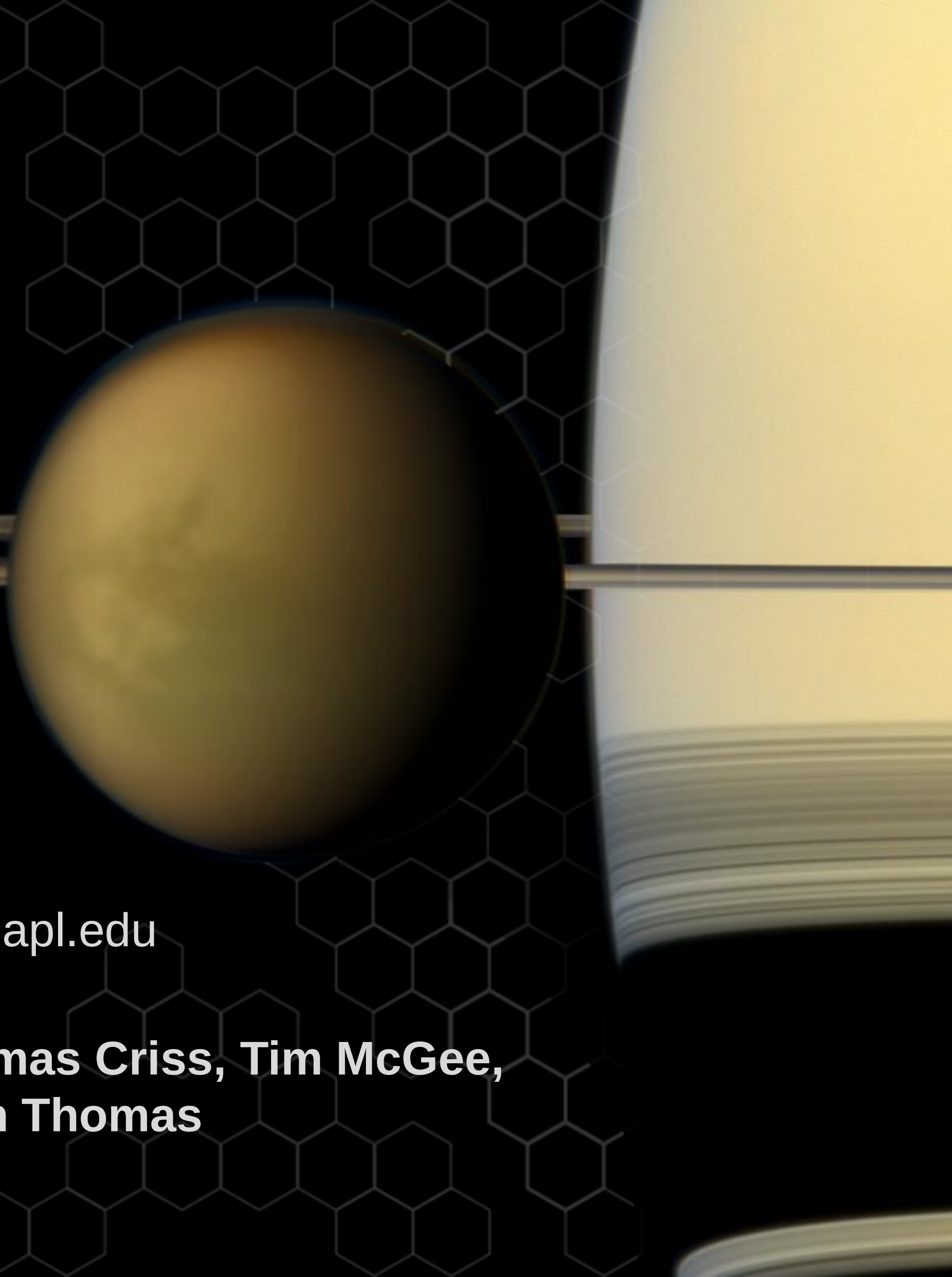
DRAGONFLY

A relocatable lander to explore Titan’s prebiotic chemistry and habitability



Preliminary Electro-Optical Terrain Sensing Algorithm

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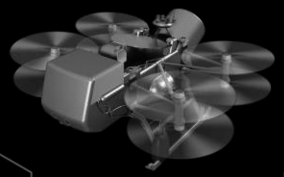
October 14, 2021

