Japanese Rover Test-bed for Lunar Exploration

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Abstract

Lunar exploration missions including landesr and rovers are earnestly under studying in Japan. One of main missions for lunar robotics exploration is to demonstrate the technologies for lunar or planetary surface exploration. They will cover landing technology and surface exploration rover technology. Lunar geologic survey will be also performed for utilization and scientific investigation of the moon. The working group has been conducting the feasibility study of advanced technologies for lunar robotics exploration. Unmanned mobile robots are expected for surface exploration of the moon, because mobile robots can travel safely over a long distance. This paper presents system overviews of developed test-bed roves, guidance and navigation schemes, smart manipulators and some experimental results.

1. Introduction

Japanese lunar exploration missions including landers and rovers are earnestly under studying. The missions will follow up SELENE (SELenoligical Engineering Explorer), a lunar global remote sensing mission launched in September 2007. Post SELENE series missions [1] will cover geological observation, investigation of surface or subsurface material, interior structure examination using a seismometer, potential resource investigation (ice, volatile), environment research (radiation, dust, etc), safe and precise autonomous landing demonstration, surface mobility demonstration, power generation with fuel-cell demonstration etc. [2]. The following top science will also be conducted in the robotics mission [3]. Lunar geologic survey will be performed to investigate the underground materials [4][5]. In-situ analyses of the surface rocks and soils are also conducted with a special emphasis on the investigation into the organization, structures, and composition by cutting or grinding the collected samples. The characterization of the site can be observed by multi-band imaging, X-ray spectroscopy and Gamma-ray spectrometer. These are the key information to study the lunar inner structure and to understand the origin and evolution of the moon, as well as to investigate the evolution of magma ocean and later igneous processes [6][7]. For detailed geological exploration, the lander and rover cooperative exploration is under studying as shown in Fig.1. The robotics technologies are expected to perform those missions.

The working group has been conducting the feasibility study of advanced technologies for lunar robotics exploration. Unmanned mobile robots are expected for the detailed surface exploration of the moon, because rovers can travel safely over a long distance and observe what to see by some scientific instruments. Therefore the rover R&D group has developed innovative test-bed rovers with a new mobility system, lightweight manipulators, and advanced guidance and navigation functions.

The developed test-bed has a new suspension system, which consists of a four-wheel drive suspension system and two actives wheels. The proposed system is designed to distribute the load of weight equally to all six wheels whenever the rover climbs up or down, and then provides high degree of mobility for the rover. Smart manipulators with a new end-effector are also developed to perform the in-situ analysis or direct observation on the surface. The developed end-effector has two kinds of functions, gripping and scooping. The experimental results for sample collection show the effectiveness of the developed end-effector. The test-bed rover installed a single camera system, a stereo vision system, an inertial measurement systems, a scan typed laser range finder etc. The authors developed advanced navigation methods including a terrain recognition scheme, a path planning algorithm, a self-positioning method, an intelligent tele-driving system.

This paper presents a lunar robotics exploration by the lander and rover cooperation. Then this paper describes the system configuration of the developed test-bed rover for long traverses and rover-based scientific observation. This paper also presents the detailed functions and shows the performance of the developed rover test-bed. The developed rover test-bed will be used for feasibility study of the future lunar or planetary exploration missions. The exploration scenario or strategy will be tested by the developed rover test-bed.

Fig. 1 Lunar Exploration

2. Lander-Rover Exploration

To achieve the efficient and effective geological exploration, a lander and rover cooperation is proposed as shown in Fig.2. Scientific instruments should be installed in both the lander and the rover. The rover performs basic characterization of the surface rock and regolith. The detailed observation of samples is conducted at the lander after the rover returns to the lander. The rover should travel in wide areas and carry at least five samples of 2-3cm size back to the lander. For the lander-rover cooperative geologic mission, some scientific instruments are considered as candidates. The rover should have a macro/micro camera with a spectroscopy and a gamma ray spectrometer in addition to the navigation cameras. Not only determination of elemental and mineral compositions but also analyses of the mineral textures are desirable. Observation of rock fragments in breccia rocks is necessary. For this purpose, it is desirable that the rover should have a cutting or surface-grinding and coring mechanism for rocks. If the weight is available, the rover may also have magnetic instruments to measure the change of surface magnetic properties. Matured soils should have more anaphase iron particles which have strong magnetic effects [8].

