Construction of Validation Bench for Testing of Vision-Based Navigation Methods in the Korean Lunar Exploration Program

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INTRODUCTION

As part of the first phase of the Korean lunar exploration program, Korea Aerospace Research Institute (KARI) began developing a lunar orbiter in 2016. In parallel with this effort is the acquisition of technology required to land a lunar lander by 2020 and the construction of test facility to validate the technology. A vision-based navigation test bench in the facility provides functionality to test image filtering, recognition and navigation algorithms. The test bench consists of two parts: A pure software simulator and a hybrid hardware-software simulator. In particular, a camera mounted on the hybrid bench can acquire images while moving in three dimensions. A lunar terrain scale model representing 240 km by 60 km was constructed to simulate a possible candidate landing site. Digital elevation model (DEM) data from the Lunar Orbiter Laser Altimeter (LOLA) instrument of the Lunar Reconnaissance Orbiter (LRO) was used as the initial terrain source data. The entire terrain was then sliced into blocks before printing each block with a 3D printer. Finally, the blocks were assembled into a single terrain model and illuminated with a spotlight beam to simulate sunlight. The low cost and fast turnaround of making the terrain using 3D printing gave us flexibility to reconfigure the test environment for various purposes. Furthermore, boulders were made in a variety of sizes and affixed to the surface of the integrated terrain model. These can be easily moved to test different distributions of boulders. The camera moves automatically at a programmed speed and velocity, acquiring images while in motion to simulate a spacecraft in proximity with the lunar surface.

This paper introduces the construction of the vision-based navigation test bench, its key characteristics, and describes a procedure for using the bench in the future to validate vision-based navigation.

CONSTRUCTION OF THE ENTIRE TEST FACILITY

Since the end of 2014, KARI has developed a virtual simulation environment for developing lunar exploration technologies and built the entire facility at the end of 2016. The facility provides an environment that simulates spacecraft and ground control stations during a lunar landing mission, and provides a set of test tools that can be used for verifying data from payloads and validating mission scenarios. Fig. 1 shows the conceptual structure of the components that make up the entire facility and the relationships between them.

- ▷ **"Virtual" Data Sets & Simulated Imagery**: This component includes storing and managing the virtual input data required for a simulation run. This data can be existing and currently acquired data from real probes, or synthetic data artificially generated basing on existing data. For example, images received from LRO[1], SELENE[2], Chang-e[3] can be read and images can be rendered based on LRO LOLA data as well.

- ▷ **Dynamic System Simulator**: This component realistically simulates the behaviour of the lunar probe and the ground system that controls it. To do this, we model the functions of the sub-devices and implement them in software. Ultimately, the user can quickly set various test conditions and repeat numerous tests.

- ▷ **Virtual Image Processing**: This component provides an environment to verify pre-processing and post-processing algorithms of images from a camera model of the simulator.

- ▷ **Vision Test Bench**: This component is designed to test vision-based navigation methods for lunar orbit and landing. It provides functions enabling users to design, implement and verify performance of image acquisition and pre-processing as well as higher-level applications such as navigation algorithms. It consists of two type of benches. The first is a pure software-based simulation bench and the other is a hybrid test bench containing of a lunar terrain scale model and control equipment to move a camera. The remainder of this paper describes this component in detail.