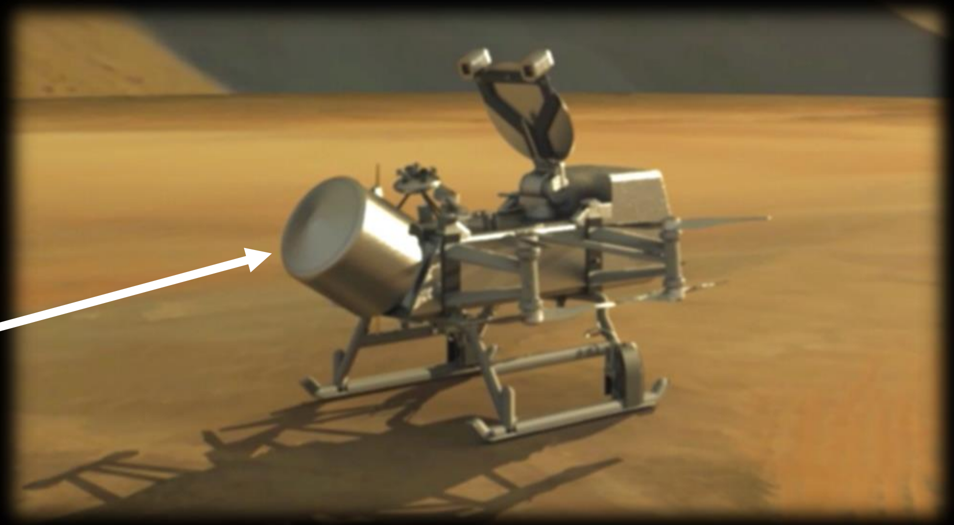
Overview



- Dragonfly Mission and Mobility Subsystem
- Electro-optical Terrain Sensing (ETS) Algorithm
- Testing Methodology

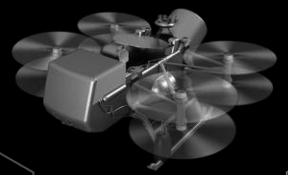
The Dragonfly Mission

- Mission
  - To explore the prebiotic chemistry occurring on Titan
  - Launch 2027*
  - Arrive at Titan 2036*
- Titan
  - Largest moon of Saturn (2nd largest in Solar System)
  - Atmospheric density 4x higher than Earth's
  - Gravity 1/7th that of Earth
- Spacecraft
  - Dual-quadcopter relocatable science laboratory
  - Power provided by a radioisotope thermoelectric generator (RTG)

