National Aeronautics and Space Administration

NASAfacts

Smoothing-Based Relative Navigation & Coded Aperture Imaging

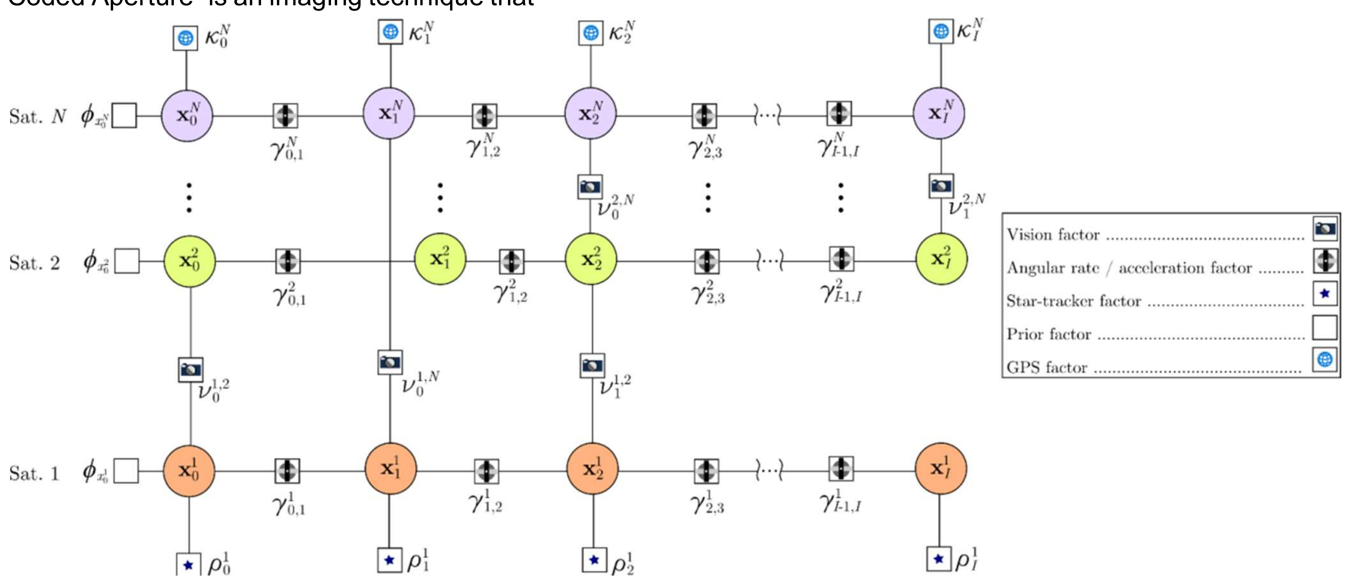
Time-windowed Smoothing for Multi-Satellite State Estimation

This project proposes to develop time-windowed, efficient smoothing software for incremental estimation of the relative poses and velocities between multiple, small (potentially differently instrumented), spacecraft as well as a small, long range depth sensor based on coded aperture imaging capable of sensing other spacecraft in the formation. The smoothing algorithm will obtain the maximum *a posteriori* estimate of the relative poses between the spacecraft through the use of all available sensor information. It will be inherently portable between different satellite platforms possessing different sensor suites and computational capabilities, and adaptable in the case that one or more satellites become inoperable. It will obtain a solution which approaches an exact solution, as opposed to one with baked-in linearization errors typical of filtering algorithms. Thus, the algorithms developed and demonstrated as part of this program will enhance the applicability of small spacecraft to multi-platform operations, like precisely aligned constellations and fractionated satellite systems. "Depth from Coded Aperture" is an imaging technique that allows a depth map to be computed. It operates using a typical passive monocular camera whose circular aperture is replaced by a patterned, or coded, aperture that has high frequency components. By setting the scene out of focus, the size of the imaged aperture code is a function of the depth of the scene.

Smoothing is an estimation approach that seeks a solution which maximizes the *a posteriori* probability of all estimated variables $\boldsymbol{\Theta}$ given the observations $\mathbf{Z}$, and control inputs $\mathbf{U}$ and measurement model $h(\boldsymbol{\theta}_i)$. The problem can be stated as a nonlinear optimization problem.

