Autonomous Nanosatellite Swarming (ANS) Using Radio Frequency and Optical Navigation

A Distributed Approach to Low-Cost Small Body Exploration

The Autonomous Nanosatellite Swarming (ANS) subsystem is a dynamics, guidance, navigation, and control software unit based on commercial-off-the-shelf avionics, which is distributed and deployed on a cluster of cooperative nanosatellites to enable future exploration missions to near-Earth objects (NEOs). ANS allows multiple nanosatellites to act together as a single large spacecraft through radio-frequency (RF) cross-links, optical navigation, and low-thrust control. In particular, ANS-equipped nanosatellites can utilize images of a NEO taken from multiple viewpoints to achieve stereo-vision capabilities and characterize the target body’s shape, gravity field, and dynamical properties. All this is enabled by the fusion of major advances to the state of the art in the astrodynamics of relative motion, RF and vision-based navigation, as well as low-thrust control.

The backbone of ANS is a new accurate and efficient closed-form propagation of the satellite relative motion in the presence of all perturbations of interest based on relative orbit elements. The analytical nature of this novel theory allows the design and coordination of swarms with exceptional long-term properties. ANS combines RF and optical observables to robustly determine the carrier-phase integer ambiguities and consequently exploit range measurements with millimeter-level noise for relative navigation. The raw measurements used by ANS are provided by a customized nanosatellite sensor suite including cameras for vision and infrared navigation, and high-frequency RF links for communication and ranging. Even in the absence of RF links, ANS can navigate the swarm through angles-only measurements obtained from centroids of the co-orbiting vehicles seen in an individual camera’s field of view. To this end, a nonlinear filter formulation is used to improve the observability of the dynamics system in the absence of range measurements.

The primary application of ANS is the robust onboard characterization of NEOs using swarms of small satellites, potentially reducing the cost of small-body missions while dramatically increasing their scientific output. NEOs are of particular interest to the space exploration community for their accessibility and resource value. However, the ANS subsystem could be readily applied to the characterization of other space-resident objects, including main belt and trojan asteroids and man-made objects. The potential new applications are manifold, and ANS is designed to support the broadest range of operational scenarios and inter-satellite distances. These encompass diverse orbit regimes including swarm deployment from a mothership spacecraft, quick forced-motion control reconfigurations, and long-term passively safe and stable relative orbits in close proximity with minimal actuation.

ANS is being developed by the Space Rendezvous Laboratory (SLAB) in Stanford University’s Department of Aeronautics and Astronautics, in collaboration with NASA Ames Research Center. SLAB features custom high-fidelity virtual reality devices and a 7-degree-of-freedom robotic testbed for the real-time stimulation of ANS in closed-loop under realistic illumination conditions. The project lever-
ages algorithms, software, and hardware under development at SLAB, as well as state-of-the-art techniques demonstrated on recent formation-flying missions such as the Hyperspectral Precursor of the Application Mission (PRISMA) by OHB Sweden, the German Aerospace Center (DLR), and the National Center for Space Studies (CNES) as well as NASA's CubeSat Proximity Operations Demonstration (CPOD) mission.

The ANS project is managed and funded by the Small Spacecraft Technology Program (SSTP) within the Space Technology Mission Directorate. The SSTP expands U.S. capability to execute unique missions through rapid development and in space demonstration of capabilities for small spacecraft applicable to exploration, science, and the commercial space sector. The SSTP will enable new mission architectures through the use of small spacecraft with goals to expand their reach to new destinations, and challenging new environments.

For more information about the SSTP, visit: www.nasa.gov/directorates/spacetech/small_spacecraft

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High-fidelity verification testbed at Stanford University’s Space Rendezvous Laboratory (SLAB).
Left: high-performance Kuka Agilus robotic arm in space environment simulator with photometrically-calibrated illumination panels.
Top right: virtual reality optical stimulator.
Bottom right: Tyvak Nano-Satellite Systems, Inc. flatsat microcomputers and satellite-to-satellite cross-link.