Proceeding of the 7th International Symposium on Artificial Intelligence, Robotics and Automation in Space: i-SAIRAS 2003, NARA, Japan, May 19-23, 2003

SELENE-B: Proposed Lunar Mission with Lander and Rover

Ichiro Nakatani
Institute of Space and Astronautical Science
3-1-1 Yoshinodai, Sagamihara, Kanagawa, 229-8510, Japan
nakatani@nnl.isas.ac.jp

Kohtaro Matsumoto
National Aerospace Laboratory of Japan
7-45-1 Jinndaiji-higashimachi, Chofu, 182-8522, Tokyo
matumoto@nal.go.jp

Tatsushi Izumi
National Space Development Agency of Japan
2-1-1 Sengen, Tsukuba, Ibaraki, 305-8505, Japan
izumi.tatsushi@nasda.go.jp

Key words:
lunar mission, lander, rover, pin-point landing, obstacle avoidance

Abstract

SELENE-B, the 2nd of the SELENE (SELenological and ENgineering Explorer) series lunar missions, is now in the study phase being proposed for the launch in 2008. The main purpose of the SELENE-B mission is to establish the advanced technologies for precise and safe landing on the lunar/planetary surface, but it will also conduct scientific observations using instruments both on a lander and onboard a small rover and also will conduct the research on the possibility of the future utilization of the lunar resources.

Although there have been up to now quite a few landing missions either on the moon or on Mars, no missions have ever achieved autonomous pin-point landing at the pre-selected small target area avoiding obstacles on the surface.

This paper presents an overview of the SELENE-B mission from the standpoint of engineering technologies with an emphasis on space robotics and AI.

1. Introduction

SELENE(SELenological and ENgineering Explorer) is a series of Japanese lunar missions with the first launch of the series scheduled for mid 2005. The first mission includes a lunar orbiter and two small daughter satellites to conduct scientific observation of the moon.

SELENE-B, the 2nd of the SELENE series, is now in the study phase being proposed for the launch in 2008. The main purpose of the SELENE-B mission is to establish advanced technologies for precise and safe landing on the lunar/planetary surface, but it will also conduct scientific observations using instruments both on a lander and onboard a small rover and will also conduct the investigations on the possibility of the future utilization of the lunar resources.

This paper presents an overview of the SELENE-B mission from the standpoint of engineering technologies with an emphasis on space robotics and AI.

2. Overview of the SELENE-B Mission

Although there have been up to now quite a few landing missions either on the moon or on Mars including the Apolo project which successfully conducted manned flight to the moon, no missions have ever achieved an autonomous pin-point landing at the pre-selected small target area. Also, a safe landing autonomously avoiding obstacles on the surface of the moon or planetary bodies has never been conducted.

The main mission for SELENE-B is to demonstrate the technologies for the lunar/planetary surface explorations which will cover the following :

- pin-point landing technology at the pre-selected target area using image sensors
- reliable landing scheme avoiding obstacles on the lunar/planetary surface using camera image data
- reliable landing mechanism for landing onto rough terrains with a steep slope and/or scattered rocks with moderate size
- tele-science of the lunar/planetary surface using manipulators and a rover.

Although the main mission for the SELENE-B is the technology demonstration, top science will also be conducted as follows:

- lunar geologic survey in the vicinity of central peak of impact craters to investigate the underground materials
- in-situ analysis of the surface rocks and soils, with a special emphasis on the investigation into the organization, structures, and composition by cutting and/or grinding the obtained samples
- characterization of the site by multi-band imaging and X/gamma-ray spectroscopy.

These are the key information to study the lunar inner structure and to understand its origin and evolution, as well as to investigate the evolution of magma ocean and later igneous processes.

This paper focuses on only engineering technology aspects of the SELENE-B from the viewpoint of the robotic technologies.

3. Organization for SELENE-B Program

Three of the Japanese space related organizations have jointly been conducting the feasibility study of the SELENE-B mission since 2000. They are ISAS(Institute of Space and Astronautical Science), NASDA (National Space Development Agency of Japan) and NAL (National Aerospace Laboratory of Japan). It is to be noted that in the midst of this joint study, the Ministry of Education, which supervised ISAS, and the Science and Technology Agency, which supervised NASDA and NAL, were integrated into a new Ministry. In addition to this, ISAS, NASDA and NAL will be merged into a new space organization in the fiscal year 2003, which means that currently collaborating three organizations will be integrated into one to achieve more efficiency in the SELENE-B project activities.

