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Stochastic Optimal Control to Minimize State Uncertainty

Thesis directed by Prof. Daniel J. Scheeres

In many spacecraft control scenarios, the standard design procedure begins with a deterministic propellant minimization that does not consider random errors due to navigation uncertainty, control noise, unknown parameters, or mismodeled dynamics. However, these random errors can render a deterministic trajectory infeasible or result in large state deviations that are resource-intensive to correct. Therefore, a deterministic design is followed by feasibility studies to ensure that potential errors will not compromise the mission performance. Alternatively, this dissertation investigates the more direct approach of stochastic optimal control. Stochastic control techniques include uncertainty within the optimization process such that error statistics can be minimized or constrained directly. Two novel stochastic control problems are investigated in this dissertation: 1) open-loop multi-objective trajectory optimization to minimize state error covariance and control energy using indirect methods and 2) closed-loop guidance to minimize mean squared error using dynamic programming. These techniques may be employed independently or in tandem to improve mission robustness. Both approaches consider control-dependent noise that is proportional to the magnitude of the nominal control (a structure that is common in spacecraft thrusters). The stochastic control methods in this dissertation are demonstrated for various mission scenarios including asteroid orbits in microgravity and multi-body orbits in the Earth-Moon system.

Moreover, the growth of state uncertainty over time is dependent on the dynamical system in question, with the degree of nonlinearity playing an important role. This dissertation also studies the relationship between uncertainty and nonlinearity and proposes a semianalytical measure of nonlinearity that is based on the eigenpairs of higher-order tensors. The nonlinearity measure can be used to identify regions of strong nonlinearity, estimate the size of the "linear" region about a nominal trajectory, and inform navigation and control algorithms. Collectively, this research results in a generalized guidance and control framework that facilitates robust performance.