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Ground-In-The-Loop Backup System for SLIM's Vision-based Navigation

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Abstract

Smart Lander for Investigating Moon (SLIM) landed on the moon on January 20, 2024. Terrain Relative Navigation (TRN) is one of the key technologies for realizing pinpoint landing, and SLIM achieved the world's first pinpoint landing on the moon using TRN technology using navigation camera images. INGSS is a system with the function of monitoring the status of TRN, called Vision-Based Navigation (VBN), on the ground in real time. In addition, it has the function of performing TRN image processing independent of VBN using downlinked navigation camera images, and in the unlikely event that VBN fails, INGSS can send a command to forcibly update the navigation values of the onboard system using the image processing results in INGSS. In INGSS, the operators decide the correctness of the results of VBN and image processing on the ground. The supervisor consolidates the operator's decisions and decides whether to send a command to the spacecraft. Since the landing sequence on the moon proceeds in a short time, the operators' and supervisor's decisions and operations had to be completed within 5 seconds of receiving the navigation camera images. This paper presents an overview of the SLIM landing operation and reports on the concept, design, training, and operational results of INGSS.

Keywords: SLIM, Terrain Relative Navigation, Vision-Based Navigation, Ground-in-the-loop system

Acronyms/Abbreviations

CST – coasting
DIO – data I/O module
GILS – ground-in-the-loop system
GUI – graphical user interface
IMP – image processing module
INGSS – Image matching Navigation Ground Support System
JAXA – Japan Aerospace Exploration Agency
JST – Japan Standard Time
LEV – Lunar Excursion Vehicle
OPV – onboard processing validation module
OSM – optimal solution selection module
PDM – Perilune Descending Maneuver
PPD – Pre-Powered Descent
SLIM – Smart Lander for Investigating Moon
TRN – Terrain Relative Navigation
VLD – Vertical Lunar Descent
VBN – Vision-Based Navigation

1. Introduction

On January 20, 2024 (JST), Smart Lander for Investigating Moon (SLIM) landed near the SHIOLI crater located near Mare Nectaris on the Moon. SLIM is a lunar lander developed by Japan Aerospace Exploration Agency (JAXA), and the purpose of the project is to demonstrate high-precision landing technology on a gravitational body using a small, lightweight probe. One of the key technologies to demonstrate high-precision landing is autonomous and precise estimation of the probe's position using Terrain Relative Navigation (TRN) [1]. Vision-Based Navigation (VBN) [2] is a TRN technology that autonomously estimates its position relative to the lunar terrain using navigation camera images, and was developed to achieve high-precision landing on the lunar surface. VBN was performed a total of 14 times in seven areas, two times each, during the landing descent phase on the lunar surface, and all were successful. As a result, SLIM achieved the world's first pinpoint landing on the lunar surface with 100 m accuracy.

VBN is a very challenging technology, and if it fails, it will have a major impact on the mission. Although we have confirmed that the success rate is sufficiently high through prior software verification, we needed to prepare a backup method in case VBN fails. Extremely severe cases in which VBN can fail include anomalies in the navigation camera or inertial sensor. However, in some of these cases, the correct position can be estimated by using the computing power on the ground. Therefore, a ground-in-the-loop system (GILS) was developed that monitors the navigation camera images and VBN results in real time on the ground during landing and descent operations, and can immediately send commands from the ground to override the VBN results in the event of failure. We call this system the "Image matching Navigation Ground Support System (INGSS)."

An example of missions in which GILS was used in the landing operation of a spacecraft is GCP-NAV of Hayabusa [3] and Hayabusa2 [4]. When Hayabusa landed on the asteroid Itokawa, an operator on the ground matched ground control points (GCPs) between the downlinked navigation camera image and the 3D model of the asteroid to estimate the relative position and attitude of the asteroid, and commands were sent based on that. Hayabusa2 also performed a similar operation when landing on the asteroid Ryugu, and successfully returned an asteroid sample. GILS, which is based on manual operation by an operator, is an effective means of landing on a celestial body with a very slow descent speed in microgravity, but landing on the moon, a gravitational body, requires ground operators to decide and operate in a short time. In addition, the amount of information that can be obtained in a short time is small, making it difficult for the operator to make correct decisions.

The main roles of INGSS are to "monitor the onboard VBN status in real time" and "send commands if VBN fails." The results of VBN during landing operations are transmitted to the ground in real time along with compressed navigation camera images and monitored on the ground. Immediately after VBN is executed, INGSS receives the VBN results and generates a simulated image that the navigation camera is expected to capture if VBN succeeded . An operator immediately checks whether this expected image matches the downlinked image. This determines whether VBN was successful. Furthermore, image processing independent of VBN is performed on a ground computer using the downlinked image. Another operator determines whether it was successful. Based on the operators’ decisions, a supervisor decides whether to send a command to the spacecraft. If necessary, the supervisor sends a command to override the VBN result. If VBN is determined to be successful, no command is sent.

Because the landing sequence on the moon was a short one, INGSS operations had to be done within 5 seconds of the navigation camera image being downlinked. In order to make the correct decisions and perform the correct operations in a short time, extensive training was conducted. At the same time, a dedicated graphical user interface (GUI) and input device were developed and introduced.

