Sensing Controls for Space-Based Planet Finding

2015 US Frontiers of Engineering Symposium, 9-11 Sept 2015

Dr. Jonathan Black, jonathan.black@vt.edu

Associate Professor, Aerospace Engineering

Associate Director of Research for Aerospace Systems, Hume Center

Northrop Grumman Senior Faculty Fellow in C4ISR

Abstract

Detection and characterization of Earth twins, defined as Earth-sized planets with Earth's geometric albedo of 0.2 in the habitable zone, is the most challenging of the space-based planet finding missions. Proposed designs include direct imaging missions requiring formation flying of starshades dozens of meters in diameter with telescopes up to four meters in diameter. To achieve imaging, formation flying requires laterally aligning the telescope to within 1 meter of the starshade-star axis at 25,000 km – 50,000 km standoff distances. While sub-meter position control is routine in orbital rendezvous and docking, sensing is altogether more challenging. If positions must be sensed 3 to 5 times more finely than the control requirement, the lateral offset of the starshade must be sensed to 30 cm at max separation. This offset corresponds to a bearing measurement precision of 6 nrad (1.25 mas).

This paper presents the cutting-edge in sensing controls for formation flying and satellite proximity operations primarily focused on enabling autonomy for small satellites, and discusses current challenges and limitations on advances that are required to apply those technologies to space-based planet finding missions, recent work in the field, and the long-term challenges.

Background

Detection and characterization of Earth twins is the most challenging of the space-based planet finding missions. For the purposes of this paper, Earth twins are defined as Earth-sized planets with Earth's geometric albedo of 0.2 in the habitable zone. NASA recently commissioned two studies to produce exoplanet direct imaging design reference missions (DRMs), one based on a coronagraph observatory (Exo-C 2015) and one based on a free-flying starshade dozens of meters in diameter with a telescope up to four meters in diameter (Exo-S 2015). The Exo-S DRMs were based on the Kepler observatory and leveraged satellite technologies with extensive flight heritage. The Exo-S graphical overview is shown in Figure 1.

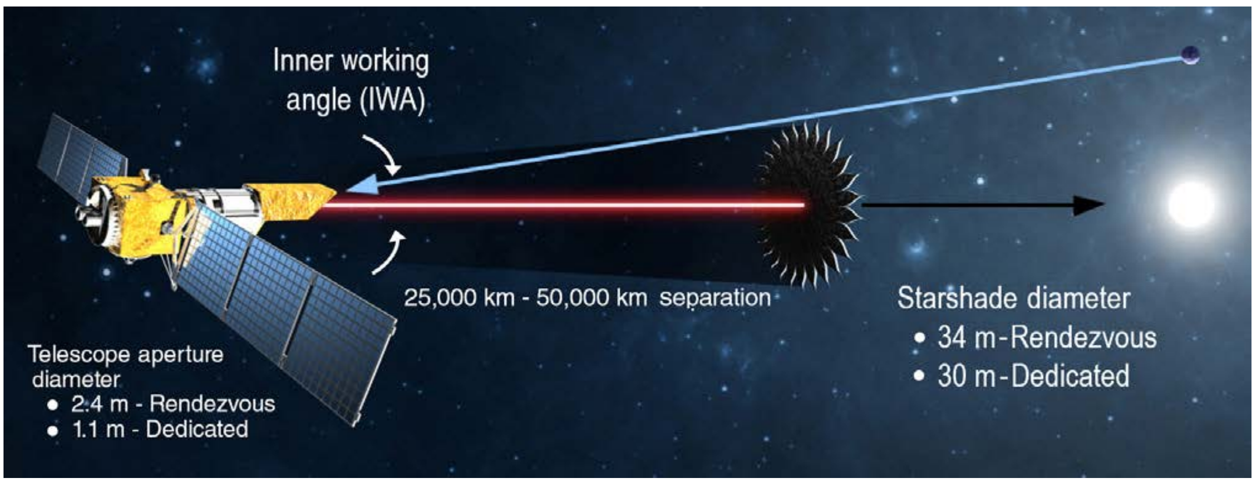

Figure 1. Exo-S mission overviews for "Rendezvous Mission" in which starshade works with existing WFIRST observatory and "Dedicated Mission" in which starshade is co-launched with dedicated small observatory (Exo-S 2015).

