Closed Loop Guidance Trade Study for Space Launch System Block-1B Vehicle

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NASA is currently building the Space Launch System (SLS) Block-1 launch vehicle for the Exploration Mission 1 (EM-1) test flight. Since EM-1 has an exo-atmospheric flight profile similar to the Space Shuttle, Block-1 guidance utilizes the shuttle-heritage Powered Explicit Guidance (PEG) algorithm. The Block-1 implementation of PEG has been thoroughly tested, and is robust to certain failure scenarios, including loss of a single core engine.

Meanwhile, the design of the next evolution of SLS, Block-1B, is well underway. The Block-1B vehicle is more capable overall than Block-1, however the Exploration Upper Stage (EUS) has a relatively low thrust-to-weight ratio, particularly when compared with the very high acceleration of the core stage. The low thrust of the EUS, combined with insertion into a higher energy orbit, creates a significantly longer ascent profile for Block-1B (on the order of 1000 seconds). This flight profile presents a challenge for any guidance law, especially when considering failure scenarios such as a single engine failure.

A trade study was conducted to evaluate potential alternative guidance algorithms for the Block-1B and follow-on SLS vehicles. Two algorithms were examined, PEG and OPGUID. The Block-1 implementation of PEG was used as a starting point for the trade study. OPGUID is a closed loop guidance algorithm developed in-house at Marshall Space Flight Center, and was used for the Constellation program, official Block-1 Interim Cryogenic Propulsion Stage (ICPS) in-space insight trajectories, and advanced GN&C projects.

During the trade study, the SLS guidance team was divided into two mini-teams, with each one specifically focused on investigating, understanding, and improving one of the algorithms. Each team had access to an expert consultant who had many years of experience with their respective algorithm.

PEG was used for the duration of the Space Shuttle program, and an updated implementation will be used for Block-1. As such, PEG has significant heritage, including both flight heritage on actual launch vehicles and experience by guidance analysts who have used the algorithm and published papers on it, yielding a significant knowledge basis.

OPGUID has its basis in optimal control theory, solving the full state and co-state equations. OPGUID avoids many of the assumptions made by PEG and other ascent guidance algorithms, and thus better avoids many of the difficulties inherent to the long-duration, long burn arc ascents of the Block-1B vehicle. OPGUID has been used successfully at MSFC for a variety of projects.

The chosen algorithm needs to support a wide variety of mission operations: ascent burns to LEO, apogee raise burns, trans-lunar injection burns, hyperbolic Earth departure burns, and contingency disposal burns using the Reaction Control System (RCS). In addition to these known types of burns, the trade study teams were given a new targeting mode to implement, showing that both algorithms will be extensible to future missions. Finally, the chosen algorithm must be able to respond to a single engine failure scenario.

For the trade study, a reference SLS Block-1B vehicle configuration was chosen. A nominal, no-failure mission was analyzed, in addition to cases with a single engine failure at selected times during flight. Monte Carlo analysis was used to characterize how each algorithm behaved for the nominal mission and in the failure cases. The teams were allowed two “rounds” to arrive at their version of the algorithm. After a first round of Monte Carlos, the teams examined results and applied lessons learned to develop the final algorithm.

Each algorithm was scored based on pre-selected criteria, including insertion accuracy, algorithmic complexity and robustness, extensibility for potential future missions, and flight heritage. Independent reviewers determined the weightings and final scores for the various criteria.

This paper covers the design criteria, approach, and results of this trade study. In addition to the details of the trade study, this paper also shows impacts and considerations when adapting launch vehicle guidance algorithms to a wider variety of missions.