4. Mission Scenario

A typical mission sequence is as follows:

- The SELENE-B spacecraft with the wet weight of about 2 tons will be launched by H-IIA launch vehicle as one of the two payloads in a double launch scheme. The spacecraft will be injected into a geo-synchronous orbit by H-IIA and then into the trans-lunar orbit by the bi-propellant main thrusters onboard the spacecraft.
- The SELENE-B spacecraft will be injected into a lunar circulating polar orbit with the altitude of 100 km by a bi-propellant motor.
- Firing a bi-propellant motor, the spacecraft will leave the lunar circulating orbit and will start powered descent.
- During the powered descent phase, a hybrid navigation system will be used with INS (Inertial Navigation System) and camera image data. Camera data which will be used to compensate the drift of the IMU(Inertial Measurement Unit) is essential to achieve high precision landing. The main thruster used during this phase is a bi-propellant engine with the nominal thrust level of 1700N.
- At the altitude of 3.5 km a vertical descent will start during which phase stereo camera data together with single camera images will play an important role to achieve pin-point landing and also to avoid hazards on the lunar surface.
- The target landing area is near a central hill inside one of the craters where significantly large hazardous rocks exist, which should be recognized by onboard cameras.
- The landing will be conducted in the morning and the mission life on the surface of the moon will be about 15 days during the daytime of the moon.
- After successful soft landing, a rover with a weight of 30kg will be released from the lander. The rover will conduct several expeditions around the lander including short, medium and long range trips sampling rocks with manipulators to bring back to the lander for analysis. The range of the longest trip will be up to 500 m.
- Samples will be collected by manipulators onboard the lander as well as on the rover. The in-situ analysis of the collected samples will be conducted by the instruments either on the lander or on the rover. The rover will also carry collected samples to the lander for analysis.
- The communication between the rover and the ground tracking station will be either via a direct link or via the lander transponder. The direct link and the one via the lander will provide bit rates of 2 and 40 kbps respectively in the worst conditions.

The limited communication link and some 2.5 sec round trip propagation delay make it essential to develop highly autonomous rover operations to realize efficient operations during the mission life on the moon.

5. Navigation and Guidance during Descent Phase

To achieve pin-point landing at the pre-selected target with the accuracy of 100 m, we need a navigation scheme based on the lunar surface referenced coordinate frame and also it is essential to avoid hazardous objects like large rocks and craters on the surface of the moon. For these purposes, the inertial sensors alone do not provide enough accuracy and we need to use image based system, which will be described here. The other reason why we need image based navigation is because we do not, in advance of landing, have 3-D map whose resolution is precise enough to locate all the obstacles.

5.1 Orbit plan

A wide range of orbit scenario schemes has been studied, one of which will be described below as a typical descent phase orbit plan. An orbit scheme with a coasting phase, generally speaking, is superior to the one without coasting from the viewpoint of propellant consumption. The extreme case is the Hohmann transfer where only a coasting phase exists between two impulsive thruster firings. A longer coasting phase, however, means a longer descent time which results in more battery weight and also more complex operations with significantly long period during which the spacecraft is not visible from the earth tracking stations. Hence, we here assume two-phase orbit plan as shown in Fig. 5-1 being comprised of a powered descent phase and a vertical descent phase.

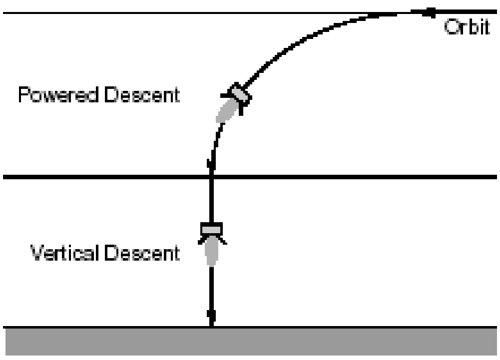


Fig. 5-1 Lunar surface descent orbit plan

5.2 Powered descent phase

The spacecraft is de-orbited from the 100 km altitude lunar circulating orbit by firing the 1700 N thruster semi-continuously. The thruster force level is constant, but it can be turned off/on at a selected duty cycle, which means it effectively provides a variable force level.

