Kaguya DEM Improvement for Future Lunar Lander Missions

Yang Cheng, Adnan Ansar

Abstract— **A concept of lunar landing operations involving Terrain Relative Navigation (TRN) consists of high-altitude (~15km, before Powered Descent Initiation(PDI)) and low altitude (~4km-250m) TRN phases, with the required map extents, resolutions, precision, and predicted localization accuracies. The resolution of the TRN maps ranges from ~40 meter/pixel at high altitude to up to 1 meter/pixel at landing site. For a typical landing scenario, a large portion of TRN operation uses so-called low-resolution map, which has between 40 to 10 meter/pixel resolution. However, besides in the polar regions (> 80°), where suitable Lunar Orbiter Laser Altimeter (LOLA) Digital Elevation Map (DEM) is available, the most feasible map is the Kaguya DEM/map, which has nearly global coverage and up to 10 meter/pixel resolution. However, the existing Kaguya DEM/map does not have desirable data quality for TRN application. Particularly, its elevation data contains a lot of artifacts or errors, which are introduced by the stereo matching algorithm. In this talk, we will describe a new stereo matching algorithm, which can significantly reduce the stereo matching error from SOA 0.15-pixel one sigma to less than 0.03 pixel one sigma. This improvement reduces the surface elevation error from 10s meter to a few meters, which is highly beneficial for future lunar lander missions.**

I. INTRODUCTION

The NASA Human Landing System (HLS) program under NASA's Artemis program aims to return humans to the Moon and establish a sustainable presence there. The HLS program specifically focuses on developing crewed lunar landers capable of carrying astronauts to the lunar surface. Another NASA initiative, Commercial Lunar Payload Services (CLPS), allows rapid acquisition of lunar delivery services from American companies for payloads that advance capabilities for science, exploration, or commercial development of the Moon. All of those planned or proposed lander missions will rely on so called terrain relative navigation (TRN) technology to guide spacecrafts land precisely and safely to targeted landing site. A critical component to a TRN system is the high-quality reference maps of the surface because it is used for localization and is likely the major error sources TRN performance [7].

Two recent examples of flight TRN systems are the Mars2020 Lander Vision System [2][3] and the OSIRIS-REx Natural Feature Tracking algorithm [1], both of which navigated their respective spacecraft to targeted site. Each of these missions approached the problem of map generation and validation in different ways, but accurate maps played the critical role in the success of these mission. For example, significant amount error was removed from the MRO CTX imagery during the Mars2020 LVS reference map construction and the potential map error was reduced from 10s meters to a few meters [3]. Similar map development for lunar missions is underway. NASA is funding a project called Lunar Navigation Maps (LuNaMaps). The LuNaMaps project, which consists of lunar scientists and navigation engineers, has the goal of developing procedures and map products that can meet the specific needs of TRN and (Hazard Detection) HD systems. These map products will be shared with the community in the form of benchmark data sets and an outline for the process, methods, and tools that were used to build and subsequently validate the lunar map products [4][5][6]. One of the map products is the Kaguya (Terrain Camera) TC DEM and its orthorectified maps.

II. KAGUYA TC IMAGE MATCHING IMPROVEMENT

The Kaguya TC instrument is a pair of push-broom imaging cameras with a spatial resolution of 10 m from 100 km altitude. It has two slant telescopes for stereo imaging. TC map product covers almost all the Moon's surface except both polar regions [8].

Due to its resolution and coverage, Kaguya TC map product is the most suitable data resource for TRN application at high altitude (> 10km) and nonpolar regions. However, the Kaguya DEM does not have desirable data quality. Fig.1 shows a DEM patch that is noisy and missing small topographic features.

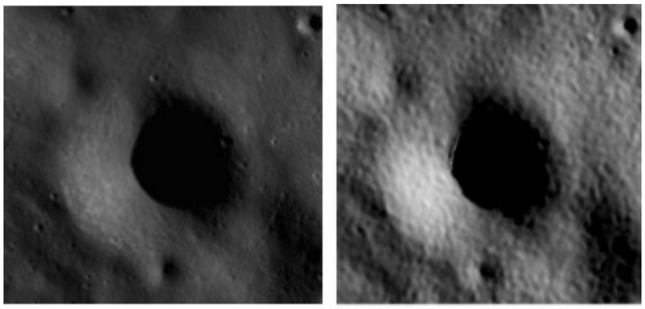

Figure 1: A piece of Kaguya TC image and its associated DEM (right). The DEM is too noisy.

To improve the KAGUYA DEM quality is one focus of the LuNaMaps project. To do this, we took the following steps to improve the Kaguya DEM quality.

1. Kaguya TC camera model validation and refinement.
2. Kaguya TC image bundle adjustment.
3. Kaguya stereo matching precision improvement.

In this paper, we focus on the stereo matching precision

Dr. Yang Cheng is a member of the Mobility and Robotics Systems section at the Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Dr., Pasadena, CA 91109 USA (email: ycheng@jpl.nasa.gov).

Dr. Adnan Ansar is a member of the Mobility and Robotic Systems section at the Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Dr., Pasadena, CA 91109 USA (phone: +1-818-393-7242, fax: +1-818-354-5007, email: ansar@jpl.nasa.gov).

improvement.