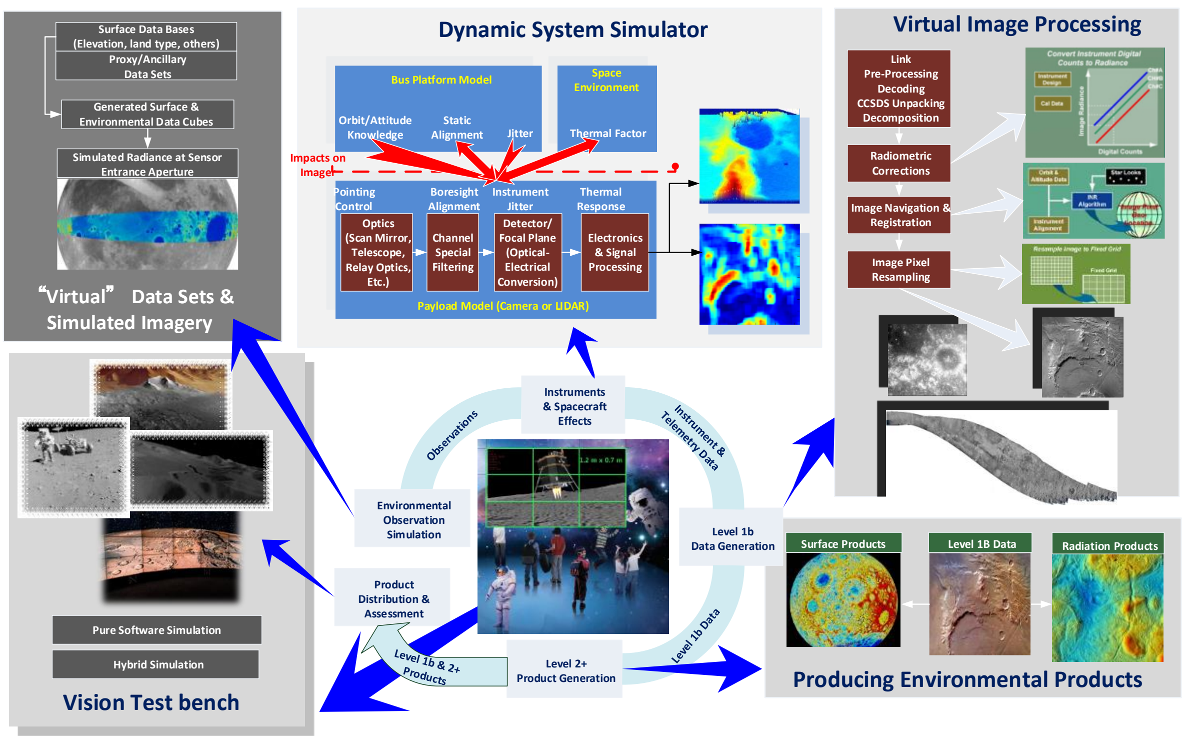

Fig. 1. Entire Test Facility for Virtual Lunar Environment

PURE SOFTWARE SIMULATION

One of the components of the Vision Test Bench mentioned above, the pure software-based simulation environment, provides lunar images according to the positions and attitudes of the Sun and spacecraft using only software. It is useful for testing lunar probes equipped with cameras and is especially suited to simulating lunar topography for the purpose of testing lunar landing guidance and navigation.

An 8K-resolution (7920x4320) display wall can display images currently being viewed by the probe, and astronomical location and lunar location and attitude information for a specific time can be provided by the Dynamic System Simulator. Also, various devices necessary for ease of use are included in the environment, such as a tablet that allows users to sound and video input sources and display layout, and human interface devices such as motion sensors and gyroscopic mice.

Fig. 2 illustrates the overall system. Users conduct tests in front of a large multi-monitor in an enclosed darkroom. Remote functional testing is also possible via network (lower right).

The display wall shown in Fig. 3 plays an important role in the pure software simulation process. This 8K-resolution display consists of sixteen 55-inch passive stereoscopic 3D monitors. Users perceive depth via polarized glasses. Planetary surfaces, spacecraft, and trajectories are displayed in real-time.

The display wall can also be used to prepare tests. For example, as shown on the left-hand side of Fig. 3, users can display high-resolution maps of areas to be navigated by a probe according to a mission scenario, and perform collaborative actions such as choosing landing ellipses. To support these tasks, various applications such as Lunar Mapping and Modeling Portal (LMMP) [4] are used.