Extensive simulations have been conducted and the nominal terminal target of this phase is determined as 3.5 km altitude with zero horizontal velocity and 40 m/s descent velocity.

Selection of the sensors for measuring the position and velocity is critical in achieving specified accuracy of 100 m for landing with allowable weight and power consumption also with minimum development risk and cost. The candidate feasible sensor data are as follows(Group 1):

1) 2-D camera image
2) 3-D topography data by stereo camera images
3) 1-D altitude sequence data from the altimeter
4) 3-D topography data by scanning range measurement instrument

The candidate matching schemes, on the other hand, are as follows(Group 2):

a) matching the measured 3-D data with the pre-stored onboard DEM(Digital Elevation Map) data
b) matching the measured data with the output of the onboard "pseudo-sensors" processing the stored DEM data
c) matching the feature parameters extracted from the measured data with the ones stored onboard

The global images of the lunar surface were obtained by Clementine mission, but their resolution was 100 to 200 m and we have to wait until the SELENE(-A) is launched in 2005 to obtain a global DEM with the resolutions of 10 m in the horizontal plane and 20 m in the vertical direction.

Extensive studies have been conducted analyzing various combinations between Groups 1 and 2. We have selected (1 - b), (1 - c) and (3 - b) as the most promising combinations.

As a typical example, the case (1-c), where the craters on the lunar surface are used to identify the spacecraft position, is briefly described below (See Fig.5-2):

- The crater distribution near the nominal flight path are stored onboard the spacecraft with the information on the center coordinate and the radius of each of the craters.
- During the powered descent phase the craters are extracted from the camera images on a real time basis.
- The identification of the craters is carried out by a separation angle method which is conventionally used by the star identification for a spacecraft attitude determination. In this method the separation angles of selected crater pairs are compared with those of the stored crater map and voting is conducted to identify the most probable craters.

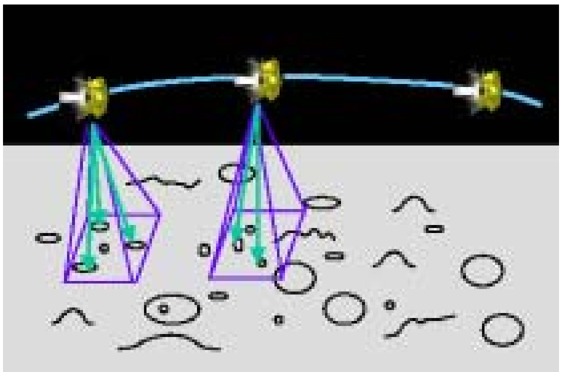
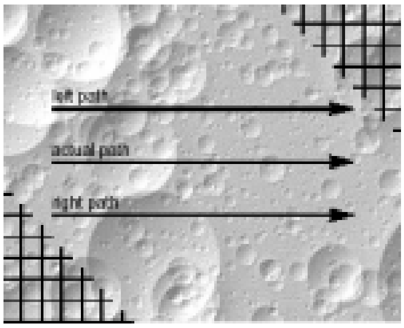


Fig. 5-2 Concept of the navigation using crater information

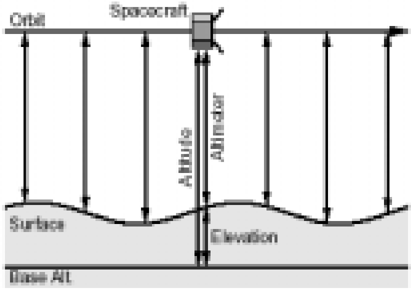
Another typical example for the case (3-b) is as follows where a laser altimeter is used.

- The one dimensional terrain height sequence data is extracted from a DEM in the vicinity of the nominal flight path and is stored in the onboard memory(See Fig. 5-3).
- A laser altimeter is used to obtain the terrain height sequence along the actual flight path which is compared with the stored one on a real time basis.
- A typical example of the simulation results is shown in Fig.5-4 where the proposed method is compared with conventional one. In the areas where the craters are densely distributed an excellent success rate for the flight path estimation has been obtained.

