

Trade Space Exploration of Satellite Datasets Using a Design by Shopping Paradigm^{1,2}

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Abstract—One of the goals of early stage conceptual design is to execute broad trade studies of possible design concepts, evaluating them for their capability to meet minimum requirements, and choosing the one that best satisfies the goals of the project. To support trade space exploration, we have developed the Advanced Trade Space Visualizer (ATSV) that facilitates a design by shopping paradigm, which allows a decision-maker to form a preference *a posteriori* and use this preference to select a preferred satellite. Design automation has allowed us to implement this paradigm, since a large number of designs can be synthesized in a short period of time. The ATSV uses multi-dimensional visualization techniques, preference shading, and Pareto frontier display to visualize satellite trade spaces.

Keywords—Multi-dimensional Data Visualization, Design by Shopping, Multiobjective Optimization

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1. INTRODUCTION

Traditional research on computational design methods has focused on optimization and its use in the design process. For complex systems design, the discipline of multidisciplinary design optimization (MDO) has risen to fill the need for design optimization. MDO itself rests on the extensive body of work in the theory of games and decisions, of which there is an extraordinary body of research. However, the strict focus on computational design optimization has a critical failing in that it requires designers to specify their preferences and constraints *a priori* and typically in a mathematical form that is alien to how humans actually think. In many cases this may be justified, such as when a preference can be easily distilled to a single metric, but problems arise in multi-objective analyses where the decision-maker must not only decide on what objectives to optimize but also on the relative ranking of those objectives.

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In support of a different paradigm, one of broad trade space exploration followed by a determination of preference after the fact, the authors have been assembling design automation applications for conceptual design, running them to generate large databases of candidate designs spanning the trade space, and using n-dimensional visualization to explore the database of designs. Interactions with our customers have repeatedly shown that they appreciate the capability to gain an understanding of the underlying relationships of the different design variables prior to forming a final set of preferences and constraints.

Balling identifies this approach as a design by shopping paradigm [1]. This paradigm can be classified as an *a posteriori* articulation of preference to solve a multiobjective optimization [2]. To support this process, he states the need for research in the following two areas:

1. interactive graphical computer tools to assist decision-makers in the shopping process
2. efficient methods for obtaining Pareto frontiers

The focus of our research has been to develop a graphical user interface that allows decision-makers to implement a design by shopping paradigm. To this end, we have developed the Advanced Trade Space Visualizer (ATSV).

In the next section, we discuss our motivation and different systems that have been developed to visualize multi-dimensional data sets. In Section 3, we present our interface for multi-dimensional data visualization. In Section 4 we illustrate its use by visualizing different preference structures and resulting Pareto frontiers for a spacecraft design example. Closing remarks and future work are given in Section 5.

2. MOTIVATION AND RELATED WORK

Several freeware and commercially available software packages have been developed to visualize multi-dimensional datasets [3-18], and these existing interfaces incorporate many widely used multi-dimensional visualization techniques that include scatter matrices, glyph plots, parallel coordinates, dimensional stacking, reduction of dimensions, linked displays, and brushing.

Previously developed software visualizes data without the ability to shop for the best design. The goal of our research is to develop an interface that allows a decision-maker to view different preference structures *a posteriori*. Additionally, we would like to visualize tradeoffs amongst variables by displaying Pareto optimal designs for each preference structure. The shopping interface introduces a new form of optimization by allowing a decision-maker to visualize many preferences structures and corresponding Pareto frontiers until a preferred design is selected.

Previous interfaces such as 3DVDM [3], Glyphmaker [5], Miner3D [7], Virtual Data Visualizer [14], and N-vision [9,10] have used immersive virtual reality environments. While traditional graphic capabilities and interaction devices are powerful tools for assessing computer data, virtual reality provides unique visualization and interaction capabilities not offered by a traditional interface, and these capabilities can enhance the decision-maker's ability to understand complex design problems [19].

Using the same code base, ATSV is able to support the following scenarios:

1. active stereoscopic display on monitor using a desktop computer
2. passive stereoscopic display using mobile projectors connected to a notebook computer
3. the ability to port the ATSV to our four-sided virtual reality environment (SEALab)

The ATSV interface and functionality are described next.

3. ATSV INTERFACE

The ATSV has the following functionality:

1. Visualize complex datasets using multi-dimensional visualization techniques
2. Assign variables to glyph, histogram, and parallel coordinates 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 dataset (linked views)
5. Visualize different regions of interest, using preference shading and corresponding Pareto frontier identification
6. Create multiple views of glyph, histogram, and parallel coordinates plots of the same trade space
7. Select a design from the glyph plot to display quantitative information, 3D geometries, and other files such as images and documents
8. Use advanced visualization hardware to view graphs and 3D geometries in stereo mode

Specific capabilities of the ATSV interface are discussed in the following sections.