Formation Flying

Achieving direct imaging requires laterally aligning the telescope to within 1 m of the starshade-star axis at 25,000 km – 50,000 km separation between the star shade and the observatory, as shown in Figure 1. While this sub-meter position control is routine in orbital rendezvous and docking, sensing in this case is altogether more challenging as positions must be sensed three to five times more finely than the control requirement. The lateral offset of the starshade must therefore be sensed to 30 cm at maximum separation, yielding a bearing measurement precision of 6 nrad (1.25 mas) during imaging

(Exo-S 2015). The sensing requirements during all phases of observatory operation are shown in Figure 2 and Figure 3.

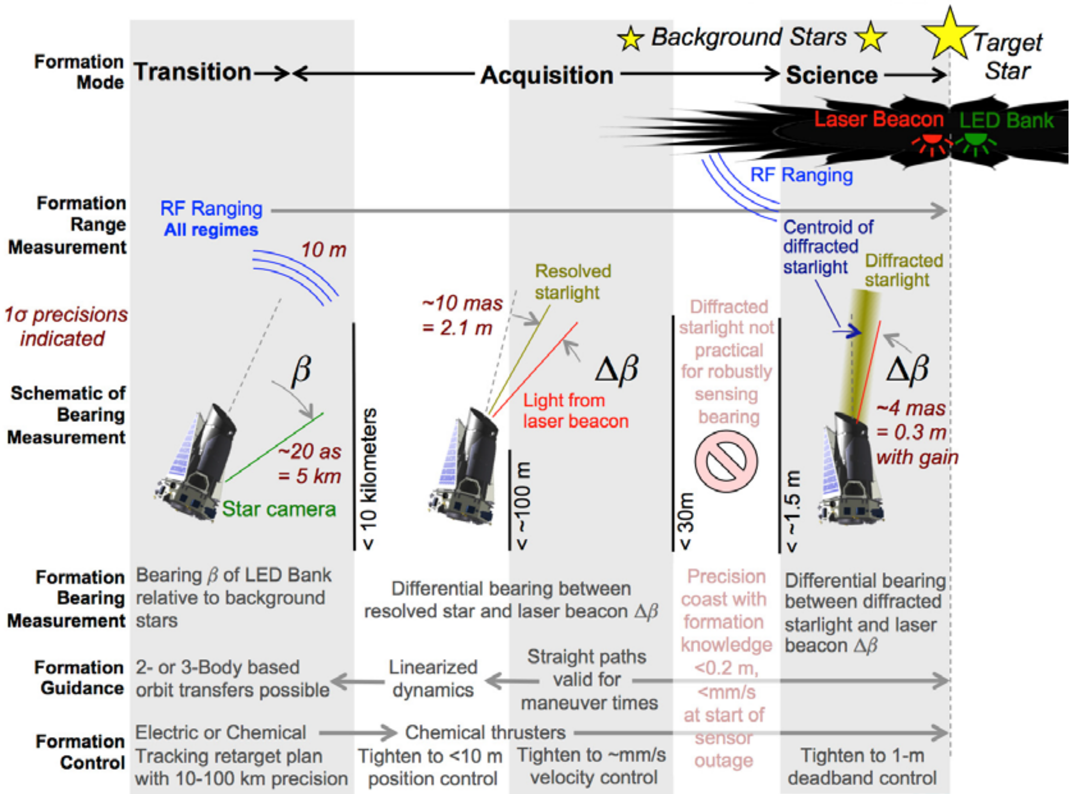

Figure 2. Formation sensing, guidance, and control by formation mode (Fig. 6.3-2, Exo-S 2015).