Table 5-1 shows an example of the results of the numerical analysis of various navigation methods during the powered descent phase. The figures on the table show the diagonal elements of the covariance matrix at the end of the powered flight phase or at the start of the vertical descent one.



(a) Flight paths on the DEM



(b) Height sequence along a path

Fig. 5-3 One dimensional terrain height sequence for flight path identification

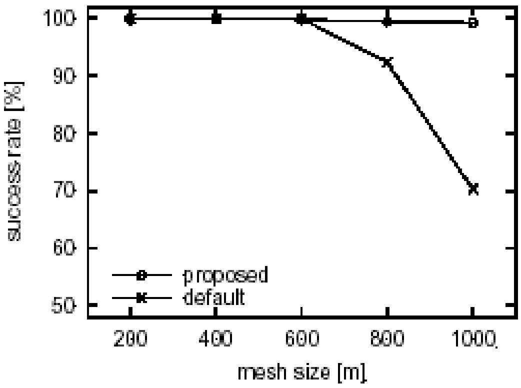


Fig. 5-4 Flight path identification success rate

Table 5-1 Example of the results of the numerical analysis of various navigation methods during the powered descent phase.

The figures on the table show the estimated 3 σ errors at the end of the powered descent phase(or at the start of the vertical descent phase).

SENSOR	H [m]	CR [m]	DR [m/s]	V_H [m/s]	V_{CR} [m/s]	V_{DR} [m/s]
IMU	823.6	2928.2	2235.8	2.545	5.314	0.751
IMU+Altimeter	4.4	643.0	406.6	0.063	1.015	0.067
IMU+Cameras	49.5	71.7	23.2	0.169	0.295	0.089
IMU+Altimeter +Cameras	4.0	41.7	17.2	0.049	0.239	0.056

H: Height, CR: Cross Range, DR: Down Range, V_H: Horizontal Velocity, V_{CR}: Cross Range Velocity, V_{DR}: Down Range Velocity

5.3 Vertical descent phase

It is expected that there are lots of obstacles, including rocks and craters, in the area where the Selene-B spacecraft will land. The size of the rocks we are requested to avoid is 0.5 m(height) x 1 m(width) or larger. Also it is necessary to avoid a slope with the inclination of 30 degrees or higher. One of the requirements for the vertical phase navigation is to autonomously avoid those obstacles and slopes while minimizing the distance from the specified target point. Using a scanning type radar either by laser beam or millimeter radio wave is one of the possibilities for achieving this, but it has disadvantages in power consumption, weight and development risk. We have, thus, determined to use image data from the cameras to meet the above requirement.

To achieve enough reliability in using camera image data, we propose a hybrid algorithm where 3 methods - stereo vision, light intensity processing and the usage of shadow information - will be used in a complimentary manner. Extensive simulations using actual moon surface photos and CG pictures have been conducted. Following is a brief description of each of the 3 methods.

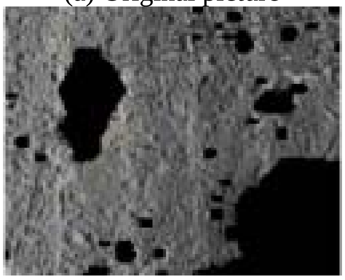
Stereo camera method: This is the only way, among the above mentioned 3 methods, to obtain the absolute distance between the object and the spacecraft and also it has an advantage that it requires no a-priori knowledge of the optical parameters for the objects such as reflection coefficients. It is, however, difficult to meet the requirement for the identification of the rock height of 0.5 m from the altitude of 200 m or higher due to the limitation of the baseline length of the cameras.

Processing light intensity: The area where landing is possible can be modeled as the one with small inclination and unevenness, where inclination is expressed by a mean plane inclination and unevenness by a local dispersion of the light intensity. More specifically, we can use local 2nd moment of light intensity and semi-global statistical measure based on the Hapke model to identify the landing area[1].

Shadow area extraction: The spacecraft will land in the morning area of the lunar surface to maximize the daytime activity period. This will make it feasible to detect the obstacles with the height of 0.5 m or higher by their shadows. Shadows have two meanings: the existence of hazardous obstacles to be avoided and more directly the areas where solar battery cannot provide power.

Fig. 5-5 shows an example of the obstacle detection by shadows.