Glyph/Histogram/Parallel Coordinate Plots

The ATSV displays multivariate information using glyph, histogram, and parallel coordinate plots. Illustrated in Fig. 1, the ATSV displays seven dimensions using the position, size, color, orientation, and transparency of cubed glyphs. The spatial position of each glyph cube represents three dimensions of an individual design. The size of the glyph displays a fourth dimension. A fifth dimension is represented by the glyph cube's color, in which blue cubes represent low values and red cubes represent high values. Glyph cube orientation displays an additional dimension, in which higher values are represented by cubes rotated about the x, y, and z axes. The final dimension is represented by transparency, where lower values are more transparent. The

user can apply a constant value to any of these physical characteristics, removing a dimension from the glyph plot display.

Histograms, shown in Fig. 2, partition a variable's range in the data set and count the total number of occurrences in each bin. Histograms are used to visualize the distribution, skewness, variance, and outliers of variables.

Parallel coordinates, proposed by Inselberg [20], displays multivariate designs by using a polyline that intersects equally-spaced axes. Each polyline in the parallel coordinates display represents one design; a polyline's n-intersections with the horizontal axes represent the n variables of a design (shown in Fig. 3).

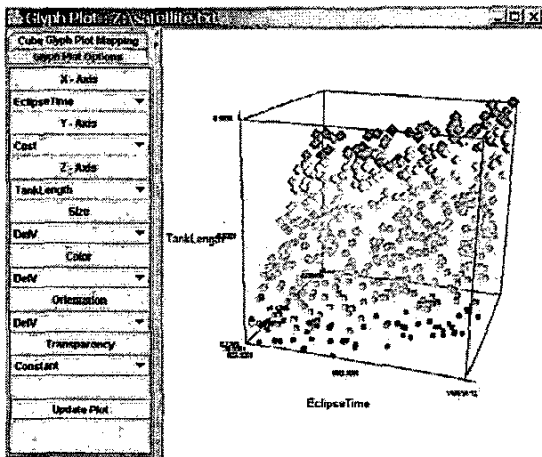


Figure 1 - Glyph Plot

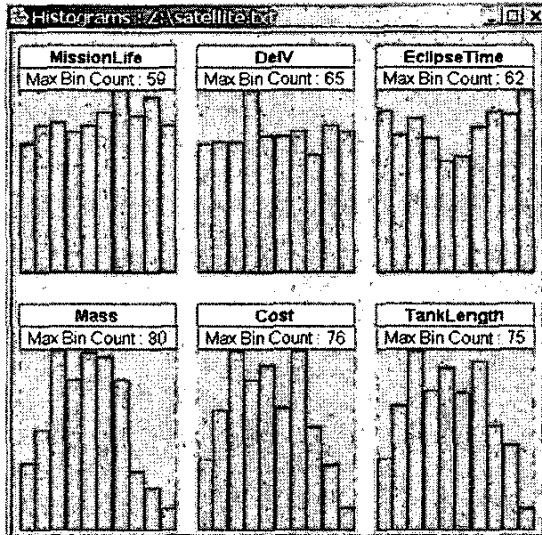


Figure 2 - Histogram Plots

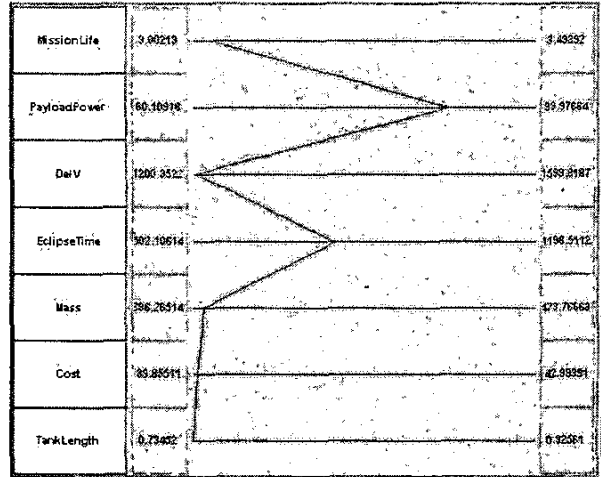


Figure 3 - One Design in a Parallel Coordinates Plot

Brushing/Linked Views

A brush is a user-defined region within a multivariate data set in which designs that fall within this region are highlighted, deleted, or masked [17, 21]. Linking is the process of displaying information across multiple views of data [22]. Figure 4 displays brushing and linked views using the ATSV by only displaying satellite designs that have low ΔV values in both plots simultaneously.

