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OPTICAL SENSORS IN OBSTACLE DETECTION AND AVOIDANCE FOR MOON LANDING

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Abstract

In this paper, we will present the role and subjects of optical sensors in the obstacle detection of the moon lander, that is proposed as the SELENE follow-on mission SELENE-B. For more precise and safe moon landing, optical sensors are the most promising sub-systems, though it has many technical problems before using it as the primary space system sensor. For the optical obstacle sensor, monocular and stereo sensors are possible. Both type optical sensors and many image processing algorithms have good and weak points in their reliability of the results and CPU capabilities for the image processing. Comparison of those algorithms will be reported and a new hybrid system will also be proposed.

Keyword: Moon, Landing, Image Processing, Obstacle Detection

Introduction

For Japanese SELENE-B, that will be the Japan's first moon lander, the safeties and preciseness of landing are the most significant technological requirements.

In 2000, SELENE-B was separated from the SELENE, that Japan's first moon observing satellite would be launched in 2005, as the results of the project technical evaluation. SELENE-B was started as the research phase program by NASDA, ISAS, and NAL. The lack and immaturity of the safe landing technology were strongly pointed out through this technical evaluation, the landing safety was set as the primary and hardest requirements for SELENE-B study phase.

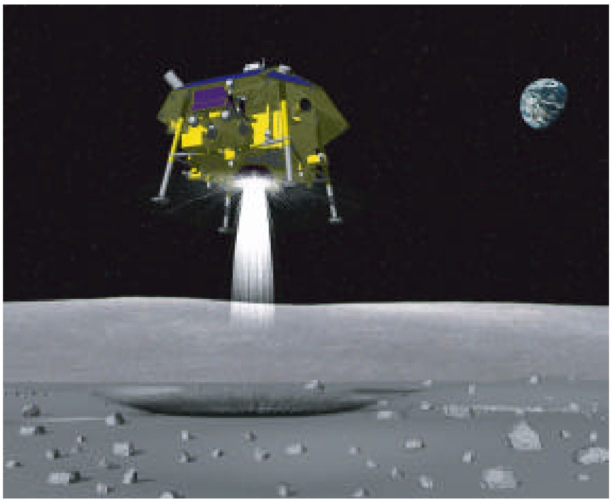

Fig. 1 SELENE-B: Concept of Moon Lander

30 years after the Apollo, there is much drastic progress in the technologies. Especially in the field of information processing and computer technologies, the progress might be almost beyond imagining of the Apollo era's engineers. The latest laptop PC's computing capability might easily exceed the whole computing capabilities of the Apollo mission control center in 30 years ago. For our SELENE-B landing, these advanced computer science's fruits will be fully applied to accomplish the safe and precise moon landing against the severe scientific requirements for the unexplored moon site, such as a vicinity area of a large crater central hill.

Landing site

From the scientific viewpoint, the unexplored and sciencefull zones were examined as the SELENE-B landing target. After intensive science discussion, a central hill of a large crater is selected as our first exploring target. For the science results, central hills are expected to reveal the moon origin, and were never visited by human being and/or artificial explorers, such as Surveyors and Lunokhods. For the central hills, only a few photographs are available from the Apollo inheritance. Unfortunately, these photos' resolution is nominally over 10m/pixel, and is not enough to identify the landing obstacles exactly. The 1m/pixel is the best resolution, but only for few shots around a crater central hill. Even from the preceding SELENE, the best expected ground resolution will only be 10m/pixel using its LISM.

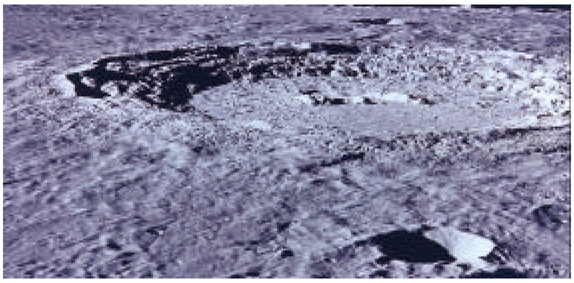

Fig.2 Landing Site Candidate for Scientific Exploration

Obstacles

Based on the scientific consideration for the geophysical process of a crater and a central hill, the following assumptions are presented from the science side as the landing site situation for the lander design conditions.

*Rock distribution is assumed to be the same level as the Surveyer-7 landing area as the worst case.

