FLASH-LIDAR BASED TERRAIN RELATIVE NAVIGATION FOR AUTONUMOUS PRECISION LUNAR LANDING

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Abstract: *For autonomous lunar landing, reliable navigation results are affect to landing position precision. Since the remote communication from the ground station and Global Positioning System service are not available in the lunar environment, the vision based navigation is useful to estimate the current status. Among the vision based navigation, the terrain relative navigation is the absolute position estimation by comparing terrain measurements from sensor with prepared terrain map. Camera, laser altimeter, or LIDAR systems can be used for terrain relative navigation sensor. But the camera has a limitation for lightning condition and laser altimeter required long time data series. Using LIDAR, terrain measurements can obtain a certain area whenever regardless of illumination condition in a short time. In this paper, the LIDAR system, especially the flash LIDAR system, for terrain relative navigation is considered in powered descent phase of the lunar landing. The goal of this paper is design terrain relative navigation based on the flash LIDAR sensor for autonomous precision lunar landing. The simple mission is defined and available navigation sensors are selected for mission requirements. With the sensor suite, the terrain relative navigation is designed.*

Keywords: *Terrain Relative Navigation, Flash LIDAR, Autonomous Precision Lunar Landing.*

1. Introduction

Many countries have a goal to launch the lunar lander and rover in the next few years. Since the scientific significance and future value of the moon, the interest of lunar exploration is rising more and more in space development. Specific lunar missions are also being designed continuously – finding water in lunar polar region, lunar surface sample return, exploration the gravity filed region or boundary of foreside and back side of the moon, and etc. Further, sensors and computer technologies are developing at a fast-growing rate. By advancement in these technologies, the goal of lunar landing became autonomous landing at the interesting landing site with high precision and safety, not just landing somewhere. Although the lunar orbiter collect and provide the terrain information first, it is not enough to landing precisely and safely. Unobserved hazard and unexpected situation around lunar surface can happen whenever during final landing phase. Eventually, real time information acquired in the vicinity of the lunar surface is important for precise and safe landing.
The navigation sensors attached to lander be utilized for gathering necessary information to precise and safe landing. Since the Global Positioning System (GPS) is not available in lunar environment, vision sensor has important role in navigation system during lunar landing phase. A camera is a typical vision sensor used for lunar landing since it is weight and cost effective sensor. It is also available at a very long range, but camera has a major weak point that it is much affected by illumination condition. The Light Detection and Ranging (LIDAR) is another vision sensor which can be used regardless of illumination condition. The Autonomous Landing and

Hazard Avoidance Technology (ALHAT) project, which has purpose of technology development for landing on planet or asteroid, pursued by NASA adopted LIDAR for precise navigation sensor for the first time in planet landing mission. It enables to satisfy the requirement of any lighting and any surface location condition [1-4].

In general, image based navigation using vision-sensor is mainly used for lunar landing since the GPS and real-time communication between ground station are not available. The lander has lunar map or landmark database obtained by lunar orbiter before, and estimate current status by comparing database with real-time data from vision sensor. In particular, terrain relative navigation based on lunar digital elevation map (DEM) is more useful when distinguishing landmarks are not enough over a wide area. The terrain relative navigation is applied during braking phase using Flash LIDAR in ALHAT project [1-4], vision-based absolute navigation system based on landmark with optical sensor was designed for the ESA Lunar Lander [5-7], and Chang'e 3, which landed to lunar surface in 2013, of China also used camera for navigation system [8-9].

In this paper, we focused on Terrain Relative Navigation (TRN) System design using flash LIDAR sensor for autonomous precise lunar landing. To design the navigation system, simple mission was defined first. Next, the navigation sensor suite and algorithm was selected and the sensor modeling was performed for 3-dimensional flash LIDAR which is main navigation sensor in our system. Finally, the terrain relative navigation algorithm was designed using selected sensor suite.