The lander should have a narrow-angle multi-spectral camera for observation of the surrounding area and probable rover targets. Geological characterization of the central peak from the lander should complement previously-obtained remote sensing data. AOTF (Acoustic-Optic Tunable Filter) system has been developed for imaging spectroscopy. Advantages of AOTF over a filter wheel or grating system are high resolution, high speed, random or sequential wavelengths access, no moving parts, compact size, and imaging capabilities. Moreover, since the rover has a sampling mechanism, the lander should have a mini-laboratory (sample analysis package) with an X-ray spectrometer, a microscopic spectroscopy and imaging cameras possibly using AOTF.

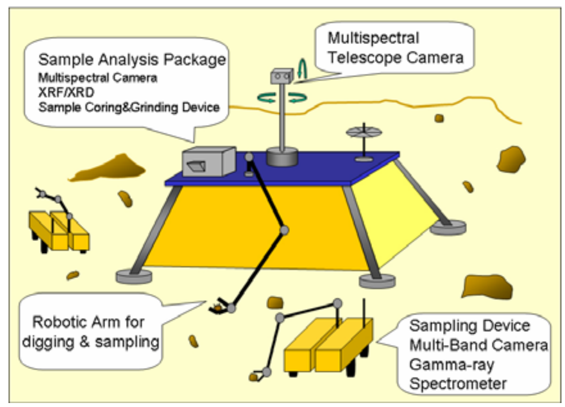

Fig. 2 Lander and Rover Cooperation

3. Rover Test-bed Model

3.1. Basic test-bed model

The authors have designed small test-bed rovers for lunar robotic exploration missions requiring long traverses and rover-based science experiments. The picture and the specification of the developed micro rover are shown in Fig.3 and Table 1 respectively. The weight of the designed rover is about 5[kg]. The rover measures about 0.53[m] wide, 0.55[m] long and 0.25[m] high. The wheel diameter is 0.1[m].

The designed rover is driven by five wheels controlled independently. The steering is controlled by the differential of left and right wheels. Those wheels are actuated by small DC motors. The velocity of the rover is about 1.5[cm/s]. The designed rover has the new suspension system called "PEntad Grade Assist

SUSpension" (PEGASUS) [9]. The climbable step of the rover is about 0.15[m] and the climbable slope is about 30[deg]. Power is supplied by solar panel. The rover is also driven by on-board batteries.

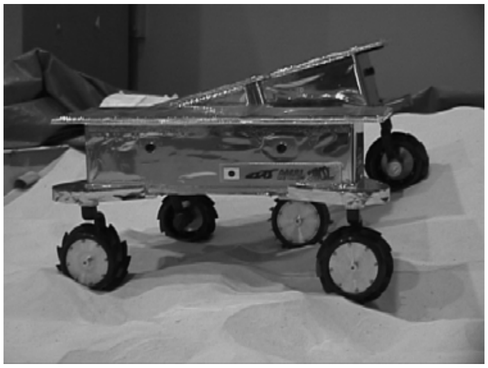

Fig. 3 Test-bed Rover Model

Table 1. Specification of Test-bed Model

Size	0.53[m](W) 0.55[m] (L) 0.25[m] (H)
Wheel diameter	0.1[m]
Weight	About 5[kg]
Mobility System	PEGASUS,
Mobility Performance	Velocity : 1.5[cm/s] Climable step : 0.15[m] Climbable slope : 30[deg] on hard surface 20[deg] on soft surface
Power Supply	Solar Panel : max 27[W] Battery : NiCd, Lithium
Power Consumption	Actuator : max 5[W] Computer : max 4[W]
Payload	4 stereo cameras

