Optimal Continuous-Thrust Trajectories Via Visual Trade Space Exploration

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Abstract

Engineering design problems often contain correlations and trade-offs that may or may not be obvious or well-understood. As design problem complexity increases, decision makers find it more and more difficult to grasp these trade-offs effectively. The rapid growth of computing power now allows the simulation of millions of design alternatives, and the ability to effectively visualize these alternatives and understand the tradeoffs associated with them has never been more important. Trade space visualization tools are designed to aid decision makers by allowing them to effectively explore a design space and grasp the underlying trade-offs and nuances particular to their specific problem. These tools provide great potential in evaluating complex dynamic systems in the aerospace industry, among others. In this article, we apply our trade space visualization software, the Applied Research Lab Trade Space Visualizer, to search for optimal constant-acceleration orbit transfers. This problem is formulated as a multi-objective optimization problem in which it is desirable to explore various competing objectives. We identify a known optimal solution and explore the input space to search for other optimal or near-optimal trajectories. Significantly perturbing the known solution to an example problem has demonstrated that the optimal solution can be converged upon successfully.

Introduction

Complex design can be considered a decision-making process, where a classic approach to the optimal decision process can be described by the following [1]:

- Identifying options
- Identifying ways to evaluate options
- Weighting each evaluation dimension

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- Doing the rating
- Picking the option with the highest score

This method, rational choice analyses, is taught in engineering and business curriculums. With this approach, rational choices are made after applying game-theoretic or statistical-theoretic methods to a problem [2]. Within the visualization community, interactive optimization-based design methods fall mainly into the category of computational steering whereby the user (i.e., designer) interacts with a simulation during the optimization process to help "steer" the search process toward what looks like an optimal solution. The steering process allows the designer to gain new perspectives on correlations within the problem and use intuition, heuristics, or some other method to adjust the design space to move towards solutions that they feel are promising. On the importance of visualization in engineering optimization, Messac and Chen [3] noted: "If effectively exploited, visualizing the optimization process in real time can greatly increase the effectiveness of practical engineering optimization." Furthermore, Ng [4] advocates the use of data visualization and interaction to support the designer in making informed decisions and trade-offs during multi-objective optimization. Many others argue that visualization should be considered a solution tool and that "human-in-the-loop" optimization has significant advantages over black-box search algorithms [5, 6].

The Applied Research Lab Trade Space Visualizer (ATSV)\(^1\) used in this research has been developed to support the exploration phase of the design process by offering the following functionality [7]:

1. Visualize complex data sets using multi-dimensional visualization techniques
2. Assign variables to glyph, histogram, and parallel coordinate plots
3. Specify upper and lower bounds of an n-dimensional design space
4. Implement dynamic brushing within glyph, parallel coordinates, and histogram plots to uncover relationships in the data set (linked views)
5. Visualize different regions of interest, using preference shading and corresponding Pareto frontier identification
6. Implement visual steering commands to navigate multi-attribute trade spaces via various Attractor/Pareto Samplers
7. Create multiple views of glyph, histogram, and parallel coordinate plots of the same trade space
8. Select a design from the glyph plot to display quantitative information, three-dimensional geometries, and other files such as images and documents
9. Use advanced visualization hardware to view graphs and three-dimensional geometries in stereo mode

This software has been implemented for the optimization of various multi-objective problems including orbital mechanics applications, although all functions are not used. The ATSV’s exploration capabilities have been previously applied to a simple impulsive orbit transfer to test its effectiveness on a simple dynamic problem with a known optimal solution [8]. In this work we apply the exploration and visual steering capabilities of our software to the more complex problem formulation of continuous-thrust orbital transfers.

\(^1\)“Applied Research Laboratory Trade Space Visualization,” http://www.atsv.psu.edu, date cited 1/01/09.