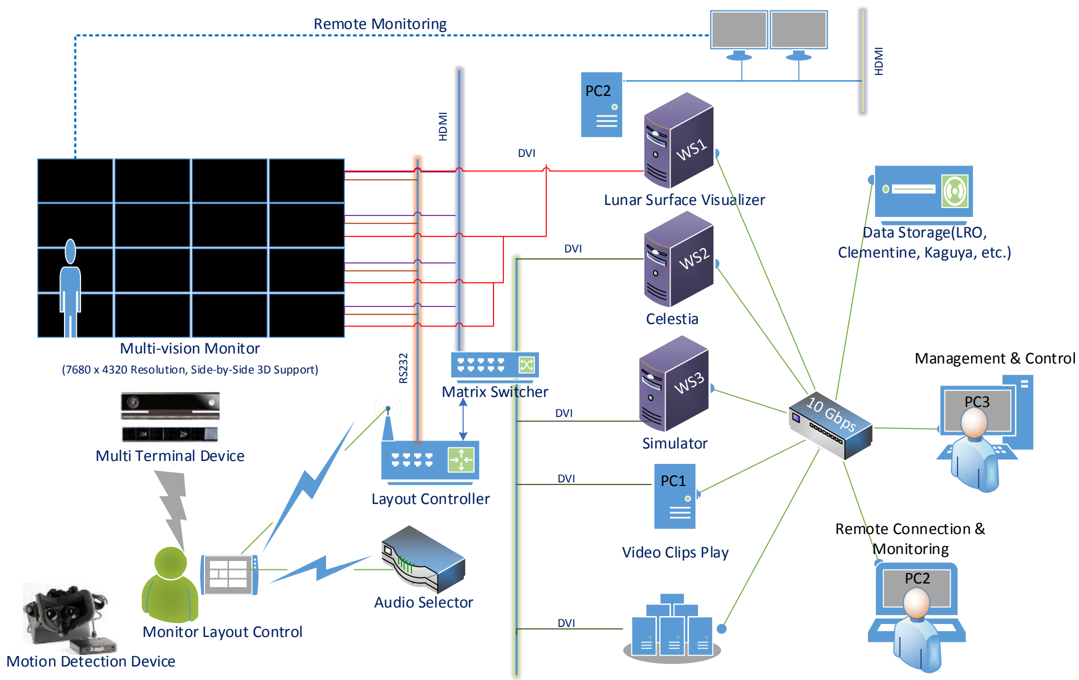

Fig. 2. Software-based System

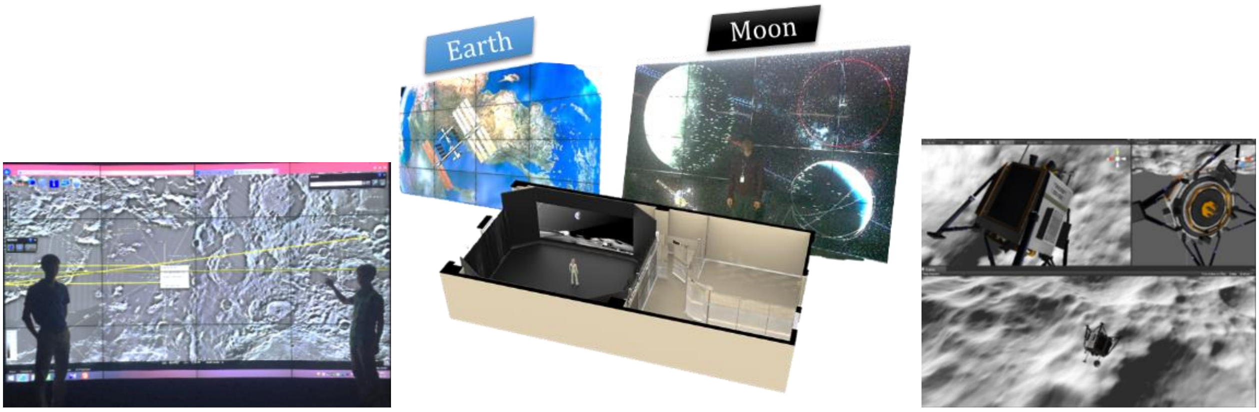

Fig. 3. Display Wall
(Left: Mission preparation, Center: a Mission from the Earth to the Moon, Right: Lunar Landing Mission)

KARI also uses the display wall to visualize interplanetary trajectories in stereoscopic 3D using a modified version of Celestia [5, 6]. The center of Fig. 3 shows the trajectory of a Korean lunar probe. In particular, it is useful to verify mission procedures and algorithms required for lunar landing. Fight trajectories, synthesized images and etc. can be simulated according to various test conditions such as sun position, lander position, hazardous objects on the lunar surface and conditions of embedded equipment. KARI also uses software to generate a lunar surface model from existing digital elevation models and to place realistic objects such as boulders [7].Behind the scenes, the dynamic simulator component dynamically simulates the entire behaviour of the probe, the operation of the internal equipment, and ground antenna operation based on a specific epoch time.

HYBRID HARDWARE-SOFTWARE SIMULATION

The hybrid hardware-software simulation bench provides an environment in which algorithms or equipment combined with algorithms can be tested realistically. The lower left of Fig. 4 shows the whole of this bench. The bench consists of a 1:60000 lunar surface model and a transport device that can move equipment such as a camera.

The currently constructed lunar surface model covers a region 240 km in length starting from the South Pole where the worst conditions for a lunar landing exist. The upper left of Fig. 4 gives a top-down view. LOLA polar stereographic digital elevation model (DEM) data was used to construct the terrain surface.