2. Mission Overview

2.1. Mission Requirements

Before designing the navigation system for autonomous precise and safe lunar landing, simple lunar landing mission was defined first based on advanced research as ALHAT project [1-4] and the ESA Lunar Lander [5-7]. Landing precision, safety and environments are mainly considered when deciding mission requirements and unmanned lunar landing was assumed in this mission. The navigation system should operate regardless of illumination condition until finding proper landing site finally. And the lander should land vertically in a safe place within 100 m from the preselected target landing site. For safe landing, hazard detection and avoidance such as craters or rocks is important. If the lander detect hazard around landing site, avoidance and landing site re-designation should be required. The hazard specify which has more than 30 cm height and 10 degree slope.

Table 1. Mission Requirements

Condition	Description
Autonomous	Should be landing fully autonomously
Light	Should be landing regardless of illumination condition
Direction	Should be landing vertically
Precision	Should be landing within 100 m from planned landing site
Hazard detection	Should be detecting hazard which has more than 30 cm height and 10 degree slope around landing site
Hazard avoidance	Should be avoiding and re-designating landing site if hazard is detected on landing site

2.2. Mission Scenario

Landing sequence is adopt a well-known Apollo guidance. The navigation system of the lander is started powered descent phase of 15 km altitude which is the last phase of lunar landing after orbit descent phase and orbit transfer phase. Powered descent phase divided to three steps as braking phase, approach phase, and terminal descent phase. These phase are to be the reference to set the navigation sensor suite and algorithms. The braking phase started from altitude of 15 km to 2 km. Here, a horizontal distance from the target landing site is from about 450 km to 7.5 km. In this phase, the navigation system calculate current position and attitude using scanned terrain data while the lander moves along the defined landing trajectory. From 2 km altitude, approach phase is continued until 30 m altitude of around landing site. The hazard detection and avoidance technique is applied in approach phase simultaneously with navigation. If hazard is detected around landing site, re-designation of target landing site and path re-setting to avoid hazard should be operated. When the altitude is about 100 m, lander is started pitch-up maneuver to prepare the vertical landing and try to reduce landing location errors. From the terminal descent phase of 30 m altitude, the lander operate descent and do vertical soft landing without horizontal movement. From the attitude of 15 km to land, it takes just within 10 minutes. It means the navigation system should make decision quickly and accurately for precision landing.

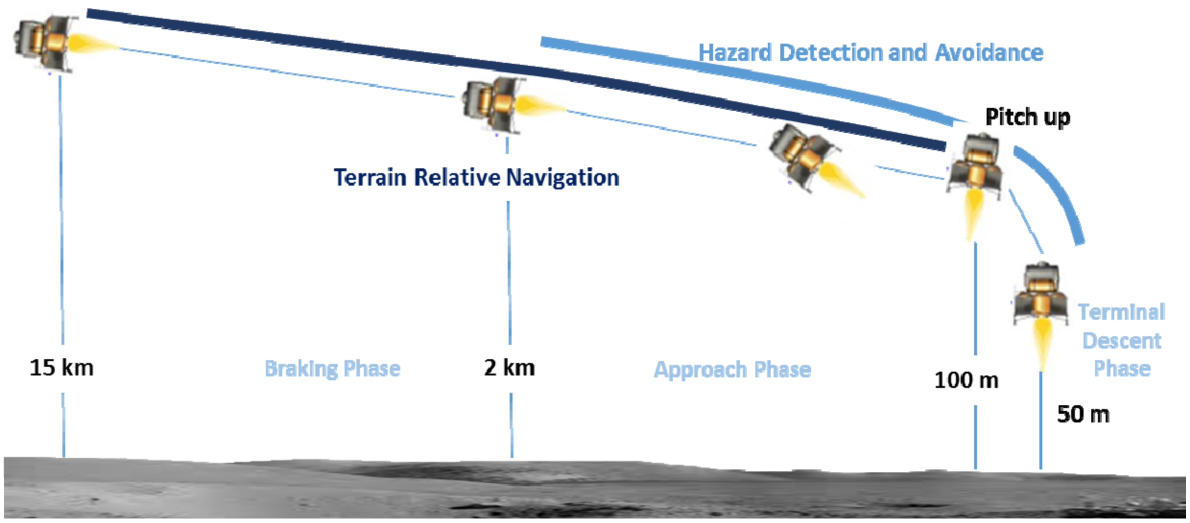


Figure 1. Mission Scenario for Lunar Landing

This section is introduced simple mission scenario and requirements over the whole powered descent phase in lunar landing. In this paper we will just discuss about navigation system to estimate current status of lander for precise landing except hazard detection and avoidance and soft landing techniques.