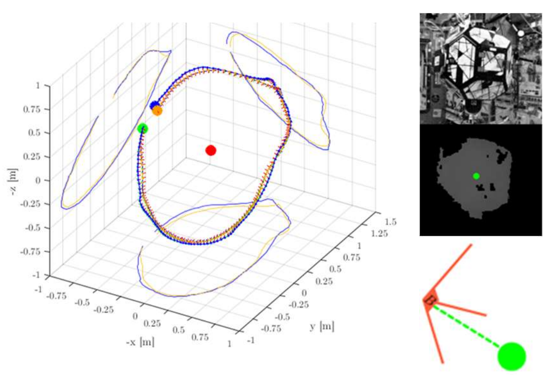
$$\begin{aligned}\boldsymbol{\Theta}^* &= \underset{\boldsymbol{\Theta}}{\operatorname{argmax}}\, P(\boldsymbol{\Theta}, \mathbf{Z}, \mathbf{U}) \\ &= \underset{\boldsymbol{\Theta}}{\operatorname{argmin}} \frac{1}{2} \sum_i \parallel h(\boldsymbol{\theta}_i) - \mathbf{z}_i \parallel^2_{\boldsymbol{\Sigma}_i}\end{aligned}$$

The probability distribution $P(\boldsymbol{\Theta}, \mathbf{Z}, \mathbf{U})$ is separated into the product of several independent factors, allowing the problem to be visually represented as a factor graph



An example factor graph representation of the joint probability distribution for multi-satellite pose and velocity determination.

(see Figure) and solved efficiently. N small satellites make occasional visual observations of one another (vision factors v). Long sequences of high frequency angular rate and acceleration data are lumped into individual factors γ. The positions of the satellites can be further constrained by star-tracker measurement factors ρ and GPS measurement factors κ, which constrain the absolute rotation and position, respectively, of the satellite to which they are applied. A sliding time window can be used to limit the number of variables in the factor graph and bound the processing and memory requirements associated with obtaining a solution. Each satellite with adequate computational power solves the full factor graph. A communications link is used to send measurements from one satellite to another. The smoothing algorithm will be implemented in C++ and make use of the publicly available GTSAM software library that provides an extensive set of modular tools for creating and solving factor graphs. It will be verified experimentally using SPHERES-VERTIGO on the ISS. The Coded Aperture imaging technique relies on the use of long-range cameras that include a mask at its aperture instead of a traditional circular aperture. This mask includes high frequency components that enable an intentionally out-of-focus scene to be captured. The size of the resulting imaged aperture code provides a direct measure of the depth of the objects within the scene. The depth accuracy using this technique is linearly related to the depth resolution of the camera; this project develops a set of coded aperture depth cameras that can be integrated with the



Visual-inertial (blue) and range- bearing-inertial (orange) smoothing results.

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smoothing algorithms to perform relative navigation maneuvers to provide multi-satellite relative pose and velocity estimation rapidly and autonomously.

The project's computationally efficient smoothing algorithm for determining relative pose and velocity is applicable to a wide variety of NASA missions. It could enable constellations of small spacecraft with less sophisticated instruments to fly in close formation by making better use of the available sensor information. For satellite servicing missions, this technology could be used to enhance the accuracy and precision with which relative pose and velocity estimation is performed, improving the probability of mission success. Inspection of space debris or defunct satellites prior to their deorbit or servicing is a potential commercial application of the proposed technology. All software developed by this program will be made publicly available under an open source license to simplify and encourage its adoption by other missions. Coded aperture cameras that can provide long range depth sensing would be applicable to a number of NASA missions including formation flight, planetary entry, descent and landing and UAV flights (specifically on Mars and other planets and in GPS denied environments).

The project is managed by the Small Spacecraft Technology Program (SSTP), which is chartered to develop and mature technologies to enhance and expand the capabilities of small spacecraft with a particular focus on communications, propulsion, pointing, power, and autonomous operations. The SSTP is one of nine programs within NASA's Space Technology Mission Directorate (STMD).

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