The ARL Trade Space Visualizer: An Engineering Decision-Making Tool

Gary M. Stump*, Mike A. Yukish†, and Jay D. Martin‡
Applied Research Laboratory, Penn State, P. O. Box 30, State College, PA, 16804 USA

Timothy W. Simpson§
Department of Mechanical and Nuclear Engineering, Penn State, University Park, PA 16802 USA

To support trade space exploration early in the conceptual design stage, researchers at the Applied Research Laboratory (ARL) at Penn State University have been developing the ARL Trade Space Visualizer (ATSV). The ATSV uses multi-dimensional visualization techniques to display complex trade spaces, which are populated using conceptual models. Recent efforts have focused on extending the ATSV capabilities. One such effort has been to visualize design uncertainty, which can be displayed using the multi-dimensional plotting capabilities in the ATSV. Since the ATSV is a stand-alone application, efforts have focused on linking the conceptual model design rules to interesting features within trade spaces, resulting in the development of the feature finder tool. Additionally, the ATSV can calculate and display derivative information about a selected point in the trade space. All of these capabilities are demonstrated using data generated from rail gun and power subsystems in a fighting vehicle conceptual model.

I. Background

Researchers at the Applied Research Laboratory (ARL) at Penn State University have been conducting research in applying multi-dimensional data visualization techniques to the conceptual design process, recently culminating in the development of the ARL Trade Space Visualizer (ATSV).[1-3] The ATSV is a software application that allows a user to explore a multi-dimensional trade space for complex systems such as satellites and aircraft in a visually intuitive manner. To use the ATSV, first the designer must populate the trade space with thousands of point designs, using design automation capabilities to generate them. As each design can have many attributes, the result is thousands of point designs occupying a multi-dimensional space. The decision-maker then explores this space using the ATSV, identifying relationships between different design variables, dynamically applying constraints and preferences to the trade space in real time. This provides the decision-maker with the intuition needed to make a best decision.

Recently, this work has been extended to include uncertainty visualization, the feature finder tool, and derivative display. Our conceptual models have the ability to capture a design's uncertainty, and this capability has provided the motivation to develop uncertainty visualization within the ATSV. Also, recent efforts have been focused on explaining why interesting features occur in the trade space. The ATSV is a stand-alone data visualization program that has no direct link to the conceptual models that populate trade spaces. The feature finder tool attempts to fill the void and validate which conceptual model design rules cause interesting features within trade spaces. Our third effort has been focused on developing algorithms to calculate and visualize derivative information.

In the next section, we discuss the existing capabilities of the ATSV. In Section III, we present recent efforts in the ATSV development. These efforts will be demonstrated using data from subsystems in a conceptual model of a fighting vehicle. Closing remarks and future work are given in Section IV.

* Research Assistant, Department of Product and Process Design, **Corresponding Author**, Phone/Fax: (814) 863 – 9911/4128, Email: gms158@psu.edu.
† Head, Department of Product and Process Design, Phone/Fax: (814) 863 – 7143/4128, Email: MikeYukish@psu.edu.
‡ Research Assistant, Department of Product and Process Design, Phone/Fax: (814) 863 – 5930/4128, Email: jdm111@psu.edu.
§ Associate Professor, Mechanical Engineering and Industrial Engineering, Phone/Fax: (814) 863 – 7136/4745, Email: tws8@psu.edu, Member AIAA.

II. Existing ATSV Capabilities

The ATSV currently provides many tools that aid the decision-maker in visualizing engineering trade spaces. The ATSV has the capability to view trade spaces using multi-dimensional visualization techniques that include glyph plots, histogram plots, parallel coordinate plots, scatter matrices, brushing, and linked views. Also, the ATSV uses preference shading and Pareto frontier display to aid a decision-maker in forming a preference structure. A decision-maker can select a design and view its quantitative information along with any documents specific to the selected design. Along with data visualization capabilities, the ATSV uses advanced visualization hardware to display images in stereo mode.

