Design of Space Shuttle External Fuel Tank Using Two Different Optimization Tools

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Introduction

This report describes the design processes our team used to design the space shuttle fuel tank using two different design software tools. The design experiment was conducted in conjunction with our Complex System Design course where the class was split up into teams of three and four. The design problem was provided to us and described in "Designing an External Fuel Tank for the Space Shuttle," authored by Timothy Simpson, Michael Yukish, and Irem Tumer.

Problem Description

The purpose of this experiment is to compare and contrast Microsoft Excel with the Advanced Trade Space Visualizer (ATSV), two design software tools, for their ability to solve the same fuel tank problem. Each software tool is qualitatively compared against a set of criteria in a later section of this paper.

The goal of the problem is to maximize the return on investment (ROI) for launching a payload into orbit. Maximizing the ROI is subject to six design variables: cylinder length, tank radius, cone ratio, and the sphere, cylinder, and cone thicknesses. The problem also includes five hard constraints for volume, stress, and vibration which are directly affected by the six design variables.

Background

ATSV was developed by the Applied Research Laboratory (ARL) at Penn State University as a tool to facilitate the execution of broad trade studies and visualize the outcomes with multi-dimensional visualization techniques (Stump et al. 2004). Using either historical point designs related to a design of interest, or using mathematical relationships, ATSV will populate the trade space using multi-dimensionality to show relationships between selected input parameters. This type of design process allows decision makers to view thousands of point designs and form design preferences *a posteriori.* This process is known as a design by shopping paradigm.

Benefits of using ATSV in theory are many. Using design automation techniques, the trade space is populated quickly with thousands of point designs represented by multiple attributes which occupy a multi-dimensional space. This space is then explored using ATSV where relationships between different design variables can be identified, constraints and preferences applied, unattractive designs are weeded out, and finally, decisions made as perspective is provided. Besides displaying quantitative relationships, ATSV can be used to generate rapid trade space exploration useful to "jog the imagination" of designers directing them at a broader base of possible design solutions.

As a new tool, its merits must be evaluated against existing tools. This experiment proceeds with this objective in mind.

Training

Dr. Simpson conducted a two hour presentation on ATSV which included a one hour background and one hour training during which time each design group had downloaded ATSV onto laptop computers. In addition, the slide show used during this presentation including slides based on key ATSV functions, was made available.

No special or undated training was provided for Microsoft Excel; however, all groups included individuals who are familiar with the solver function in Excel.

Approach

Our design team conducted most of our design sessions as a group with one member operating the computer with the other two generating techniques and ideas to solve the problem. Turns were taken serving these roles. No definitive structure other than this was used in our process.

Our first attempts were conducted with Excel since we felt we had the best grasp on operating this tool. Once we were confident we found quality answers and confirmed them with other groups, we moved on to ATSV.

Excel Design Methods

Two, one-hour sessions were dedicated to using Excel during which time two main tasks were addressed in these sessions. First, we reviewed the code and made changes to the constraint relations. Second, several solver starting points were used to ensure that the solver was not stuck on a local maximum.

ATSV Design Methods

Three, two-hour sessions were used to develop five separate search methods in an attempt to result better and better ROI solutions. The first method was simply to populate the design space with a high volume of point designs. 15, 25, and 100 thousand point designs were created with the basic sampler in the first three design sessions. The second method uses the attractor on the ROI vs. Tank Volume Constraint scatter plot were a definite trend was identified used to direct the attractor for further point generation.