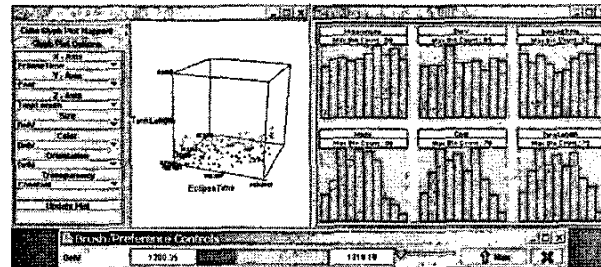


Figure 4 - Brushing/Linked Views

Preference Shading/Pareto Frontier Display

Preference shading allows a user to experiment with different preference structures, observing dynamically how the designs order themselves in response. The designs are then sorted using a standard weighted-sum:

$$f = \sum_{i=1}^n w_i x_i \quad \begin{matrix} w_i : \text{Weighting Vector} \\ x_i : \text{Performance Parameters} \end{matrix} \quad (1)$$

Eq. 1 is used to set the preference value of each design, with higher values as more preferred designs and lower values as less preferred designs. Fig. 5 displays two different highlighted regions that correspond to preference structures indicated by the arrow. Preference shading can be applied to any glyph plot feature, such as position, size, color, orientation, or transparency, as shown in Fig. 5.

The number of highlighted designs is controlled by a range slider bar, in which the user can set upper and lower limits on preference shading. A user has the ability to view a subset of preferred designs, whether the designs are most preferred, least preferred, or fall within a middle range of preferred designs. In addition, the user can dynamically brush through different levels of preferred designs.

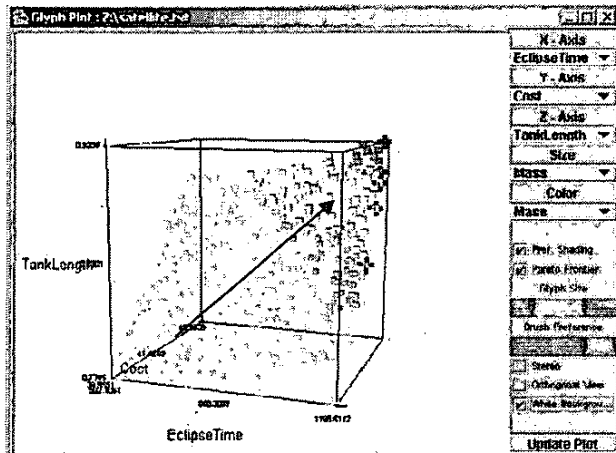


Figure 5 - Preference Shading/Pareto Frontier Display

While preference shading uses slider bars to smoothly vary a weighting vector, the only aspect used for determining the Pareto frontier is whether more or less of the attribute is preferred, or if the attribute is to be ignored (i.e., weight equal to zero). Using the same preferences as displayed in Fig. 5, designs that fall on the Pareto frontier are distinguished using black markings.

Picking a Design Point

A user can select an individual glyph (using a double mouse click) to display additional information of a satellite design. A new frame, shown in Fig. 6, appears and displays all associated information, such as quantitative information, 3D geometries, images, and documents of the selected satellite design.

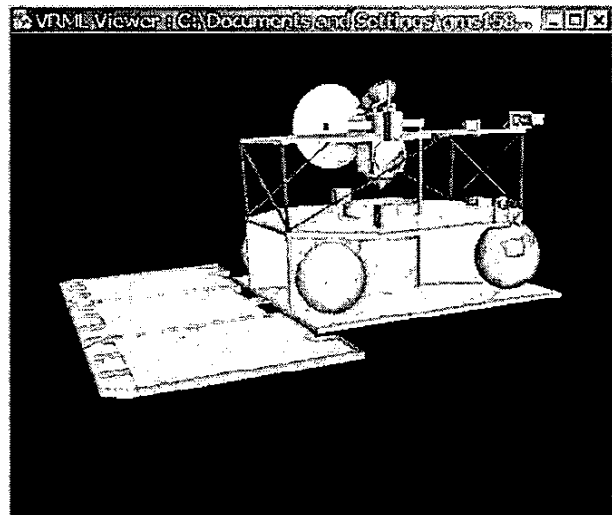
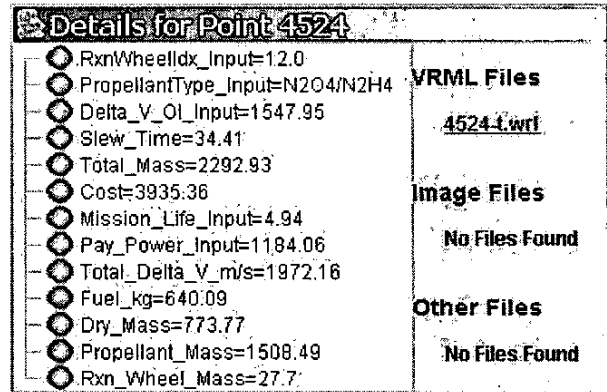


Figure 6 - Quantitative Information and 3D Geometry of a Selected Design

Program Architecture

The ATSV front-end is displayed in Fig. 7. The ATSV program architecture includes the Visualization Toolkit (VTK) [23], JFC/Swing, and Java3D (see Fig. 8). VTK includes wrapper Java classes, allowing one to use JFC/Swing coupled with VTK. JFC/Swing is a platform-independent language used to develop graphical user interfaces that have features such as scroll bars, combo boxes, internal frames, and menus. 3D geometry files with a VRML extension are displayed using a Java3D VRML loader.