This paper presents an overview of the SLIM landing operation and reports on the concept, design, training, and operational results of INGSS.

2. SLIM lunar landing operation

During the powered descent to the lunar surface, SLIM uses VBN to accurately estimate its own position on the lunar surface. In addition, the flight trajectory is autonomously corrected based on the position information obtained from VBN, allowing the spacecraft to accurately approach the target landing site. Fig. 1 shows the SLIM lunar landing sequence. Before starting the powered descent, SLIM is in a 600 × 150 km elliptical lunar orbit. Perilune Descending Maneuver 2 (PDM2) is used to lower the perilune altitude to 15 km, and the powered descent phase begins from the perilune. The conditions for go/no-go decision of the powered descent start include success of VBN, which is performed in three areas just before the start of the powered descent. The flight speed is reduced by braking, and the horizontal speed becomes almost zero above the target landing site. The vertical descent phase begins at an altitude of approximately 7 km. During the vertical descent phase, the altitude and speed are also obtained by the landing radar. Obstacle detection [5] is performed using the navigation camera 50 m above the lunar surface, and the safest area within the camera's field of view is selected. Just before landing, Lunar Excursion Vehicle (LEV) is separated and the spacecraft lands on the lunar surface.

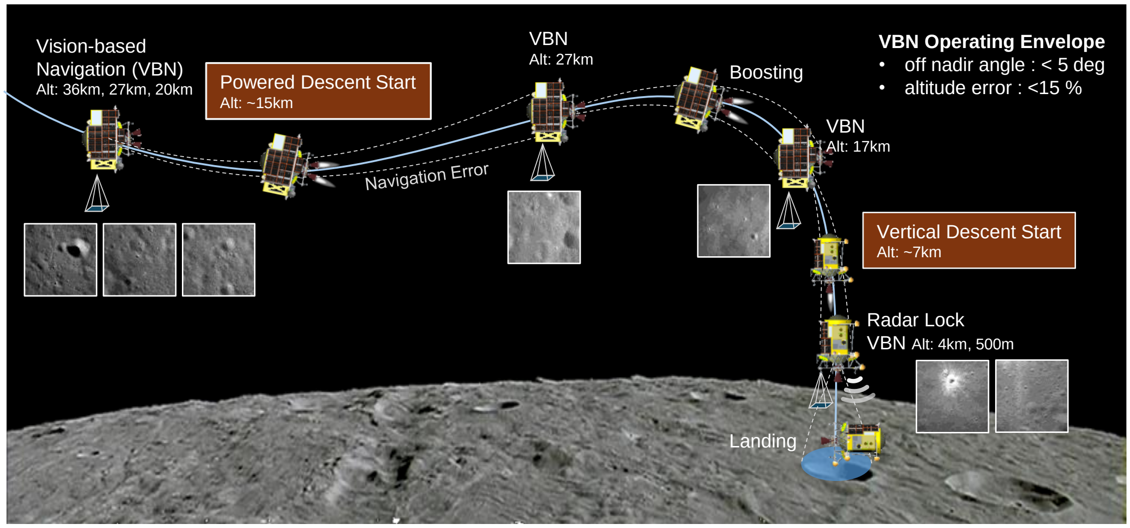

Fig. 1. SLIM lunar landing sequence

VBN is used in seven areas: three areas before the powered descent (PPD1, PPD2, PPD3), two areas during the powered descent phase (CST1, CST2), and two areas during the vertical descent phase (VLD1, VLD2). It is performed twice in each area, for a total of 14 times. During the powered descent phase, the main engine is temporarily shut down for VBN and the spacecraft enters a coasting state. During coasting, which lasts for about 45 seconds, attitude change, VBN execution, navigation value update, guidance calculation, and attitude return are performed. Navigation value update and guidance calculation are basically performed based on the results of VBN. If a command to override the VBN results is received from the ground during this coasting, the process can be re-executed based on the command. However, for the command to take effect, the spacecraft needed to receive it before the next boosting began.

3. Image matching Navigation Ground Support System (INGSS)

In the SLIM landing sequence, if VBN fails in a certain area, the inertial navigation error is not reset and accumulates until the next VBN execution. The increased navigation error will deviate from the search range of the next VBN, and there is a high possibility that all subsequent VBNs will fail. In other words, failure of one VBN may lead to failure of the pinpoint landing mission itself. Although VBN technology has not been proven in orbit and is immature, prior verification has shown that VBN will have a sufficiently high success rate and accuracy. Taking these risks into consideration, we required a system that can instantly send commands from the ground to override the VBN results. Here, we will describe the details of the design of INGSS.

