generate enough traction forces over soft-soil environment, parallel grousers are mounted on the surface of the wheel. In the given configuration design, each wheel has 200 mm in diameter plus 10 mm in grouser height. Total mass of the rover is 10 kg.

3.1 Mobility design consideration

MoonRaker uses independent four wheel drive. In general, more wheels are considered to result in higher performance, due to the additional contact points with the surface. A primary advantage of the popular six-wheel configuration is from rocker-bogie suspension, which facilitates stable traversal over rocky and uneven terrain. This advantage, however, does not apply to the primary mobility challenge of slippage on steep soft regolith slopes of the target lunar mare environment.

We consider wheel diameter and grouser height are two primary wheel parameters that effect slippage on loose soil, as a result of our substantial previous research in this domain (for example [6][7].) Given the physical volume envelope and total mass for the rovers, the six-wheel design is not a good option to have a large wheel diameter. In our case, 550 mm was the maximum length constraint, then we decided two-200 mm wheels on each side.

It is also well known that the grousers significantly improve the traction performance in loose-soil environment, particularly in slope climbing. In our MoonRaker design, we implemented 10 mm grousers. As a result of a number of testing with indoor sand-box test-bench and out door field testing in sand beach and volcanic ash environments, we can conclude that the MoonRaker shows good mobility performance up to 10-degree slope climbing, but a large degrees of wheel slip is observed in 15-degree

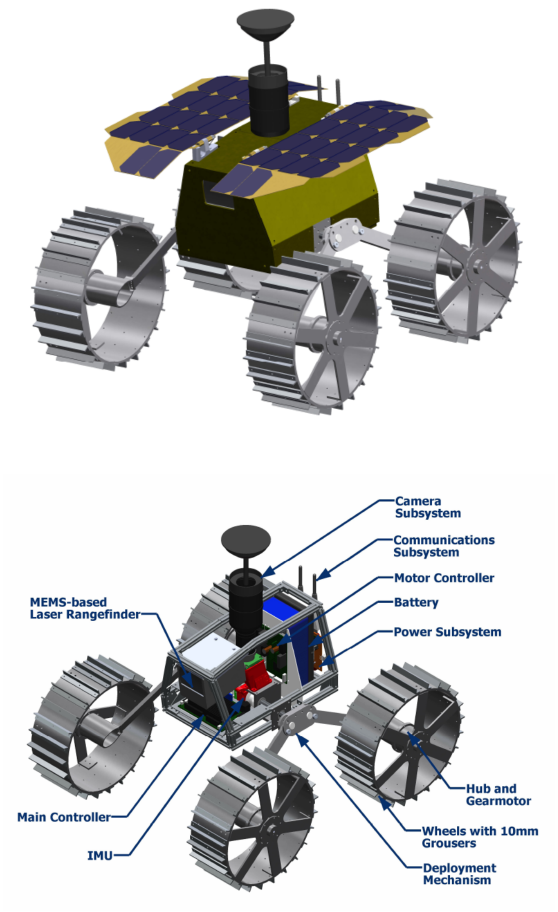

Figure 4. A CAD model of MoonRaker: exterior with solar panels (top) and interior with subsystems (bottom).

slope. We also confirmed that with 25 mm grousers, no measurable slip occurred even at 16 degrees. Additional trade-off study is needed when we design a flight-ready model of the rover.

3.2 On-board sensors

The MoonRaker will be remotely operated from the ground station via a lander on the Moon as a data relay station. We need to anticipate the data transmission rate is not so high and non-negligible time-delay exists during the operation. Therefore the rovers should be equipped with a sensor system that can detect hazardous obstacles and provide useful information for situation awareness to the operators on the Earth.

Moonraker uses an omni-directional camera, giving full 360-degree views of the surrounding environment and a MEMS-based laser range finder (LRF) to measure 3D positions of any imminent obstacles, in addition to conventional wheel odometry and a MEMS-based compact IMU.

A. Omni-Directional Camera

A standard camera equipped on a pan/tilt mechanism is known to be useful, but such a mechanism requires the additional mass and subject to potential motor failure. In order to circumvent these challenges, wide FOV camera options were evaluated and an omni-directional camera with a hyperbolic mirror was selected as the primary vision sensor. Using a static camera pointed vertically towards a hyperbolic mirror, the omnicamera system is able to construct 360-degree panoramic images in single frames.

