Augmenting Parametric Optimal Ascent Trajectory Modeling with Graph Theory

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It has been well documented that decisions made in the early stages of Conceptual and Pre-Conceptual design commit up to 80% of total Life-Cycle Cost (LCC) while engineers know the least about the product they are designing [1]. Once within Preliminary and Detailed design however, making changes to the design becomes far more difficult to enact in both cost and schedule. Primarily this has been due to a lack of detailed data usually uncovered later during the Preliminary and Detailed design phases. In our current budget-constrained environment, making decisions within Conceptual and Pre-Conceptual design which minimize LCC while meeting requirements is paramount to a program's success.

Within the arena of launch vehicle design, optimizing the ascent trajectory is critical for minimizing the costs present within such concerns as propellant, aerodynamic, aeroheating, and acceleration loads while meeting requirements such as payload delivered to a desired orbit. In order to optimize the vehicle design its constraints and requirements must be known, however as the design cycle proceeds it is all but inevitable that the conditions will change. Upon that change, the previously optimized trajectory may no longer be optimal, or meet design requirements. The current paradigm for adjusting to these updates is generating point solutions for every change in the design's requirements [2]. This can be a tedious, time-consuming task as changes in virtually any piece of a launch vehicle's design can have a disproportionately large effect on the ascent trajectory, as the solution space of the trajectory optimization problem is both non-linear and multimodal [3]. In addition, an industry standard tool, Program to Optimize Simulated Trajectories (POST), requires an expert analyst to produce simulated trajectories that are feasible and optimal [4].

In a previous publication the authors presented a method for combatting these challenges [5]. In order to bring more detailed information into Conceptual and Pre-Conceptual design, knowledge of the effects originating from changes to the vehicle must be calculated. In order to do this, a model capable of quantitatively describing any vehicle within the entire design space under consideration must be constructed. This model must be based upon analysis of acceptable fidelity, which in this work comes from POST. Design space interrogation can be achieved with surrogate modeling, a parametric, polynomial equation representing a tool. A surrogate model must be informed by data from the tool with enough points to represent the solution space for the chosen number of variables with an acceptable level of error. Therefore, Design Of Experiments (DOE) is used to select points within the design space to maximize information gained on the design space while minimizing number of data points required. To represent a design space with a non-trivial number of variable parameters the number of points required still represent an amount of work which would take an inordinate amount of time via the current paradigm

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of manual analysis, and so an automated method was developed. The best practices of expert trajectory analysts working within NASA Marshall's Advanced Concepts Office (ACO) were implemented within a tool called multiPOST. These practices include how to use the output data from a previous run of POST to inform the next, determining whether a trajectory solution is feasible from a real-world perspective, and how to handle program execution errors. The tool was then augmented with multiprocessing capability to enable analysis on multiple trajectories simultaneously, allowing throughput to scale with available computational resources. In this update to the previous work the authors discuss issues with the method and solutions.

First, the shortcomings of the preceding work are identified and solutions developed. The major issue is the selection of initial guesses for POST's trajectory optimizer. In the previous work, uniformly distributed random numbers were assigned to each entry of the guess vector. Although this first-cut method produced meaningful results, it had several drawbacks. By randomly sampling a multimodal solution space, the number of trials required to find a non-local optimum with some degree of statistical confidence cannot be known a priori. In addition, this method provided no means of determining whether or not a vehicle was capable of performing the mission other than a protracted campaign of random sampling. Due to the multimodal nature of the optimal trajectory response space, many valid trajectories can be found with significant variance in payloads delivered for a single data point. Therefore, two very similar vehicles could have very different ascent trajectories, causing higher error in a surrogate model of the overall design space. This resulted in larger errors in the surrogate model than were acceptable without resorting to over-fitting the data.

Secondly, an approach to solve the aforementioned issue is discussed. The approach relies on graph theory and a previously optimized point within the design space. The optimized point, or seed, can be produced using the previous method of random guesses or manual analysis. This point, along with points from a DOE, are represented as the nodes of a graph. The nodes are connected by edges whose weight is calculated as standardized Euclidean distance. This complete graph is then pruned to a minimally spanning tree, which connects all nodes with minimum total weight. By walking the edges of this graph starting at the seed node, initial guesses for un-optimized cases are provided by the optimized vectors from a close neighbor. This approach has yielded far quicker analysis times and smoother data for surrogate modeling. It is not without its drawbacks however, which will be detailed in the full paper.

Finally, a side-by-side comparison of the previous method to the updates is presented to quantitatively explore benefits in both analysis time and surrogate modeling. Depending on several factors, the new method can complete analysis in a quarter of the time and produce data which is more consistent which eases the surrogate model creation process.

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