(a) Original picture



(b) Estimated obstacle areas

Fig. 5-5 An example of simulation results to detect obstacles by shadows

6. Rover System

The Selene-B lander has a manipulator for sampling materials near the spacecraft, but the reachable area is limited and it is essential to have a moving robot. A small rover, hence, with the weight of 30 kg will be carried by the lander to conduct scientific investigation within up to 500 m distance area. Major technologies for the rover to be established are:

- Locomotion technologies in the unstructured terrain under hostile environment of high temperature and vacuum.
- tele-operation from the Earth with limited communication capacity and propagation delay in the order of seconds.
- autonomy technology for obstacle avoidance, contingency operation and behavior planning.
- sampling mechanism for material collection and analysis with manipulators, rock crashers and slicers.

The rover operation scenario during the 2 week mission period is as follows:

- The rover will be released from the spacecraft main body using the lander manipulator over the distance of around 1m.
- Initial investigation is conducted within the areas several tens of meters from the lander and soil or rock samples are collected by the rover manipulator.
- The collected materials are either analyzed by the

rover instruments or are transferred to the lander for different analysis onboard the spacecraft.
- The rover moves up to 500 m to approach the central hill of the crater and collects samples which again are analyzed by the instruments either onboard the rover or lander.
- As an option, a long range "one-way" excursion is conducted for further scientific investigations at the end of the two-week operation.

Major features of the rover are summarized in Table 6-1 and the picture of the drawing of the rover is shown in Fig.6-1.

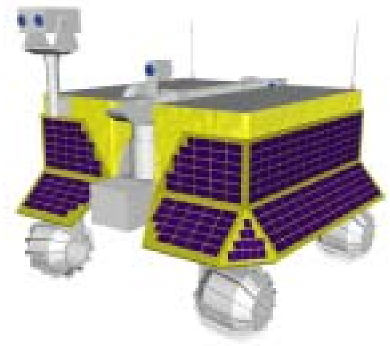


Fig. 6-1 Drawing of the Selene-B rover

Table 6-1 Major features of the rover

Required features	Target specification
Total moving distance during mission period	2km
Maximum speed	3 cm/sec
Maximum slope(with no land sled)	30 degrees
Maximum obstacle size to go over	20 cm
Telemetry via lander	20 kbps
Direct telemetry to the Earth	2 kbps
Number of wheels	5
Manipulator DOF Dimension	5 1 m
Navigation sensors	-stereo cameras -2 dimensional sun sensor -earth sensor -2 dimensional inclinometer -gyros -accelerometers

7. Spacecraft System

Basic configuration: A wide range of SELENE-B spacecraft configurations has been compared from the viewpoints of total weight, development cost, operational simplicity, complexity of the whole system and the resulting system reliability. In the adopted configuration, the spacecraft main body together with a rover will directly land on the lunar surface without leaving any orbiter in the moon circulating orbit. The rover will be separated from the lander after it has reached the lunar surface. The drawing of the spacecraft is shown in Fig. 7-1. The weight of the spacecraft at the launch is about 2,000 kg with the dry weight of 520 kg which includes science instruments and a 30 kg rover.

Fig. 7-1 Drawing of the SELENE-B spacecraft

Attitude and orbit control system: The baseline of the attitude control system for SELENE-B is 3-axis stabilization, mainly because at the time of landing onto the surface of the moon 3-axis attitude control is mandatory. During the trans-lunar and lunar orbiting phases, however, slow spin is given to the spacecraft body to reduce propellant consumption with the spin axis directed towards the sun and the pointing accuracy requirement is about 10 degrees.

As for the attitude control actuators only thrusters are used due to the comparatively short operation period. For this purpose 50 N-class thruster x 4 and 20 N-class thruster x 4 are used in addition to the bi-propellant 1,700N thruster dedicated to orbit maneuvers.

Landing legs: The mission for SELENE-B requires landing onto a relatively rough terrain and the design of the shock absorbing mechanism for the legs is one of the critical factors. A wide range of mechanisms has been studied by conducting numerical simulations as well as hardware experiments. A cantilever type leg has subsequently been selected which, as shown in Fig. 7-2, consists of a main leg with two sub-legs for each of the 4 legs. Both the main and sub-legs contain honeycomb core(s) which will be crashed at the time of the touch down to absorb the resulting shock.