3D printing was chosen to make the lunar surface model as it was considered easier and faster than other machining methods. Considering the maximum operational area of the printer, the total DEM was divided into 4 sections. Each DEM section was converted to stereolithography (STL) file format for printing. A typical STL file consists of a series of linked triangles describing the surface geometry.

3D printing reduced processing time and cost, but considerable post-processing effort was required. It took as much time as printing to accurately bond the individual printed pieces. The horizontal error and vertical errors are 0.5 mm (3σ) and 0.3 mm (3σ) respectively.

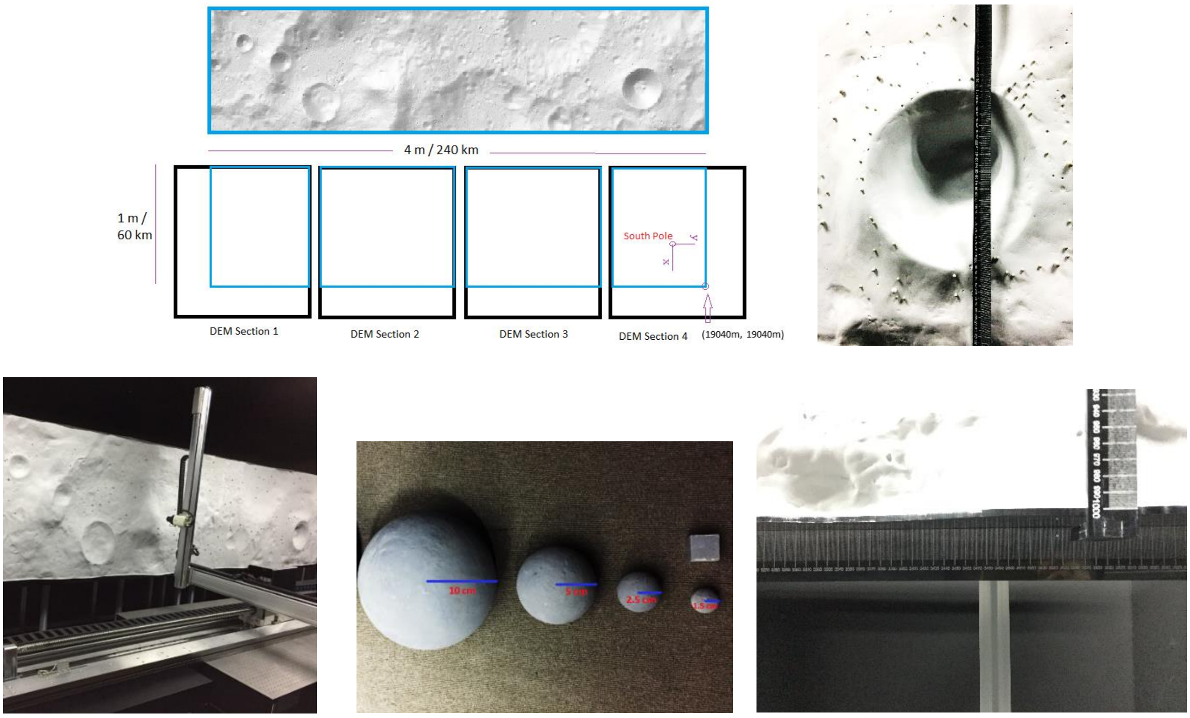

Fig. 4. Hybrid Hardware-Software Simulation Bench

In addition, two rulers were attached to measure the actual positions on horizontal axes of the lunar surface model. One shown in the bottom right of Fig. 4 was attached perpendicularly across the model to be used as geometric reference measures and the other shown in top right was attached horizontally at the bottom of the model.

In order to simulate the installed location and flight trajectory of navigational equipment in the lunar probe, the translation table shown in the left of Fig. 5 and the tilting mechanism on the right were designed.

The x-y plane of the translation table is parallel to the lunar surface model and provides horizontal positioning relative to the lunar surface. The z-axis provides positioning perpendicular to the x-y plane and "vertical" relative to the lunar surface model. The operational ranges of motions in the x, y and z axes are 4180 mm, 1300 mm, 850 mm respectively from their origins located at the top left corner of the lunar surface model. The static errors of x, y and z positions are 1.8 mm, 1.3 mm, 1.1 mm (3σ) respectively, which are relative to the reference rulers.