3.1 System concepts

The SLIM mission required a ground system with a function to monitor VBN status and to send commands to override the VBN results. INGSS is a ground-in-the-loop system developed to meet these requirements. Fig. 2 shows INGSS and the onboard software related to VBN. During landing operations, SLIM continues inertial navigation and performs VBN in multiple areas. VBN extracts craters from images acquired by the navigation camera [6] and compares them with the onboard crater map to obtain three-degree-of-freedom positions relative to the map [7,8]. The navigation camera can output compressed images at the same time as uncompressed images used for VBN. Due to communication rate restrictions, images sent to the ground need to be strongly compressed, but excessive compression will interfere with the operator's visual decision. To meet these restrictions, the navigation camera’s 512 × 512 pixel 8-bit grayscale image (262 kilobytes) was compressed to approximately 8 kilobytes with a JPEG quality factor of 9. The compressed images from the navigation camera and the results of VBN are downlinked to the ground in real time and can be monitored by INGSS.

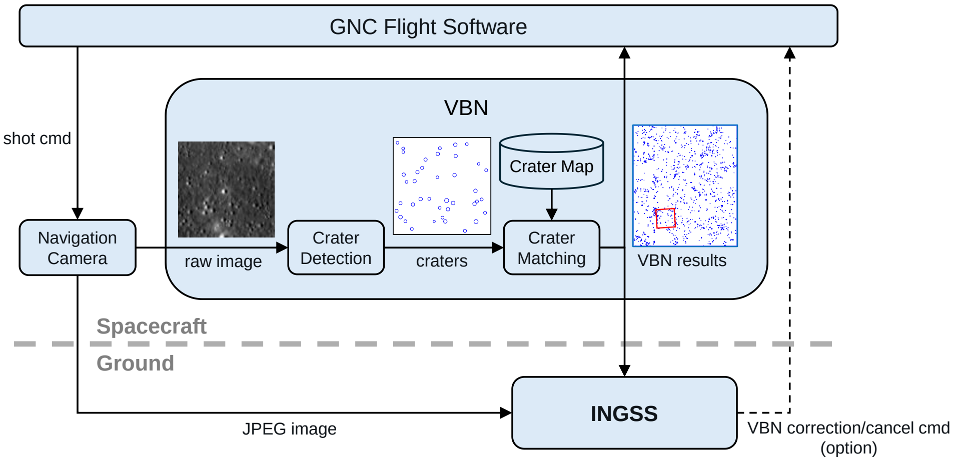

Fig. 2. Relationship between onboard software related to VBN and INGSS

INGSS can send commands to override the VBN results as needed. There are two types of commands: "correction command" and "cancel command." Correction command is command to override the VBN results with the results of image processing on the ground, while cancel command is command to force the inertial navigation to continue without using the VBN results to update the navigation values. In the worst-case scenario, VBN outputs an incorrect position estimation result, and the navigation values are updated based on that false result, causing the descent trajectory to deviate significantly from the target trajectory. The probability that VBN will output a false result is less than 0.1%, and is even lower when the probability of image processing on the ground failing is taken into account, but the cancel command was prepared for this scenario.

As mentioned in Chapter 2, the command sent from INGSS must be received by SLIM before the coasting of about 45 seconds ends. Considering the propagation delay of downlinking the navigation camera image, the transmission time depending on the data size, and the image processing time on the ground, it was required that the command be sent within 5 seconds after the image was received by INGSS. INGSS checks the VBN results and the image processing results on the ground as a backup, and it sends a command if needed. If all processing is performed automatically, it is possible to send a command in a short time, but this decision and command is critical on the landing sequence. Therefore, the decisions of the image processing results on VBN and the ground and the judgment of command transmission are made by ground operators. Furthermore, since it is necessary to decide multiple processing results in parallel, INGSS is operated by multiple operators and one supervisor. There are three operators, one of whom decides the correctness of VBN results. The other two decide correctness of two image processing results executed on the ground computer using the downlinked navigation camera images. The operator's decision is sent to the supervisor via a dedicated input device, which will be described later. The supervisor terminal automatically displays the recommended command based on the operator's decisions and a preset priority logic. The supervisor makes the final decision on whether to send a command based on the displayed recommendation and the results of image processing.

3.2 System designs

INGSS is composed of four computers, each assigned to three Operators and one Supervisor. The INGSS software mainly consists of five modules. Fig. 3 shows the INGSS system configuration. Basically, all telemetry input/output processing and image processing is performed on the supervisor computer, and the operator computers display the processing results. However, the operator computers also have the same modules as the supervisor’s, and serves as a backup in case the supervisor computer malfunction. In addition to the screen for various decisions, another screen plots the SLIM's orbit over the lunar surface in real time. This plays an auxiliary role in allowing the supervisor to check the timing of image downlinks. In addition, the operators and the supervisor each have their own input devices. The elements of INGSS are described in detail below.