A. Glyph Plots/Histogram Plots/Parallel Coordinate Plots/Scatter Matrices

A glyph plot displays multivariate information by using the physical characteristics, such as color, size, orientation, scale, texture, and transparency, of an icon to display additional information. As shown in Fig. 1a, the ATSV can display 7-dimensional information within a glyph plot using the spatial position of an icon to represent three variables of one design while an additional four variables can be represented by the size, color, orientation, and transparency of the icon. The dimensionality of the glyph plot can be reduced by applying a constant value to any of the glyph plot features.

A histogram partitions a variable's range and counts the total number of occurrences in each bin. Multiple histogram plots can be displayed within a single window by selecting variables from the list located to the left of the display, as displayed in Fig. 1b.

Parallel coordinate plots, proposed by Inselberg,[4] display multivariate designs by using a polyline that intersects equally-spaced axes. The user can select which variables to include in the trade space using the list located to the left of the parallel coordinates display (shown in Fig. 1c).

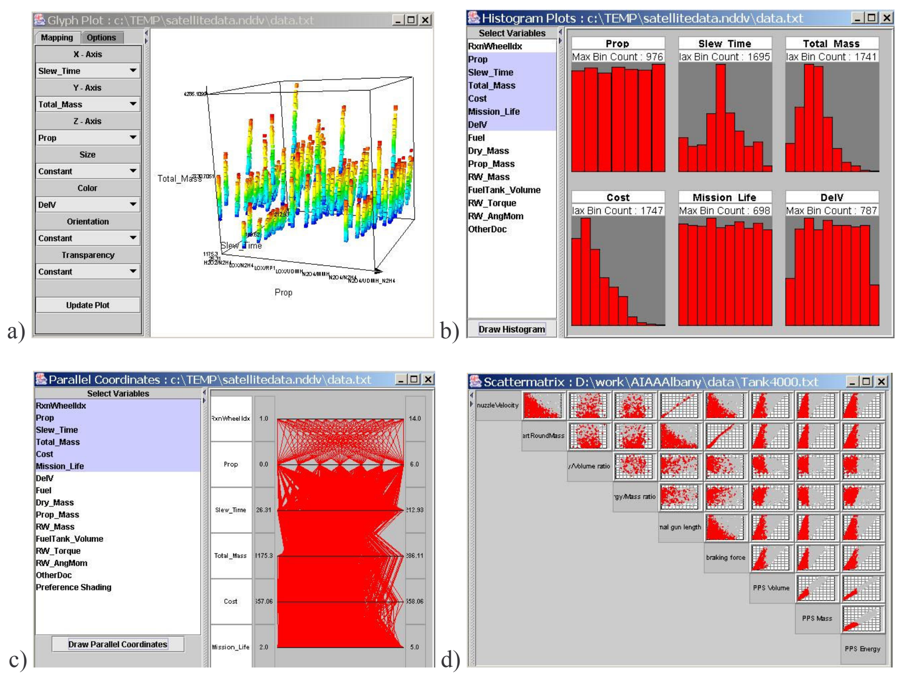

Figure 1. a) Glyph Plot, b)Histogram Plots, c) Parallel Coordinates, d) Scatter Matrix.

Scatter matrices (illustrated in Fig. 1d) display a matrix of scatter plots, where variables in the trade space are plot against each other at least once. To reduce computational time, the ATSV only displays scatter plots in the upper triangular matrix. Additionally, the ATSV allows a user to select all or a user-defined number of designs to include in the scatter plot.

B. 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.[5] Linking is the process of displaying information across multiple views of data.[6] The ATSV implements both visualization strategies as shown in Fig. 2.