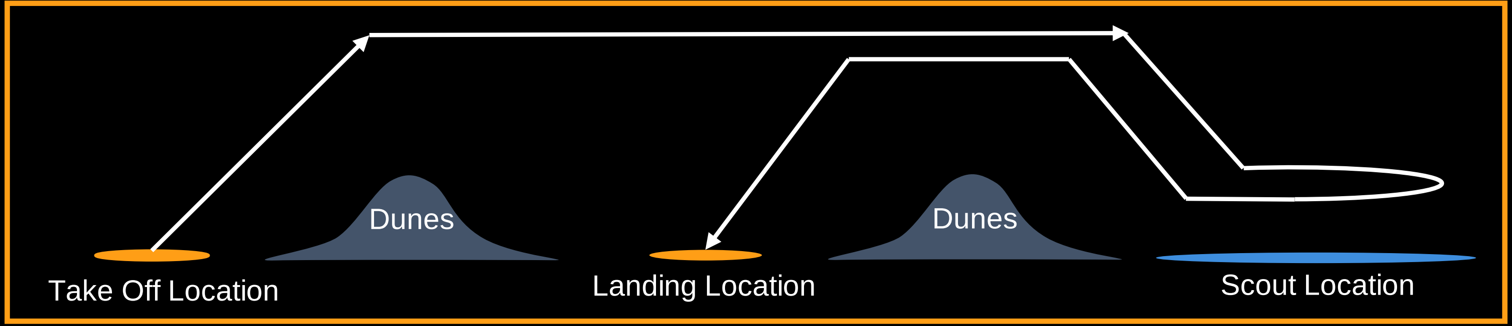


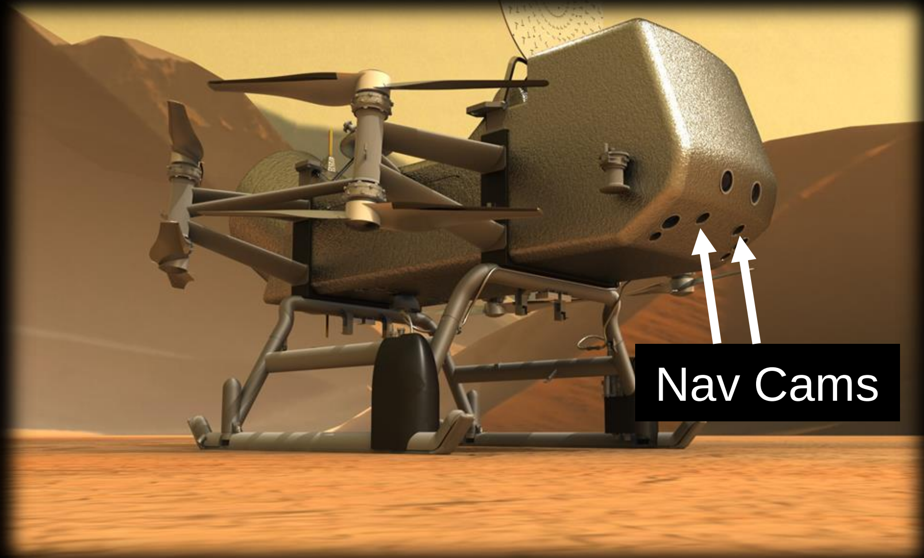
* Subject to change

Mobility Overview

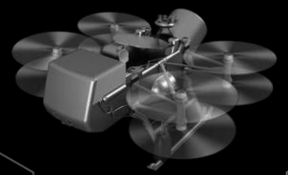


- Dragonfly will autonomously traverse kilometers over the surface of Titan
  - Initial landing location is in the Shangri-La Dunes
- Navigation sensors
  - IMU, LIDAR, RADAR, Barometer, Ultrasonic
  - Two navigation cameras (Nav Cams)
- Leapfrog flight path to scout future landing sites

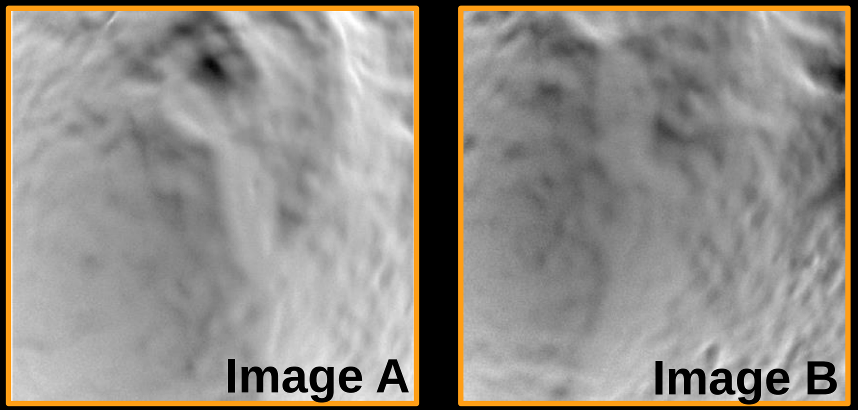




Electro-Optical Terrain Sensing (ETS)