In addition, a two-axis tilting device was mounted on the translation arm. It allows the user to manually change the attitude of cameras and sensors. The operational ranges of rotations in both axes are 60 degrees and the errors are 0.05 degrees.

Fig. 6 shows the entire hybrid simulation bench illuminated by light coming through a rectangular slit. The lighting device was initially selected to have a brightness similar to that of the Sun, but the intensity of the light caused the surrounding room to light up with too much diffuse illumination. We switched to ordinary LED lighting to mitigate this effect. Also, the LED device was placed far away from the lunar surface model to minimize light attenuation and spreading with distance. This was

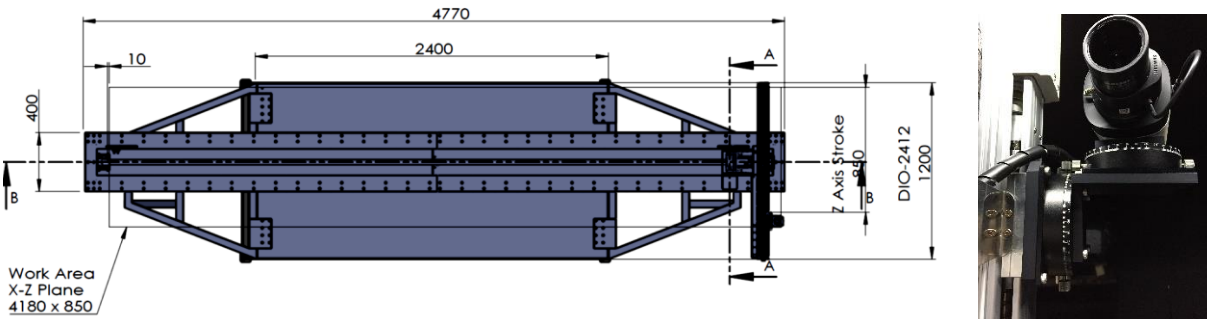

Fig. 5. Translation Table (Left), Rotation Drive Mechanism (Right)

done by hand; a future improvement would be to install a rail guide for the light in order to facilitate accurate positioning.

We also added boulders to the lunar surface model to test automatic hazard avoidance algorithms. The top right of Fig. 4 shows boulders around Shackleton crater. Five sizes of boulders were made with diameters: 1, 3, 5, 10, 20 cm respectively. Some of them are shown in the bottom center of Fig. 4. Boulders were spherical to make the shapes of boulder shadows consistent, and easily attached/detached to simulate various test conditions.

In an analysis of the Moon surface by [8], the degree of self-similarity in maria is low, but very high in the highlands and the polar regions. Since the experimental area is aimed at the polar regions with very high fractal-like characteristics, topographic features can be considered to be *scale-free* and thus we were free to make our boulder sizes larger than 1:1 scale.

According to [9], the largest boulders are roughly 11 m in diameter and 50 % of boulders are more than 4 m in diameter within the 9 km^2 zone of the Malapert massif peaks. In case of the Shackleton crater near the south pole, there are 820 boulders in a 4 km by 2.5 km zone. The largest one was 18 m and the smallest 1.3 m in diameter. 500 or 50 % of all boulders are 1~3 m in diameter and the others numbered at around 400, 90, 10 with 3~4 m, 4~10m, 10~20m diameters respectively. This provided a guide as to the relative numbers of boulders that we should use.

Fig. 6. Illuminated Hybrid Hardware-Software Simulation Bench

CONCLUSION

KARI is developing and researching the necessary technology to carry out a lunar exploration program. A virtual environment was built indoors to verify these required technologies. This environment is specifically designed to verify the performance of navigation algorithms and navigation equipment of lunar probes under various mission scenarios. The environment is comprised of a software simulation component consisting of a large display wall and computer, and a software-hardware hybrid test bench consisting of a lunar surface model, Sun-like illumination and the ability to mount and pose equipment. The software simulation environment can be used to read, edit, or synthesize data acquired from existing probes and can also be used for initial design and performance validation of navigation algorithms by linking a lunar probe simulator and graphical rendering of the lunar surface. In the hybrid environment, sensors such as terrain navigation cameras and altimeters can be mounted, tilted in two axes and translated in three axes near a configurable lunar surface model with attachable boulders. It can be used to test the performance of various landing algorithms.

ACKNOWLEDGEMENTS

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