*Crater distribution is assumed to be same level of the high land region of the moon.

*Angle of hill slope is assumed as steep as 30° possibly.

*Surroundings of the landing point are assumed to be covered with a thick legolith layer.

From the mechanical specification limit, SELENE-B lander will be able to land safely over only small obstacles. For the design assumption based on the above conditions, the followings four are assumed as the obstacles in the SELENE-B study team. Those will have great impacts for the design of mechanical constraints of the lander, such as landing legs, landing speed, mechanical clearance under the lander, and so on. (Fig. 3)

Obstacles :=

:=Rocks of 0.5 m or more in height, 1m or more in width.

:=Craters with radius of 2m or more.

:=Slopes inclined at an angle of 30° or more.

:=Shadow area

In addition, for the post landing missions, such as the small rover exploration, the following conditions are more desirable. However, although the obstacle detection shall be done in real time and autonomous, those intelligent and/or complicated judgments might need more intellectual guidance systems, and will be the future study subjects.

- Landing site never be in shadow for all mission days long.
- As near as possible to the exploration target (Central hill).
- Better ground condition for the rover running. (Rocks of 0.3m height, slopes of 15 degree, etc.)

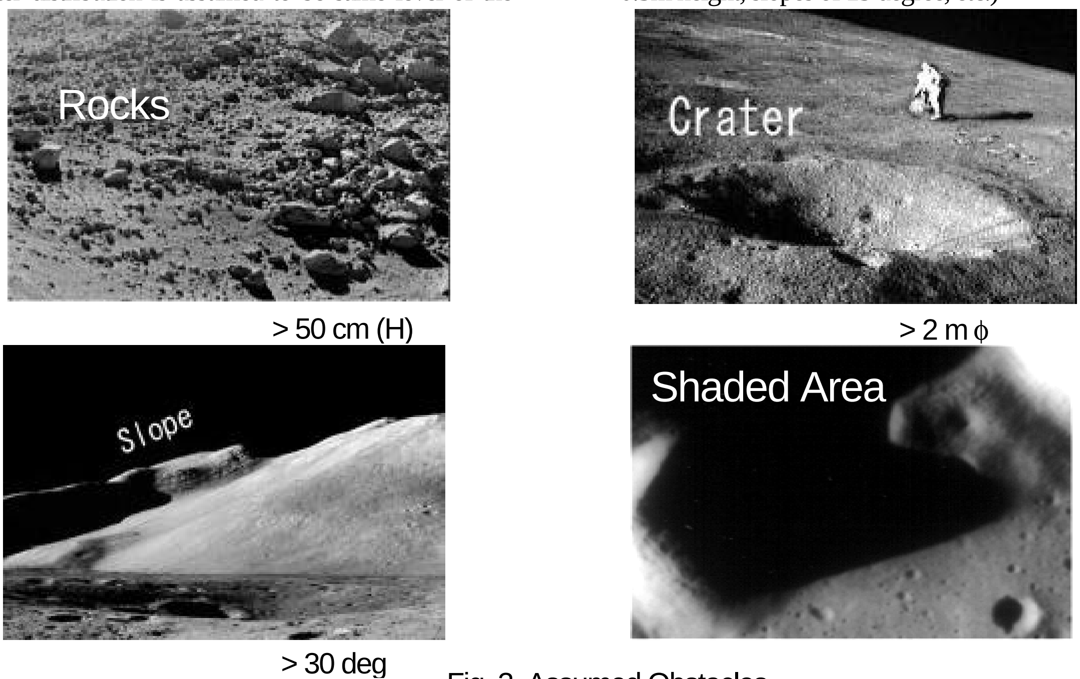

Fig. 3 Assumed Obstacles

Moon lander concept outline

The SELENE-B lander system concept is summarized in Table 1. It will be launched by H2-A rocket, as a half payload. It will enter into the moon polar orbit after 5 days flight. The orbit height is assumed as 50-100km. Those orbit conditions are assumed as it to SELENE as possible, to reduce development cost and utilize SELENE experience and observed data. In the SELENE observed data, the DEM (Digital Elevation Map) data is the most expected and promising data for the SELENE-B safe and precise landing.