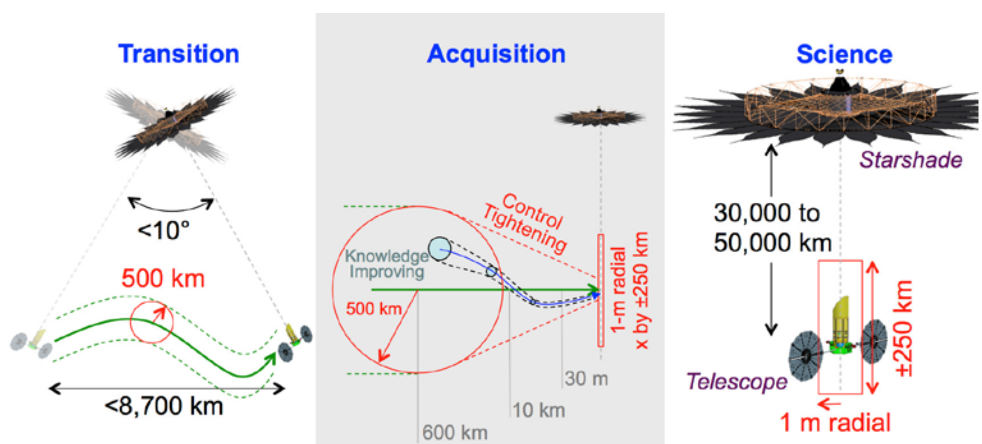

Figure 3. Formation flying modes and requirements (Fig. 6.3-1, Exo-S 2015).

Small Satellite Proximity Operations and Formation Flying

Automated proximity operations (proxops) has enabled new mission capabilities and enhanced space situational awareness (SSA), but previous missions had limitations requiring additional technology development for the exoplanet direct imaging application. Several successful flight missions, including DARPA's Orbital Express and the SpaceX Dragon capsule docking with the International Space Station require active external illumination and sensing (DARPA 2014, Ogilvie 2008), which will not be possible in the planned deep space orbits of the exoplanet direct imaging observatories.

Computer vision (CV) based sensing methods only require a camera and CPU, and no a priori knowledge of the target. Star tracker-like subsystems on smaller spacecraft can also be used. Research so far in this field has developed a monocular simultaneous localization and mapping (SLAM) method for implementation on a proxops simulator. The use of monocular SLAM results in a 3D map from relative motion while tracking the camera pose (location and orientation). Initial results of the space-specific monocular SLAM method produced depth and pose estimates of targets, is robust to the dynamic backgrounds and highly reflective surfaces in the space environment, has shown average error on the order of 0.31° (0.27° standard deviation, 0.46° RMS), and runs in near real-time of 11.8 frames per second (fps). It is again important to note that no a priori target knowledge is required to generate 3D models. These results, samples of which are shown in Figure 4 and Figure 5, pave the way for automated proxops on platforms as small as a CubeSat.

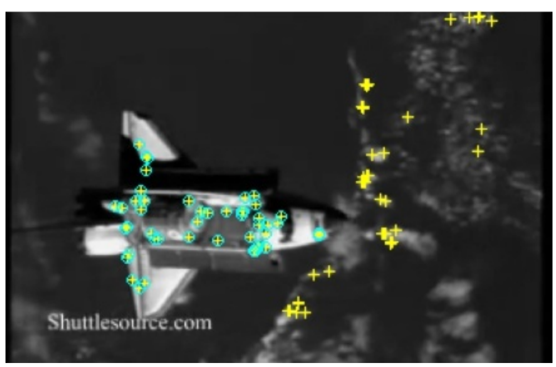

Figure 4. Frame from processed shuttle video showing identified feature points

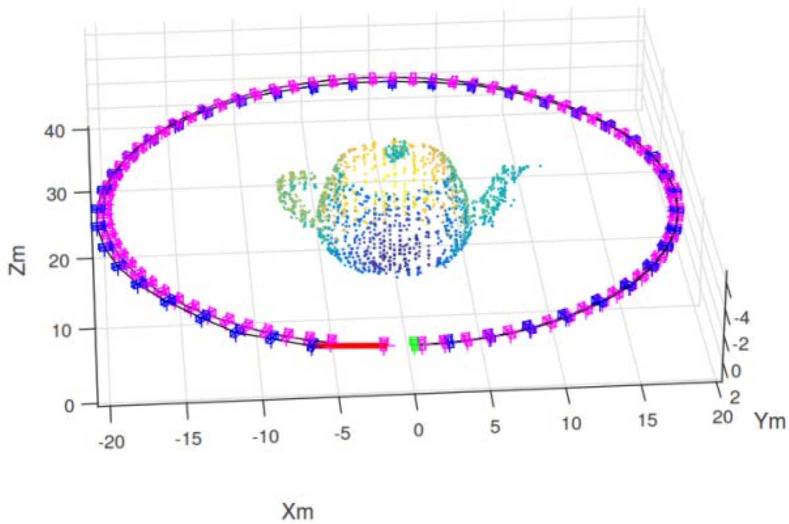

Figure 5. Sample monocular SLAM results showing truth (blue) and estimated camera position and pose

