Sensing Controls for Space-Based Planet Finding

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Outline

• Overview
• Sensing challenges on Probe-Class Exoplanet Direct Imaging mission concept
• Computer vision (CV) based methods for small satellite proximity operations
• Applications
• Future challenges and future directions
Overview

- Detection and characterization of Earth twins is the most challenging of the space-based planet finding missions.
  - Earth-sized planets with Earth's geometric albedo of 0.2 in the habitable zone
- Proposed designs of direct imaging missions require formation flying of starshades dozens of meters in diameter with telescopes up to four meters in diameter

Figure 4.7-1. Simulated Exo-C image of the 47 UMa system for V band and 2 days integration. The occulted star is at center. Planet c is seen near the inner working angle at top right, while planet d is visible to top left. A hypothetical debris disk extends around them and out of the field of view. [2]
Exo-S: Starshade Probe-Class Exoplanet Direct Imaging

- Design Reference Mission Configurations
  - Kepler-based
  - Extensive flight heritage

Exo-S mission overviews for “Rendezvous Mission” in which starshade works with existing WFIRST observatory and “Dedicated Mission” in which starshade is co-launched with dedicated small observatory. [1]
Figure 6.3-1. Formation flying modes and requirements. [1]
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Formation Flying

- To achieve imaging, formation flying requires laterally aligning the telescope to within 1 m of the starshade-star axis at 30,000 km – 50,000 km range
- Sub-meter position control is routine in orbital rendezvous and docking
  - Sensing is altogether more challenging
  - Positions must be sensed 3 to 5 times more finely than the control requirement
    - Lateral offset of the starshade must be sensed to 30 cm at max separation
    - Bearing measurement precision of 6 nrad (1.25 mas).

Figure 6.3-2. Formation sensing, guidance, and control by formation mode. [1]
Small Satellite Proximity Operations and Formation Flying

Overview

- Gravity Recovery And Climate Experiment (GRACE) [3]
  - Two identical satellites orbit one behind the other in the same orbital plane at an approximate distance of 220 km
  - K-band Ranging System (KBR)
    - Provides precise (within 10 µm) measurements of the distance change between the two satellites needed to measure fluctuations in gravity.
  - Ultra Stable Oscillator (USO)
    - Provides frequency generation for the K-band ranging system
  - GRACE-FO, 2017 (planned)
    - Will include laser ranging

- Space mission and instrument design to image the Habitable Zone of Alpha Centauri (SSC15-XII-1) [4]
  - SMEX-Class, 45 cm dia coronagraph
  - Mini-COR: A Miniature Coronagraph for Interplanetary CubeSats (SSC15-XII-6) [5]
    - Science grade observations of corona and coronal transients from a miniaturized coronagraph
    - Pointing accuracy requirement 60 arcsec
    - Pointing stability over 20 second exposure requirement 10 arcsec
Small Satellite Proximity Operations and Formation Flying

Motivation

- Automated proximity operations (proxops) enable new mission capabilities and enhance SSA
- Current technology has limitations
  - Active illumination (DARPA’s Orbital Express, SpaceX Dragon capsule, ISS SPHERES)
  - Pose estimation based on current view and target model
  - Size, weight, and power (SWAP) limited
- Computer vision (CV) based methods only require camera and CPU
  - No prior knowledge of target required
  - Star tracker-like subsystem on smaller platforms

Research thus far

- Developed a monocular SLAM method for implementation in a proxops simulator
  - SLAM – building a 3D map from relative motion while keeping track of the camera pose (location and orientation)
  - Monocular – explore what is possible with one camera for minimal size constraints
- Designed for the space environment (reflective surfaces, dynamic backgrounds)
- Near real-time operation
- Characterized achieved run-time and accuracy
- Ease of code porting to multiple platforms
**Methodology**

- **Perspective-n-point (PnP) problem**
  - Estimating the pose of one image (Pn) from 2D points with known 3D locations

- **Sequential model construction**
  - Track 2D points from initialization to subsequent frames
  - Use PnP to estimate new pose
  - Proactively triangulate new points as they appear (based on relative motion rate)

Triangulating new points as they appear
CV Feature Detection and Tracking

• Features from Accelerated Segment Test (FAST) corner detector – designed to operate at real-time frame rate [7]
• KLT tracker – sparse optical flow algorithm [8]
  • Updates feature location in next video frame
  • Searches for the most similar window in vicinity
• BRIEF feature – very fast running feature descriptor [9]
  • Used to verify point tracks over larger time scale

Initial FAST corner detection

KLT tracking through rotation without BRIEF
CV Methodology

- Points rotate out of view, new target locations appear
  - Point re-detection based on density in sub-regions
- Error reduction
  - Random sampling and consensus (RANSAC) on the PnP problem
  - Point life threshold based on current motion rate
  - Bundle adjustment – 3D structure and pose optimization based on multiple images
CV Accuracy Analysis Results

- **Sequence 1 stats/pose estimate:**
  - Avg. err: 0.31°
  - STD: 0.27°
  - RMS: 0.46°

Sequence 1 estimated vs. actual vertical axis rotation

Sequence 1 SLAM results: truth and estimated camera pose

Synthetic sequence accuracy results
Summary of CV work

- **Goals accomplished** – space-specific SLAM method
- **Advantages**
  - Produces pose estimates from single target in portion of FOV
  - Robust to dynamic backgrounds and reflective targets
  - Acceptable accuracy, near real-time (avg. 11.8 fps)
  - No target knowledge required, low SWAP requirement
- **Limitations**
  - Sun in FOV, target structural changes, motion blur
- **Paves way for automated proxops on platforms as small as a CubeSat**

Video sequence with saturation [10]
Additional Video Processing

- **Bayesian Point Tracking** [11]
  - Bank of Kalman filters
  - Linear image-plane dynamics
  - Global nearest neighbor association

- **Applications**
  - Object-of-interest segmentation
  - Close-proximity motion estimation
  - Combine with traditional feature tracking techniques

- **Implement on UAS/CubeSat-class hardware**
Autonomous State Estimation and Control For Proximity Operations

- State estimation and observer design for orbit determination [12]
  - High-fidelity propagation incorporating perturbations
- Trajectory optimization for spacecraft relative motion
  - Minimum time
  - Minimum energy
- Nonlinear tracking controller design
  - Robust control (e.g. sliding mode)
  - Adaptive control (e.g. model reference)
Future Challenges and Future Directions

- Sensing and control as mission support
- Combined orbit and attitude control
- Combined estimation and tracking control
- Show system feasibility with small sats / COTS hardware
- Cognition applied to satellite autonomy
Thank you!

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References