The size of the lander is assumed about 3.7m in diameter, that is the nominal fairing size of H2-A. On the lander, a small moon rover will be embarked for the geological exploration on the moon. The dry weight of the lander is assumed around 520 kg, including 50kg science mission payload and an exploration rover. (Fig. 4)

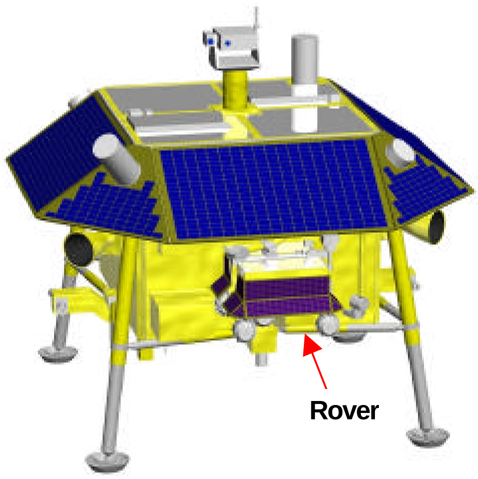

Fig. 4 Concept of SELENE-B Lander & Rover

Table 1 System Concept of SELENE-B

Launch Weight	1860 kg
Landing Weight	520 kg
Payload	50 kg
Height	2.3 m
Width	3.7 m
Length	3.7 m
Landing Speed	< 3 m/s
Landing Acceleration	< 10G
Obstacles	
Slopes	> 30 deg
Rocks	H > 50cm, W > 1m
Mission Period	
	2 weeks, Day Time

Major technical missions for SELENE-B were summarized as;

- Pin-point landing enduring the moon gravity distortion.
- Autonomous obstacles detection and avoidance during vertical descent.
- Moon landing mechanism

Landing for such severe areas, where a lot of obstacles exist essentially, will be inevitable for the future moon various activities. Those interested areas are such as inside regions of a crater, mountainous regions, or polar regions etc. To land safely and accurately at such severe areas, the highly precise guidance navigation and control technology, the reliable and robust obstacle detection and avoidance technology, and the tough landing mechanism that can accept and allow the obstacles for some extent, are indispensable. In SELENE-B, those technological demonstrations will be the main technological mission.

After landing, the geological exploration by the small moon rover will be done as the science mission. Since the assumed rover size is only about 50-80cm, it can get over only the rocks lower than 20cm, it may not be able to get over the steep rim of crater, those diameter is more than a few meters. For the rover exploration, the obstacles distribution might be more serious problem than the landing. Thus obstacles detection will be required not only for safe landing but also for effective rover exploration.

For a small rover, the traveling distance and the scientific results might be in inverse proportion. If the lander could find a safe landing zone, very close to the central hill, and could guide and control to that zone precisely, better scientific results could be expected.

Obstacle Detection Sensors

As the obstacles detection sensors, two sensor types were considered in the first stage. To reduce the required fuel for the vertical descent, the SELENE-B obstacle detection subsystem is required to detect obstacles from higher altitude (>300-500m), for wide area (>1000x1000m), and in higher frequency (> 1Hz).

The Laser Range Finder (LRF) seemed to be most promising, since LRF could measure 3D shape of the landing site directly with less computing process. The only problem left might be the low scanning frequency against the fast vertical descent speed (20-50m/sec for SELENE-B).

However, if we intend to measure 3D shape from higher than 200m, it was revealed that LRF should solve the contradictive problems that are high scanning speed with lower laser power from long distance.

On the other hand, since TV camera images from the lander will be captured at instance with very low power, they are the most promising and natural data for the obstacles recognition during the fast vertical descent. Two major subjects for the camera images sensors are

(1) Computer resources for onboard image processing.
(2) Reliable and robust algorithms from images to obstacles/3D measurement.

At the Apollo era, computers were too large and too poor, and the onboard image processing was a fantasy. However, in these 30 years, the computers' development have been so drastic that autonomous image recognition/processing are not fantasy already, and are realistic and might be the most promising choice for the landing obstacle recognition.

Onboard Image Processing

Recently for the laboratory and factory use, the real-time image and stereo processors with customized large-scale logic array and high speed CPU become feasible. The huge calculation for the image processing is done almost real timely by ASICs or FPGA. For the space use ASIC, Japan's MUSES-C ONC is equipped with gate array, to process an asteroid image at remote site. For ONC, the ASIC gates size is 200k, but for more complicated and advanced space data processing, 1M gates array is already classified for space use by NASDA.