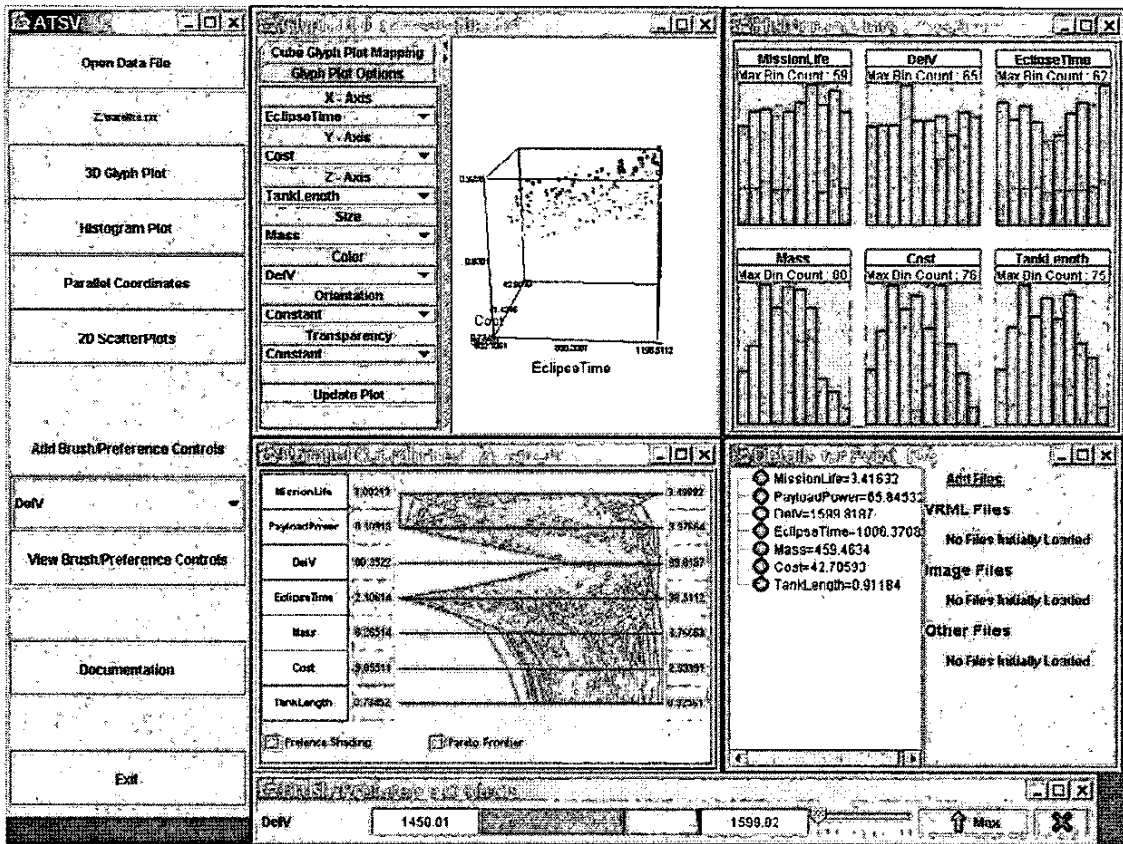


Figure 7 - The ATSV Graphical User Interface

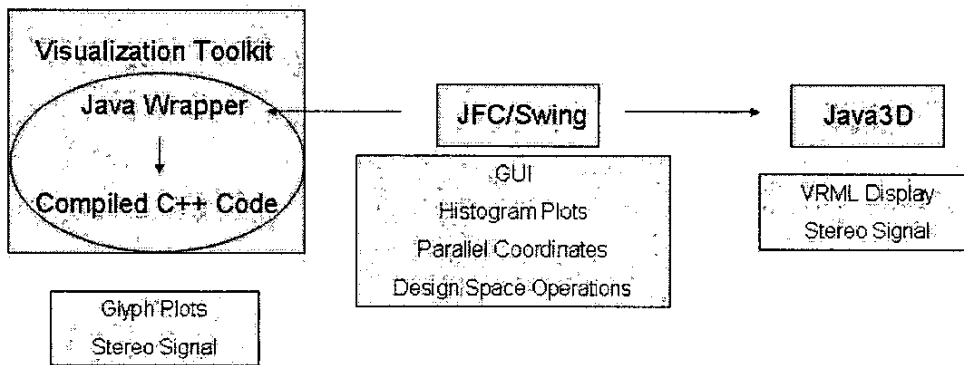


Figure 8 - Program Architecture

The program architecture has been structured to display multiple windows simultaneously, allowing a user to view different representations of the same data. Actions within individual graphical displays, such as choosing which variables to show on which axes, are independent and do not affect others. A user can toggle stereo mode in individual glyph plots and 3D geometry windows. All glyph, histogram, and parallel coordinate plots are linked together, by only displaying designs within brush limits; also, preference structure and corresponding Pareto optimal

designs are simultaneously displayed in all plots.