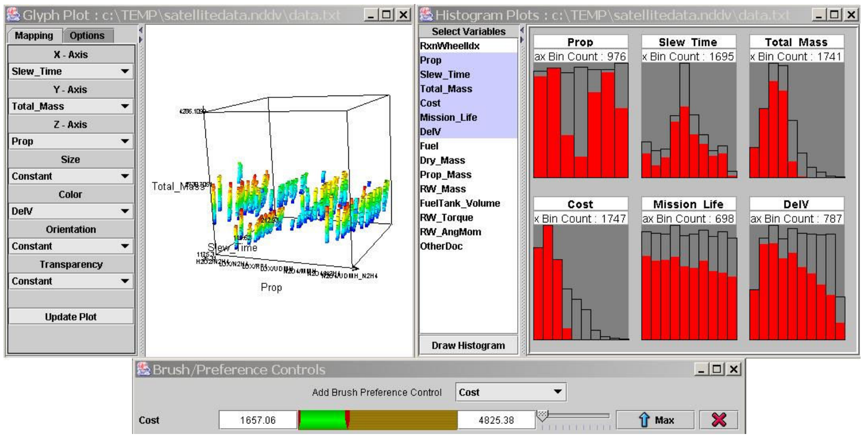

Figure 2. Brushing/Linking Illustration.

C. Preference Shading and Pareto Frontier Display

The ATSV can display different preference structures using preference shading and Pareto frontiers. Preference shading ranks designs according to a user-defined preference structure. Decision-makers can vary the relative weightings in real-time, and the resulting preference structure is updated within the graphical displays. Additionally, each preference structure will generate a set of Pareto optimal designs. The ATSV contains algorithms to find Pareto optimal designs within discretely sampled trade spaces.[3] Figure 3 displays preference shading, which corresponds to highlighted designs, and Pareto frontier display, denoted using white markings.

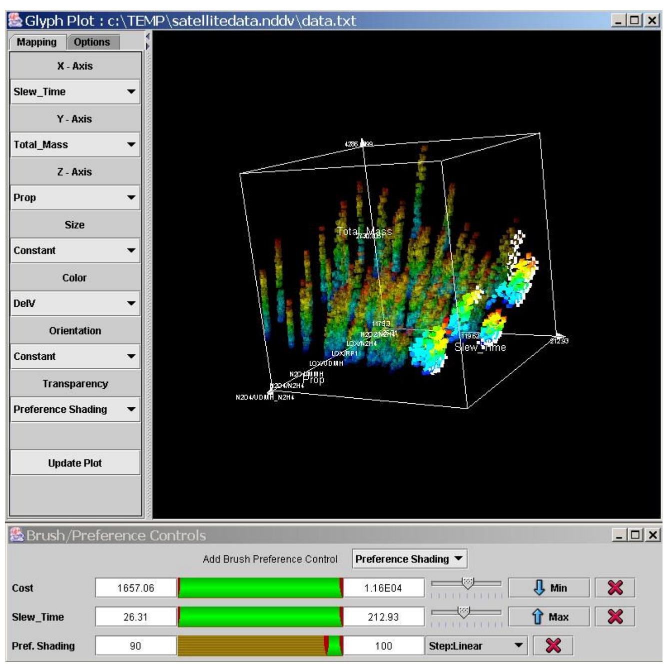

Figure 3. Preference Shading and Pareto Frontier Display in a 3D Glyph Plot.

D. Virtual Reality

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

The ATSV interface uses the advanced visualization setups displayed in Fig. 4.

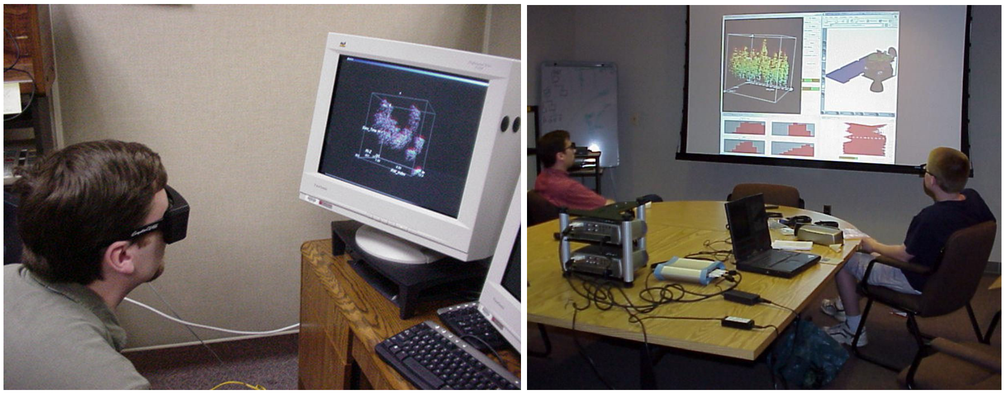

Figure 4. Active and Passive Stereoscopic Display.[1,2]