3.2. PEGASUS system

Various kinds of the mobility systems for traverse on rough terrain have been proposed. The suspension system is the key issue for realizing high degrees of mobility. NASA/JPL developed a rocker-bogie suspension in a series of the project called "Rocky" [10]. That system consists of a pair of two links called the rocker and the bogie, which are attached to each other by a passive rotary joint. This combination of the rocker and the bogie makes it possible for the rover to climb rocks 1.5 times its wheel diameter in height smoothly. The rocker-bogie suspension system provides extremely high degree of mobility for the rover. However this is not a perfect system for smaller rover. Many wheels system needs many motors and gears. That causes to increase the weight. Another problem comes from the structure that wheels are attached at the end of the long links and the links are connected by rotary joints as a chain. So very strong stress would act on the links and the joints

A small long-range rover is required to have both a simple and lightweight mechanism like four-wheel drive system and a high degree of mobility like rocker-bogie suspension system. In order to achieve these opposed requirements, the authors developed a suspension system. The proposed suspension system PEGASUS consists of a conventional four-wheel drive system and a fifth active wheel connected by a link. The fifth wheel, which is attached to the end of the link, and the other end of the link, is attached to the body with a passive rotary joint. This joint has restriction from neither spring nor actuator, can move freely. The proposed system is designed to distribute the load of weight equally to all five wheels whenever the rover climb up or down. That means that the fifth wheel supports the load taken to the front wheels when the front wheels climb up rocks, and it also supports that taken to the rear wheels when the rear wheels climb up the rocks.

When the rear wheel climb a step as shown in Fig.4, forward force generated by the traction of the fifth wheel backward as #2. These forces produce nose-dive moment #3, and then the moment turns to a vertical force of the front wheel #4 to support traction. By this mechanism, when the rover moves forward, this mechanism works at maximum performance. When the rover moves backward, the mechanism works as a conventional four-wheel drive system. Most of all times during the mission, the rover moves forward. Therefore, the unidirectional characteristic is not a problem. This system can be realized to be simple and light in weight, because the design is based upon a simple four-wheel drive system.

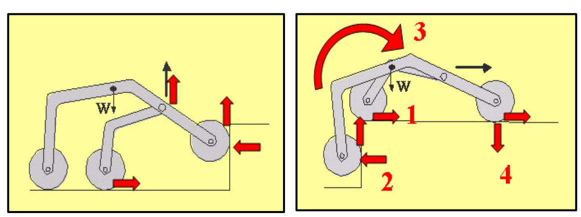

Fig. 4 Kinematics of PEGASUS

4. Micro5 Series

4.1. Micro5 #1, #2, #3

Based on the basic model, the authors have developed Micro-5 series as test-bed rovers. Figure 5 shows the developed Micro5-#1, and Micro5-#2. Micro5-#1 was developed for investigation of the mobility performance. The performance on the mobility of Micro5 is demonstrated by tele-operation. Micro5-#1 does not have any active steering mechanism. The surface of the moon is covered with regolith like sand. So the steering is controlled by differential of left and right wheels. To turn easily, special tires with spiral fin are developed.

Micro5-#2 has a micro-manipulator for sample collection. The developed manipulator [11] is mounted on the middle of the rover. The manipulator is located in the space between right and left body, where it does not disturb power generation of solar panels. The feature of the manipulator is described in Table.2. The motor drives each joint with harmonic drive gear, and almost all of links are made of carbon fiber plastics (CFRP). For sample collection, a new end-effector was developed. The developed end-effector has two kinds of functions, gripping and scooping. Micro5-#3 is developed for evaluation of the use of brush-less DC motors.

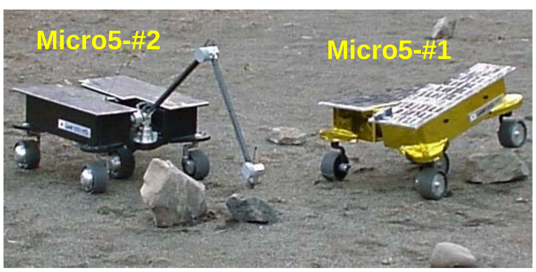

Fig. 5 Micro5 #1 and #2

Table 1. Specification of Smart Manipulator

Total Length	0.920[m]
Total Weight	1.45[kg]
Conveyable weight	0.3 [kg](on the earth)
Actuator	Ultra-Sonic Motor
Reducer	Harmonic Gear

4.2. Micro5 #4, #5

Figure 6 shows the overview of Micro5-#4 (TOURER) developed by Meiji University and Fig.7 shows the overview of Micro5-#5 (SciFER) developed by Chuo University respectively. Micro5 #4 and #5 are developed for tests of navigation. Micro5 navigation strategy is based on both tele-operation and autonomous behavior.

