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Stochastic Analysis of Constellation Performance and Mass Margins

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A new method for analyzing margins in the Constellation program is described and applied to the performance and mass margins for the integrated transportation system returning humans to the lunar surface. The approach treats the Ares-V Earth-departure-stage gross payload-delivery capability and the translunar injection masses of Orion and Altair as random variables. For various vehicle requirements, vehicle control masses, and design reference missions, a Monte Carlo simulation estimate is used to estimate the critical probability that the delivery capability exceeds that injected mass. This critical probability can be used to establish program performance and mass margins and, in conjunction with other measures, to manage vehicle selection and trades at the program level.

Nomenclature

$F(\ldots)$, $G(\ldots)$	=	cumulative distribution functions
$f(\ldots)$, $g(\ldots)$, $\zeta(\ldots)$	=	probability density functions
I_{sp}	=	specific impulse, s
$\vert J\vert$	=	absolute value of the transformation Jacobian
M^t_{TLI}	=	translunar injection stack mass, kg, estimated at time t
P^t_{EDS}	=	Ares-V Earth-departure-stage gross payload-delivery capability, kg, estimated at time t
β	=	mass growth coefficient
Δv	=	maneuver change in velocity
ε	=	normally distributed error term

I. Introduction

ESTABLISHING and managing margin requirements provides a way for programs to better their chances of meeting key performance and physical parameters in the face of uncertainties. These margin requirements provide resiliency against less-than-favorable outcomes during system development and mitigate risks inherent in complex space missions. During development, technical managers can compare the actual margin against the margin requirement and take corrective action as necessary. The actual margin at time t is generally defined as the difference between the measured (or demonstrated) value for a key performance or physical parameter and its controlled (or allocated) value at that time. Typically, as remaining uncertainties diminish, so do margin requirements, reaching or approaching zero at the completion of the development cycle.

The Constellation program is an immense undertaking involving the development of a number of new systems designed to enable crew transfers to the International Space Station, a human lunar return, establishment of an outpost on the moon, and an eventual human voyage to Mars. The systems being developed (Orion, Altair, Ares-I, and Ares-V among them) must work together to provide transportation for both crew and cargo in a complex supply chain. The physics of space travel makes it necessary to carefully assess the launch vehicle performance and spacecraft masses throughout development to ensure that this system-of-systems is capable of meeting the top-level program requirements. To this end, a new type of integrated analysis was performed, treating both performance and spacecraft masses stochastically. Such an analysis was suggested by Shishko and Chamberlain [1].

The principal question addressed by the analysis was simply, "Does Constellation have a sufficient mass margin across program elements to ensure that Ares-V performance will exceed the stack mass at translunar injection (TLI) with high probability?" Though the analysis approach can be applied generally, the analysis described in this paper was performed for the Constellation lunar sortie Design Reference Mission (DRM). In that DRM, the Ares-V is the launch vehicle for the Altair lunar lander and includes an upper stage, known as the Earth departure stage (EDS). The EDS provides the Δv for both orbit circularization and then TLI, once the Orion crew vehicle, launched separately on the Ares-I, docks with Altair. In this paper, the performance of the Ares-V/EDS is its gross payload-delivery capability measured kilograms. The payload is defined as the total injected mass at the end of TLI less the burnout mass of the EDS. The TLI stack consists of the Altair, Orion, and the Altair-to-EDS spacecraft adapter.

Figure 1 is a depiction of the Constellation lunar sortie DRM. Lunar sorties are representative of Apollo-style missions that enable crew members to explore a single site anywhere on the moon with the length of stay limited by the amount of consumables brought by the lander and Δv margins. Aside from the larger crew size and the length of stay on the lunar surface planned by the Constellation program, there are several key differences between the Constellation and Apollo lunar sortie DRMs. One is the use in Constellation of separate launches for Orion and Altair and their subsequent docking in an Earth rendezvous orbit. The other key difference is the use of Altair's main engine to perform lunar orbit insertion (LOI), in contrast to Apollo's use of its service module (SM).

II. Basic Concepts

Setting the program manager reserve (PgMR) and project manager reserve(s) (PMR) in the Constellation program is part of the margin management process. Figure 2 provides the canonical view of mass margin concepts used in the Constellation program. Analysis of requirements associated with performing a variety of DRMs helps to establish control masses for each element of the TLI stack. Typically, the project manager for each element establishes a (time-phased)

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