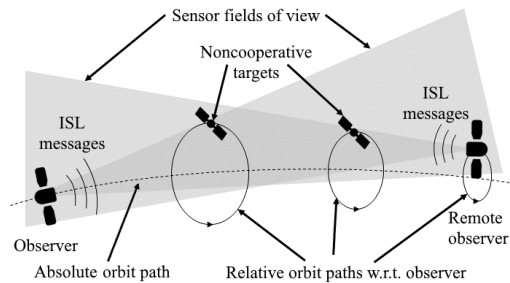


Absolute and Relative Trajectory Measurement System (ARTMS)

Autonomous Angles-Only Navigation for Spacecraft Swarms

The Absolute and Relative Trajectory Measurement System (ARTMS) is a software payload that enables swarms of cooperative observers equipped with low-cost optical sensors to simultaneously estimate their own orbits and the orbits of nearby non-cooperative resident space objects using only bearing angle measurements. ARTMS improves upon the state of the art in angles-only navigation by overcoming key limitations of previous flight demonstrations, including: 1) reliance on accurate a-priori relative orbit information from the ground, 2) inability to accommodate multiple observers or targets, 3) reliance on maneuvers to improve observability, and 4) reliance on external metrologies such as GPS to estimate the observer absolute orbit. In contrast, ARTMS applies innovative algorithms within a multi-agent framework to estimate the orbits of multiple observers and targets autonomously onboard in real-time. ARTMS meets key needs of future deep space missions by providing autonomous, robust, and scalable absolute and relative navigation using low-cost smallsat hardware and with minimal reliance on maneuvers and ground interaction.

Angles-only navigation in orbit is characterized by weak observability due to the lack of range information provided by the measurements. To overcome this, the ARTMS architecture applies three core algorithms. First, Image Processing (IMP) leverages domain-specific modeling of target kinematics and multi-hypothesis techniques to identify and track multiple targets in images from a single camera without a-priori relative orbit knowledge. Second, a new Batch Orbit Determination (BOD) algorithm applies a relative orbital element state definition to provide initial estimates of the orbits of all spacecraft in the local swarm, using a one-dimensional sampling scheme to resolve the weakly-observable range to each target. Third, a Sequential Orbit Determination (SOD) algorithm based on the unscented Kalman filter



An example ARTMS scenario. Two cooperative observers (outside) with vision-based sensors obtain bearing angles to each other and to two noncooperative targets (inside). Measurement information is exchanged between observers via the ISL.

continuously estimates the orbits and auxiliary parameters of the local swarm by seamlessly fusing measurements from multiple observers shared over an inter-satellite link (ISL). The ARTMS instance on each observer can autonomously 1) form batches of bearing angles corresponding to each visible target, 2) initialize an orbit estimate for each target, and 3) refine the complete swarm state estimate over time. The only a-priori information required is a coarse orbit estimate for each observer.

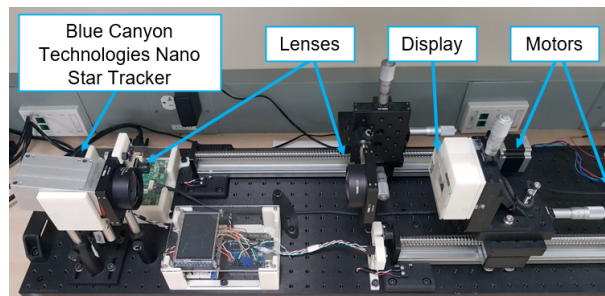
ARTMS will be flight-tested on board the NASA Starling mission (2022), which aims to be the first-ever demonstration of angles-only swarm navigation in orbit. It has also been proposed as an enabler for future swarm missions in deep space that require distributed or repetitive measurements at spatial/temporal scales impossible to obtain with a single spacecraft. Example objectives are characterization of solar winds, planetary atmospheres, and magnetic fields. ARTMS can be used to support a more accurate primary swarm navigation system, or to provide distributed navigation for a larger flagship via a deployed nanosatellite swarm. ARTMS additionally enables more

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general use of smallsat swarms in deep space – for example, to act as communications relays in lunar orbit or for monitoring of the Lunar Gateway.

ARTMS is developed by the Space Rendezvous Laboratory (SLAB) at Stanford University's Department of Aeronautics and Astronautics, as part of Starling efforts, and in collaboration with NASA Ames Research Center and the NASA Jet Propulsion Laboratory. The project leverages algorithms, software, and hardware developed by SLAB, as well as state-of-the-art research demonstrated on formation-flying missions such as PRISMA (SSC, DLR, CNES).

The project is funded by the Small Spacecraft Technology Program (SSTP) within the Space Technology Mission Directorate. The SSTP develops and matures technologies to enhance the capabilities of small spacecraft applicable to exploration, science, and the commercial sector. The SSTP will enable new mission architectures through use of small spacecraft and will expand their reach to challenging new destinations and environments.



ARTMS is validated using the SLAB Optical Stimulator (OS) and a Blue Canyon Technologies Nano Star Tracker. The OS is a variable-magnification testbed consisting of two lenses and a microdisplay. Synthetic space scenes are generated and shown on the display. By moving the lenses and display, the tested sensor is stimulated with similar radiosity and geometry to what would be observed in orbit.

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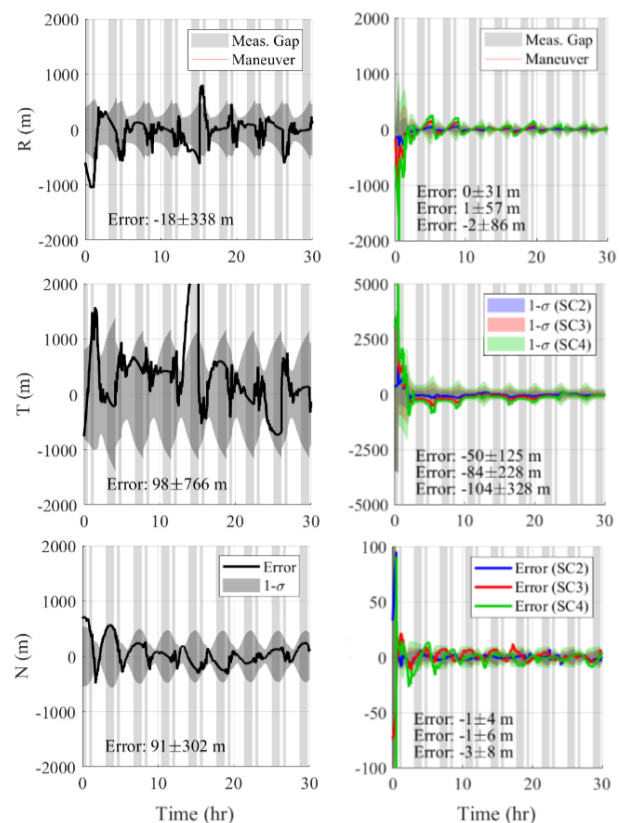
FS #2021-05-01-ARC

For more information about SSTP, visit:
<http://www.nasa.gov/smallsats>

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ARTMS absolute (left) and relative (right) position navigation errors and 1- σ covariance bounds in the (R)adial, (T)angential, (N)ormal directions. The swarm consists of two observers and two targets in an eccentric Mars orbit at 50-150 km inter-satellite separations. Results show 1km absolute position accuracy and relative position accuracy of $\leq 0.2\%$ of target range. Clock offsets between observers are estimated to within 0.02s.