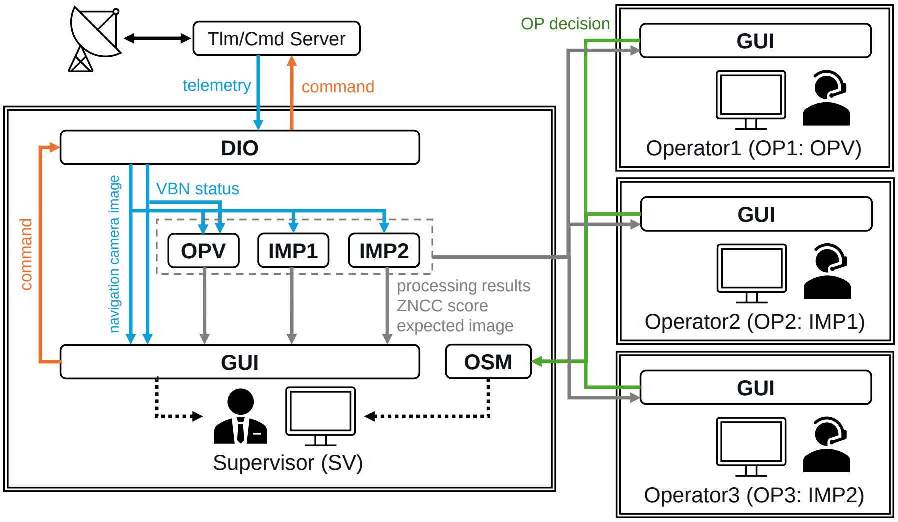

Fig. 3. INGSS system configuration

3.2.1 Data I/O module (DIO)

DIO communicates with the telemetry server and receives packets. It also decodes the received packets into JPEG format that can be read by the image processing module and saves them together with the VBN results and orbital navigation values. When it receives JPEG images and VBN results, it invokes the image processing module described below. It also performs command transmission processing when any command is selected as the result of the supervisor's decision.

3.2.2 Onboard processing validation module (OPV)

OPV is a module written in C++/OpenCV, and outputs information that allows the operator to judge the validity of the results of onboard VBN. OPV creates an expected image based on the received VBN results. This expected image is a simulated image of the lunar surface that would be expected to be captured by the navigation camera if the VBN results are correct. The operator compares this expected image with the downlinked actual image and determines whether the image centers match. If the VBN is successful, the image centers will match, and if it fails, the centers of these two images will not match.

3.2.3 Image processing module (IMP)

IMP is a module written in C++/OpenCV, and performs position estimation processing independent of VBN, using compressed image files decoded by DIO. VBN estimates the position of spacecraft based on craters extracted from images, but IMP estimates it using general feature-based methods such as AKAZE [9] and ORB [10]. The features from the lunar surface map is extracted in advance and saved as external files to reduce image processing time. Like OPV, IMP also outputs an expected image based on its own position estimation results, and provides it for operator decision. Two IMPs are executed simultaneously using different algorithms, and are called IMP1 and IMP2, respectively.

3.2.4 Graphical user interface (GUI)

GUI is a Python-based application that has the function to show various processing results to the operators and the supervisor. GUI contains sufficient information to enable the operators and the supervisor to make the right decision in a short time. Fig. 4 shows GUI screen when VBN outputs a false estimate. The details of the display elements are shown below.

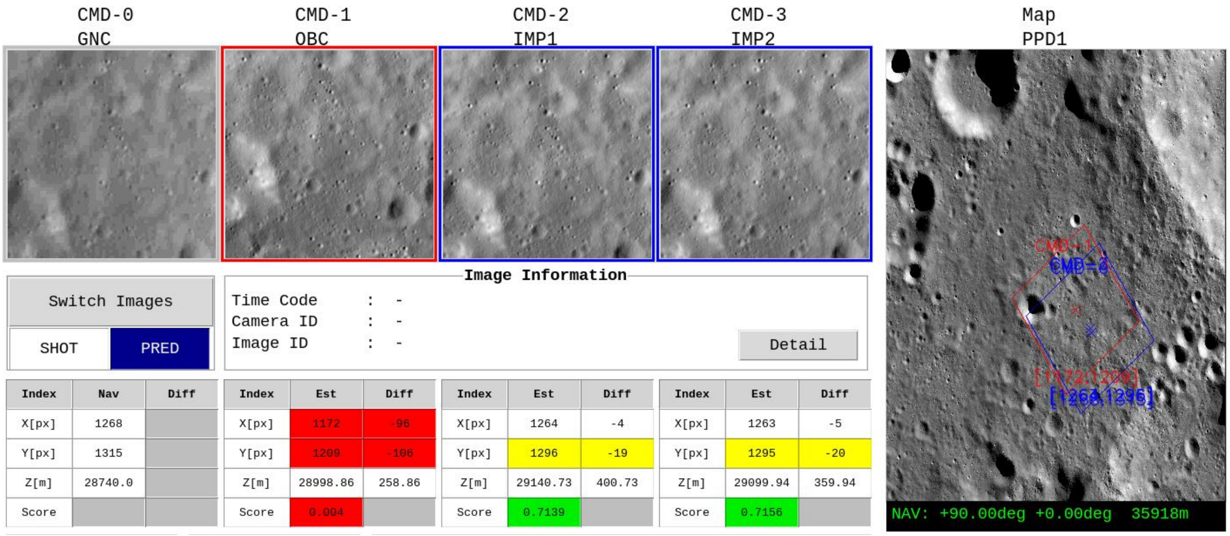

Image Information

Time Code : -
Camera ID : -
Image ID : -

Index	Nav	Diff
X[px]	1268	
Y[px]	1315	
Z[m]	28740.0	
Score		

Index	Est	Diff
X[px]	1172	-96
Y[px]	1209	-106
Z[m]	28998.86	258.86
Score	0.004	

Index	Est	Diff
X[px]	1264	-4
Y[px]	1296	-19
Z[m]	29140.73	400.73
Score	0.7139	

Index	Est	Diff
X[px]	1263	-5
Y[px]	1295	-20
Z[m]	29099.94	359.94
Score	0.7156	

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Fig. 4. GUI screen

a. Compressed image of navigation camera and VBN expected values (CMD-0)