For the SELENE-B stereo image processing, using 1024x1024 images, the implementation of the ground use real-time stereo processing logic into the ONC was evaluated. Fig. 4 shows the processing blocks of the evaluated stereo processing. For the implementation of those processes, three configurations are considered, assuming ONC and 1M gates array. (Table 3)

Engineering estimation of the data flow and gates size required for each process were done. As the quick results, shown in Table 3, the latest stereo processing could be implemented within acceptable cycle time for SELENE-B obstacle detection for safe landing.

Table 2 Real-time Stereo Processing for Space Use

Weight	3.8 kg
Power	36 W
Size	280 x 240 x 80 mm
Stereo Processing Frequency	0.5 - 0.4 Hz

Obstacle Detection by Optical Sensors

Many optical obstacle detection algorithms were already proposed for the safe moon landing. (Table 4) Those optical algorithms assume either a monocular camera or a set of multiple cameras. The difference is not only the number of cameras, but also the applicable situations.

The monocular camera system is simple, lightweight, and less system requirements for a spacecraft. However, the monocular camera usually could get information of the target landing site as its color and brightness for a point, and a texture as the set of points information, those algorithms shall estimate the ground physical statuses by some "understanding" or "estimation" under each prerequisites. Roughly speaking, monocular algorithms might be suitable for the

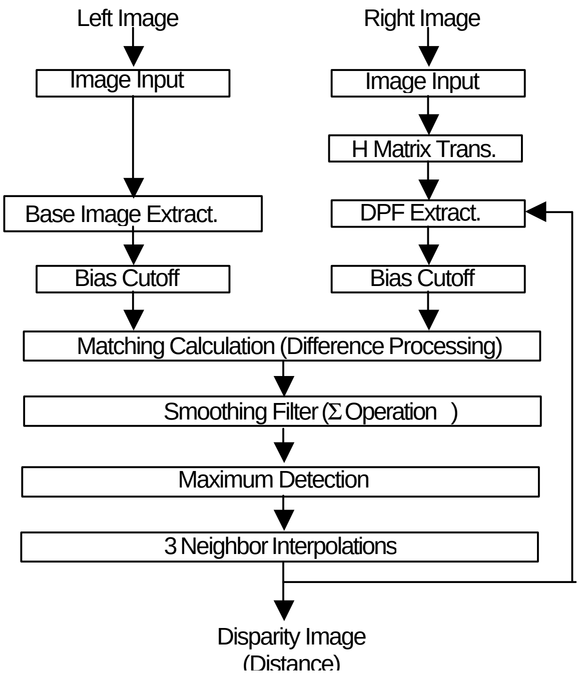

Fig. 5 Assumed Stereo Processing Algorithm for Space Use

Table 3 Performance of Space Use Stereo Processor Example

	H Matrix Transformation	Bias Cutoff	Gates	Cycle Time
#1	Nearest Neighbor	Edge Filter	90K	1.9 sec
#2	4 Points Interpolation	Edge Filter	130K	2.0 sec
#3	4 Points Interpolation	LOG Filter & Histogram Equalization	700K	2.3 sec

For Image : 1024x 1024, DPF : 16

understanding of the outline, tendency, or global identification of obstacles, and not suitable for the detail.

On the other hand, multiple camera system requires two times system resource for a spacecraft at least, with excessive system tasks, such as the severe mechanical and optical calibration between multiple cameras. However, it theoretically could add additional vertical position information for the target site, using 3D stereo measurement algorithm. From the vertical ground pattern information, the obstacles information is reached straight forward..

In the following, a few major algorithms were examined using CG images. A pair of CG images was set to simulate the expected images for the conditions in Table 5.

Rocks distribution is assumed as similar to the Surveyer-7 landing site, as the worst rock distribution case. Craters distribution is assumed as the theoretical distribution of the moon high land area. For the slope distribution, some arbitral topography was assumed, since no exact distribution was ever reported from the science side.