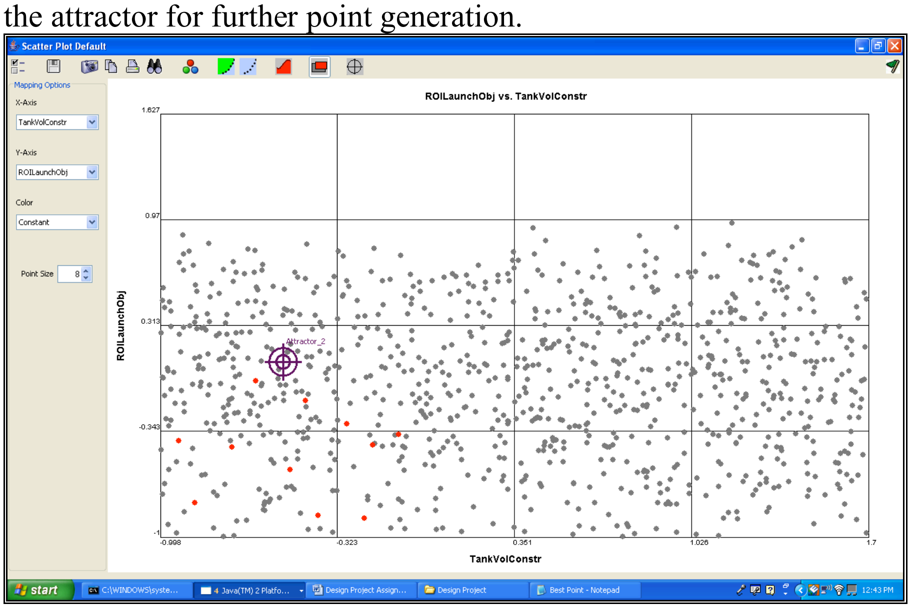

Figure 1 – The attractor targets an interesting region in the design space where potential future solutions may exist

Third, using the line graph to show historic input values for feasible designs, the basic sampler input ranges were decreased to represent these ranges and shrink the design space.

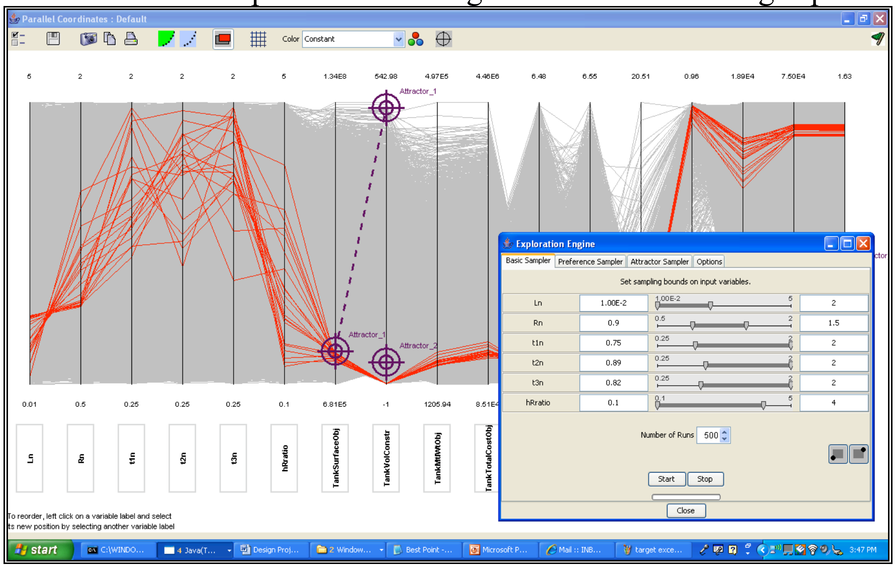

Figure 2 – The line graph shows input value ranges were previous feasible designs were generated. These input ranges are used to narrow the trade space exploration in the basic sampler.

The four methods uses the preference sampler by adding ROI into the brush/preferences tool bar and given 100% preference. All other constraints were given -100% preferences.

