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Title

Multi-phase Robust Optimization of a Hybrid Guidance Architecture for Launch Vehicles

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Abstract

Trajectory optimization is one of the crucial aspects of launch vehicle design which determines the economical feasibility and the safety assurance of the mission. Epistemic and aleatoric uncertainty quantification and propagation represent a critical technology to reduce the overall required computational time, increase the robustness against design constraints and minimize the risk of mission failure. In the current literature of robust trajectory optimization, this comes with a price of either using nested optimization loops with heuristic algorithms or re-formulating the trajectory optimization as a robust optimal control problem where states and uncertain variables are rewritten in terms of polynomial expansions via sparse-grid based non-intrusive Polynomial Chaos Expansion methods. Subsequently, their outputs can be used to form a meta-model [1] for Uncertainty Quantification in uncertainty-based Multidisciplinary Optimization studies [2-4].

However, primary drawbacks of the former [5-6] approach include the excessive computational time and no guarantee of local optima. Latter utilize nonlinear programming [7-11] with high dimensional state spaces which are, if not impossible, quite difficult to converge for low-dimensional uncertainties. In response to that, recently proposed methods are based on convex optimization [12] which requires either a re-formulation of the original constraints as convex constraints or successively linearizing both the dynamics and the constraints, leading to a reduced optimality of the solution for long flight durations. Additionally, all of the aforementioned methodologies generate open-loop trajectories with a common fixed flight duration for each phase of the flight vehicle including the orbital insertion which results in very conservative results since most of the launch vehicles adapt closed-loop guidance algorithms based on Iterative Guidance Method (IGM) or Powered Explicit Guidance (PEG).

To include the closed-loop guidance phase in the exoatmospheric flight inside of trajectory design and also reduce the adversary impact of the dispersed states at the end of open-loop guidance phase, a novel computational framework is developed that can optimize both guidance modes, resulting in a hybrid guidance architecture. A benchmark multi-phase launch vehicle optimization problem is rewritten as a robust uncertainty-aware trajectory optimization problem with a novel hybrid guidance architecture which consists of open and closed-loop phases in a single nonlinear programming algorithm to maximize the expected payload mass. A robust open-loop reference trajectory is generated for the endo-atmospheric phase while the closed-loop guidance phase is optimized independently for each ensembled trajectory. The problem is solved by utilizing the recently developed Sparse Grid based Ensemble Pseudospectral Optimal Control Software (SG-EPOCS) for uncertainties in thrust, aerodynamic coefficients and the dry mass by sampling

from uncertainty space according to the quadrature rule generated according to the Conjugate Unscented Transformation (CUT) and reformulating the robust trajectory optimization problem in a vectorized formed. This in turn greatly reduces the computational time requirement and robustly converges by scaling the variables and the objective function according to the number of the ensembles. This approach requires less number of cubature nodes while preserving the nonlinearity of the dynamics in propagating the uncertainties. Resulting ensemble trajectories are then solved by implementing the mesh generated via the Legendre-Gauss-Radau collocation method in the time domain and open-source interior-point solver IPOPT. Optimality conditions are derived and the resulting Hamiltonian is shown to prove the optimality of the results.

This architecture has the advantages of fast optimal trajectory optimization which increase the safety of the flight by minimizing risks against a variety of uncertainties, reduce the overall burden on the control system and reduce the state dispersions at the end of open-loop guidance phase and as a result increase the expected value of deliverable payload by incorporating the closed-loop phase.

An example is given in the Figure 1.