FOV and stereo base line were set according to the current lander concept. The sun angle was set to the planned landing moon day. 150m are the altitude to begin the 2nd precise obstacles avoidance navigation to the final landing site. (Fig. 6)

In the following analysis example, each color is used as;

Red area : Area identified as obstacle
Green area : Not detected obstacle area
Blue area : Remaining shadows area
White area : No obstacle area

Table 4 Major Optical Obstacle Detection Methods

*Shade Method
*Topography from Brightness
*Pattern Matching
*Shape from Shading
*Hapke Reflectance Model
*Structure from Motion
*Stereo Measurements

Table 5 CG Image for Algorithm Evaluation

Altitude	150 m
Angle of View	30 deg
FOV	80 m
Stereo Base Line	3 m
Sun Angle	30 deg from Left
Obstacles Rocks	> 0.5 m (H)
Craters	> 2 m f
Slope	> 30 deg

Obstacle Detection by Stereo Viewing

The stereo method could estimates the depth distance to the surface using images from different aspects. Though this method does not need any physical assumption about the target area, it essentially requires identifying the very precise camera physical parameters, such as the lens focal length, image center position, direction of line of sight, and relative position of cameras, by some calibration process.

For SELENE-B moon lander, the baseline distance between two cameras is limited around 3m, from the lander size. Since the depth resolution degrade inverse proportionally to the distance square, and upgrade proportionally to the baseline distance, practical obstacle detection becomes available only at low altitude. For SELENE-B lander, only after the lander reaches about 150-200m, the stereo method begins to identify the rock obstacles of 0.5m in height.

Fig. 7 shows the results of stereo 3D measurements by the brightness. The matching with 7x7 windows was applied to decide the stereo correspondence. The major stereo calibration parameters are used with the exact theoretical value. The black area shows the unmeasured points, due to the dark shadow of the rocks, craters, and steep slopes. The measured 3D results do well match with the simulated vertical distance. The topography inclination is estimated using small plane adjusted by the minimum square approximation. In Fig 8, the red area shows the identified slope obstacles of steep inclination more than 30 deg.

Obstacle Detection by Topography from Brightness

On the moon, the surface brightness variation is weakly

Fig. 6 CG Image for Obstacle Detection Evaluation

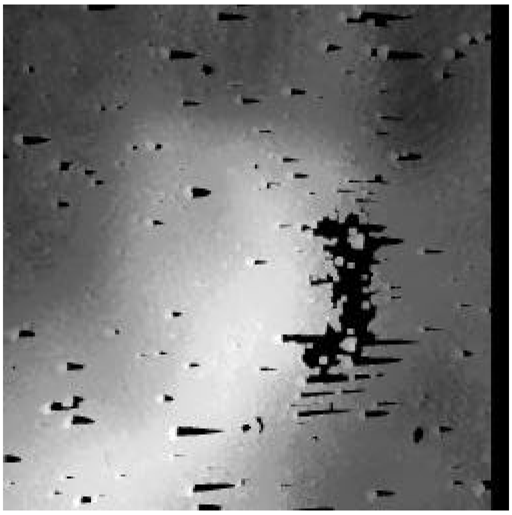

Fig. 7 Vertical depth measured by "Stereo"

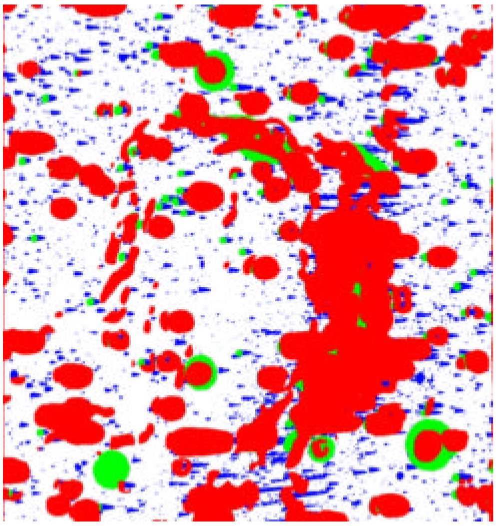

Fig. 8 Steep Slopes (>30°) detected by "Stereo"

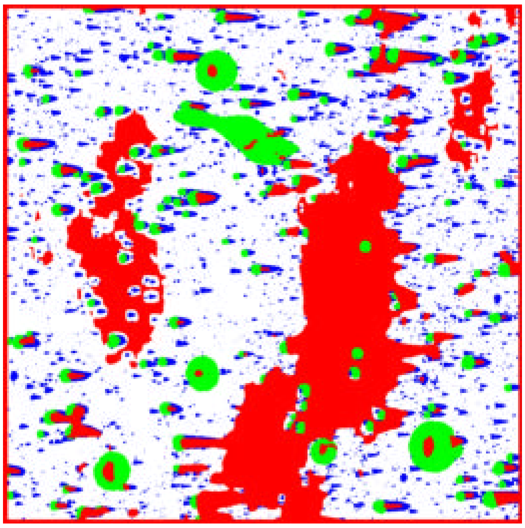

Fig. 9 Steep Slope area detected by "Mean Brightness"