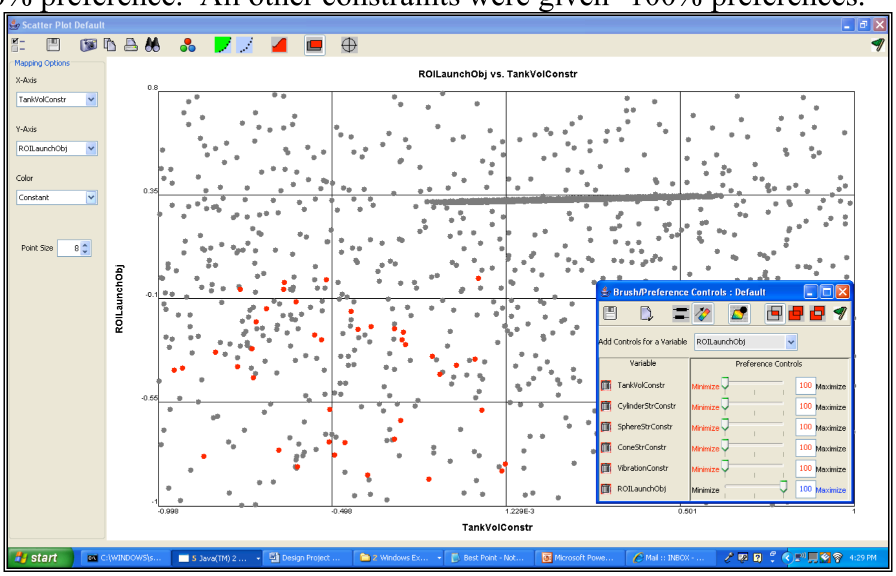

Figure 3 – Preferences are set on all constraints including ROI to focus point generation on ROI maximization.

The last method used the basic sampler with the input ranges set to mimic the inputs created in Excel.

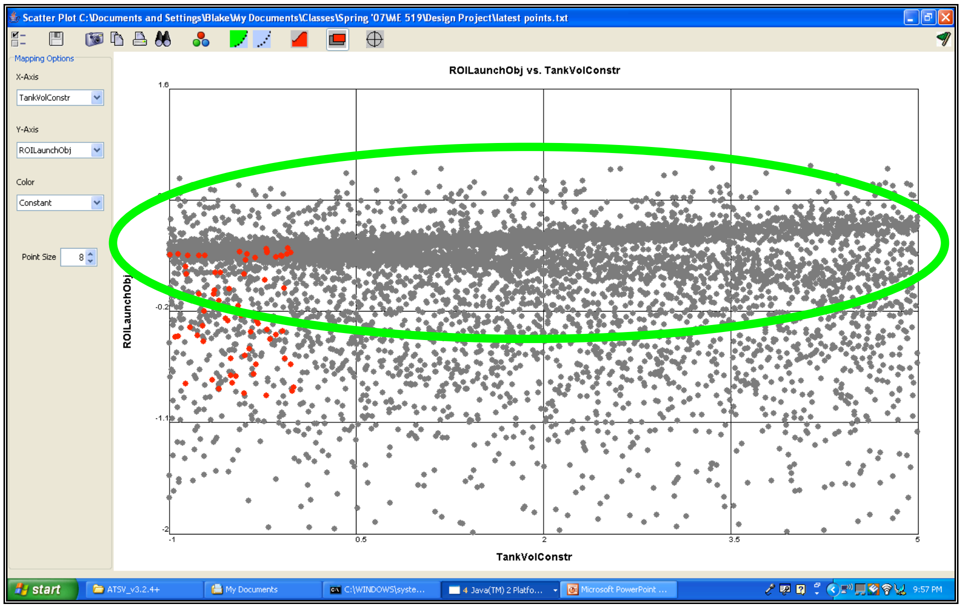

Figure 4 – The "machine gun" blast shows the high concentration of points generated in close proximity to Excel input values.

Questions:

A.1. Were you able to find equally good solutions using the Excel Spreadsheet and ATSV?

In the end yes, but this was only accomplished by targeting the Excel solution input values. The Excel spreadsheet was much more direct finding the most optimized ROI answer. It was difficult to check and verify that an answer was truly optimized in the ATSV program. With the Excel program coupled to a math software package, you could plot the equations and find out where you were on the curve and relative to the constraint boundaries.

A.2. Which version of the problem was easier to solve, excel or ATSV? Why?