Mathematical models for this type of optics have been studied well and then the original circular images can be easily transformed to undistorted views as seen in Figure 5. With a 70mm diameter mirror and 10 megapixel camera in our system, the average visual acuity is estimated to approach 0.3 mrad per pixel.

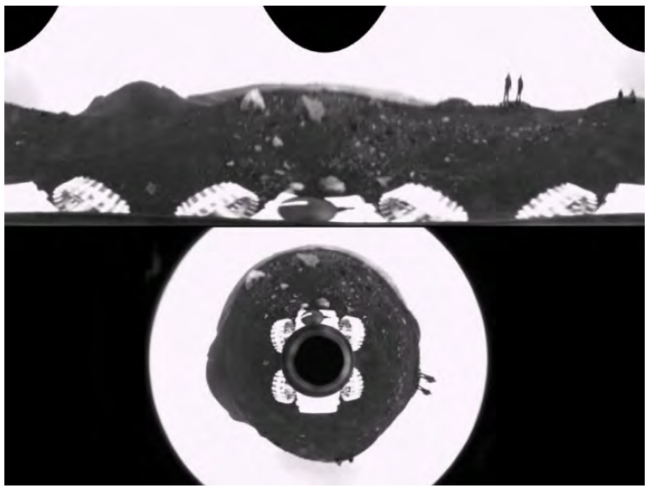

Figure 5. Omnicamera raw image (bottom) and corresponding panoramic projection (top).

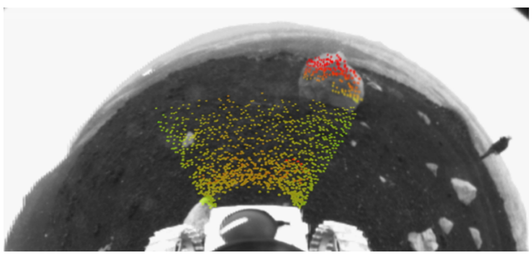

Figure 6. An example of superimposition of LRF data on the omnicamera image.

B. MEMS Laser Range Finder

Although the omnicamera system enables collection of data on the surrounding environment over a wide area, it requires computation time for image processing to recognize the existence of hazardous obstacles. As an additional sensor for detecting imminent obstacles and determining their accurate position relative to the rover, a laser ranging finder (LRF) was investigated.

A drawback in conventional LRFs is it requires a scanning mechanism. To achieve a 3D scan, two-axis rotational actuators, such as pan-tilt rotators, are needed. However, brand-new design of LRFs do not have such conventional actuators, but use a MEMS mirror. The MEMS mirror is a compact flat mirror supported by torsion bars that function as two-axis gimbals. In the mirror part, there is a build-in coil that generate Lorentz forces in a magnetic field to twist the mirror. All is made of a single piece of silicon wafer, therefore it is compact, light weight and strong against external shocks or vibrations.

The MEMS LRF sensor selected for Moonraker (FX8, from Nippon Signal Co.) is able to scan 6000 points over a 60 degree by 50 degree region four times per second. Effective measurement range during our field tests are about 3 m. Based on the signals from this sensor, autonomous avoidance maneuvers against imminent obstacles can be implemented easily. Moreover, the ranging information can be superimposed onto the omnicamera images such as Figure 6.

Further more, an advanced localization and mapping system is now under the construction by integrating the whole information from the omnicamera, the MEMS LRF, wheel odometry and on board IMU.

4 Field Testing

Field tests of Moonraker were conducted in various locations under an appropriate permission. The locations include Mt. Aso in Kyushu, Japan (2011), Mt. Mihara at Izu Oshima, Japan (2012), Mauna Kea, Hawai'i (2012), and Nakatajima sand dune at Hamamatsu, Japan (2013). Each of the test sites provided a range of environments from very soft, loose volcanic ash to rocky pumice, on and near slopes of mountains and volcanic craters. Exceptionally, Nakatajima sand dune is a beach sand area, but the place offers another good example of natural up-and-down slops with very loose soil materials (less adhesive dry sand.)

These types of environment are the closest available, on Earth, to what can be expected on the lunar surface. In each test MoonRaker successfully traveled over 500 m towards points of interest. Issues in mobility and teleoperation efficiency were identified in each case, informing iterative improvements.