The slant angle θ of TC camera is about 15 degrees, and the delta elevation error is a function of the disparity error, dB, as follows.

$$\boxed{\begin{aligned} H &= Btan(90-\theta)/2 \\ dH &= \tan(90-\theta)\, dB/2 \end{aligned}} \quad [1]$$

With one-pixel matching error (~10m ground resolution), the elevation error is about 18.6m and traditional stereo matching error (~0.15-pixel one sigma) will has about 6m elevation error. If we improve the subpixel error from ~0.15 to less than ~0.02 pixel, we can significantly improve the DEM quality.

The idea of the stereo matching improvement originated from [9], in which an autocorrelation scheme was used to model the stereo matching error and the real stereo matching error is then removed based on the error model. Under the ideal situation, the stereo matching error can be reduced to 0.01 pixel.

However, the improvement was based on binocular stereo imagery from framing cameras, where the relative pose between the left and right camera is known and fixed. To port the algorithm to pushbroom cameras we added the following new enhancement.

1. Add a disparity search for X direction to commentate the pushbroom camera uncertainty along the x direction.
2. Add the TC1 and TC2 image intensity profile correction.
3. Add a finite element method for disparity refinement.

These enhancements result in significant improvement in the stereo matching and DEM precision.

Under the simulated environment, the new approach can achieve more than 0.01-pixel precision and about 10 folds improvements over the SSD solution.

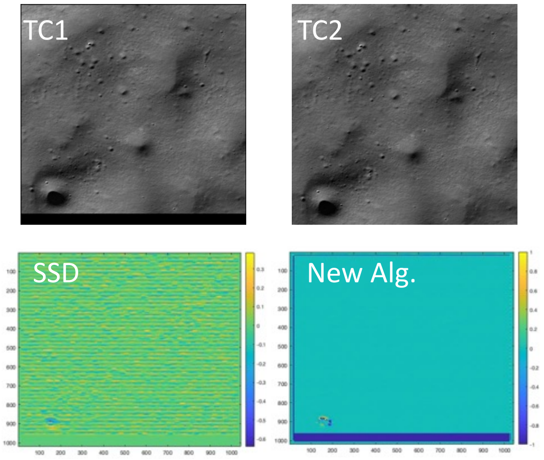

Figure 2: A simulated Kaguya TC image pair (top) and the disparity error comparison (SSD vs the new approach).

We also tested this approach using real Kaguya imagery and saw significant reduction in artifacts commonly found in the DEM produced by traditional methods.

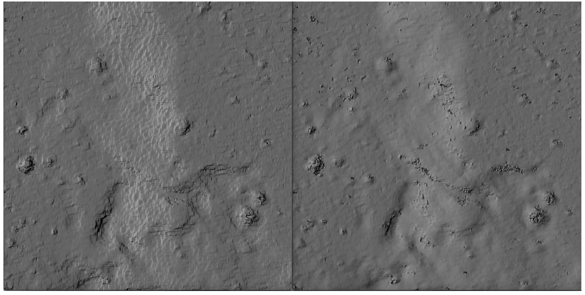

Figure 3: The rendered image from the DEM using sum squared difference (SSD) (left) and the new stereo matching approach(right). The block artifact which is commonly found in SSD DEM is largely gone in the new DEM.

III. CONCLUSION

Under the NASA LuNaMaps project, we have developed a new stereo matching approach for Kaguya DEM construction. This approach has the potential to improve the DEM precision from current 10s meters to a few meters.

ACKNOWLEDGMENT

This research was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration. © California Institute of Technology.

REFERENCES

[1] Sostaric, R. R., et al. "The SPLICE Project: Safe and Precise Landing Technology Development and Testing", AIAA Scitech 2021 Forum.

[2] Johnson, A. E., et al. "The Lander Vision System for Mars 2020 Entry Descent and Landing", AAS Guidance and Control Conference, 2017.

[3] Cheng, Yang, Ansar, Johnson, " Making an onboard Reference Map from MRO/CTX Imagery for Mars2020 Lander Vision System", August 2021Earth and Space Science 8(8).

[4] Barker, M. K., "Improved LOLA Elevation Maps for South Pole Landing Sites: Error Estimates and their Impact on Illumination Conditions", Planetary and Space Science (2020)

[5] Beyer, Ross A., Alexandrov, Oleg, McMichael, Scott (2018). "The Ames Stereo Pipeline: NASA's Open Source Software for Deriving and Processing Terrain Data". Earth and Space Science. American Geophysical Union (AGU). 5 (9): 537–548.

[6] Carolina I. Restrepo, et. al. "Building Lunar Maps for Terrain Relative Navigation and Hazard Detection Applications," AIAA 2022-0356. AIAA SCITECH 2022 Forum. January 2022

[7] Andrew E. Johnson, et al.. "Mars 2020 Lander Vision System Flight Performance," AIAA 2022-1214. AIAA SCITECH 2022 Forum. January 2022.

[8] Haruyama, J., Matsunaga, et. al. LISM Working Group (2008). Global lunar-surface mapping experiment using the Lunar Imager/Spectrometer on SELENE

[9] Cheng, Yang, and Larry H. Matthies. "Stereovision bias removal by autocorrelation." 2015 IEEE Winter Conference on Applications of Computer Vision. IEEE, 2015