Set up of the problem would have been more difficult with ATSV due to learning of the code format, but both are rather elaborate in that one still had to formulate and apply all the relative base equations.

Computing time for Excel was fairly short and consistent. Computing cycles for ATSV beyond 10,000 were significantly longer on a standard laptop.

It was easier to use Excel's solver tool to find a solution to the problem. For the solver all we had to do was input the design constraints and let the program run. Even though I had never used the solver before I found it to be self explanatory. Although ATSV was easy to use, the design problem was so tightly constrained it took a long time to find one solution to the problem.

A.3. On a 1-5 scale, to what extent did you feel that you understood the problem using:

a. Excel: 2- **Pros**: One had good confidence that you arrive to the most optimal answer for a given region, but relations would need to be plotted to verify that the solution was at a global optimum and not just a local optimum. Variable sensitivity is also difficult to ascertain without plotting. Excel Solver can also indicate that the problem was not properly bounded because it refuses to run. **Cons:** There was little to no understanding of the possible problem solutions beyond the boundary constraints.

b. ATSV: 4- **Pros:** Given an adequate amount of design point regions of feasibility became visually apparent within certain design variables definition of that region increased with more design points. One definitely knew what one is missing on the other side of a design constraint boundary. This is useful for making design tradeoffs. **Cons:** This program provides no information that the design problem was properly bounded with applied constraints or whether or not one was working with in a feasible region. Arrival of the most optimal solution is also questionable. There is no way to know whether not an adequate sampling of points was used to attain an optimal answer.

A.4. On a 1-5 scale, how useful were the visualization capabilities within ATSV?

The strength of the ATSV visualization is that one was able to recognize the shape and spread of the feasibility regions relative to different combinations of design variables. Regions may be easily identified which were beyond the design boundaries of the problem for certain combinations of. Many regions appeared between two “S” or parabolic curves. One also receives the most common or robust region where most of the possible solutions are located. One does not necessarily get that type of information from an optimization program such as Excel Solver.

However, because our design group was only interesting in maximizing one output, ROI, usefulness of trends identified in the trade space is minimized. If our design group had somehow incorporated interest in other design variables, which represent stakeholders in real design groups (structure, geometry, power, etc.), the visualization qualities would have been more central in maximizing several parameters.

Two-dimensional visualization was the most useful since we were mostly interested in one design variable. For the most part a graph of ROI and some other variable showing a strong relation with ROI was used.

A.5. What capabilities did you find most useful within ATSV?

Two-dimensional visualization was the most useful since we were mostly interested in one design variable. For the most part a graph of ROI and some other variable showing a strong relation with ROI was used.

The axis scale adjustment was useful in allowing the team to zoom into a given region of interest. The population targeting function was useful in concentrating the design point to a desired region while minimizing unnecessary calculation cycles. The brushing command allowed us to narrow our search to regions within bounded constraints of the problem by allowing only those design points within that region to be highlighted.

The brushing tool was the useful because it allowed us to see how many viable solutions that we had in the trade space.

For this problem the attractor was not very useful because of the size of the design space. Once zoomed into an area of interest, the attractor zooms out to a broader scale failing to generate points at a desired density and location.

A.6. Are there capabilities that you wish ATSV had as you tried to solve the problem?

ATSV could incorporate an algorithm to giving a suggested "ball-park" population trial size for a given stage of the problem based upon the following criteria:

- The number of input variables in the problem
- The accumulative sensitivity of each variable relative to its effect on the target result
- The size of the feasibility region given the boundary constraints and/or the target location.

The user could also have the option of easily interchanging the constraint formula and range with a single value constant much like that of an optimization problem. This should only be used when the user has high degree of certainty that the optimized solution is located along the maximum or minimum boundary. Or in other words when the constraint at optimally bounded. This would eliminate input variables and thus simplify the problem, drastically lowering the suggested trial size. The user would have to periodically check to see if his assumption is valid through comparison of results from a non-simplified trail run of otherwise the same configuration.