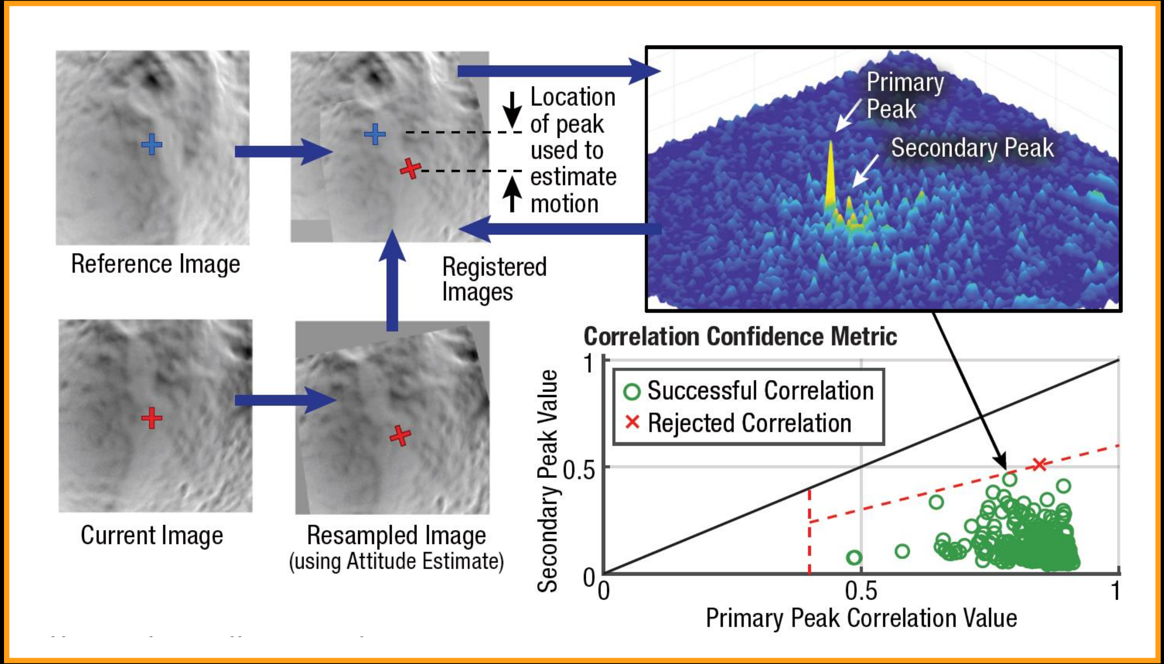
- Optical signal processing algorithm to provide relative state measurements to the Navigation subsystem
- Operates on pairs of images from the Nav Cam
  - Normalized phase-only cross correlation approach
- Three measurement types
  1. Lateral position offset relative to last acquired image (Image to image measurements)
  2. Lateral position offset relative to previously seen keyframe (breadcrumb measurements)
  3. Yaw offset relative to previously seen keyframe



Expected quality of image pair to register

Normalized Phase-only Cross Correlation

- Fourier transform technique to register two images taken from different poses
- Algorithm Process [1]
  1. Normalize and undistort newly acquired image B
  2. Resample image B to the estimated pose of a reference image A with projective transform
  3. Apply Fourier transform to both images (I_a and I_b)
     $$G_a = \mathcal{F}\{I_a\}, G_b = \mathcal{F}\{I_b\}$$
  4. Combine image spectrums with element-wise multiplication and divide by the magnitude of each element
     $$R = \frac{G_b \circ G_a^*}{|G_b \circ G_a^*|}$$
  5. Apply inverse Fourier transform to the resulting matrix to produce correlation surface (r)
     $$r = \mathcal{F}^{-1}\{R\}$$
  6. Find location of peak value in the correlation surface and compute confidence metrics
- Processing is accelerated by an implementation on a radiation-hardened FPGA