The top left of the screen shows the compressed image obtained from the navigation camera, while the bottom left shows the center of the image in lunar map coordinates and the altitude predicted from the inertial navigation values.

b. VBN results (CMD-1)

The expected image output from OPV is at the top, and the downlinked VBN results are at the bottom. The color of the VBN results indicates the difference between the expected values from the inertial navigation system and the actual VBN estimate results. If these differences exceed 1σ of the navigation error obtained by pre-analysis, they are displayed in yellow, and if they exceed 3σ, they are displayed in red.

At the bottom, the score of ZNCC (Zero-mean Normalized Cross-Correlation), which indicates the correlation between the compressed image and the expected image, is displayed. If the VBN result is correct, the compressed image and the expected image will roughly match, so high correlation value is expected. If the VBN outputs a false position, the expected image will differ from the actual image, so low correlation value is expected. Although the correlation value tends to be lower than ideal due to the strong compression of the downlinked image, in pre-analysis, ZNCC score exceeded 0.5 in most cases when the VBN was correct. Therefore, in GUI, if ZNCC score exceeds 0.5, it is displayed in green, and if the correlation is below 0.5, it is displayed in red, which helps the operators make decisions.

The expected image at the top can be toggled with the compressed image by the dedicated input device described in 3.2.5. This is an important function for the operator to check if the center positions of the expected image aligns with the actual image. The operator mainly compares this expected image with the actual image, and secondarily refers to the color of the correlation score to decide the correctness of VBN results.

c. IMP results (CMD-2, CMD-3)

The expected image output from IMP is shown at the top, and the position estimation result and correlation score by IMP are shown at the bottom. The image toggling function and display color are the same as the VBN results described above.

d. Lunar surface map

The lunar surface map is shown in the right side of GUI screen. The current orbital navigation values, as well as VBN and IMP position estimates, can be overlaid on a lunar surface map.

3.2.5 Dedicated input device

A dedicated human-machine interface was introduced to reduce human error of the operators and the supervisor and enable them to perform the required operations in the shortest possible time.

a. Device for operators

The operators decide the correctness of the image processing (VBN, IMP1, or IMP2). Dedicated hardware is used to make the decisions and input its results. The left side of Fig. 5 shows the input device for the operators. Since decisions and operations must be performed in a short time, a dedicated keyboard specialized for operating INGSS was introduced to minimize the possibility of human error. The leftmost button has the function of toggling between the expected image and the downlinked compressed image. When deciding the result of each algorithm, the operator presses this button to confirm that two images align each other. The second and third buttons from the left are for inputting the operator’s decisions. If VBN or IMP is decided to be successful, the "OK" button is pressed, and if it is decided to be failed, the "NG" button is pressed. After inputting the decision result, the rightmost “Send” button is pressed to send the decision results to supervisor.

b. Device for supervisor

The supervisor decides whether to send a command to the spacecraft based on the operator's decision and the type of command (correction or cancel) to send. The same input device was introduced to minimize human error in decisions and operations. The right side of Fig. 5 shows the input device for the supervisor. The functions of the buttons differ slightly between the operator’s and the supervisor’s. The leftmost button has the same image toggling function as the operator, but the other three buttons correspond to the type of command to send. The second from the left has the function of a cancel command that forces the continuation of inertial navigation. The third and fourth from the left are correction commands that force the onboard navigation values to be updated based on the results of IMP1 or IMP2, respectively. Pressing any of these three buttons displays a pop-up and asks for confirmation of the command transmission. By pressing the external button firmly, the selected command is immediately sent to SLIM. If it is determined that VBN was successful, command transmission is not required.

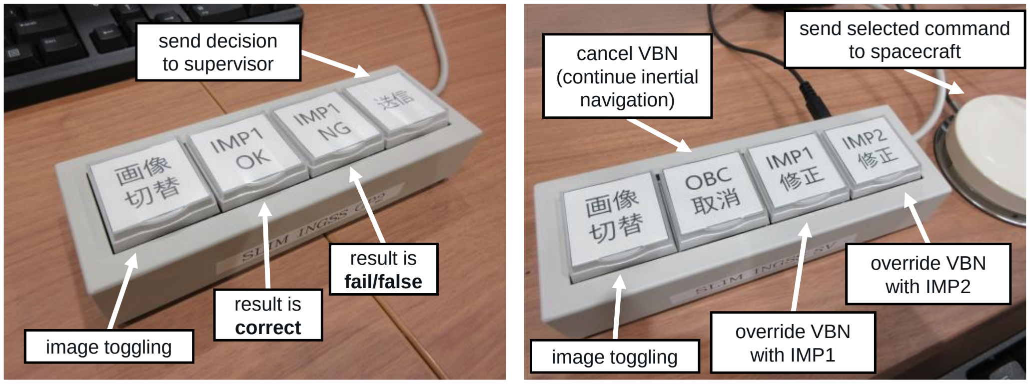


Fig. 5. Dedicated input device for INGSS operator (left) and supervisor (right)