Virtual Reality

VTK, along with a stereo compatible graphics card, outputs a signal in frame sequential stereo signal format; this signal can be used on desktop computers, stereo projectors, and immersive virtual reality environments to visualize stereoscopic images. The ATSV interface uses the advanced visualization setups displayed in Fig. 9 [24] and Fig 10.

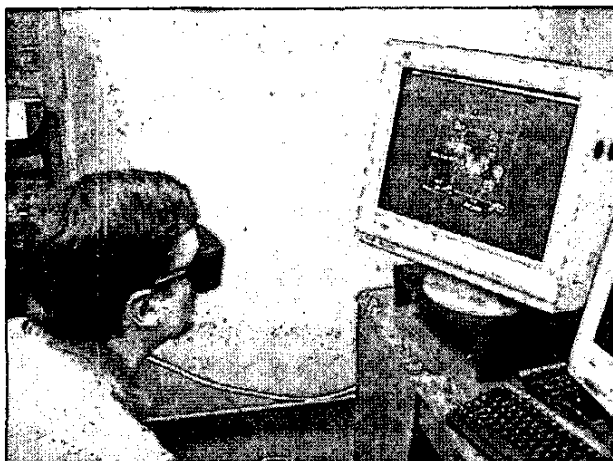


Figure 9 - Stereoscopic Visualization Using LCD Shutter Glasses Along with a 22" Monitor

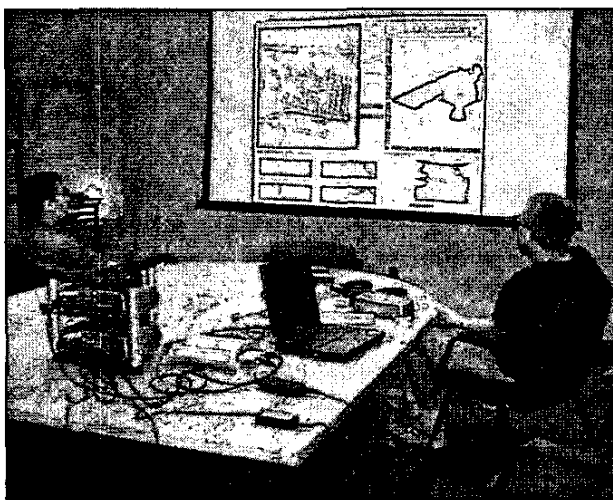


Figure 10 - Passive Stereoscopic Visualization Using Projection Screens

4. TRADE SPACE EXPLORATION

Mars Orbiter Satellite

Trade studies are often done by simulating performance of each design on a computer. The data used to illustrate the ATSV was generated using a conceptual model of a Mars space probe, with rules based on satellite design textbooks and Mars Odyssey mission characteristics available through the open literature [25-30]. The 2001 Mars Odyssey satellite (shown in Fig. 11) [31] is currently orbiting Mars, and its primary functions are to measure the elements and minerals on the surface of Mars, to search for the presence of water, and to measure radiation levels that would be experienced by manned-missions to Mars.

The primary design variables for this example are:

- RW Index: The index into the catalog of reaction wheels, of which there were 14 choices
- Propellant Type: Either N_2O_4/MMH or N_2O_4/N_2H_4

- ΔV : The change in velocity available over the mission
- Slew Time: The time for the vehicle to traverse a designated slew angle
- Mass: The mass of the vehicle with propellant
- Cost: The cost of the vehicle
- Mission Life: The overall duration of the mission
- Payload power: The power of the payload, an independent variable in this exercise
- Fuel Mass : The fuel mass
- Propellant Mass: The combined fuel, oxidizer, and pressurant mass.
- Dry Mass: The mass of the vehicle without propellant
- RW Mass : The reaction wheel mass

The two key trades for this exercise are to see how (1) the amount of propellant affects the ΔV available over the mission, the total spacecraft mass, and the cost, and (2) the choice of reaction wheel affects the ability of the probe to slew its cameras from one target to another. Additionally, the trades are coupled through the total mass properties of the probe.

These design variables were chosen to illustrate the ability to show both smooth and discrete relationships and to highlight the capability to visualize the indirect coupling between variables that occurs in complex systems design.