Stereo cameras are used for a forward terrain sensor. The rovers are equipped with pitch and roll clinometers for attitude detection and encoders for dead-reckoning. On-board computers perform sensor data processing and control. The RISC-CPUs are dedicated to the function of environment recognition, path planning and navigation. The rovers have communication system to communicate with the ground system. The rovers can send obtained images, house-keeping data, and scientific data to the ground system. Operators can control the robot based on image data by tele-operation techniques. Autonomous navigation functions are also installed. The micro rover has the sampling system. The lightweight manipulator with a CMOS camera has been developed, which is attached to the front of Micro5-#5. Some scientific instruments are under development.

Fig. 6 Micro5 #4

Fig. 7 Micro5 #5

5. Tele-Driving Scheme

In the case of a remote environment time-delay occurs between the master and slave system due to their distance and the limited capacity of communication bandwidth. It is thus difficult to compose a closed loop control structure between a master and slave system. Conventional tele-driving methods cause some strange behavior called "Move & Wait" to a movement of a rover, because of the time-delay. A rover has to wait for commands while the operator's planning the path, which is carefully considered and as a consequence, is time consuming. Moreover, to avoid collision between the waypoint path and obstacles, a rover requests the operator to regenerate its waypoint path, which causes further delay until new path data is received. Therefore, a tele-driving scheme is necessary for efficient and continuous driving of the rover, which should be a low-level intelligence that can understand human intentions in the operator's path command for obstacle avoidance [12].

Here, a human machine cooperative tele-driving system is discussed, consisting of a global and a local path-planning, for long range traversability, as shown in Fig.9. The operator can create any desired command-path as a sequence of waypoint by using a 3D terrain model measured as DEM by an on-board sensor, transmitted to the ground station. A dangerousness map is then calculated using the received terrain data. However, the measured terrain model may include some errors and cause some problems. For example, generally, data measured by a sensor has proportional errors depending on the distance from a sensor to a measured target, and unknown obstacles might be found by moving on the path, because of an occlusion problem of sensors such as a stereo camera. Of course, a rover itself also causes position estimation errors and dead reckoning errors, because of slips of wheels etc. For corresponding to an unknown obstacle, a conventional autonomous path planning algorithm is a solution, and it can be applied for short range path planning between each waypoint (Fig.6).

On the other hand, a rover is continuously updating the environment data set, and calculates the difference between original terrain data sets used for initial path planning done by the operator and the data sets acquired by the on-board sensors of the rover. The original path may result the rover to follow a trajectory that might cause a collision to obstacles, due to the difference between the distorted original and the more accurate, recently acquired data sets, as shown in Fig.8. Therefore, waypoints has to be compensated by using the latest measurement data which can be assumed to be more reliable than previous data sets. This is because the measurement data of a certain area is more reliable, when a rover is getting closer to that area. Here, let's assume that the difference between those terrain maps is the distortion between data sets, and the path would be compensated by using a distortion compensation matrix which is the mapping between the old and new terrain data sets. This command path compensation and its compensation matrix will be mentioned in the next subsection.