The following is a list of additional suggestions that would be useful during our design session:

- Manually select a region to populate. For example, parameters that correlate in bands or other obscure shapes would best be explored with point generation regions that resembled those shapes.
- After zooming in on a region of interest, additional point generations in those regions should be performed on a density scale relative to the zoomed frame, not the trade space as a whole. Furthermore, this will allow interesting regions to be more densly populated than the rest of the trade space.

- A manual zoom commanded by a mouse scroll in addition to zooming by setting the axis ranges.
- Color coded constraint brushes will allow users to distinguish infeasible points as failing specific constraints.
- Optimization will allow users to intelligently guide point generation to productive regions. Especially useful with enormous design spaces and high constraints were the trade space cannot be too densely populated with random points. Optimization will decrease the need for dense populations of the entire trade space, only those regions of interest and promise.
- Discrete input values which match de facto input ranges. For example, a designer may only want to select certain thicknesses of sheet metal which he/she knows is readily available from the market.
- The ability to select and display grey point designs when they are not highlighted should be removed.

A.7. Did you feel that you received adequate training before using ATSV? (1-5)

No, there were key essential functions that were either left out or glossed over during the training session. One of the most important of those was the scale adjustment of the X, Y, and Z axes. Without them we were unable to zoom in on a region of the trade space volume to identify the individual points with in that region. Only after asking other classmates who have spent significant time with the problem were we able to access that function. The icon symbol to that function was not intuitive to us regarding the function, which also kept us from finding that function in the first place.

Another ATSV training session would have helped, however, after using the program for a few sessions I felt adapt to using the program the way it is meant to be used. Previous experience with other computer programs has helped expedite the learning process.

A.8. Was the problem described clearly enough for you to be able to solve it? (1-5)

The problem was described clearly and was simple enough to do without knowing anything about space shuttle design. We weren't sure which constraints were being used in ATSV for the stress, vibration, and volume. We had to look through the JAVA code to figure out how which constraints were being used.

A.9. Are there other applications beyond optimization where you think ATSV would be helpful?

ATSV would be VERY effective in benchmarking competitive products. One could enter advertised performance/reliability specifications, and cost. One would concentrate benchmarking efforts on cameras that have higher outlying performance verses various areas which don't. One would still benchmark a lot of product, but for the outstanding performers verses cost, one would then know what to look for.

Marketing stratagem could also be developed by looking a trends verses cost and seeing how our product data points stacks up to the competition. Engineering would then be able to concentrate efforts plans to move all there tier of their product line to the more competitive regions of the design trade space.

ATSV could be useful for shopping when there are too many options to decide on. I'm not sure but maybe it could be used to find harmful states of a complex system. If you had the dynamic equations for the system ATSV could explore the system for a range of inputs and then it could allow an engineer to find dangerous states.

It could be useful for sensitivity analysis and exploring the trade space surrounding quality point designs. By understanding behaviors around specific point designs, designers can prepare for fluctuations in the design requirements which require the design to change small amounts. Flexibility is can thus be incorporated into the design.

A.10. Any suggestions to improve the project?

A design problem incorporating several stakeholders (structure, geometry, power) would increase the effectiveness of visualization capabilities.

Enriching the Design Process after Conducting Related Research

Concurrent deign techniques were used during this process as we worked together with equal say. This set-up also eliminated the presence of overbearing managers with little knowledge and powerful persuasion. Since we all have similar backgrounds and investment in the project, there was little polarization in our design team. If our team consisted of stakeholders of different interests, integrated concurrent engineering techniques could be employed to enrich the design process.

Results

The Microsoft Excel solver found the most optimal design. ATSV was eventually able to produce a comparable solution, but only after using the Excel solution to guide it. Before using the Excel solution, several techniques were used to produce results of varying success. These solutions as well as the final solutions are shown in the following tables.