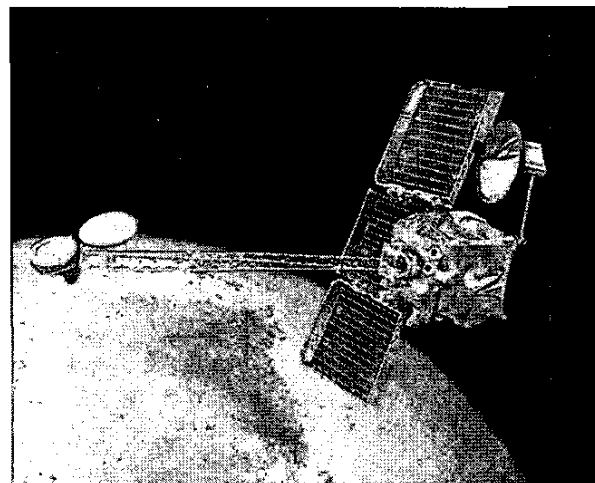


Figure 11 - Mars Odyssey Satellite

Automated conceptual design models are used to populate the satellite trade space. The design model is exercised by randomly sampling over the input space using a Latin hypercube. For each input, both the input and the resulting output of the model are recorded. This process is repeated until a sample that is sufficiently representative of the trade space has been captured.

The data set for this example includes 5000 designs, each design having the 12 design variables discussed above, forming a 12-dimensional satellite trade space populated by 5000 unique design configurations. The total elapsed time to

generate 5000 designs was about 10 hours. An example data set is shown in Fig. 12, where each row represents a design and each column represents a variable.

1	A	B	C	D	E	F	G
1	Reaction Wheel Input	Reaction Wheel Input	Reaction Wheel Input	Slew Time	Total Mass	Cost	Mission Life Input
2	8	1237.02	100.11	2164.2	3618.74	2.45	
3	6	1431.99	101.99	1921.27	3826.44	4.42	
4	6	1231.7	118.04	1520.84	2203.26	3.64	
5	13	1525.82	52.18	2063.23	4427.46	4.36	
6	9	1308.19	121.42	1747.02	2822.43	4.84	
7	13	1566.74	59.54	3363.19	7239.67	4.28	
8	1	1228.25	148.33	1621.55	2276.06	4.63	
9	1	1228.26	147.98	1520.26	2121.14	2.97	
10	5	1204.53	123.27	1647.69	2266.03	4.27	
11	12	1102.46	33.1	2188.34	3411.8	4.23	
12	12	1922.68	33.84	2725.84	5401.61	2.82	
13	7	1300.96	109.24	2144.27	3626.25	2.67	
14	3	1216.17	88.47	1573.69	2163.97	2.42	
15	11	1253.53	107.69	1718.3	2416.09	4.40	
16	3	1282.06	106.02	2110.46	3446.5	2.75	
17	10	1408.84	71.02	1913.06	3523.02	2.93	
18	1	1439.67	143.63	1686.74	2469.71	3.02	
19	5	1317.18	169.83	1906.94	2822.68	4.03	
20	14	1136.46	104.59	2195.38	2822.59	3.93	
21	1	1199.93	157.96	2046.00	3275.72	4.64	
22	13	1251.49	49.54	2063.7	3969.97	4.17	
23	9	1231.16	172.21	1724.58	2496.18	3.14	
24	13	1847.67	52.33	2488.76	4608.05	4.68	
25	6	1437.13	102.38	2299.83	4147.46	3.18	
26	9	1522.59	178.21	1895.81	2779.12	2.84	

Figure 12 - Satellite Dataset Example

Trade Space Exploration of Satellite Data

The glyph plots in Fig. 13 display the following mapping:

- X – axis : Slew Time
- Y – axis : Dry Mass
- Z – axis : Cost
- Glyph color : Preference Shading

Each glyph plot in Fig. 13 has 5000 glyph cubes, where each glyph cube represents a satellite design. In this case, a design's Slew Time, Dry Mass, and Cost are represented by the spatial position of an individual glyph cube, and color represents the design's ranking with respect to a specified preference structure. More preferred designs are shaded red, while less preferred design are shaded blue.

The two glyph plots, in Fig. 13, illustrate how decision-makers can visualize different preference structures in the trade space, thereby aiding the decision-maker in the shopping process. Each circled region represents a top percentage of designs that satisfy the desired preference structure. The two glyph plots display a preference structure of minimizing Slew Time and minimizing Dry Mass. The first glyph plots place a greater importance on minimizing Dry Mass, while the second glyph plot places a greater importance on minimizing Slew Time.