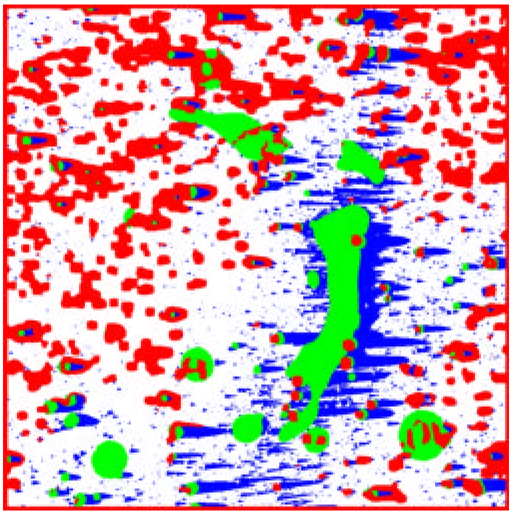

Fig. 10 Rough area detected by "Brightness Variance"

affected by the geological features, and is strongly affected by the surface topography. Based on this assumption, the geographical features in the small area could be estimated and presumed by the brightness distribution information on that area. Two evaluation factors were possible in this approach, one is the mean brightness, and other is the variance of the brightness.

Using the mean of brightness, too bright area and/or too dark area could be guessed as the steep slope, that is the obstacle. Fig. 9 shows the obstacles detected by this measure. A local area is classified as obstacle, if the local brightness mean of the 7x7 small window is too different from the global brightness mean of the image.

By the variance of the brightness, abrupt change of brightness in a small area would mean rough terrain pattern. The brightness variance of an area could be said as an index of the roughness of that area. Fig. 10 shows obstacles classified as obstacles by the brightness variance factor, using 7x7 small window.

The combination of the mean and variance of the brightness is proposed as the "Topography from Brightness" method. In this method, the weighting factor of index, mean and variance, is still open problem. However, those indexes have many advantages to other method, such as simple and light calculation, less sensitivity for the altitude, and so on. Thus these indexes might be useful as the first obstacles detection criteria.

Obstacle Detection by Shadow Method

This method identifies the obstacles, rocks and craters from their shadow. Since on the moon it is vacuum and no light dispersion by the air, rocks, craters, and steep slopes will generate clear dark shadows in the observed images. SELENE-B will land at early moon morning, before 9:00AM, the sun angle will be about 30 degree. In this situation, the shadow length will be 86.6cm length for 50cm height rocks on the flat ground, and will become more detectable from the higher altitude.

Fig. 11 shows the detected obstacles by the shadow. In this example, the shadowed obstacle area are shrunken and expanded to remove the minute shadow areas as noises.

If the obstacle detection needs the exact obstacle height and area, the shadow area shall be adjusted according to the inclination of the slope against the sun angle. However this shadow approach could not measure the slope inclination itself. Thus another algorithms to identify the slope angle are inevitable for the exact obstacle identification by shadow method.

Hybrid method for obstacle detection

Usually optical image processing algorithms have advantages under some assumptions, and also have disadvantages for another situation. For SELEN-B obstacle detection system, no sole obstacle detection algorithm might be reliable for the required situation, from high altitude to low altitude, with high speed descent flight, without any advanced real optical images for parameter tuning, autonomous processing, and with high reliability for successful obstacle detection.

In above, using CG moon landing images, three major obstacle detection algorithms were examined. Each algorithm will identify obstacles based on different information, and effectible in different situation.

"Topography from brightness" method could work even from high altitude, but might be hard to identify the obstacles itself and obstacles exact position until final landing. "Shade" method could work for wide range of high altitude to low altitude, could identify small obstacles from higher altitude than other methods, but could not recognize the inclination of the ground slope. "Shade" method essentially assumes that the slope inclination will be measured by other method. "Stereo measurement" could identify the obstacles as the exact shape, height and width, but could not measure the obstacles from high altitude. For SELENE-B, because of the 3m baselines limitation and required FOV, around 150m may be the highest altitude for stereo measurement.