III. Recent Efforts in ATSV Capabilities

This section discusses capabilities that have recently been added to the ARL Trade Space Visualizer (ATSV). Data sets from the rail gun and power subsystems of a fighting vehicle conceptual model, developed in Excel, were generated to illustrate ATSV capabilities. Key variables in these data sets include the following:

- Muzzle velocity: Velocity of the round fired from the rail gun
- Round Mass: Mass of the round fired from the rail gun
- PPS Mass: Mass of the power supply to the rail gun
- PPS Energy: Energy supplied to the rail gun
- Engine Power: Power supplied by the engine
- Battery Power: Power supplied by the battery
- % Battery Power: Percentage of power supplied by the battery
- Mass: Mass of the vehicle

A. Uncertainty Visualization

Recent efforts have focused on visualizing uncertainty information using ATSV capabilities. Our conceptual models capture design uncertainty for each point in the trade space. As a result, each design is a point cloud with a distribution that represents a design's uncertainty. The ATSV stores each design as a point cloud along with its mean average and total visible number of designs, which represents the number of designs in a group that lie within an applied brush. Feasibility of a design is calculated using Eq. (1):

$$Feasibility = \frac{VisibleDesignsInGroup}{GroupCount} \quad (1)$$

1. *Uncertainty Visualization Demonstration*

An example data set, based on trigonometric functions, illustrates how the ATSV visualizes uncertainty. Shown in Fig. 5, a scatter plot displays 16 designs, where each design is represented by a point cloud. When a constraint is applied to y1, the number of visible (red) designs in each group may change. For example, designs represented by point clouds to the right of the y1 constraint are infeasible since no designs within these groups are visible; whereas, point clouds that lie to the left of the y1 constraint are feasible since all designs within the group are visible. The one design that lies on the y1 constraint has a low

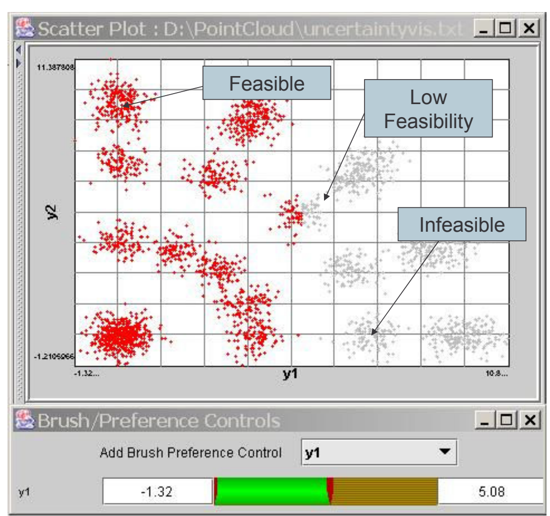

Figure 5. Feasibility Illustration in the ATSV.

feasibility, since a portion of the group’s designs are visible.

The ATSV glyph plots can combine each point cloud into a single point that displays the mean average of a design. Additionally, each point has a feasibility value, and this value can be assigned to any attribute in the glyph plot. Displayed in Fig. 6, feasibility is visualized using the size and color of the glyph. Designs with 100% feasibility or are large and red; while the design with low feasibility is small and green.