ATSV Design Method Summary		
Design Method	**# of Points**	**Best ROI**
Basic Sampling	15,000	-0.35
	25,000	-0.015
	100,000	0.02
Attractor	5,000	0.02
Narrow Inputs	5,000	0.08
Preferences	3,500	0.15
Excel Inputs	3,000	0.31

Figure 5 – ATSV sampling methods and associated ROI

Results Summary							
	Ln	Rn	t1n	t2n	t3n	h/Rn	ROI
Excel Solver	1.181	0.8994	0.8762	0.8853	0.8188	2.392	0.3219
ATSV	1.17	0.9033	0.8847	0.8932	0.8452	2.386	0.3098

Figure 6 – Input parameters and ROI outputs for Excel and ATSV

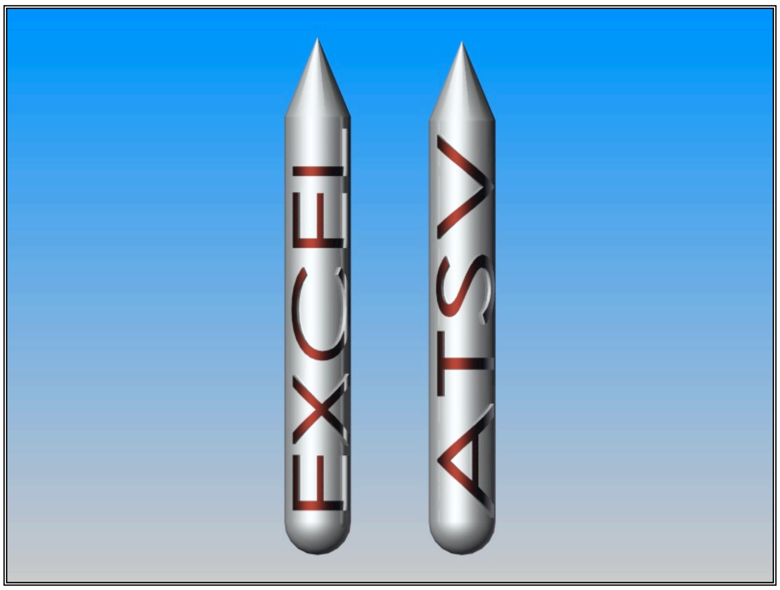

Figure 7 – Scaled representations of the Excel and ATSV derived fuel tanks

Conclusion

The design problem used in this experiment is tailored more toward an optimization tool due to the enormous design space that must be covered, tight constraints, and single design objective that must be met. In such a large trade space (due to number of inputs and their ranges), the ATSV point generator needs to be well directed to interesting regions of the design space where it can adequately populate the trade space to reveal useful point designs and relationships between input variables. Without direction, ATSV must rely on massive point generations which bogs down computation and is time consuming.

Improvements in pint generating techniques would make this design experiment more successful. In particular, higher user manipulation and ability to focus or increase the density of point generation in certain areas would help. An optimization algorithm would also help the user and ATSV locate high interest regions.

Several of the distinguishing and positive characteristics of ATSV were not capitalized due to the nature of this design problem. For instance, because our design team was only interested in ROI, the preferences shading tool did not do all that it is capable of doing, generating points based on weighted preferences. ATSV's ability to display trends was also minimized because our design team was not concerned with any thing except ROI. Stakeholders representing different aspects of the design would be more inclined to learn and understand these trends. Lastly, because our design team was not concerned with manufacture, changes in concept requirements, or other conditions which would require the fuel tank design to change, flexibility or the area surrounding valuable point designs was of no interest further minimizing the effectiveness of ATSV in this problem.

For the purposes of this experiment, Excel produced a higher quality design much quicker. Although ATSV solutions were on the same order of magnitude, a comparable solution was not produced until Excel values directed ATSV. Interesting conclusions could have been made about the trade space around these point solutions, but no stakeholders were present to draw these conclusions.

Trade Space Exploration of Satellite Datasets Using Design by Shopping Paradigm. Stump, G; Simpson, T W; Yukish, M; O'Hara, J J. IEEE Aerospace Conference Proceedings, v6, p 3885-3894.