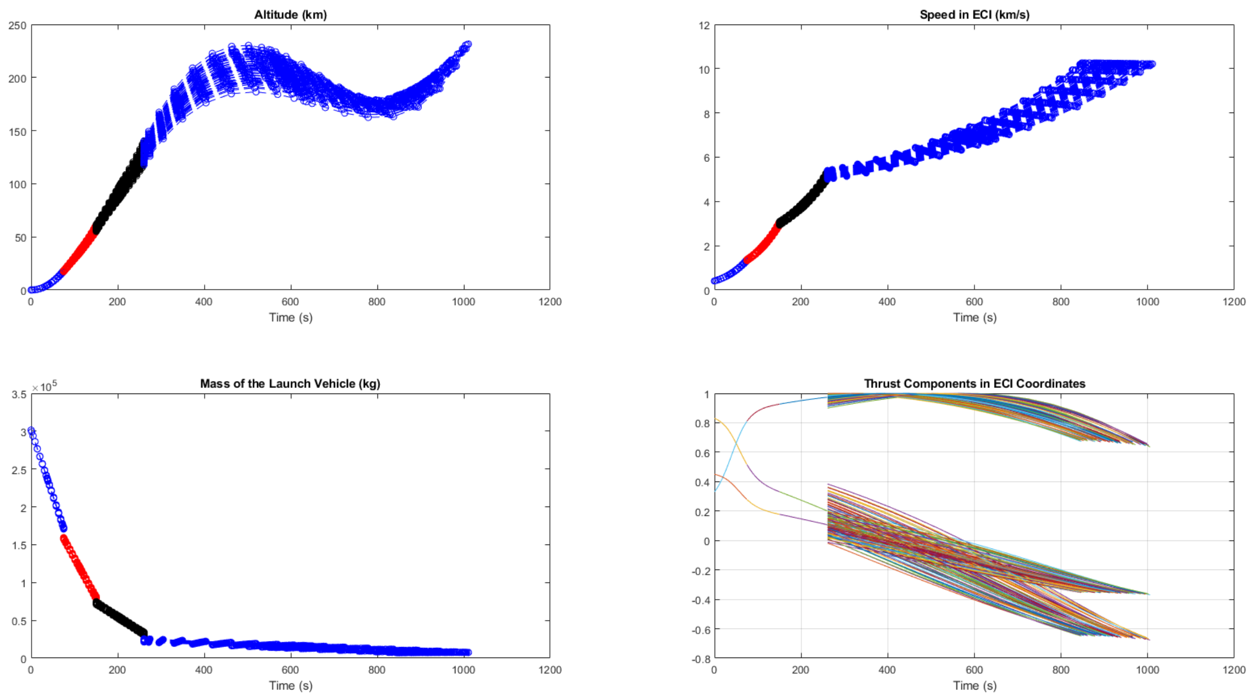

Figure 1. Robust Hybrid Guidance Architecture for Launch Vehicles

References

[1] Roshanian, J., Bataleblu, A. A., & Ebrahimi, M. (2019). A novel metamodel management strategy for robust trajectory design of an expendable launch vehicle. Proceedings of the Institution of Mechanical Engineers, Part G: Journal of Aerospace Engineering, 234(2), 236–253. https://doi.org/10.1177/0954410019860638
[2] Brevault, L., & Balesdent, M. (2021). Uncertainty quantification for multidisciplinary launch vehicle design using model order reduction and spectral methods. Acta Astronautica, 187, 295–314. https://doi.org/10.1016/j.actaastro.2021.06.040
[3] Chaudhuri, A., Waycaster, G., Price, N., Matsumura, T., & Haftka, R. T. (2015). NASA uncertainty Quantification Challenge: An optimization-based methodology and validation. Journal of Aerospace Information Systems, 12(1), 10–34. https://doi.org/10.2514/1.i010269
[4] Huang, Y., Li, H., Du, X., & He, X. (2019). Mars entry trajectory robust optimization based on evidence under epistemic uncertainty. Acta Astronautica, 163, 225–237. https://doi.org/10.1016/j.actaastro.2019.01.034
[5] Zardashti, R., Jafari, M., Hosseini, S. M., & Arani, S. A. (2020). Robust optimum trajectory design of a satellite launch vehicle in the presence of uncertainties. Journal of Aerospace Technology and Management, (12). https://doi.org/10.5028/jatm.v12.1176
[6] Roshanian, J., Bataleblu, A. A., & Ebrahimi, M. (2018). Robust ascent trajectory design and optimization of a typical launch vehicle. Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science, 232(24), 4601–4614. https://doi.org/10.1177/0954406217753460
[7] Xiong, F., Xiong, Y., & Xue, B. (2015). Trajectory optimization under uncertainty based on polynomial chaos expansion. AIAA Guidance, Navigation, and Control Conference. https://doi.org/10.2514/6.2015-1761

[8] Huang, Y., & Li, H. (2018). Reliability-based trajectory optimization using nonintrusive polynomial chaos for Mars entry mission. Advances in Space Research, 61(11), 2854–2869. https://doi.org/10.1016/j.asr.2018.03.009
[9] Li, X., Nair, P. B., Zhang, Z. G., Gao, L., & Gao, C. (2014). Aircraft robust trajectory optimization using nonintrusive polynomial chaos. Journal of Aircraft, 51(5), 1592–1603. https://doi.org/10.2514/1.c032474
[10] Yang, Y., Wang, X., Zhu, J., & Yuan, X. (2022). Robust transition trajectory optimization for tail-sitter uavs considering uncertainties. Science China Information Sciences, 66(6). https://doi.org/10.1007/s11432-020-3257-x
[11] Fisher, J., & Bhattacharya, R. (2010). Optimal trajectory generation with probabilistic system uncertainty using Polynomial Chaos. Journal of Dynamic Systems, Measurement, and Control, 133(1). https://doi.org/10.1115/1.4002705
[12] Wang, F., Yang, S., Xiong, F. F., Lin, Q., & Song, J. (2019). Robust trajectory optimization using polynomial chaos and convex optimization. Aerospace Science and Technology, 92, 314–325. https://doi.org/10.1016/j.ast.2019.06.011