Izu Oshima provides an environment covered in pumice from coarse sand to rocks. A 900 m course up to the peak of Mt. Kushigata from the south and down the north was completed, with an average ascent incline of 5.7 degrees, and a maximum of 15 degrees. The average slip ratio over the course of the ascent was 0.12, which was slightly higher than the prediction of laboratory tests for soft sand.

In Hawai'i, a 600 m course was successfully completed over a sandy area in Halewahine Valley on the southern slope of Mauna Kea. A 20 degree slope of soft dark volcanic ash, with similar mechanical properties to lunar regolith simulant, was found on the north side of the valley. Due a slip ratio approaching 1.0, direct traversal up the slope was not possible, but by progressing in alternating lateral trajectories, roughly 45 degrees from direct ascent, it was possible to climb 30 m. Over a 100 m path, at an average incline of 11 degrees, the slip ratio was 0.22.

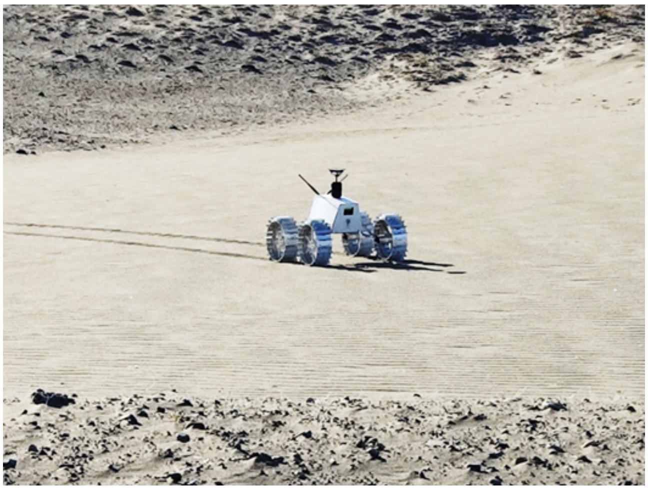

Figure 7. MoonRaker field test in Nakatajima sand dune, Hamamatsu, Japan, November 2013.

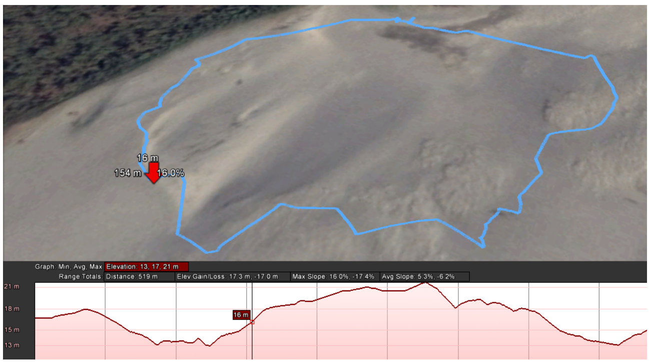

Figure 8. A ground-truth of a 500 m closed-loop test run of MoonRaker field test in Nakatajima sand dune.

In our recent field test in Nakatajima sand dune, Hamamatsu, Japan, we have conducted a number of long-run tests. Figure 7 shows a snapshot picture of MoonRaker in the sand dune. Figure 8 shows an example of ground-truth data of test run in a closed-loop path. In this case, the total traveling distance was 519 m, with average slope of 3 degrees and maximum slope of 10 degrees. The path was traveled within 30 minutes without any recharging of an on-board battery.

5 Conclusions

A micro rover, code-named Moonraker, was developed to demonstrate the feasibility of 10 kg-class lunar rover missions. Requirements were established based on the Google Lunar X-Prize mission guidelines in order to effectively evaluate the prototype. A 4-wheel skid steer configuration was determined to be effective to reduce mass, maximize regolith traversability, and fit within realistic restrictions on the rover's envelope.

A static, hyperbolic mirror-based omni-directional camera was selected in order to provide full 360 degree views around the rover, eliminating the need for a pan/tilt mechanism and motors. A front mounted, motorless MEMS laser scanner was selected for similar mass reduction qualities.

Micro rovers in the 10kg-class are an attractive option for performing an exploration mission at low cost. Although the reduction in size can limit capability, with careful design, a micro rover can still provide rich data on the explored environment while still being able to provide extensive mobility over across varied terrain.

Field tests conducted with MoonRaker validate the design by demonstrating successful completion of the case study mission goals. Slip ratio results from the field were found to deviate only marginally from laboratory tests. These real world field tests helped to highlight the performance in mobility and software interface, leading to opportunities for effective iterative improvements.

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