CAPSTONE: An Ongoing Demonstration of Navigation and Autonomy Technologies in the Cislunar Domain

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Introduction: NASA, Advanced Space, Terran Orbital, Rocket Lab, Stellar Exploration, JPL, the Space Dynamics Lab, and Tethers Unlimited have partnered to successfully develop, launch, and operate the Cislunar Autonomous Positioning System Technology Operations and Navigation Experiment (CAPSTONE) mission, which is serving as a dedicated precursor for Near Rectilinear Halo Orbit (NHRO) operations in cislunar space. Over the past 26 months, this low-cost, high-value mission has demonstrated an efficient, low-energy orbital transfer to the Moon, a successful insertion into the NRHO, and completion of ~20 months of successful operations in the NRHO while successfully demonstrating key technologies in support of the NASA Artemis program. These technologies include 1) The successful demonstration of the CAPS autonomous navigation technology using both two-way ranging with the Lunar Reconnaissance Orbiter (LRO) and one-way uplink ranging with the Deep Space Network 2) Successful demonstration of our Neural Net for Electric Propulsion (NNEP) technology for autonomous maneuver planning and execution within a neural net framework and 3) Successful demonstration of our Sigma Zero technology for anomaly detection and classification via a neural network model.

The Cislunar Autonomous Positioning System (CAPS) is a peer-to-peer real-time system for estimating absolute position and velocity for spacecraft operating in the cislunar environment. The CAPSTONE spacecraft has executed multiple successful ranging passes with LRO and validated the CAPS algorithm performance via onboard real-time execution of the CAPS software. The software has also but used estimate absolute navigation using one-way uplink ranging using the SDL Iris radio along with a high-precision Chip Scale Atomic Clock (CSAC) and embedded software algorithms provided by JPL. The CAPS software enables cislunar missions to manage their navigation functions themselves and reduces the reliance on Earth based systems.

NNEP is a maneuver design algorithm that uses neural networks as function approximators to map the current state of a spacecraft to a corresponding maneuver. The onboard test on CASPTONE successfully demonstrated a neural network trained to design the orbital maintenance maneuvers (OMMs) for CAPSTONE. The test used actual historical state estimates from CAPSTONE, and the maneuver(s) designed will be compared to the as-flown truth.

Sigma Zero performs anomaly detection and classification via a neural network model. CAPSTONE has successfully executed the onboard test of this software, downlinked the neural network output as telemetry packets, and verified that the result matches what was expected. The onboard testing used simulated data generated on the ground to correctly identify a maneuver mismodel in Kalman filter post-fit residuals. Subsequent testing was successfully executed to identify and autonomously classify eight additional types of anomalies (i.e. , mass properties mismodel, SRP mismodel, unplanned spinning spacecraft, etc.).

This presentation and paper will include an overview of the current mission status, lessons learned from the 2+ years of highly successful ongoing operations in the NRHO, a summary of the challenges encountered thus far, and overview of the successful results from the CAPS, NNEP, and Sigma Zero autonomous navigation technology demonstrations to date.

CAPSTONE Launch: 28 June, 2022