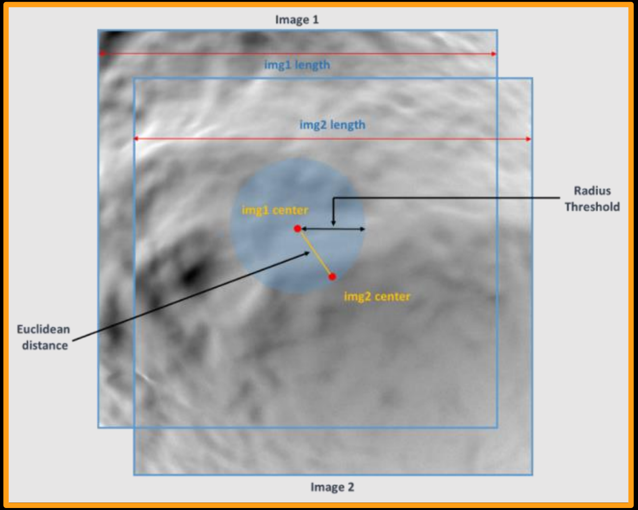


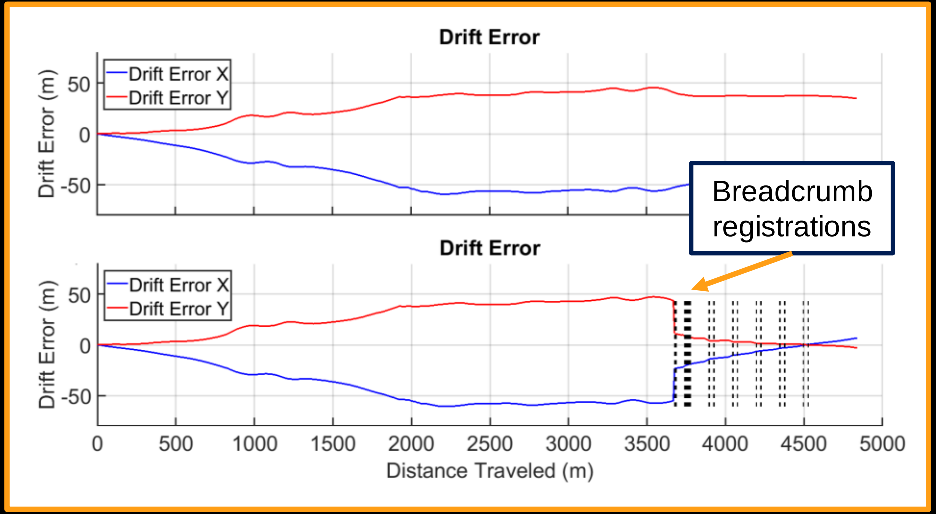
[1] No GPS? No Problem! Exploring the Dunes of Titan with Dragonfly Using Visual Odometry
Isaac R. Witte, Dmitriy L. Bekker, Michelle H. Chen, Thomas B. Criss, Steve N. Jenkins, Nishant L. Mehta, Carolyn A. Sawyer, Jason A. Stipes, and Justin R. Thomas
AIAA Scitech 2019 Forum. January

Keyframe (Breadcrumb) Navigation

Mitigating position uncertainty accumulation by correlating to spatially distributed "breadcrumbs"

- A Dragonfly "breadcrumb" is analogous to a "keyframe" in SLAM
  - Image are saved during flight for later registration
- ETS will attempt to register to a viable breadcrumb seen earlier in flight if possible to reduce accumulated state uncertainty
  - Viable means enough expected overlap, similar scales, and good image quality
- Three types of breadcrumbs provide differing information:
  - Online Breadcrumbs: Acquired during the current flight and used to "retrace our steps" back along the leapfrog trajectory after scouting
  - Historic Breadcrumbs: Acquired during a previous flight and used to follow the previous flight path during the first leg of the leapfrog
  - Terminal Breadcrumbs: Acquired during a previous flight near the newly selected landing site to provide high landing precision

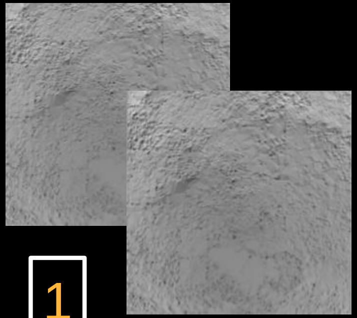




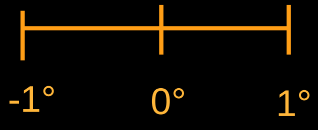
State uncertainty accumulation with and without breadcrumbs

