UNSCENTED OPTIMAL CONTROL FOR SPACE FLIGHT

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ABSTRACT

The routine use of pseudospectral (PS) optimal control techniques in space applications[1] has generated new opportunities for performance enhancement. One of these opportunities is related to the interaction of an outer guidance loop with inner control loops. In current flight applications, knowledge of the initial state vector, padded with high conservatism, is considered necessary to maintain overall controllability and stability of the flight guidance and control system. Although in-flight knowledge of the state vector is possible with the proper use of sensors and estimation techniques, the junction conditions during flight segmentation are not known to a sufficient precision during the design phase and pre-flight planning operations. In order to manage this uncertainty, the current practice is to generate an optimal guidance trajectory based on a mean value of the junction state vector and flow down the anticipated flight perturbations to inner-loop requirements of tracking and stability. In turn, the capability margins of the inner control loop are passed up to the table of guidance requirements for the outer loop. This practice of uncertainty management not only breeds overly conservative designs, it also adds significantly to the cost of both design and operations of a space system. This is because the design process involves repeated iterations between the inner and outer loops which adds to increased cost and delayed schedules. Furthermore, the operational cost is unnecessarily increased through several human-in-the-loop tests and pre-flight verifications that are driven by the need to keep the operational conditions within the design specifications. Despite all these checks and tests, the actual flight perturbations may indeed stress the control system beyond its capabilities leading to very costly failures. In this paper, we pose the fundamental question: is it possible to better design a guidance solution that accounts for uncertainties in the junction conditions? One approach is to generate a field of extremals and select the appropriate solution based on in-flight conditions. While this is technically possible, this approach generates new problems on methods to interpolate between the

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[1] I. M. Ross and M. Karpenko, "A Review of Pseudospectral Optimal Control: From Theory to Flight," *Annual Reviews in Control,* Vol. 36, pp. 182-197, 2012.

finite collection of stored extremals, the design of a real-time search engine to select the appropriate extremals for interpolation, and finally, the amount of on-board memory necessary to store an entire collection of extremals over an entire collection of segments; i.e. Bellman's curse of dimensionality. Note also that this procedure also increases the cost of design as a large number of extremals have to be generated, tested and interfaced with the inner loop for safety, stability and other practical requirements.

In the full paper, we will describe a more attractive and lower-cost alternative to the extremal-field approach by designing a single solution that meets the performance specifications tied to statistical variations in the junction conditions. We do this by combining the concept of the unscented transform with standard optimal control theory to produce a new concept of unscented optimal control. The unscented optimal control problem generates a potentially large-scale standard optimal control problem. While seemingly daunting, the concept is attractive because the problem needs to be solved only once and off-line. The resulting unscented optimal control can be directly used for flight implementation. Thus, all of the problems associated with the extremal-field approach vanish in one fell swoop. The burden of computation is completely transferred to ground and pre-flight planning operations. Thus, the unscented optimal control, once computed, is immediately flight ready.

In this paper, we further mitigate the ground computation problem by developing a PS framework for solving the unscented optimal control problem to generate a new concept of unscented pseudospectral optimal control. The unscented PS optimal control technique is then applied to generate an efficient computational framework to solve the large-scale optimal control problem generated by the unscented transform. The full paper will describe all the mathematical details. For the purpose of this extended abstract, we demonstrate the concept for a nonlinear dynamical system (whose details will be provided in the full paper). Shown in Fig. 1 (in black) is the ideal targeting condition marked by an X. The performance of a standard guidance system is shown by the blue dots generated by Monte Carlo simulations associated with variations in the junction conditions. It is starkly apparent that the unscented guidance solution (shown in red) performs significantly better than a standard guidance trajectory. It is also visually apparent from Fig. 1 that the unscented guidance solution generates a significantly lower stressing requirement on the performance of inner loop.

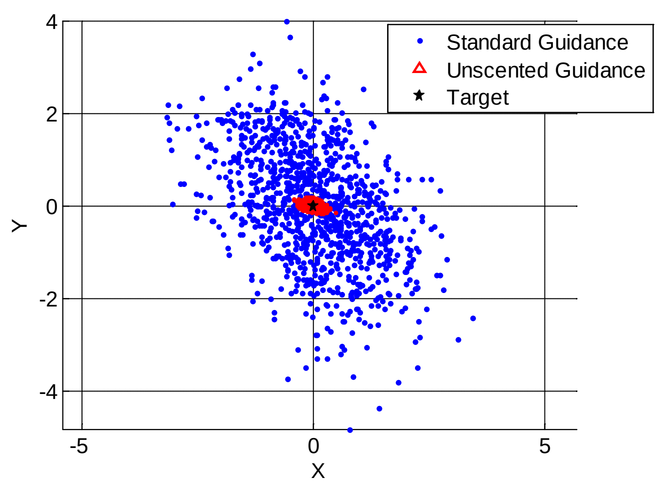

Figure 1