MACHINE LEARNING FOR AUTONOMOUS VISUAL NAVIGATION UNDER VARIABLE ILLUMINATION CONDITIONS

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Abstract. *This study explores the application of the LoFTR algorithm for autonomous visual navigation in planetary landings under varying illumination conditions. By leveraging a transformer-based architecture for global feature contextualization, LoFTR achieves robust feature matching across different lighting scenarios. Applied to NASA JPL's 2023 field test imagery, LoFTR demonstrates high accuracy in matching terrain features, suggesting its potential to enhance precision landing for future Mars missions. These findings are significant for advancing space imaging and ensuring safe, precise landings despite challenging illumination variations.*

Introduction. Autonomous visual navigation capabilities for entry, descent, and landing (EDL) on planetary bodies are critical for near-term NASA Martian missions to guarantee precision landing near sites of scientific interest. NASA has shown interest in this technology and has made investments to develop autonomous visual navigation landing techniques for future missions [1].

NASA JPL's autonomous visual navigation technique, terrain relative navigation (TRN), was used successfully on the Perseverance Rover landing in 2021 to increase a Martian landing accuracy by an order of magnitude [2]. TRN localizes the spacecraft's real-time descent imagery to an a-priori orbital terrain map of the landing site and provides an additional measurement to estimate the spacecraft's position during planetary EDL.

Visual navigation is a powerful tool for planetary landings but is restricted in its application due to its susceptibility to variations in the illumination conditions. For future Mars and other planetary body spacecraft landings, the time of day, and thus illumination conditions, between the descent imagery and the a-priori orbital map will be drastically different, causing current optical navigation algorithms to fail [3][4]. This motivates the research question of how to create an autonomous visual navigation technique that is invariant to large illumination condition changes.

In this work, we propose to leverage the inherent terrain structure of images, autonomous visual navigation systems can achieve robust performance despite varying illumination conditions. This approach involves matching terrain features that remain constant throughout the day, thereby enabling the real-time descent imagery to be localized to an a-priori map with different lighting. Consequently, image alignment can be maintained, ensuring safe and precise spacecraft landings.

Proposed Methodology. A traditional feature matching pipeline between two images includes feature detection and feature description for each image, followed by matching common features across both images. However, traditional feature detectors, like the Harris corner detector [5], are susceptible to changing illumination conditions between the two images, as they depend on tracking pixel-based image gradients, which change with large shadow and shading differences. Thus, the traditional feature matching pipeline can fail to find common features between images across different illuminations, as strong shadows and changing shading attract the focus of gradient-based detection.

An illumination invariant technique for feature description can instead consider the topographical features that remain invariant between images of the same terrain across different times of day. By leveraging the global image context, defined as the positional relationship of large-scale topographical features, features obtained in relation to the entire image context can be effectively matched across images with varying illumination conditions.

We apply the LoFTR algorithm [6] which combines multi-scale feature extraction with feature contextualization to output feature matches robust to illumination changes. LoFTR combines a convolution neural network backbone which extracts multi-scale dense feature maps with a transformer network which processes the feature maps to model long-range positional dependencies between feature matches. Effectively, LoFTR combines the feature detection, description and matching into one algorithm.

Results. Out of the box LoFTR (with pre-trained MegaDepth dataset) applied to the NASA JPL 2023 field test imagery taken in southern California at the Anza-Borrego Desert State Park in late November 2023 successfully matches over terrain regions throughout time-of-day differences. The dataset contains 90,000+ images of three field locations (1. cliffs, 2. terrain relief and 3. terrain depression) taken during two flight paths (1. NW and 2. SE) at different times of day, with sun angles differences of 0 to 35 degree sun elevation and 120 to 240 degree sun azimuth.

Fig. 1 depicts LoFTR feature matches on a sample image pair of a registered map-projected Anza-Borrego image taken at 7.28am PST to a high-resolution map of the same terrain taken at 10am PST in January. Note the dense feature matches on the flat portion of the center of the image and avoided shadowed regions. Fig. 2 depicts a heatmap of successful LoFTR feature matches between the 10am PST January map and 54 map-projected images from 7.31am PST 2.55pm PST. The map regions where LoFTR successfully matches across all the time-of-day differences are marked and can be used to weigh match confidences during TRN.

Conclusions. This study demonstrates that the LoFTR algorithm is effective for autonomous visual navigation in planetary landings under varying illumination conditions. By utilizing a transformer-based architecture that combines multi-scale feature extraction with global feature contextualization, LoFTR successfully matches terrain features invariant to lighting changes. Application of LoFTR to the NASA JPL 2023 field test imagery in the Anza-Borrego Desert shows robust performance, maintaining match accuracy across significant time-of-day differences. These results suggest that LoFTR can enhance TRN for future Mars missions, ensuring precise and safe spacecraft landings despite challenging illumination variations.

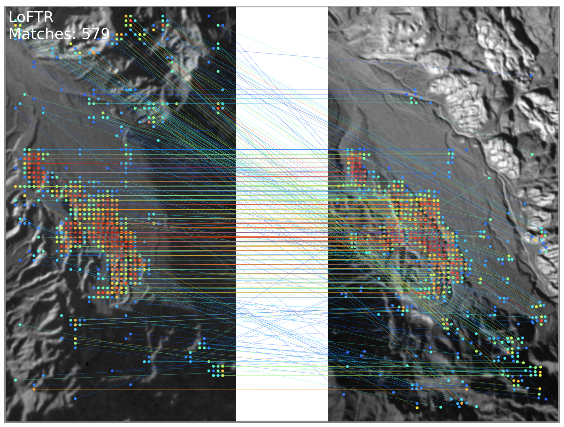

Figure 1. Example of LoFTR feature matches between an image pair. Left: map-projected terrain depression 7.28am PST image. Right: 10am PST January map. Warmer colored matches indicate a high confidence in match accuracy.

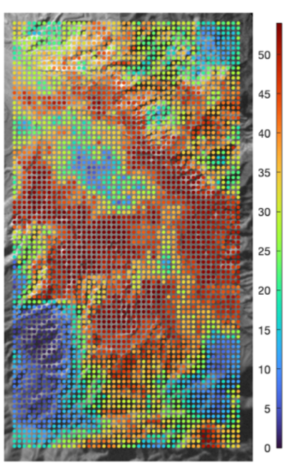

Figure 2. Heatmap of repeated LoFTR matches over 54 map-projected terrain images. Warmer coloring indicates terrain regions matchable across all images (across all time-of-day differences).

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