Thus no solo algorithm might be able to solve the obstacles detection requests for SELENE-B safe moon landing with high reliability. Every method has a weak and forte. Thus a new complex and hybrid algorithm shall be developed, that aims more robust and more reliable by running different algorithms in parallel.

For such hybrid method, the stereo method could be expected to estimate the slope inclination and identify the shape of obstacles exactly at relatively low altitude. For the monocular algorithms, it could be expected to roughly estimate the geographical trend even from high altitude. Thus the combination of the stereo and monocular algorithms could be used for more wide range of altitude, for more detailed obstacles identification, and is more robust.

Fig. 12 shows the result example of such hybrid method

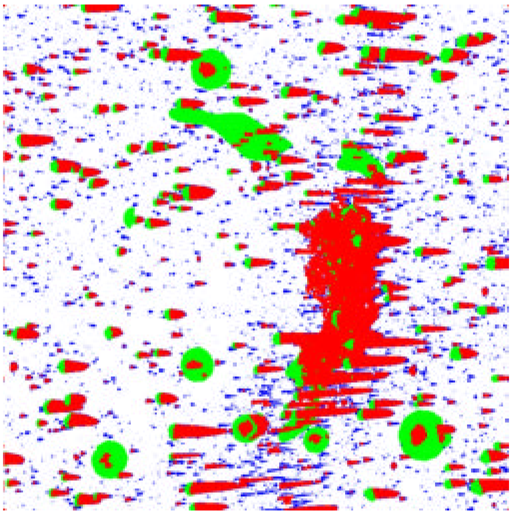

Fig. 11 Obstacles detected by "Shadow" method

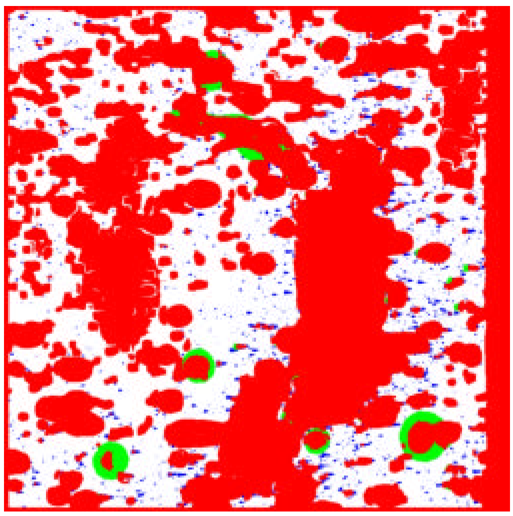

Fig. 12 Obstacles detected by "Hybrid" method

that integrates three algorithms, stereo, topography from brightness, and shade method. Almost all obstacles are detected with high reliability.

Table 6 shows the obstacles detection performance of each algorithm. The hybrid method shows high and promising performance. In table 6, each method shows also high miss-detection rate, as the results of safer obstacle judgment.

Conclusion:

Utilizing the latest advanced computer technology and image processing, the real-time and reliable obstacle detection will be available for the SELENE-B safe landing to the more risky area, such as the vicinity area of a crater central hill. Right now, the proposed hybrid image processing is only a simple combination of three methods.

As the next step of this hybrid approach, the cooperation between those methods and cross utilization of each detection result will be tried for the more robust and reliable method for wide range of landing altitude.

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Table 6 Obstacles Detection Performance & Miss-Detection Rate for Each Method

Method	Rocks	Crater	Steep Slope	Shadow	All Obstacles
Stereo	.76 (.30)	.57 (.31)	.90 (.29)	.66 (.22)	.65 (.19)
Brightness (Mean)	.18 (.24)	.36 (.23)	.73 (.21)	.54 (.15)	.46 (.15)
Brightness (Variance)	.71 (.19)	.24 (.21)	.07 (.22)	.31 (.18)	.34 (.16)
Shadow	.43 (.13)	.33 (.14)	.60 (.12)	.66 (.00)	.52 (.00)
Hybrid	.98 (.51)	.69 (.52)	.96 (.50)	.91 (.42)	.88 (.39)

Detection Performance : Ratio of detected obstacles in real obstacles area
Miss Detection Rate : Ratio of obstacle classification from non-obstacle area