3. Sensor Configuration

For the navigation system, the Global Positioning System (GPS) is one of the most commonly used sensor. But, it is not available in lunar environment. Inertial Measurement Unit (IMU), altimeter (laser range finder), star sensor, and other vision-sensor as camera or LIDAR are

typical navigation sensors which are available for lunar landing. The star sensor is useful attitude sensor in space. But since it is weak to vibrations, it cannot achieve a desired performance in powered descent phase turned on engine to reduce the velocity. Accordingly, we choose a Flash LIDAR for major navigation sensor and IMU and altimeter are used in this system.
The Light Detection and Ranging (LIDAR) sensor, which is used for generating 3-dimensional data as topographic map or surface modeling, has great advantage that it is available regardless of illumination condition. 1-dimensional or 2-dimensional LIDAR is required scanning and re-arranging procedure to obtain a certain area. Otherwise, the flash LIDAR can obtain the area information at a time as a camera, so it can acquire much more data in a short time. The IMU measures the lander's velocity, orientation and gravitational forces with accelerometers and gyroscopes. In navigation system, data from the IMU used for calculation of current position and attitude. And since it could make accumulated error, compensation is required with other sensor's data. The altimeter of the type of a laser range finder is a secondary sensor to acquire the position information. This measures of the distance to lunar surface at a point.

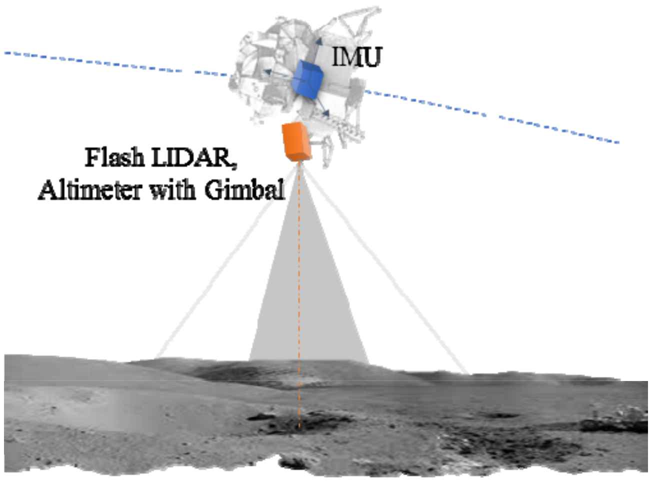
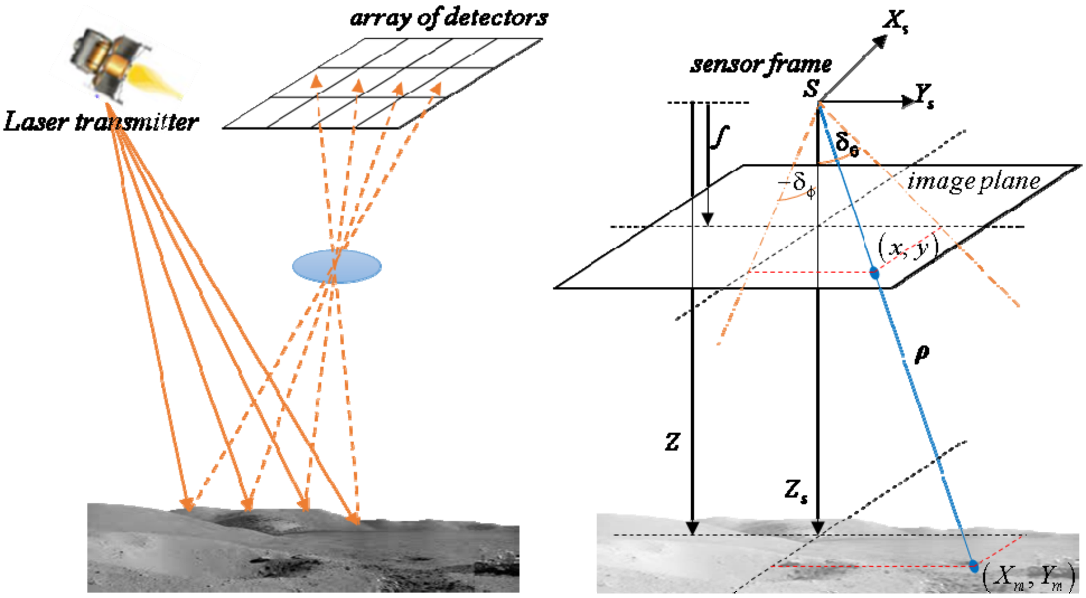