Autonomous state estimation and control is another of the key technology enablers of precision formation flying operations required by exoplanet direct imaging. This work is a unique approach to autonomous fuel/time optimal trajectory optimization for relative reconfiguration of two objects in perturbed elliptical orbits. The relative motion model for the deputy satellite with respect to the chief is well-approximated using a fully-nonlinear state transition matrix. Control is applied in the in-track and cross-track directions, making this system under-actuated but reachable for any formation flying orbit. The system is discretized using a zero-order hold on the input and the control signals are computed using a linear program which results in a bang-off-bang control profile. A balance between the time-of-flight and the required fuel are analyzed using a genetic algorithm. Combining the new estimation with the tracking control will produce a novel, robust, and computationally light (autonomous) optimal terminal guidance capability, a sample of which is shown in Figure 6.

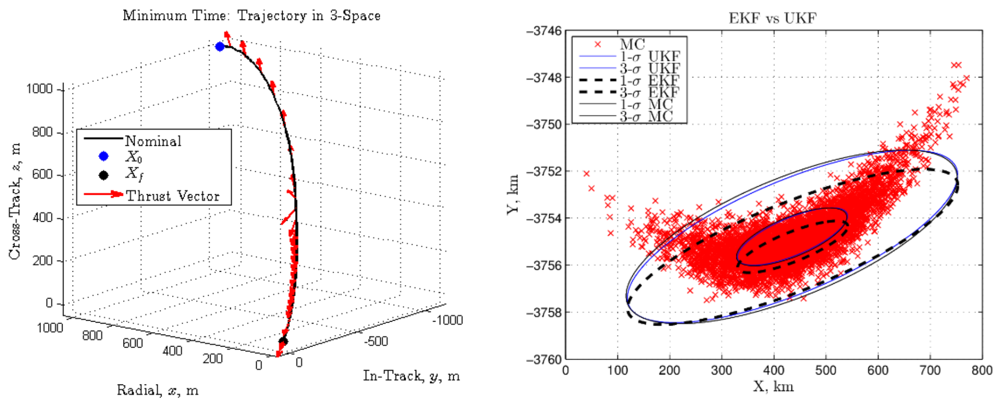

Figure 6. Control inputs for tracking minimum time trajectory (left) and high-order state estimation (right).

Future challenges and future directions

The sensing controls required to enable the precision formation flying of starshades and observatories tens of thousands of kilometers apart in deep space are an extreme engineering challenge. The current state of the art technology development in formation flying and spacecraft autonomy in small satellites will need to be adapted to the exoplanet direct imaging missions to ensure mission success. In the end it is likely that the sensing task will be coupled to the autonomous orbital and attitude control systems discussed here, and may also require machine learning and cognition.

References

"Exo-S: Starshade Probe-Class Exoplanet Direct Imaging Mission Concept, Final Report," ExoPlanet Exploration Program, Astronomy, Physics and Space Technology Directorate, Jet Propulsion Laboratory, Mar. 2015, CL#15-1155, http://exep.jpl.nasa.gov/stdt/, accessed Mar. 2015.

"Exo-C: Imaging Nearby Worlds, Final Report," Science and Technology Definition Team, ExoPlanet Exploration Program, Astronomy, Physics and Space Technology Directorate, Jet Propulsion Laboratory, Mar. 2015, CL#15-1197, http://exep.jpl.nasa.gov/stdt/, accessed Mar. 2015.

DARPA Tactical Technology Office (TTO), "Orbital Express Data Archive," http://archive.darpa.mil/orbitalexpress/index.html, accessed Nov. 2014.

Ogilvie, A., Allport, J., Hannah, M., Lymer, J., "Autonomous Robotic Operations for On-orbit Satellite Servicing, Proc. SPIE, 6958:695809-12, 2008.