Yaw Correction: Dithering Approach

Uses image correlations from multiple estimated yaw values to estimate the true heading



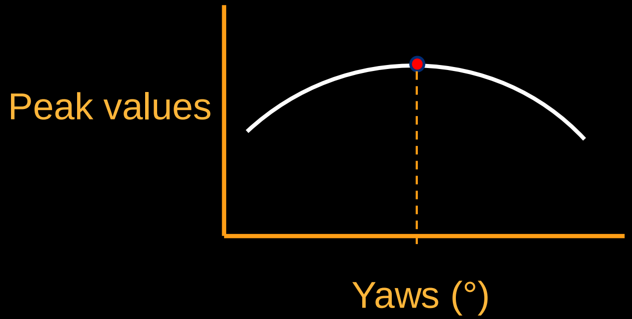
1



2

est_yaw: -1°
peak_val: 0.0291
est_yaw: 0°
peak_val: 0.0189
est_yaw: 1°
peak_val: 0.0095

3



4, *with flag*

Best yaw

est_yaw: 0°
peak_val: 0.0189
est_yaw: 1°
peak_val: 0.0095

4, *without flag*

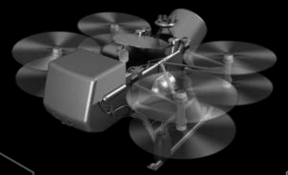
1. Takes in 2 normalized images
2. Within a range of uncertainty (the min / max yaw offset), tests a given number of values as “estimated yaws”
3. Computes the image correlation for each of these yaws, outputting a “peak ratio” and a “peak value” (point of most similarity between the 2 images, higher value indicates more similarity and is better)

When 3_pts_flag == true:

4. Find the yaws corresponding to the max peak value and its 2 neighbors; fits a quadratic to these 3 yaws and peak values; chooses the yaw that corresponds with the highest peak value

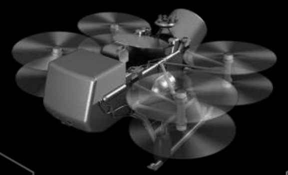
When 3_pts_flag == false:

4. Choose the yaw corresponding to highest computed peak value (no quadratic fitting involved)

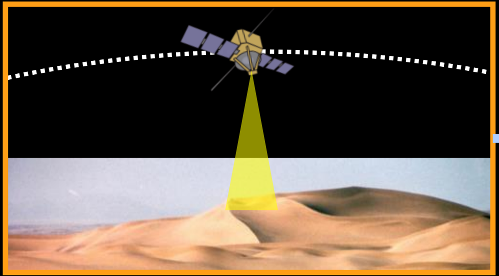


Testing Methodology

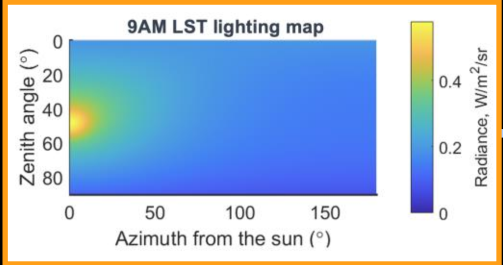
Environmental Modeling [2]



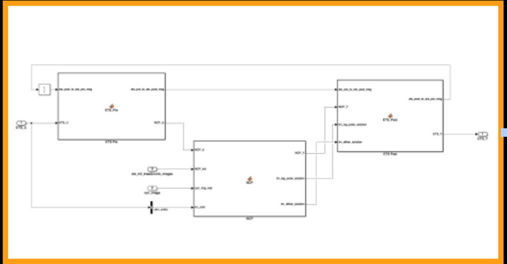
Titan Surface from *Cassini-Huygens* [3]



