Enabling Deep Space Exploration Using Inspectors Accompanying Small Spacecraft System of Systems Architecture

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The aerospace industry has widely adopted small spacecraft thanks to the miniaturization of electronics, sensors, actuators, and power systems. Thanks to these advancements, we see increasingly ambitious missions to explore the four corners of the solar system. These new exploration targets will require small satellites to travel further and faster, communicate at higher bandwidths, and operate longer. Achieving these target capabilities with miniaturization alone will be challenging. Here lies the opportunity for multiple modular small satellites to be assembled to form a structured system of systems. This aggregation of small spacecraft can enhance required redundancy, increase range and velocity, enhance communications, and achieve long mission life. The challenge, however, is to develop a robust yet reconfigurable system of systems architecture.

Given that these crafts will be operating far away from Earth, they will need to operate autonomously and handle unexpected mission scenarios. A key enabler for this aggregating architecture is its ability to be dynamically reconfigured based on needs. In response to these challenges, we are evaluating vision-based machine learning methods to simplify depth perception, navigation, and manipulation in 3D workspace using monocular cameras. The conventional approach to depth estimation involves either the use of multiple cameras, such as the case in motion capture in movie studios or the use of costly and time-consuming techniques, such as human-in-the-loop interventions or deployment of large equipment with the use of inspector spacecraft outfitters with single vision sensors.

Singular vision sensors pose difficulties in space, especially for spacecraft for attitude estimation since it becomes more challenging to estimate the target spacecraft's pose (position and orientation) over image sequences and to determine the state space of the target spacecraft module. Finding and calculating the target spacecraft module's pose and velocity using monocular image sequences will be a key milestone in this approach. For these reconfigurable deep space travelers, we envision they would carry a small fleet of miniature inspector spacecraft. This is akin to deep sea whales or sharks accompanied by a remora fish that removes parasites from the mouth and skin of these larger creatures.

Each inspector spacecraft could be a CubeSat, such as a 3U CubeSat (30 cm × 10 cm × 10cm). We propose the use of Machine Learning Algorithms such as Convolutional Neural Networks (CNNs), Recursive Neural Networks (RNNs), Autoencoders, and Random Forest Regressionors, which are tailored to the exact specifications of these spacecraft inspection missions.

The project will employ a multifaceted approach incorporating innovative technologies, such as computationally efficient frameworks, simulated settings, and computer vision algorithms with convolutional neural networks (CNNs), which allow generating bounding boxes around the target spacecraft to detect and pinpoint them within the photos. Then, pose estimation is applied, which can then be used to detect image sequence changes in the position and orientation of the target spacecraft concerning the inspector spacecraft camera. This is vital information for an accurate inspection. The training and validation data ranges from simulated synthetic data to real-world test data from lighting-calibrated test facilities. Working in simulated situations enables generating algorithms to undergo extensive testing and validation. Testing the generated algorithms in real-world situations guarantees their resilience and efficacy. Maximizing the hardware resource utilization ensures accurate range and efficient processing, two things necessary to successfully complete inspection tasks in an interplanetary environment.