3.2.6 Optimal solution selection module (OSM)

The supervisor must combine the operator's decision results to determine necessity to send a command to the spacecraft, and the type of command to send. However, it is not easy to make the right decision in a short amount of time based on multiple results. Therefore, OSM automatically displays recommended command based on each operator's decision results. Fig. 6 shows the OSM screen. OSM's recommended command display simplifies the supervisor's complex decisions and helps them make the right decision in a short time.

The right side of the OSM screen displays the results of each decision sent by the operators in real time. Each time the operators send each decision, the most recommended command is identified according to a configured recommendation logic, and the result is displayed prominently on the left side. Fig. 7 shows the flow to identify the recommended command. In this flow, not only the operators decision results but also the difference between the position estimation result and the inertial navigation value is referenced. VBN has the highest priority, followed by IMP1 and IMP2. If VBN is decided to be successful and the difference with the inertial navigation value is small enough, command is not required. If VBN is judged to failure, the results of IMP1 and IMP2 are referenced. If the position estimation results of VBN and IMP are significantly different from the inertial navigation value but output the same solutions, the inertial navigation result should not be trusted and VBN and IMP results are considered correct.


ImageID: 89

Time: 2023/08/04 01:51:57

ImageID_Time: 01:50:06.849267

OSM_Solution: OK

OP_Selection:
IMP2 | OK | OP3 | 2029ms
IMP1 | OK | OP2 | 2465ms
OBC | OK | OP1 | 2572ms

Previous_Selection:
ImageID = 88
OSM = OK | 01:50:03.911222

Message:

Fig. 6. OSM screen

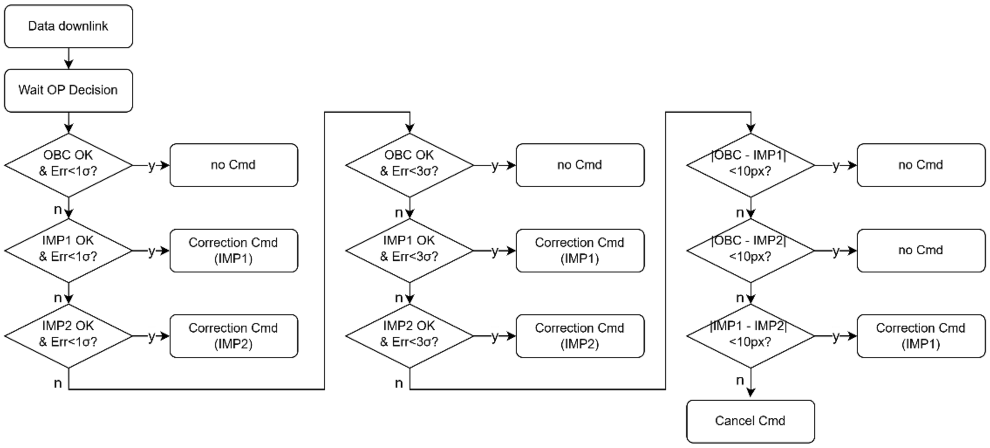
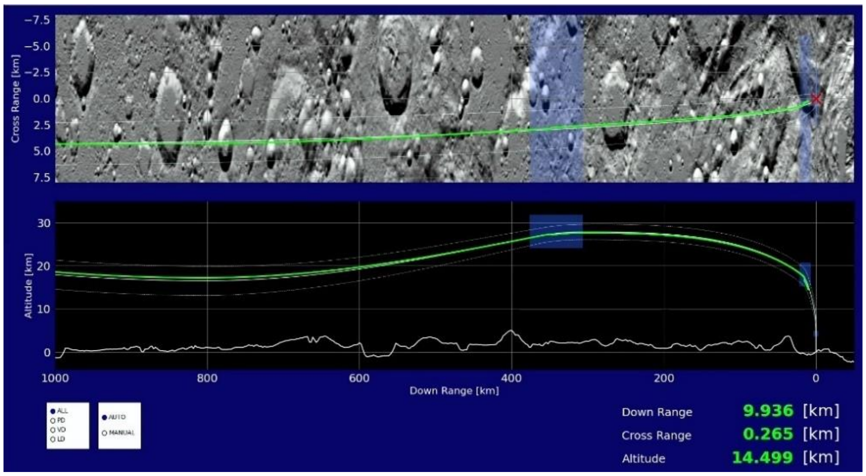


Fig. 7. Selecting flow of recommended command. |A-B| indicates the difference in distance between the position estimation results by A and B.

