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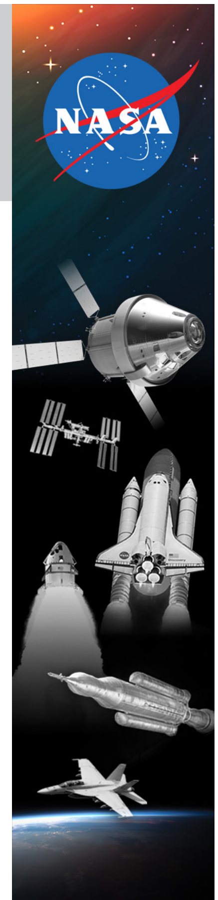

Navigation Filter Design Best Practices

Onboard navigation and attitude estimation systems are at the heart of almost all of NASA's missions, either on launch vehicles, robotic science spacecraft, or on crewed human exploration vehicles. Best practices for attitude estimation systems/filters are scattered throughout open literature, however, even within NASA there has been no previous attempt to codify this knowledge into a readily available design handbook. Without such a document, it is possible for isolated practitioners to lack understanding and appreciation of many tried and true approaches to successful and robust filter design and the implied cost/benefit trades associated with them. To aid designers of current and future missions, a handbook of navigation filter best practices has been developed and is introduced here [1]. The development of this document is also an outgrowth of a recommendation made in an NESC summary of lessons learned from the DARPA Orbital Express mission to utilize best practices for rendezvous navigation filter design [3]. With this handbook, future designers have a reference that establishes NASA's best practices.

Background

Safe and reliably-performing navigation systems are essential elements for a wide variety of missions. These include routine low-Earth orbiting science missions, rendezvous and proximity operation missions or precision-formation flying missions (where relative navigation is a necessity), navigation through the solar system, precision landing on planets/small bodies, and many more mission types.

NASA pioneered the use of the Extended Kalman Filter (EKF) for onboard navigation of the Apollo missions' lunar rendezvous. The story of the development of the EKF has been well-chronicled [2]. However, the accumulated art and lore, tips and tricks, and other institutional knowledge that NASA navigators have employed to design and operate EKFs is much less well-known. This body of knowledge has been used to support dozens of missions in the Gemini/Apollo era, well over one hundred Space Shuttle missions, and numerous robotic missions, without a failure ever attributed to an EKF.

Summary of Navigation Filter Best Practices

This bulletin only presents a few of the onboard navigation filter best practices, but sets the stage for the reader to delve into a more comprehensive set in the reference below.

a. Maintain an accurate representation of the target-chaser relative state estimation errors, including an accurate variance-covariance matrix. This allows the filter to compute an appropriate gain matrix. It also aids the filter in appropriately editing unsuitable measurements.

b. Provide a capability for measurement underweighting that adapts to the current uncertainty in the filters state estimation error, as required to be consistent with the suboptimality of the navigation filters measurement update. Multiplicative adjustment of the measurement noise covariance matrix within the computation of the residual covariance has been found to be less effective and is not recommended unless other methods are not feasible.

c. Estimate states that model biases in sensor measurements and account for unmodeled accelerations. Gauss-Markov models for these biases have been found to be more effective than random-constant or random walk models. Random-constant models can become stale, and random walk models can overflow during long periods without measurement updates.

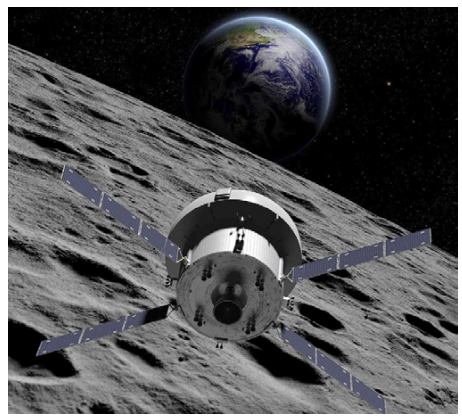

Illustration of Orion spacecraft in lunar orbit

d. Provide commands that allow for selective processing of individual measurement types. If the filter utilizes an automated residual-edit process, then the recommended command capability should be able to override the residual-edit test.

e. Maintain a backup ephemeris, unaltered by measurement updates since initialization, which can be used to restart the filter without uplink of a new state vector.

f. Provide a capability for reinitializing the covariance matrix without altering the current state estimate.

g. Ensure tuning parameters can be uplinked to the spacecraft and are capable of being introduced to the filter without loss of onboard-navigation data.

h. Provide flexibility to take advantage of sensors and sensor suites full capability over all operating ranges.

References

1. Navigation Filter Best Practices, J.R. Carpenter and C.N. D'Souza Eds., 2018, NASA/TP-2018-219822
2. S.F. Schmidt. The Kalman Filter - Its Recognition and Development for Aerospace Applications. Journal of Guidance, Control, and Dynamics, 4(1):4–7, 2016/01/09 1981.
3. C.J. Dennehy and J.R. Carpenter. A Summary Of The Rendezvous, Proximity Operations, Docking, And Undocking (RPODU) Lessons Learned From The Defense Advanced Research Project Agency (DARPA) Orbital Express (OE) Demonstration System Mission. NASA/TM-2011-217088, NASA Engineering and Safety Center, 2011.

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