Application of Design of Experiments and Surrogate Modeling within the NASA Advanced Concepts Office, Earth-to-Orbit Design Process

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Decisions made during early conceptual design have a large impact upon the expected life-cycle cost (LCC) of a new program. It is widely accepted that up to 80% of such cost is committed during these early design phases [1]. Therefore, to help minimize LCC, decisions made during conceptual design must be based upon as much information as possible.

To aid in the decision making for new launch vehicle programs, the Advanced Concepts Office (ACO) at NASA Marshall Space Flight Center (MSFC) provides rapid turnaround pre-phase A and phase A concept definition studies. The ACO team utilizes a proven set of tools to provide customers with a full vehicle mass breakdown to tertiary subsystems, preliminary structural sizing based upon worst-case flight loads, and trajectory optimization to quantify integrated vehicle performance for a given mission [2]. Although the team provides rapid turnaround for single vehicle concepts, the scope of the trade space can be limited due to analyst availability and the manpower requirements for manual execution of the analysis tools. In order to enable exploration of a broader design space, the ACO team has implemented an advanced design methods (ADM) based approach. This approach applies the concepts of design of experiments (DOE) and surrogate modeling to more exhaustively explore the trade space and provide the customer with additional design information to inform decision making.

This paper will first discuss the automation of the ACO tool set, which represents a majority of the development effort. In order to fit a surrogate model within tolerable error bounds a number of DOE cases are needed. This number will scale with the number of variable parameters desired and the complexity of the system's response to those variables. For all but the smallest design spaces, the number of cases required cannot be produced within an acceptable timeframe using a manual process. Therefore, automation of the tools was a key enabler for the successful application of an ADM approach to an ACO design study.

Following the overview of the tool set automation, an example problem will be given to illustrate the implementation of the ADM approach. The example problem will first cover the inclusion of ground rules and assumptions (GR&A) for a study. The GR&A are very important to the study as they determine the constraints within which a trade study can be conducted. These trades must ultimately reconcile with the customer's desired output and any anticipated "what if" questions.

The example problem will then illustrate the setup and execution of a DOE through the automated ACO tools. This process is accomplished more efficiently in this work by splitting the tools into two separate environments. The first environment encompasses the structural optimization and mass estimation tools, while the second is focused on trajectory optimization. Surrogate models are fit to the outputs of each environment and are "integrated" via connection of the surrogate equations. Throughout

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this process, checks are implemented to compare the output of the surrogates to the output of manually run cases to ensure that the error of the final surrogates is at an acceptable level.

The conclusion of the example problem demonstrates the utility of the ADM based approach. Using surrogate models gives the ACO team the ability to visualize vehicle sensitivities to various design parameters and identify regions of interest within the design space. The ADM approach can thus be used to inform concept down selection and isolate promising vehicle configurations to be explored in more detail through the manual design process. In addition it provides the customer with an almost instantaneous turnaround on any "what if" questions that may arise within the bounds of the surrogate model. This approach ultimately expands the ability of the ACO team to provide its customer with broad and rapid turnaround trade studies for launch vehicle conceptual design. The ability to identify a selection of designs which can meet the customer requirements will help ensure lower LCC of launch vehicle designs originating from ACO.

[1]: Blair, J., Ryan, R., Schutzenhofer, L., and Humphries, W., “Launch Vehicle Design Process: Characterization, Technical Integration, and Lessons Learned," Tech. rep., National Aeronautics and Space Administration, May 2001.

[2]: Waters, E.D., Garcia, J., Beers, B., Phillips, A., Holt, J.B., Threet, G.E. Jr., “NASA Advanced Concepts Earth-to-Orbit Team Design Process and Tools,” AIAA SPACE 2013 Conference and Exposition.10-12 Sept. 2013; San Diego, CA; United States