Figure 2. Sensor Configuration

Sensor suite for the navigation system configuration is shown in Fig. 2. The IMU aligned with body frame of the lander and the flash LIDAR and altimeter are attached to side of the lander face to lunar surface. They are combined with gimbal to widen the scope of measurement and to change the direction according to attitude of the lander.

The principle of the flash LIDAR is similar as pin-hole camera. It mounts a combination of a camera, a laser transmitter and an array of detectors arranged plane. When the laser pulse is transmitted to target, it reflected to each detectors. The detector array enables to take an image of a certain area at a time. The image includes intensity and range data of reflected object. The intensity data looks like black-and-white image and the range data is converted to 3D point clouds.
Similar as pinhole camera model, the flash LIDAR model can be described. Suppose that the sensor frame, *S*, for the flash LIDAR and optical axis and principle point are aligned to center of the sensor. The line of sight is defined with horizontal angle, δ_ϕ, and vertical angle, δ_θ as



(a) Principle of Flash LIDAR **(b) Measurement Geometry**

Figure 3. Principle and Measurement Geometry of the Flash LIDAR

$$LOS = \frac{\alpha}{\|\alpha\|} \qquad where \;\; \alpha = \begin{bmatrix} \tan\delta_\phi & \tan\delta_\theta & 1 \end{bmatrix} \tag{1}$$

and

$$\tan\delta_\phi = \frac{X_m}{Z}, \;\; \tan\delta_\theta = \frac{Y_m}{Z} \tag{1}$$

where (X_m, Y_m) is the position on lunar surface and Z is the altitude of the lander from surface. Therefore, the measurement can be expressed with measurement vector, $\boldsymbol{\rho}$, and measurement error, $\boldsymbol{\varepsilon}$, as

$$\tilde{z} = \boldsymbol{\rho} + \boldsymbol{\varepsilon} \quad where \quad \boldsymbol{\rho} = \rho \frac{\boldsymbol{\alpha}}{\|\boldsymbol{\alpha}\|}. \tag{1}$$

The gyroscope and accelerometer in the inertial measurement unit (IMU) sensor gives the measurements of angular velocity, $\tilde{\boldsymbol{\omega}}$, and acceleration, $\tilde{\boldsymbol{a}}$, of the lander. These measurements are converted to attitude, velocity and position information relative to given prior states. The measurements include bias error, $(\boldsymbol{b}_{gyro}, \boldsymbol{b}_{acc})$, and Gaussian noise, $(\boldsymbol{\eta}_{gyro}, \boldsymbol{\eta}_{acc})$ of gyroscope and accelerometer. Here, $\boldsymbol{\omega}$ and $\boldsymbol{a}$ are true angular rate and acceleration.