Commissioned Stereo Imagery from Airbus over the Namib Desert



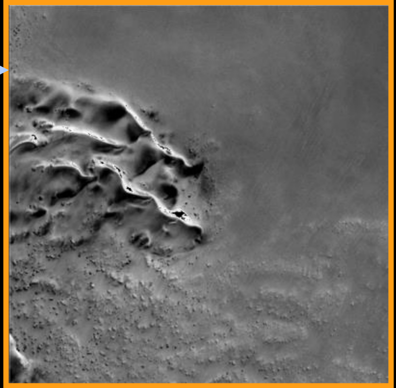
Optical Model for Titan Environment



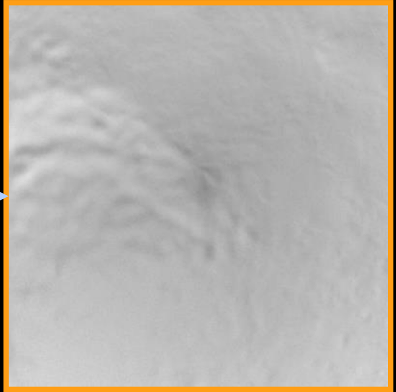
Closed Loop Simulation with Dynamics Model

APL's Renderer and Camera Emulator (RCE)

Trajectory



Visible-light image from Namib data collection



Titan Render

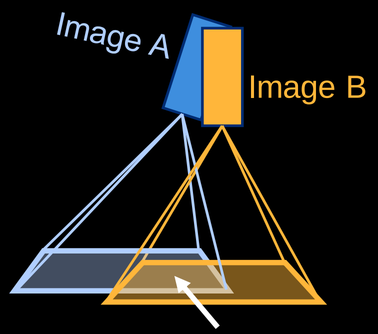
[2] Sawyer, Carolyn A. and Nishant L Mehta. "Rendering the Titan Environment for Dragonfly." 2nd RPI Space Imaging Workshop, Oct 28-30 2019.
[3] Huygens after-landing composite image, true contrast with color based on spectral data. Credit NASA/JPL/ESA/University of Arizona. https://photojournal.jpl.nasa.gov/catalog/PIA07232

Testing Methodology

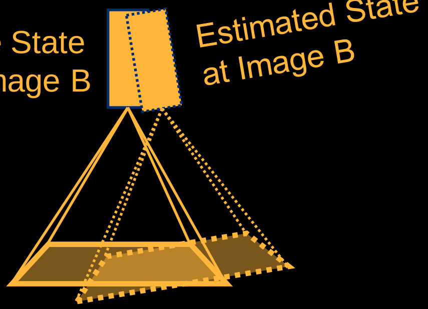
Measurement Performance

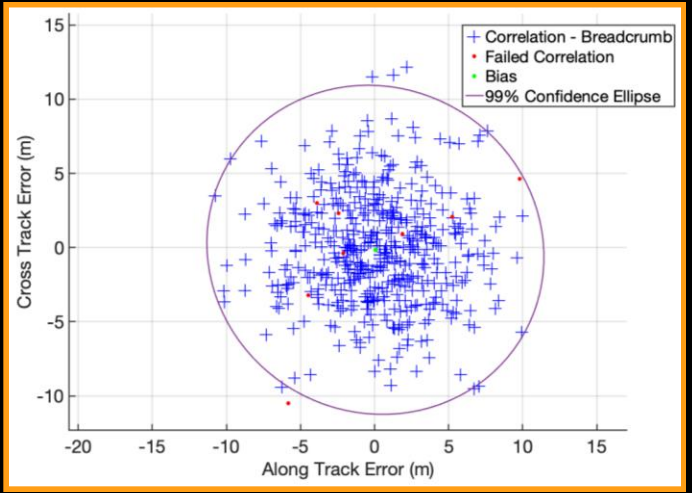
- Performance sensitivities
  - Relative state offset between image A and image B
    - Reduces overlapping signal
    - Projective transform can correct for only so much
  - Relative navigational state knowledge error
    - Error in projective transform will corrupt image registration
  - Error in image correlation due to feature-poor terrain
- Operating Regimes
  - Image to image measurements have low relative navigational state knowledge errors and highly correlated state offsets
  - Breadcrumb measurement error is dominated by higher state knowledge errors and state offsets due to long timespans between correlated image pairs