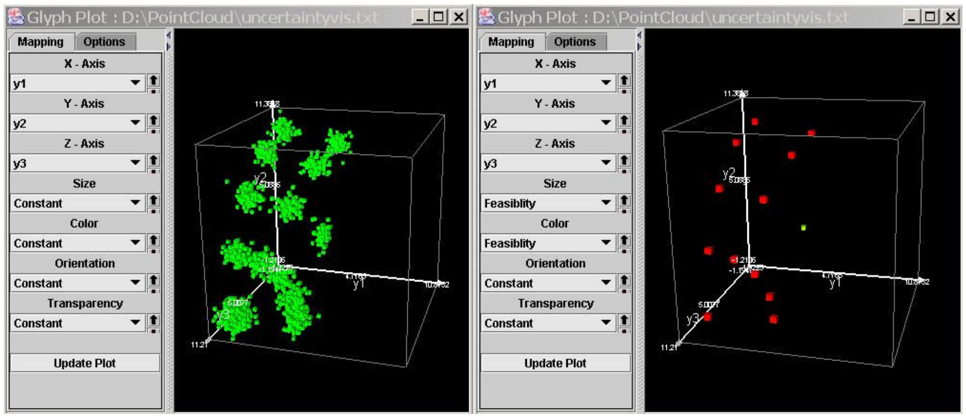

Figure 6. Uncertainty Visualization Using the ATSV.

2. *Uncertainty Visualization Using Rail Gun Data*

Figure 7 displays a rail gun trade space with two input variables, muzzle velocity and round mass, along with the output variable PPS Mass on the vertical axis. Uncertainty in conceptual model parameters causes uncertainty in the PPS Mass of the vehicle. The left glyph plot in Fig. 7 displays each point as a point cloud, and the right glyph plot represents each design by a point at its mean average. A design’s PPS Mass is uncertain, and applying a constraint to this variable will lead to design uncertainty near the imposed constraint.

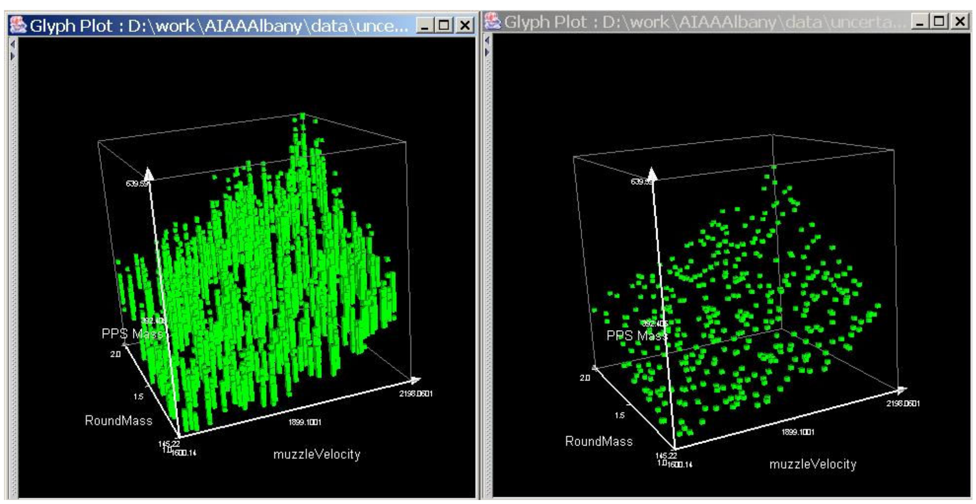

Figure 7. Uncertainty Visualization Using Rail Gun Data.

Figure 8 illustrates the same trade space, except PPS Energy is mapped to the vertical axis of the glyph plot, and an applied brush displays designs that have PPS Mass less than 360.27. Feasibility is assigned to the size and color of the glyph cubes, where high feasibility is represented by large red glyphs and low feasibility is represented by small blue glyphs. Designs that have a mean PPS Mass value near 360.27 have lower feasibility values. A common preference structure is to maximize PPS Energy, which corresponds to designs that lie higher on the vertical axes. As a result, more preferred designs are less likely to be feasible near the constraint boundary.

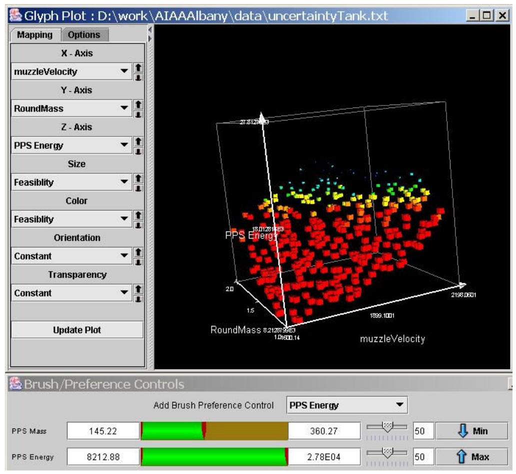

Figure 8. Design Uncertainty Near an Applied Constraint.