$$\begin{aligned} \tilde{\boldsymbol{\omega}} &= \boldsymbol{\omega} + \boldsymbol{b}_{gyro} + \boldsymbol{\eta}_{gyro} \\ \tilde{\boldsymbol{a}} &= \boldsymbol{a} + \boldsymbol{b}_{acc} + \boldsymbol{\eta}_{acc} \end{aligned} \tag{1}$$

4. The Flash LIDAR based Terrain Relative Navigation

The IMU calculate attitude, velocity and position from the measurement without other sensor for given initial value but its accumulation error is larger and larger over time. It means that the IMU alone cannot give correct navigation information. Therefore other navigation sensor is required to reduce these error for precise lunar landing. The terrain relative navigation (TRN) is the technique to compensate accumulated error using other sensor as camera, LIDAR, or laser range finder, etc. The navigation system compare the terrain measurement data from the vision sensor and saved digital elevation model and estimate current status of the lander by combining secondary sensor measurements as IMU and altimeter.

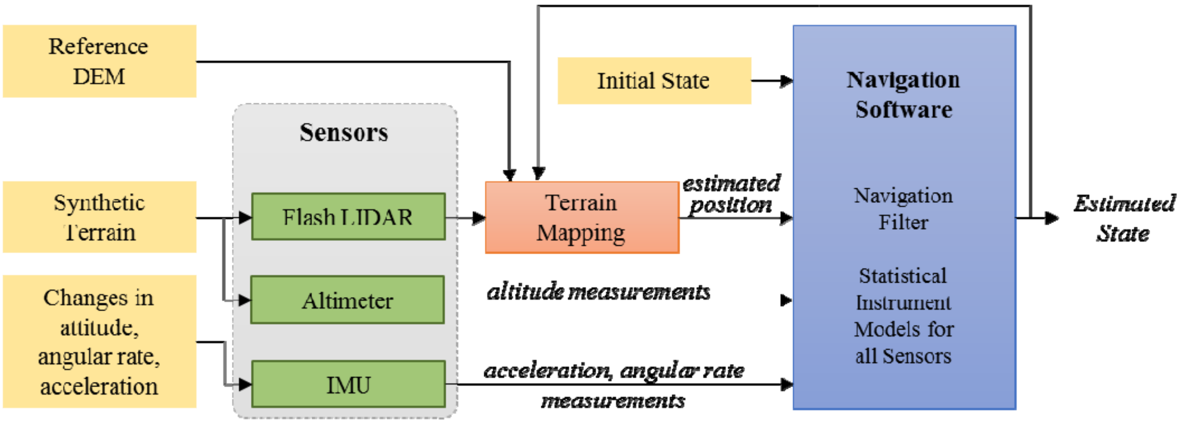


Figure 4. Overview of the Flash LIDAR based Navigation System

In proposed system the flash LIDAR, altimeter and IMU are used for navigation sensor. And the terrain relative navigation is consists of two parts of terrain mapping and navigation software. The measurements of the flash LIDAR, referenced digital elevation map of the moon and current status of the lander are input of terrain mapping algorithm. Digital elevation database is stored in on-board computer beforehand. The estimated absolute position which is the result of terrain mapping is used for input of navigation algorithm. Altitude, acceleration and angular rate measurements from altimeter and IMU are also combined for input. The navigation software includes system model, sensor models, and filter algorithm.

For state update and propagation in the navigation system, system model is defined. The state vector includes position, velocity, attitude of the lander and biases as

$$\boldsymbol{X} = \begin{bmatrix} \boldsymbol{q} & \boldsymbol{r} & \boldsymbol{v} & \boldsymbol{b}_a & \boldsymbol{b}_g \end{bmatrix}^T \quad (1)$$

where $\boldsymbol{q} = \begin{bmatrix} q_0 & \boldsymbol{q}_v^T \end{bmatrix}^T$ is the quaternion for attitude of the lander, $\boldsymbol{r}$ and $\boldsymbol{v}$ are the position and velocity vector and $\boldsymbol{b}_a$ and $\boldsymbol{b}_g$ are the bias of accelerometer and gyroscope in IMU. Then the dynamic model is given as following equations.

