Map Matching During Descent for Terrain Relative Navigation on Titan.

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Brief Presenter Biography: Larry Matthies has conducted research at JPL on vision systems for autonomous navigation in Earth and space applications since 1989. His work in this area has been used in all U.S. Mars surface missions since Pathfinder in 1997. He obtained his PhD in computer science from Carnegie Mellon University.

Introduction: Precision landing on planetary bodies uses terrain relative navigation (TRN) to estimate position during descent, by performing real-time, onboard registration of descent imagery to maps of the terrain created from prior orbital reconnaissance [1]. This is used to guide divert maneuvers to land close to desired targets or to avoid landing hazards that are known from prior reconnaissance. TRN is very mature for Mars, where descent images acquired at altitudes of approximately 3 to 4 km can be cross-correlated with map images to obtain position estimates with error on the order of 40 meters [2]. For Mars, orbital images have high resolution (30 cm/pixel) and the orbital and descent images have very similar spectral characteristics, which simplifies automatic image registration.

Titan's tall, dense, hazy atmosphere creates very different problems for precision landing. Here, we focus on the challenges of position estimation during descent. Position knowledge that is inertially propagated from entry will have large errors due to long descent times (up to 2.5 hours [3]). Position knowledge from TRN is limited by the low resolution of orbital images (currently 100s of meters to many km/pixel). TRN may be desired or required to start at altitudes of several 10s of km. However, atmospheric absorption and scattering limit the usable spectral bands for imaging and reduce image clarity with increasing altitude. We summarize progress in modeling descent imaging and in developing map matching algorithms for TRN on Titan.

Background: Descent cameras on the DISR instrument on the Huygens probe operated in a spectral band from 660 to 1000 nm (visible/near-infrared, or VNIR). Atmospheric scattering creates very diffuse scene illumination and adds significant scattered light to imagery. With post-processing, the surface was visible in DISR images beginning at an altitude around 40 km [3].

Without new orbital imaging, the only source of map imagery is the Cassini mission. Cassini's Imaging Science Subsystem (ISS) camera acquired images over much of Titan with a narrow band spectral filter centered at 938 nm. These have been processed into a mosaic with pixel sampling of 2.8 km [4]. The Visual and Infrared Mapping Spectrometer (VIMS) obtained images in the spectral region from 1 to 5 μm, which have been processed into mosaics with a best resolution of a few km/pixel [5]. This band is less affected by atmospheric scattering than VNIR, but atmospheric absorption makes only part of this spectral range useful. For TRN, the short-wave infrared (SWIR) window from 2 to 2.1 μm is of interest for descent imaging, because it is a good compromise between available light and reduced scattering. Cassini's radar obtained surface imagery with resolution of ~300 meters/pixel at closest approach [6], which is essentially unaffected by atmospheric scattering.

With these data sets, TRN can use maps from ISS, VIMS, or radar, and descent imaging spectral regions of interest are VNIR and the 2 to 2.1 μm SWIR band.

Modeling Descent Imaging: To evaluate expected imaging performance for VNIR and SWIR descent cameras, we modeled the entire process of solar illumination, surface reflection, and light propagation to the camera aperture using the DISORT radiative transfer code [7]. Atmospheric absorption and scattering data was drawn from the literature [8]. As notional camera spectral responses, for the VNIR case we used quantum efficiency curves for CMOS imagers from Mars 2020 rover engineering cameras, assuming filtering to restrict the range to 500 to 1000 nm. For the SWIR case, we used data for the H1RG infrared detector, assuming a filter for the 2 to 2.1 μm atmospheric window.

A standard paradigm for map matching with descent imagery is to use attitude and altitude data, assumed to be available from an IMU and altimeter, to project descent images onto the ground plane. These are then low-pass filtered and resampled at the resolution of the map image for use by image registration algorithms. For Titan, this effectively involves binning the descent image pixels to a degree that provides large SNR for reasonable exposure time and aperture values, regardless of the native imager well depth.

The main issue, therefore, is to model the relative amount of light reaching the camera directly from surface reflection vs. from multiple scattering in the atmosphere. Using DISORT, we evaluated this as a function of altitude. Figure 1 shows that SWIR is far superior to VNIR in this respect, so we focus on SWIR for map matching.

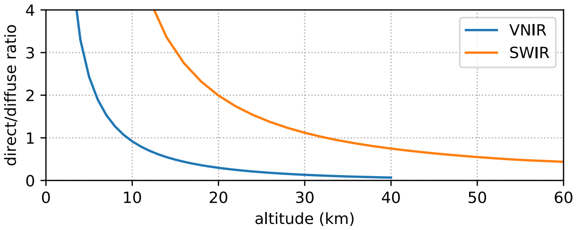

Figure 1. Modeled ratio of direct to scattered descent image irradiance vs altitude for VNIR and SWIR bands.