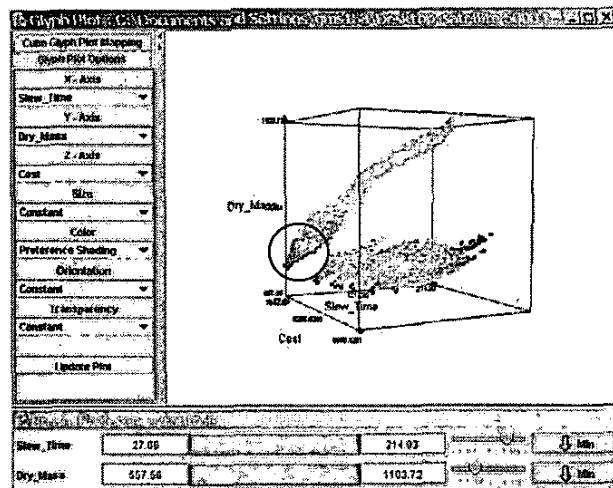
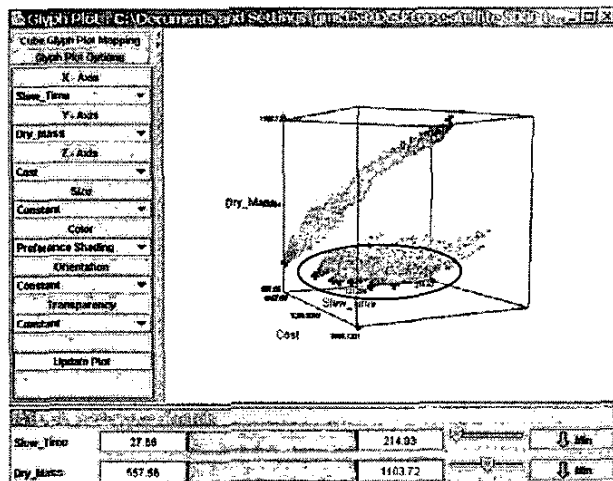


Figure 13 - Glyph Plots/Preference Shading/Pareto Frontier Display

Figure 14 displays the same preference structures, shown in Fig. 13, using parallel coordinates, where more preferred designs are shaded red. The first plot, with a greater importance placed on minimizing Dry Mass, highlights satellite designs with low Cost, Fuel Mass, Dry Mass, Propellant Mass, and Reaction Wheel Mass; however, these designs do not perform well with respect to Slew Time. The second plot places a greater importance on minimizing Slew Time. As a result, new regions are highlighted that correspond to a higher Dry Mass, Reaction Wheel Mass, and Cost. These two plots display a tradeoff between competing variables, in that minimizing slew time results in an increase in mass and cost properties of a satellite.

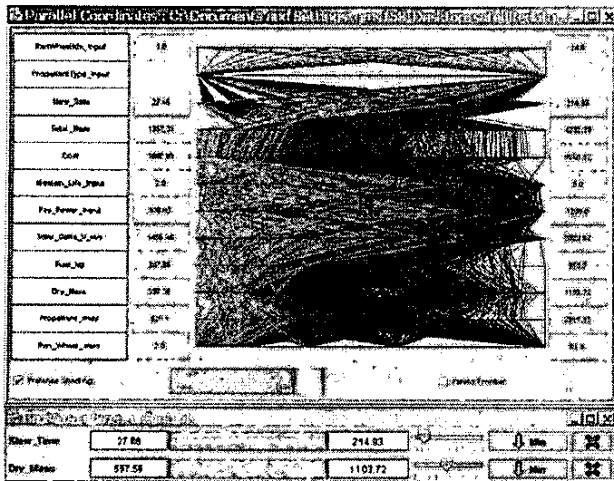


Figure 14 - Parallel Coordinates with Preference Shading

The ATSV allows a decision-maker to visualize different preference structures, by highlighting different regions within the trade space. Preference shading is used to aid the decision-maker in understanding tradeoffs between variables, and Pareto optimality will draw attention to specific satellites within these highlighted regions. Different relative weights between Dry Mass and Slew Time highlight different Pareto optimal designs, aiding the decision-maker in selecting the most preferred design. The shopping process is summarized in Fig. 15, where different preference structures will lead to different preferred designs.

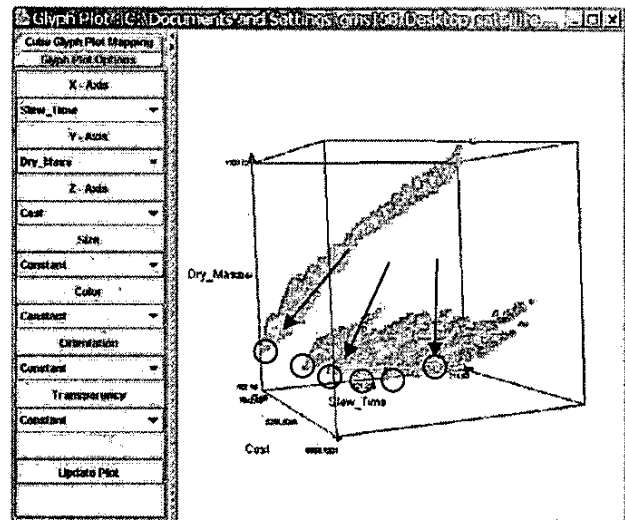


Figure 15 - Design by Shopping Process

Design Selection

The glyph plot, shown in Fig. 16, displays a satellite trade space of interest in the preliminary design stage. Figure 16 shows the entire satellite trade space of 5000 designs, each represented by an individual glyph cube. The glyph plot mapping is as follows:

- X - axis : Reaction Wheel Index
- Y - axis : Cost
- Z - axis : Propellant Type
- Glyph size : ΔV
- Glyph color : Slew Time

Users of the ATSV can display additional information by selecting a design in the glyph plot (see Fig. 16 and 17). Additional information such as quantitative data, 3D geometries, images, and other files about a design is displayed to the decision-maker.