$$\begin{aligned}
\dot{\boldsymbol{q}} &= \tfrac{1}{2}\Omega(\boldsymbol{\omega})\boldsymbol{q} \\
\dot{\boldsymbol{r}} &= \boldsymbol{v} \\
\dot{\boldsymbol{v}} &= \boldsymbol{a} - 2[\boldsymbol{\omega}\times]\boldsymbol{v} - [\boldsymbol{\omega}\times][\boldsymbol{\omega}\times]\boldsymbol{r} + \boldsymbol{g}_m \\
\dot{\boldsymbol{b}}_a &= \boldsymbol{\eta}_a \\
\dot{\boldsymbol{b}}_g &= \boldsymbol{\eta}_g
\end{aligned} \tag{1}$$

$$\Omega(\boldsymbol{\omega}) = \begin{bmatrix} -[\boldsymbol{\omega}\times] & \boldsymbol{\omega} \\ \boldsymbol{\omega}^T & 0 \end{bmatrix}, \quad [\boldsymbol{\omega}\times] = \begin{bmatrix} 0 & \omega_z & -\omega_y \\ -\omega_z & 0 & \omega_x \\ \omega_y & -\omega_x & 0 \end{bmatrix} \tag{1}$$

Here, $\boldsymbol{g}_m$ is the lunar gravitational acceleration at the position, $\boldsymbol{\eta}_a$ and $\boldsymbol{\eta}_g$ are the Gaussian noise of accelerometer and gyroscope, and $\boldsymbol{\omega}$ is the angular velocity of the lander.

Terrain mapping is the procedure to estimate absolute position in the moon by comparing the measured terrain data from the flash LIDAR with pre-stored terrain data. 1) The synthetic terrain data is accumulated and processed by the flash LIDAR sensor. These data is distorted according to the lander's motion as attitude, velocity and position. 2) By considering current status of the lander, data correction for motion should be required first. The measured data is re-arranged in view of vertically. 3) With corrected data, elevation map can be generated for the certain area. 4) Generated elevation map is inspected correlation with terrain elevation map in database. 5) After terrain identification, absolute position is estimated by considering the motion of the lander. These estimated position is entered to filter algorithm with measurement of other sensors.

The Extended Kalman Filter (EKF) is chosen for filter of the navigation system which can apply nonlinear system. Since the use of multiple sensors, sensor fusion procedure is included. Using the acceleration and angular rate measured by the IMU, state variables are estimated by integrating. Since the sampling rate of the IMU is high frequency, fast update of state variables is possible. But it makes divergence of the system by accumulated errors of sensor noise and bias as time passes. On the other hand, outcome of the vision-sensor as the flash LIDAR measured surrounding information in time enables to estimate reliable states but it is updated with low frequency. Therefore fast update of reliable states can be obtained using the IMU measurements by correcting of state errors with vision-sensor measurement.

5. Conclusion

This paper has presented the design of the flash LIDAR based terrain relative navigation for autonomous precision lunar landing. It include the simple mission description and navigation sensor configuration. And the terrain relative navigation system is designed including terrain mapping and filter algorithm for estimating current status. For future work, sensor systems will be implemented and tested with the flash LIDAR hardware.

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6. References

[1] Chirold D. Epp, Edward A. Robertson, and John M. Carson Ⅲ. "Developing Autonomous Precision Landing and Hazard Avoidance Technology from Concept through Flight-Tested Prototypes." AIAA Guidance, Navigation, and Control Conference, AIAA SciTech, Kissimmee, Florida, 2015.

[2] T. Brady, and J. Schwartz. "ALHAT System Architecture and Operational Concept." IEEE Aerospace Conference, 2007.

[3] Andrew E. Johnson and James F. Montgomery. "Overview of Terrain Relative Navigation Approach for Precise Lunar Landing." IEEE Aerospace Conference, 2008.