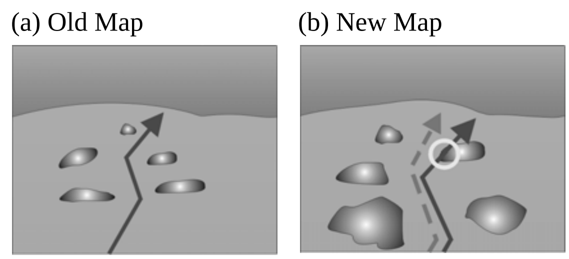

Fig. 8 Proposed Tele-Driving System

6. Experiments

Tele-driving experiments are performed by using Micro5-#5 as shown in Fig.9. The test-bed rover could avoid obstacles. Sample collection performance is also tested by using Micro5-#5. The experimental results for sample collection show the effectiveness of the developed end-effector as shown in Fig.10.

Mobility performance is tested by using Micro5-#1. Figure 11 shows the image sequences of outdoor experiments. Micro5 can get over small crater and step. The experimental results show the good performance of the designed micro-rover.

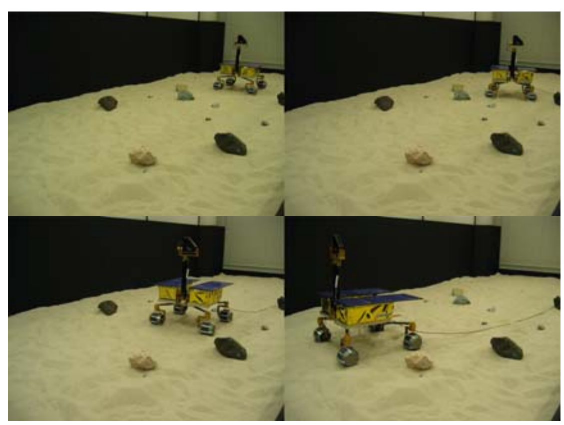

Fig. 9 Experimental Results (A)

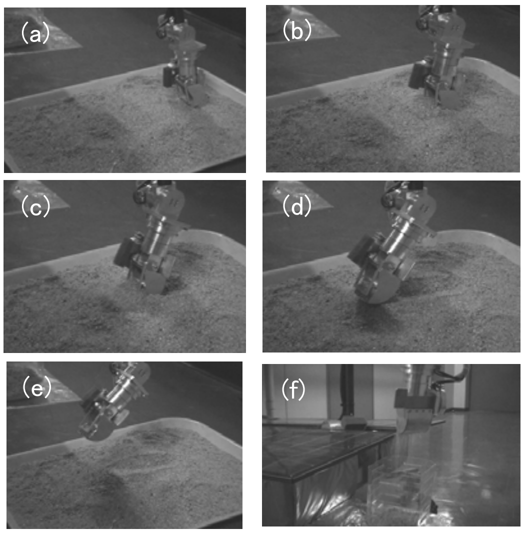

Fig. 10 Experimental Results (B)

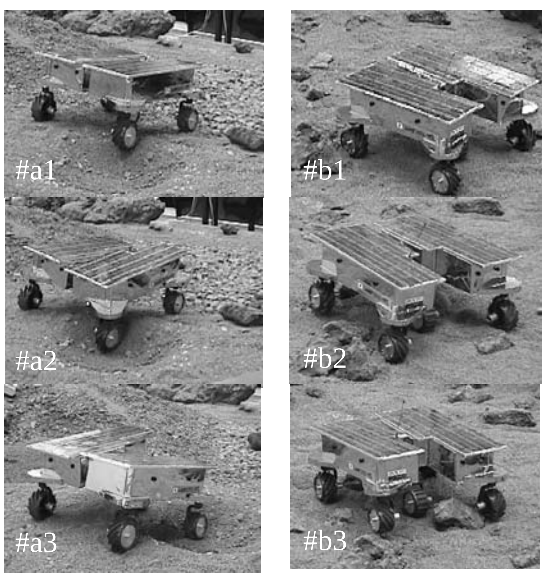

Fig. 11 Experimental Results (C)

7. Conclusions

This paper has presented Japanese lunar robotics exploration. The lander and rover cooperation based exploration has been proposed. A lunar rover has been also studied for the future lunar missions requiring long traverses and rover-based scientific experiments. This paper presented the small test-bed rovers with novel mobility and smart manipulator. This paper also described a guidance scheme based on tele-driving. Some experiments and demonstrations showed that the good performance of the test-bed rover.

8. References

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