As with trade space variables, a decision-maker can apply constraints based on feasibility. In Fig. 9, the first glyph plot displays designs that are 90% - 100% feasible, whereas the second plot only displays designs that are less than 90% feasible.

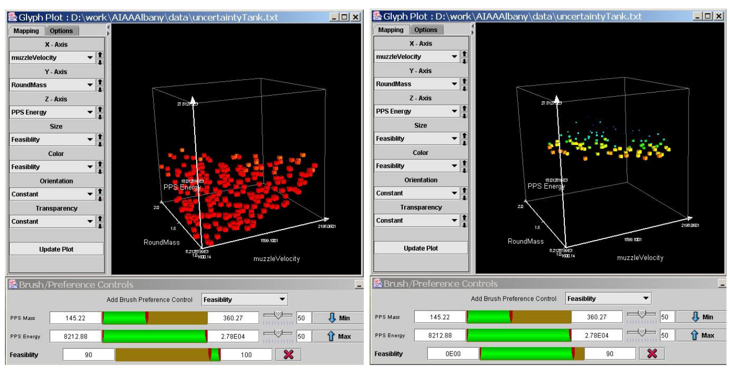

Figure 9. Brush Trade Space Based on Design Feasibility.

B. Feature Finder Tool

The feature finder tool attempts to link the trade space visualized in our stand-alone data visualization application (ATSV) to the conceptual model design rules that generate the trade space. Before implementing the feature finder tool, the decision-maker could formulate ideas on why trends or relationships within the trade space occur; however, there was no method of visualizing which design rules cause such interesting relationships. This aspect of our research attempts to validate which designs rules cause interesting features within the trade space such as those seen in Fig. 10.

Two kinds of data, flags and sequences, are stored in data files visualized using the ATSV. Flags record design rule states by storing the values of function calls, which include Min's, Max's, If's, and Switches's. Additionally, sequences trace program

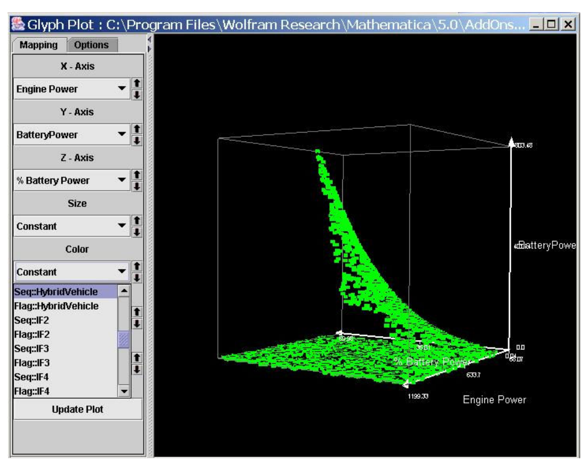

Figure 10. Assign Feature Finder Variables to a Glyph Plot Mapping.

logic through the conceptual model and store precedent and dependency information of flagged functions.

Our approach uses glyph plots and node/link diagrams to identify interesting relationships in the trade space. Scroll buttons provide a way for decision-makers to rapidly scroll through variables in the trade space. The user can toggle through all variables in the trade space and determine which flagged variables cause interesting features. Each flagged variable has a sequence, which can be visualized using node/link diagrams. Node/link diagrams within the ATSV use custom Java classes along with layout algorithms from the JGraphpad[7] package. The four layouts included in JGraphpad are the spring-embedded,[8] simulated annealing,[9] graph embedder (GEM),[10] and Sugiyama[11] layout algorithms.

Figure 11 displays the trade space with a similar mapping as shown in Fig. 10, except the flagged variable HybridVehicle is displayed as glyph color. Each isosurface is identified with a unique color indicating that all designs in their respective isosurfaces have the same HybridVehicle value, which indicates that this variable leads to design rules that cause the interesting feature.