3.2.6 Landing path display

The Landing path display visualizes the received trajectory navigation values. The screen shows an overhead view and a side view of the SLIM landing path, with the nominal trajectory, 3σ error range, and actual navigation values, respectively, allowing the operators to check the soundness of the landing sequence. The screen also plots the area where VBN will be performed, allowing the supervisor and the operators to predict the timing of VBN execution. Fig. 8 shows the landing path display during the powered descent phase.



Down Range 9.936 [km]
Cross Range 0.265 [km]
Altitude 14.499 [km]

Fig. 8. Landing path display

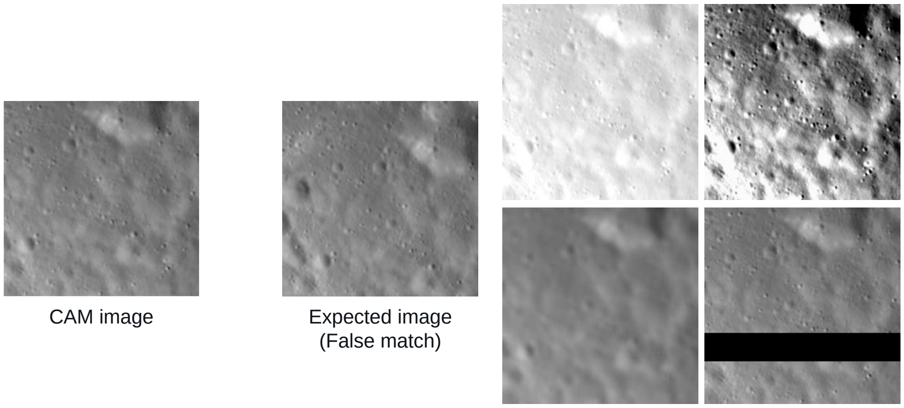
3.3 Training

INGSS is a ground-in-the-loop system, and decisions are made by the operators and the supervisor on the ground. Because human decisions have a major impact on the mission, training was important to ensure that the operators and supervisor had a short enough time to make decisions and operate correctly.

The operators have three options for decision: whether VBN or IMP processing result is correct, false, or failed. If the processing fails, the status is displayed on GUI, making the decision easy. The most important thing for operators is to correctly decide a false estimation as false, and to correctly decide a correct estimation as correct, and to make these decisions in a short time. The training cases included many severe cases that included off-nominal conditions such as brightness/contrast anomalies, blurring, radiation noise, and partial image loss due to degraded communication. Fig. 9 shows some of the test images used in training.

It is important for the supervisor to decide whether the recommended commands displayed on OSM are correct, to send commands as necessary, and to execute them in a short time. In actual operation, the supervisor and the approver checked the same screen and double-checked the decisions verbally. In order to communicate as quickly as possible, confirmation and response calls were defined in short, concise terms.

The training was conducted until all operators and supervisor were able to execute the necessary decisions and operations correctly 100% in the training cases and within the required time. The training continued until just before the lunar landing operation.


CAM image

Expected image
(False match)

Expected image
(Correct match)

Fig. 9. Test lunar images for training of INGSS operator and supervisor

4. Operation results

At 23:53, 23:55, and 23:57 on January 19 (JST), 2024, SLIM performed VBN at an altitude of 36 to 20 km above the lunar surface. The results were monitored by INGSS, and after confirming success, SLIM began its powered descent. After about 20 minutes of powered descent and vertical descent phases, SLIM landed on the lunar surface at 00:20 on January 20. VBN was performed a total of 14 times, twice in each of the seven regions from before the powered descent to the vertical descent. During that time, the status of VBN and captured images were normally monitored by INGSS. In six of the seven regions, except for the last, a decision was required to send a command, but since VBN was successful in all cases and the operators correctly decided it to be "successful," there was no need to send a command from INGSS.

Fig. 10 shows INGSS GUI in PPD1 area where VBN was first performed. The image captured by the navigation camera is displayed on the far left, and to the right of that is the expected image based on the processing results of VBN and two IMPs. Since the centers of the acquired image and the expected image match, the operators decided the results of the three image processing to be successful. PPD1 is the darkest area with the lowest solar altitude in the landing sequence, and the actual image is slightly darker than the expected image. The operators were able to robustly respond to such image disturbances and make the correct decisions. The bottom of the expected images for VBN and two IMPs shows the difference between the position estimation results and the inertial navigation values, both of which are displayed in yellow. This indicates that the actual position of the spacecraft had an error of 1σ to 3σ compared to the inertial navigation values, and that VBN and IMPs correctly estimated it.

Fig. 11 shows the time taken for computer processing and decision making at each operator terminal. Since no commands were sent from INGSS, only the processing time at the operator terminal is shown here. In all cases, the operators executed the decision making within the required time. The average time taken for decision making for all operators was 1.75 s, with a maximum of 2.10 s (3.66 s including computer processing time), which met the required time.

