A VISION-BASED NAVIGATION CAPABILITY FOR PRECISE LUNAR LANDING
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Abstract. Draper is developing a vision-based navigation capability to support precision lunar landing, incorporating three types of algorithms. These algorithms include unknown feature tracking and two types of known feature matching, one that uses image templates and another that uses craters. This abstract will provide an overview of these algorithms, the lunar image generation capability that Draper is developing to support testing of these algorithms, as well as some preliminary results.

Introduction.
Draper has a long history of developing vision-based navigation (VBN) software for both space and terrestrial applications. Space applications include lunar and asteroid landing, docking to the International Space Station (ISS), and tracking astronaut motion within the ISS[1]-[7]. Terrestrial applications include pedestrian navigation, autonomous driving, UAVs, and guided parachutes[8]-[10]. Recently, Draper has been leveraging expertise and algorithms from these efforts and developing a vision-based solution for lunar landing. This is an internally funded effort that leverages both Draper’s NASA CLPS award as well as Draper’s collaboration with ispace and their lunar landing mission.

The mission profile used for this development is based on the ispace reference mission (Figure 1). In this reference mission, the vision-based navigation starts at a 100km altitude orbit and continues providing updates needed for precision landing through descent. It is important to note that while this profile is used for testing and development, it is not expected that these algorithms are limited to these conditions. The actual VBN algorithm performance is dependent on the camera specs and available lunar imagery for a given lunar mission.

Algorithm Overview.
Draper’s VBN software consists of two types of algorithms to generate measurements – unknown feature tracking and known feature matching. For unknown feature tracking, unique points (features) in each image are detected and tracked from frame to frame, providing a relative update since there is no prior knowledge about the location of these features. For known feature detection, Draper’s algorithms search the camera image for previously defined features with known absolute locations. Once these known features are successfully detected in the image, the VBN output is a set of image pixel locations and their corresponding locations in a fixed reference frame, providing an absolute update.

Draper currently has two algorithms for known feature detection: Image-Based Absolute Localization (IBAL) and Catena. Both of these known feature algorithms are being developed so that the capability is ready for future lunar missions. Additional testing will determine which particular algorithm, or if both, will be used for a particular mission.

Image Based Absolute Localization (IBAL)
IBAL uses a set of image patches called templates as known features that are defined from pre-existing imagery and terrain of the surface. These templates are then warped to the image frame using the predicted state and matched to the image using normalized cross-correlation. IBAL was developed for satellite imagery for terrestrial applications[10] and is currently being updated for available lunar imagery from sources such as the Lunar Reconnaissance Orbiter (LRO).

Catena
Catena uses a map of craters also defined from LRO or other available lunar imagery as known features in order to provide absolute updates. Craters are then detected in each image by searching for pairs of bright and dark regions, which is a common pattern for craters when the sun is at an angle, and fitting them to an ellipse. These ellipses are then matched to a pre-loaded crater database[1].

VBN Testing.
One of the challenges in developing VBN software for space applications is the lack of available test images with real camera imagery. When VBN software is running onboard during nominal spacecraft operations, that is usually the first time that the VBN software is processing images under those conditions (lighting, altitude, camera orientations, etc.) with the flight camera. In order to ensure success under those conditions, significant testing must occur prior to descent to validate the VBN algorithms.

To support this need, Draper has been developing a lunar image generation (IG) capability (see Figure 2). This IG will support both open- and closed-loop testing of the VBN software with Draper’s navigation filter, as well as sensitivity testing of Draper’s VBN algorithms to understand performance across all lighting conditions.
and camera positions and orientations. This tool will also serve to generate image templates for IBAL.

**Figure 2. Example Image from Draper’s Diamond Visionics Lunar Image Terrain Generator for testing.**

**Preliminary Results.**

The following figures show preliminary results for all three algorithms using an early version of Draper’s lunar IG. Performance is expected to improve once development of the IG is finished.

Figure 3 shows the results of the unknown feature tracker running on simulated imagery. These blue lines on the image show the features being successfully tracked. The long lines are promising and show the features are able to be tracked through multiple frames. Figure 4 then shows preliminary IBAL results for a single feature. In this figure, the left image shows the template itself, the middle image shows the camera image the template is matched to as well as the match location within the image, and the right image shows a close up of the match location in the image, which matches the original template. Lastly, Figure 5 shows preliminary results from projecting the database crater centers into the simulated image. These projected centers do not exactly line up with the crater centers due to terrain errors in the preliminary version of the IG used for this test.

This presentation will further expand on Draper’s Lunar TRN capability and future development and validation plans.

**Figure 3. Unknown feature tracking results. Blue lines represent tracked features.**

**Figure 4. IBAL template matching result. Match location matches template location in image.**

**Figure 5. Results from crater database center coordinates projected onto simulated image in red.**

**References.**