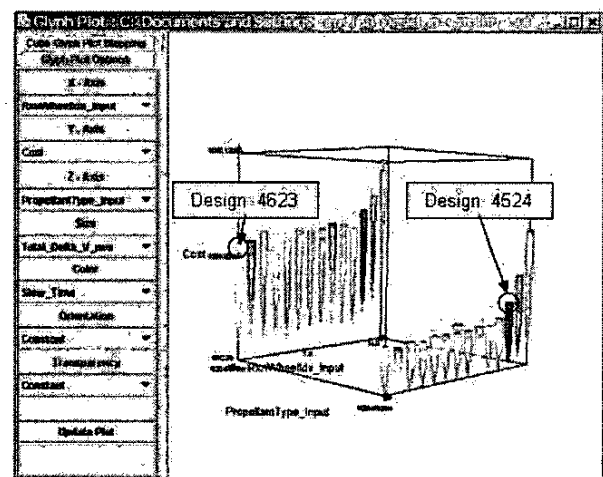


Figure 16 - Glyph Plot Displaying Satellite Trade Space

Figure 16 illustrates that satellites with a propellant choice of N_2O_4/N_2H_4 achieve high ΔV at a lower cost compared to satellites that use N_2O_4/MMH as the propellant. The selected designs have similar ΔV performance; however, the 3D geometries in Fig. 17 display different sizes for the fuel tanks, located on the lower platform (shaded blue). Fuel tank radii are held constant, while the barrel length changes to accommodate additional volume need by the fuel. Design 4524 uses N_2O_4/N_2H_4 as propellant, where the density of N_2H_4 is 1.01 g/cc; Design 4623, which uses N_2O_4/MMH as propellant, has larger fuel tanks than Design 4524, since the density of MMH is lower (0.88 g/cc). As a result, additional fuel tank mass is added, increasing overall mass and cost properties of the satellite.

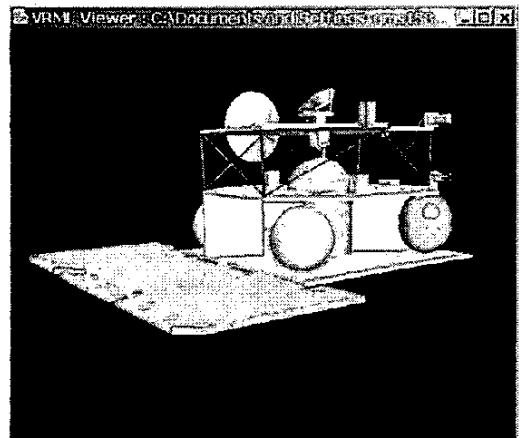
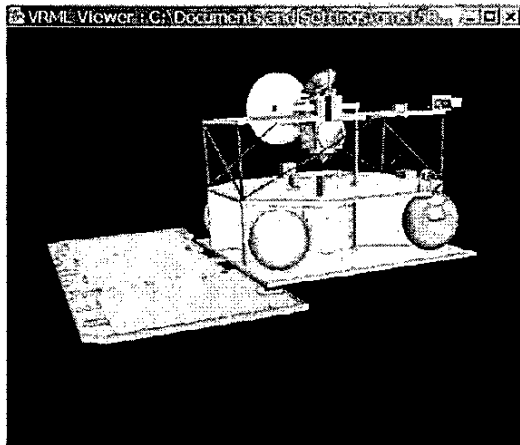


Figure 17 - 3D Geometries for Designs 4524 and 4623, Respectively

Illustrated in Fig. 17, placement of the upper platform changes to accommodate the volume needed for the reaction wheels and oxidizer tank. The reaction wheels are located underneath the upper platform, and the oxidizer tank, grey grey only visible in Design 4623, is located in the center of the satellite. Design 4524 has a very good performance with respect to slew time, since this satellite has large reaction wheels.

5. CONCLUSION

We have developed a graphical user interface that allows a decision-maker to incorporate a design by shopping paradigm to help select a preferred solution. Using the ATSV, the decision-maker is able to visualize different preferences structures within the trade space, introducing the capability to shop for a desired solution. The ATSV uses multi-dimensional visualization techniques to display trade spaces; additionally, glyph plots and 3D geometry files can be viewed in stereo mode, using environments that include projection screens and desktop monitors.

Future work will focus on porting the ATSV to our immersive virtual reality environment (SEALab). Also, interface capability will be improved such as adding user-defined glyph icons, additional preference shading functions, algorithm efficiency, and overall interface usability. Additionally, new methods to visualize a design's uncertainty and risk will be implemented into the ATSV.

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