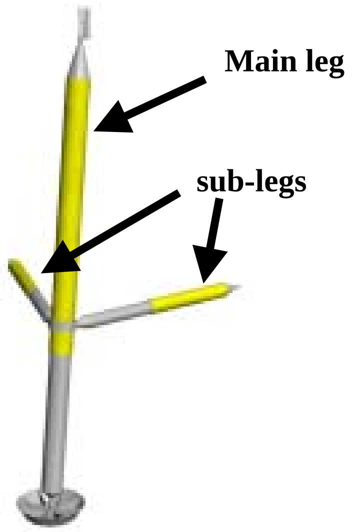


Fig. 7-2 SELENE-B leg mechanism

Communication system: As for the ground stations, 64 m and 34 m antennas in Usuda and in Kagoshima, respectively, are used. The communication between the spacecraft main body (or lander) and the ground tracking stations uses S-band for up and down links. The onboard antennas are omni-directional LGAs(Low Gain Antennas) which provide 40 kbps telemetry and command capability, but addition of MGA(Medium Gain Antenna) is also being studied to have 256 kbps down link for image transmission.

The rover has two kinds of communication links: one is the X-band direct up and down links to the ground stations with 4 kbps down link capacity and the other is the S-band link to the lander with 2 Mbps capacity.

Power system: The spacecraft power is provided by the body-mounted solar cells which generate 1,100 W power at noon on the lunar surface under the worst attitude condition.

During the lunar orbiting phase the Selene-B spacecraft will experience sun eclipses, which requires 235 Ah battery capacity. During the descent phase, when the attitude cannot be kept favorable to the sun incidence angle, a battery capacity of up to 86 Ah is required which is significantly smaller than what is required during eclipse periods. A lithium ion battery with the capacity of 311 Ah is used to generate enough power for these periods.

Thermal control system: The Selene-B spacecraft will have following 4 phases from the viewpoint of thermal design:

1) Trans-lunar phase: The upper panel will be directed to the sun so that the sun incidence angle to the solar cells be within plus/minus 10 deg. range. The major thermal input, hence, is through the upper panel.
2) Lunar orbiting phase: The attitude control scenario is similar to that for the trans-lunar phase with the main power source from the solar cells, but additional thermal input is expected due to the albedo from the moon surface.
3) Descent phase: The attitude is controlled relative to the moon fixed coordinate system, not that of the inertial one. The sun incidence direction will change along the flight path and the battery is the power source. The albedo from the moon surface will get increasingly intense as the spacecraft altitude becomes lower.
4) Lunar surface phase: The mission period on the lunar surface is limited to the daytime and the landing site is outside any shadows, so the solar cells are the only power source. The inclination of the landing site will be in the range of +30 deg. to -30 deg. which will result in a large sun angle range. In addition to this wide range, the sun incidence angle will change from very low to high during the daytime, which means the thermal input will significantly change during the two-week mission life on the lunar surface. Another point is that the thermal input from the lunar surface is intense and so the spacecraft lower panel cannot be used for thermal radiation.

Based on the above mentioned conflicting requirements, the basic idea for the thermal design is as follows:

- The severest thermal condition is that on the lunar surface where the sun incidence is from above and the spacecraft has a thermal input from the regolith on the surface whose temperature could be above 100 ℃. The basic design, hence, starts with meeting the requirement in this severest phase and then is modified to cope with other phases.
- The lower panel and the side panels are covered by MLI to thermally isolate the spacecraft body from the heat input. The reverse side of the solar panels are also thermally shielded as opposed to the conventional way of using the reverse side as thermal radiators.
- A significant part of the upper panel is covered by OSR's (Optical Solar Reflectors) which play the role of the only major thermal radiator. The parameters of the OSR's are designed for the maximum thermal input, so heaters are used at other times.

8. Conclusions

SELENE-B, which is in the proposal phase, with the missions of challenging engineering technology validation and scientific investigation has been described from the viewpoint of the space robotics. The study is still going on and one of the future issues includes the longer mission life on the lunar surface which requires development of low temperature devices.

References

[1] K.Nishiguchi, "Obstacle Detection and avoidance Method to Achieve a Soft Landing on the Moon and Planets," Transactions of the Society of Instruments and Control Engineers Vol.38, No.4, pp.1-9 2002.