Relative State Offset



Relative State Knowledge Error





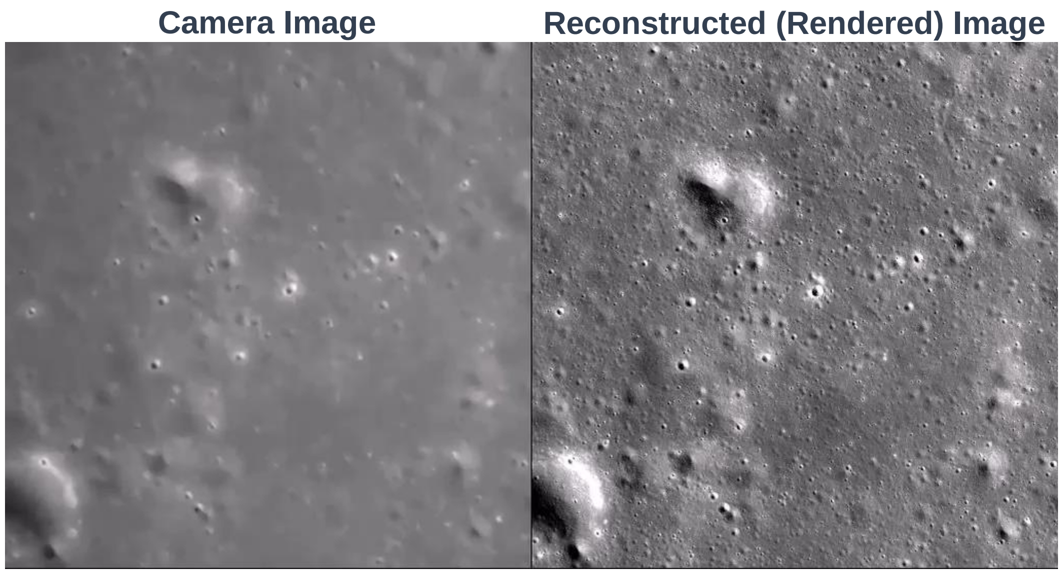
Expected performance of breadcrumb measurements at 400 meter cruise altitude over a dune crest

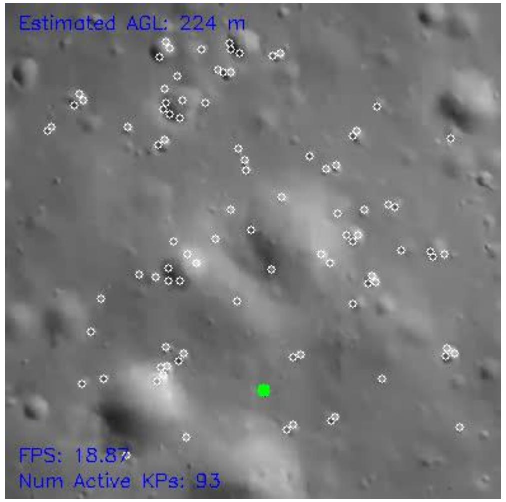
Generalization to Low Altitude Exploration

- Dragonfly's breadcrumb "SLAM-lite" approach could be useful for other resource-constrained missions that are unable to rely on reference maps for navigation
  - Resource constrained, full SLAM not viable
  - Low altitude relocation & scouting
  - Elements are separable (different TRN could be used with BCs)

- Designing for many flights also comes with additional challenges
  - Algorithms to mitigate influence of dust accumulation on TRN, camera degradation
  - Offsets/errors between reference frames between flights
  - Revisiting previously imaged/visited sites

- More modern niche TRN algorithms are also being investigated for extreme precision when terminal descent begins
  - Could supplement traditional lunar & Dragonfly TRN algorithms when approaching landing site





* Chang'e 4 Imagery located at http://moon.bao.ac.cn/

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