Estimating Position From Descent Imagery: The question now is how to register SWIR descent images to map images created from ISS, VIMS, or radar data. The best global mosaics are available from ISS; the best spatial resolution is available for selected locations from radar. Registering SWIR to either ISS or radar is a multi-modal registration problem. This problem has been explored for Titan data sets with some success using mutual information as registration criterion [10]. This approach has potential to apply to any landing site on Titan where the orbital imaging was adequate.

Regions of small lakes in northern latitudes are an interesting scenario, because they offer distinct science possibilities and the highest image contrast (between lake and ground regions) available on Titan, which may provide the best image registration performance. This scenario opens possibilities for a different approach to registration, because the contrast should enable reliable onboard segmentation of lake and non-lake regions in descent images, especially in the SWIR band. These binarized images could be registered to similarly binarized radar maps. This removes the differences in sensor phenomenology between radar and SWIR, and can benefit from the higher resolution of radar images.

We have experimented with both of these approaches by using Cassini VIMS mosaics to generate simulated descent images, with ISS and radar data as the map (Figure 2). We used the radiative transfer model to synthesize noisy descent images with a 90° field of view at a variety of altitudes. At several test altitudes, we created simulated descent images for many test locations to measure the mean and standard deviation of registration error (Figure 3). Results were better at higher altitudes because descent images project to shrinking patches on the ground as altitude decreases, which produces noisier matches. Non-zero mean errors are due to multiple factors, including imperfect registration of the Cassini mosaics used in the experiments; this could be improved with further work. Standard deviations of 1 to 1.5 km for altitudes of 30 to 40 km are quite promising.

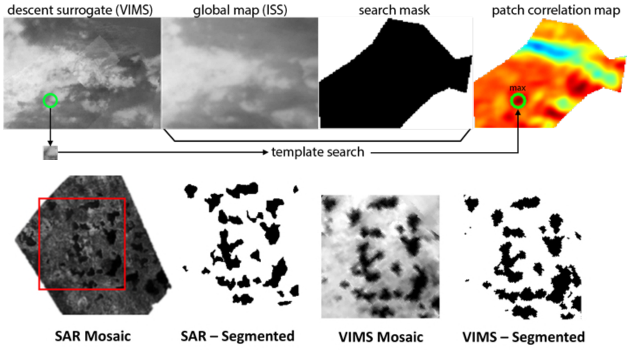

Figure 2. Top row: experiments with mutual information-based matching used data from the Huygens landing site region. The search mask limited tests to areas of the mosaics without distinct seams. The false color image shows match scores for one trial (deep red best, blue worst). Bottom row: Orbital mosaics of the Maracaibo Lacus region used for binary correlation experiments, which were constrained to the area in the red rectangle.

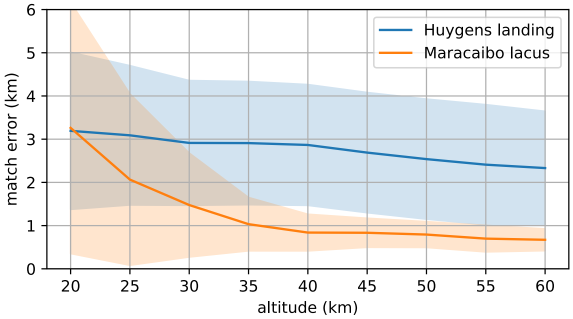

Figure 3. Match matching simulation results: mean position error and 1σ interval vs. altitude for $\sim$ 1000 trials at each altitude. See text for interpretation.

Discussion: These results are encouraging and will be tested for other regions on Titan. Map matching will not work all the way to the ground, so other sensors and image processing algorithms are needed to bound position and velocity error growth at low altitude. Ongoing work will address this in simulations of navigation error from entry to landing.

References: [1] Johnson A. E. et al. (2007) *AIAA Infotech@Aerospace Conf.* [2] Johnson A. E. et al. (2015) *AIAA GNC Conf.* [3] Lebreton J.-P. et al. (2005) *Nature, 438,* 758-764. [4] Karkoschka E. et al. (2018) *AAS/DPS Meeting, 50.* [5] Le Moulic S. et al. (2018) *LPSC 49*, abstract 1889. [6] Stephan K. et al. (2009) ch. 19 in Brown R.H et al. *Titan from Cassini-Huygens.* [7] Stamnes K. et al. (1988) *Appl. Opt.*, 27, 415-419. [8] Doose L. R. et al. (2016) *Icarus, 270*, 355-375. [10] Ansar A. and Matthies L. H. (2009) *IROS Conf.*, 3349-3354.