[4] F. Amzajerdian, D. Pierrottet, L. Petway, and M. Vanek. "Development of LIDAR Sensor Systems for Autonomous Safe Landing on Planetary Bodies." International Conference on Space Optics, Rhodes, Greece, 2010.

[5] Richard Fisackerly, Alain Pradier, Bruno Gardini, Berengere Houdou, Christian Philippe, Diego De Rosa and James Carpenter. "The ESA Lunar Lander Mission." AIAA SPACE 2011 Conference and Exposition, Long Beach, California, 2011.

[6] Murray L. Derr, Miguel Hagenfeldt, Jose A. Ospina, Jose Miguel Ramon, Luis F. Penin, Marco Mammarella, Ambroise Bidaux, and Pablo Colmenarejo. "ESA Lunar Lander: Approach Phase Concept and G&C Performance." Guidance, Navigation, and Control and Co-located Conference, Boston, MA, 2013.

[7] Baltazar Parreira, Jose F. Vasconcelos, Javier Montano, Jose Ramon, and Luis F. Penin. "ESA Lunar Lander: Approach Phase Concept and G&C Performance." Guidance, Navigation, and Control and Co-located Conference, Boston, MA, 2013.

[8] Huang Yong, Hu XiaoGong, Li Peijia, Cao Jianfeng, Jiang Dongrong, Zheng Weimin, and Fan Min. "Precise Positioning of the Chang'E-3 Lunar Lander Using a Kinematic Statistical Model." Chiness Science Bulletin, Vol. 37, No. 35, pp. 4545-4551, 2012.

[9] Liu Zhaoqin, Di Kaichang, Peng Man, Wan Wenhui, Liu Bin, Li Lichun, Yu Tianyi, Wang Baofeng, Zhou Jianliang, and Chen Hongmin. "High Precision Landing Site Mapping and Rover Localization for Chang'e-3 Mission." Science China Physics, Mechanics and Astronomy, Vol. 58, No. 1, pp. 019601, 2015.

[10] Andrew E. Johnson, Adnan Ansar, Larry H. Matthies, Nikolas Trawny, Anstasios I. Mourikis, and Stergios I. Roumeliotis. “A General Approach to Terrain Relative Navigation for Planetary Landing.” AIAA Infortech at Aerospace Conference and Exhibit, Rohnert Park, California, 2007.

[11] Samil Temel, Numan Unaldi, and Fuat Ince. “Novel Terrain Relative Lunar Positioning system Using Lunar Digital Elevation Maps.” Recent Advances in Space Technologies, Istanbul, 2009.

[12] Andrew E. Johnson and Tonislav I. Ivanov. “Analysis and Testing of a LIDAR-Based Approach to Terrain Relative Navigation for Precise Lunar Landing.” AIAA Guidance Navigation and Control Conference, 2011.

[13] Todd A. Ely, Martin Heyne, and Joseph E. Riedel. “Altair Navigation Performance During Translunar Cruise, Lunar Orbit, Descent, and Landing.” Journal of Spacecraft and Rockets, Vol. 49, No. 2, pp. 295-317, 2012.

[14] Jack Brazzel, Fred Clark, and Zoran Milenkovic. “FLASH LIDAR based Relative Navigation.” IEEE Aerospace Conference, Big Sky, Montana, US, 2015.

[15] Mark J. Verweld. “Relative Optical Navigation for a Lunar Lander Mission.” Advances in Aerospace Guidance, Navigation and Control, pp. 661-679, 2013.

[16] V. Simard Bilodeau, S. Clerc, R. Drai, and J. de Lafontaine. “Optical Navigation System for Pin-Point Lunar Landing.” 19^{th} The International Federation of Automatic Control, Cape Town, South Africa, 2014.

[17] John A. Christian, Shane B. Robinson, Christopher N. D’Souza, and Jose P. Ruiz. “Cooperative Relative Navigation of Spacecraft Using Flash Light Detection and Ranging Sensors.” Journal of Guidance, Control, and Dynamics, Vol. 37, No. 2, pp. 452-465, 2014.