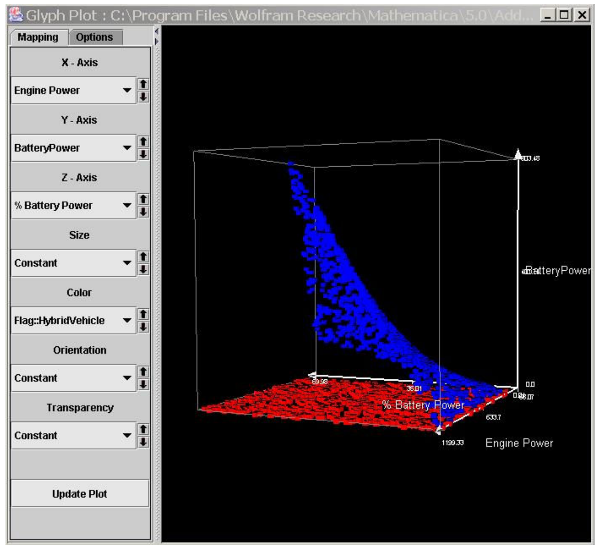

Figure 11. Flagged Variable With Similar Values in Each Isosurface.

Selecting a sequence in the quantitative display window creates a new node/link diagram with the selected sequence, highlighted using green nodes and black links. The sequence that corresponds to the flagged variable HybridVehicle will lead to a set of equations that causes this interesting feature. Shown in Fig. 12, the highlighted sequence shows that the Excel frontend called the MaxBatteryVelocity function; as a result, the decision-maker can trace back to this function in the conceptual model.

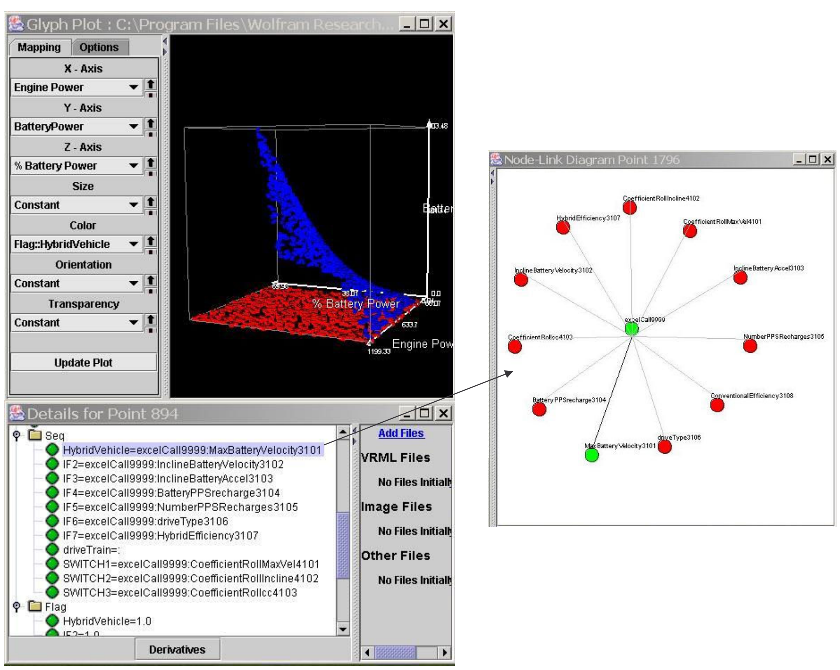

Figure 12. Sequence Visualization Using Node/Link Diagrams.

C. Polynomial Regression

The ATSV uses a response surface approximation through trade space designs to calculate derivative information at a selected point. The derivatives at a point are calculated using the first derivatives of the response surface approximation and substituting the selected point into the first derivative equations. Custom Java code and algorithms from Jama,[12] a Java matrix manipulation package, are used in the polynomial regression analysis.

