Landing Autonomously on the Moon using Reference Maps: Needs and Challenges

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Abstract— **There is renewed interest in landing on the Moon under NASA's Artemis program. Mission concepts include crewed and uncrewed landers, landing sites ranging from polar to equatorial, and access and approaches covering all possible illumination conditions. In every case, there are challenging requirements for landing precision relative to the targeted landing site. This is addressed by any of several approaches to Terrain Relative Navigation (TRN), which seeks to localize the spacecraft with respect to the lunar surface during De-orbit, Descent and Landing (DDL). This can be done passively with cameras, actively with LIDAR or RADAR, or with a combination of the two. In every case, on-board data is matched in real-time to a reference map during DDL. In this abstract, we describe some of the requirements and challenges associated with building maps that satisfy the requirements for TRN.**

I. Introduction

Precise, autonomous landing on the moon requires a TRN system that can localize the spacecraft with respect to the lunar surface during approach and DDL. This is accomplished by matching sensor input from passive (i.e. optical) or active (LIDAR or RADAR) systems on-board with a model of the lunar surface. That model, which we will call a reference map, is typically a digital elevation model (DEM) in the case of active sensors or a combination of DEMs, ortho-projected imagery and associated meta-data in the case of optical TRN.

Reference maps for TRN have unique requirements distinct from maps used for science applications. They must be correctly localized in a body-fixed lunar coordinate frame and free of geometric distortion to a degree informed by the TRN algorithm. In the case of optical TRN, they must also have associated radiometric data with enough fidelity to allow robust matching to descent imagery. The moon also presents some unique challenges for TRN mapping. These include limits on available data at required resolution, uncertainty about fidelity of some of that data and its associated meta-data, and challenges resulting from the harsh illumination environment at the moon, particularly at the poles. Further, data access through NASA systems can be cryptic, particularly for commercial performers with limited experience in navigating some of the publicly available resources.

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We will describe methods for reference map generation, validation, and access with the unique requirements and constraints of the lunar environment.

II. Map Considerations for TRN

TRN requirements dictate reference map requirements. The details are mission and TRN algorithm specific. However, the factors that contribute to the fidelity of the reference map are universal:

- Map errors: The error sources for the map are universal. These are dominated by uncertainty in absolute position, orientation, elevation, and most critically, by non-uniformity or local distortion [1]. A key objective in building a reference map for flight is to characterize these error sources so that they can be adequately incorporated into the error budget of the TRN system.
- Map resolution: Independent of the TRN approach, map resolution dictates landing precision. It is, thus, critical to evaluation the native resolution of any reference map, independent of the published map posting or sampling.
- Illumination: In the case of optical TRN, characterizing illumination is critical. This is a factor in both map building and in matching on-orbit imagery to the reference map. Without adequate characterization of albedo or reflectance, rendering of map imagery will not match descent imagery.

As a general principal, requirements on the map and impact of the map on TRN can be derived by explicit propagation of error from the map to the TRN algorithm. This can be accomplished analytically or via statistical means (e.g. Monte Carlo simulation). The details will depend on the specific mission and TRN approach used.

III. Building and Validating Maps

Map building can range from assembling existing map data from public source to generating new map products using novel reconstruction approaches. For the majority of commercial performers (e.g. participants in NASA's Commercial Lunar Payload Service (CLPS) program), the former will be the baseline, while landing near especially challenging topography may require maps with higher resolution and precision than those readily available.

The primary data source for lunar TRN reference maps are the DEMs produced by the Lunar Orbiter Laser Altimeter (LOLA) aboard the Lunar Reconnaissance Orbiter (LRO). This includes the SLDEM2015 dataset[2], which uses additional data from the Japanese Aerospace Exploration

Agency's (JAXA) Selenelogical and Engineering Explorer (SELENE) spacecraft, alternatively called Kaguya. The LOLA DEMs have resolutions ranging from 60m at the equator to higher (nominally 5m, but natively coarser) at the poles. Other data sources include Kaguya's stereo Terrain Cameras (TC), nominally at 10m image resolution, and the Narrow Angle Cameras (NAC) aboard LRO, with 0.5m nadir resolution. The DEMs derived from these systems are typically a factor of 2 (typically worse) coarser than the native image resolution of the imagers. Other available data include imagery and DEMs from both the Indian Space Research Organization's (ISRO) Chandrayaan missions and the China National Space Agency's (CNSA) Chang'e orbiters. However, the latter have limited public data with less complete meta-data.

For each of LOLA and Kaguya, global lunar DEMs exist. For NAC, there are of limited coverage. For each of these sources, and depending on TRN requirements, refinement, cleanup and co-registration of data may be necessary. In the case of imagery, it may be necessary to fully reconstruct DEMs from source image data. Work in-progress includes on-going refinement of LOLA [3], development of novel sub-pixel stereo algorithms as part of a full processing pipeline for Kaguya TC data, and high-resolution shape-from-shading DEMs from NAC [4].

Since no large-scale ground truth exists for the moon, validation of maps generated from any of these products typically amounts to cross-validation across differing datasets. Included in these efforts are refinement of the orbit determination of the spacecraft and refinement of the camera models associated with the imagers on-board. Along with the referenced data sources, imagery from NASA's Clementine mission, while lower in resolution, may be useful. Unlike the other source listed, Clementine's High-Resolution Camera (HIRES) is a framing instrument, rather than a push-broom camera or scanning laser. Thus, distortion in the HIRES data is not a function of orbital dynamics but of optics alone.

IV. Accessing Data

Another challenge for developing reference map products for the moon is simply in assembling existing data. The NASA Planetary Data System (PDS) can sometimes be unwieldy. We list below some alternate, direct links to some of the data referenced above:

- LOLA:https://ode.rsl.wustl.edu/moon/pagehelp/Content/Missions_Instruments/LRO/LOLA/Intro.htm
- Kaguya:https://darts.isas.jaxa.jp/planet/pdap/selene/product_search.html
- NAC: https://wms.lroc.asu.edu/lroc/search, https://pilot.wr.usgs.gov

V. Conclusion

This abstract presents a quick survey of some of the considerations that go into developing TRN reference maps for lunar landing. These include a need to understand how the map impacts the TRN algorithm, considerations for assembling and building maps, and the factors that influence map validation. Another practical aspect of this work is in navigating and assembling existing data from the many varied public sources available.

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