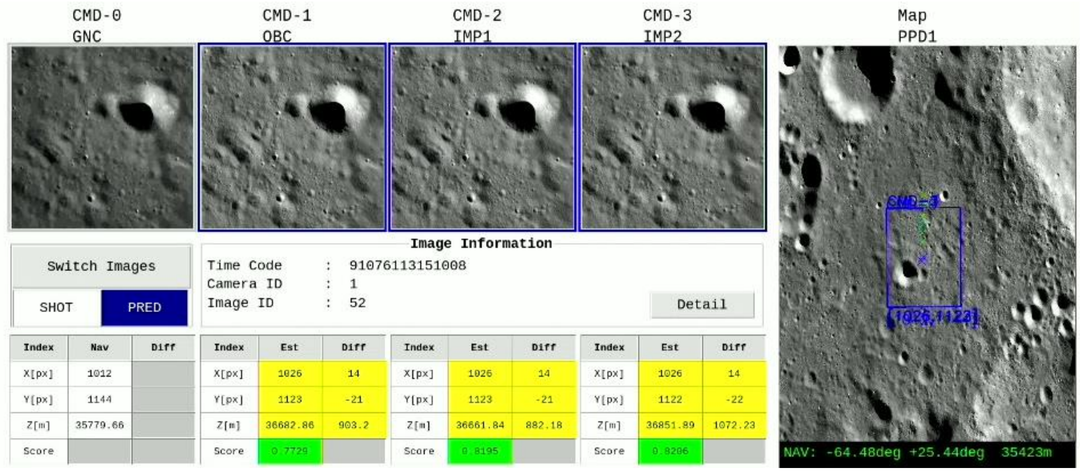


Image Information

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Camera ID : 1
Image ID : 52

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Y[px]	1144	
Z[m]	35779.66	
Score		

Index	Est	Diff
X[px]	1026	14
Y[px]	1123	-21
Z[m]	36682.86	903.2
Score	0.7729	

Index	Est	Diff
X[px]	1026	14
Y[px]	1123	-21
Z[m]	36661.84	882.18
Score	0.8195	

Index	Est	Diff
X[px]	1026	14
Y[px]	1122	-22
Z[m]	36851.89	1072.23
Score	0.8206	

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Fig. 10. GUI screen at PPD1 in lunar landing sequence

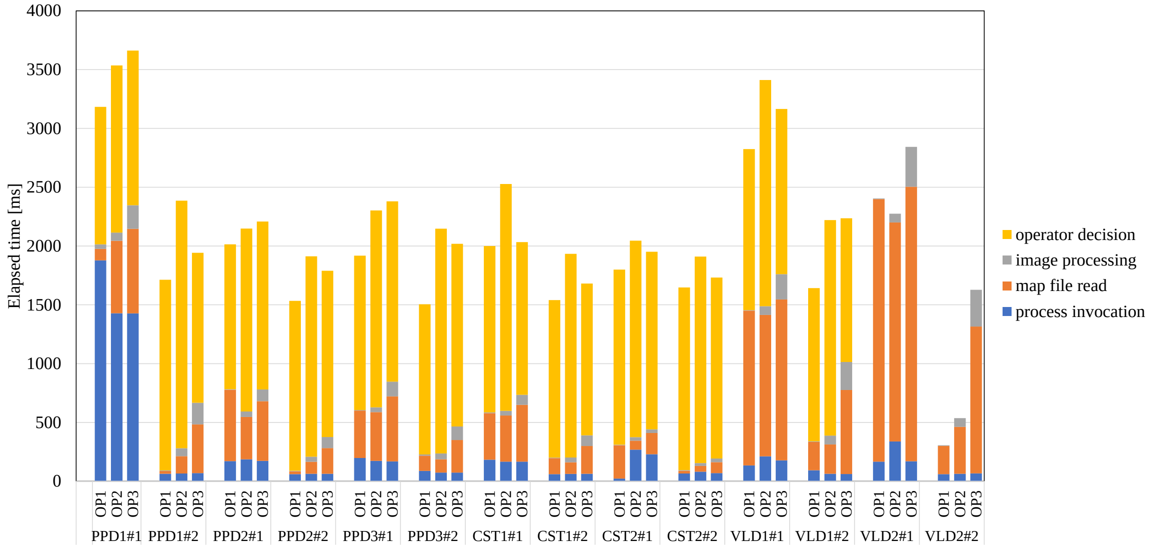

Fig. 11. Elapsed time of each INGSS process during landing operation

5. Conclusions

INGSS is a ground-in-the-loop system that monitors the status of SLIM's VBN from the ground and sends commands to override the results if VBN is not successful. The lunar landing sequence is short, so the time required for the ground operators and supervisor to make decisions and operate is very short, and they had to execute within 5 seconds after the images were downlinked. The developed software, especially INGSS GUI, succeeded in shortening the time required for decision-making. In addition, the dedicated input device suppressed human error of the operators and supervisor, enabling them to make correct and quick decisions. Training was conducted over a long period of time, up until the day of the landing operation. During the landing operation, INGSS operated normally and monitored the VBN status in real time. From the information displayed by INGSS, the operators were able to correctly decide VBN and IMP processing results in all cases. As VBN was successful in all areas, there was no need to send commands from INGSS to override VBN results.

Acknowledgements

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