1. ATSV Polynomial Regression Analysis

A least-square fit, Eq. (2), is used to calculate the coefficients of the polynomial regression equation[13]:

$$b = \left(X^T X\right)^{-1} X^T y \qquad (2)$$

where X is matrix of the levels of independent variables
y is a column matrix of observations

Singular Value Decomposition (SVD) is used to perform the inverse operation on the (X^TX) matrix. Any m x n real matrix A can be decomposed into a form shown in Eq. (3).

$$A = UDV^T \qquad (3)$$

where U and V are orthogonal matrices
D is a diagonal matrix with singular values (σ_1, σ_2, …, σ_m) of the original matrix

This inverse of A is calculated using Eq. (4).

$$A^{-1} = VD_o^{-1}U^T \qquad (4)$$

$$if \sigma_i > t$$

$$D_{0i}^{-1} = \frac{1}{\sigma_i}$$

$$if \sigma_i < t$$

$$D_{0i}^{-1} = 0$$

where t is a threshold value

This approach is more robust, since the inverse of the hat matrix (X^TX) can be approximated even if it is singular. Using SVD prevents the ATSV from throwing an exception each time a singular matrix is encountered. We have found that trade spaces with discrete variables sometimes lead to singular hat matrices, since designs in a local neighborhood may have the same constant value for at least one dimension. This constant value will cause a singular matrix.

For each output included in the analysis, a polynomial regression model is calculated based on the selected input variables. A set of least squares regression coefficients, along with the corresponding goodness of fit is calculated for each output variable. The R-Squared value is calculated using Eq. (5):

$$r^2 = \sum_{i=1}^{n} \frac{\left(\hat{y}_i - \bar{y}\right)^2}{\left(y_i - \bar{y}\right)^2} \qquad (5)$$

where $\hat{y}_i$ are the fitted values using the polynomial regression equation

y_i are the actual values

$\bar{y}$ is the average of all y_i included in the regression analysis

The polynomial regression models are then used to estimate the derivatives at the selected point as described next.

2. ATSV Derivative Display

Shown in Fig. 13, the general procedure to display derivatives using the ATSV is as follows:

- Select a design in the trade space
- Open a derivative analysis window for the selected design
- Select inputs and outputs to the polynomial regression model
- Fit a response surface approximation to the discretely sampled trade space
- Plot derivatives using scatter plots and matrix displays at the selected design

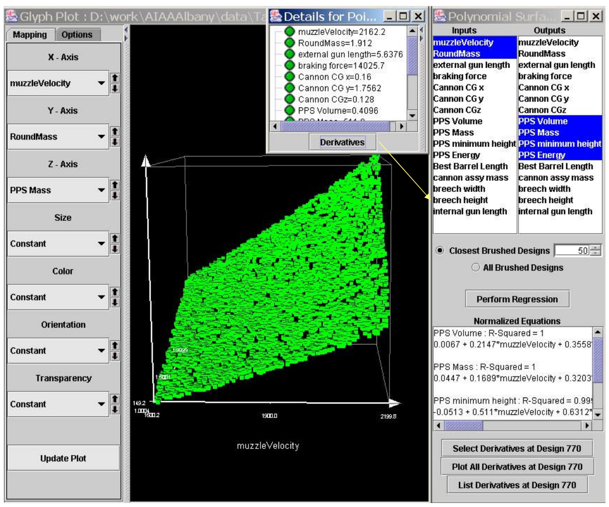

Figure 13. Procedure to Display Derivative Information.

A user has a selection of two options, which includes the set of designs in the regression analysis. The first option finds a user-defined n nearest designs to the selected point, where n has lower limit as calculated in Eq. 6 and an upper limit equal to the total number of visible designs in the trade space.

$$n = \frac{SF(k+1)(k+2)}{2.0} \tag{6}$$

where k is the total number of input variables
SF is the safety factor = 1.5

The second option includes all designs currently visible within ATSV plots.

The ATSV visualizes derivative information using 2D scatter plots and matrix displays as shown in Fig. 14. Scatter plots display all designs included in the regression analysis, along with the normalized derivative at the selected design. Above the scatter plot, numerical information such as index number, normalized derivative, and the actual derivative are listed. Additionally, we can display a matrix of derivatives at the selected point, which allows a user to scan through a large set of derivatives. Each row has the same input variable; each column has the same output variable. One can select a grid within the matrix to display the normalized (red) and actual (blue) slope of the selected derivative.

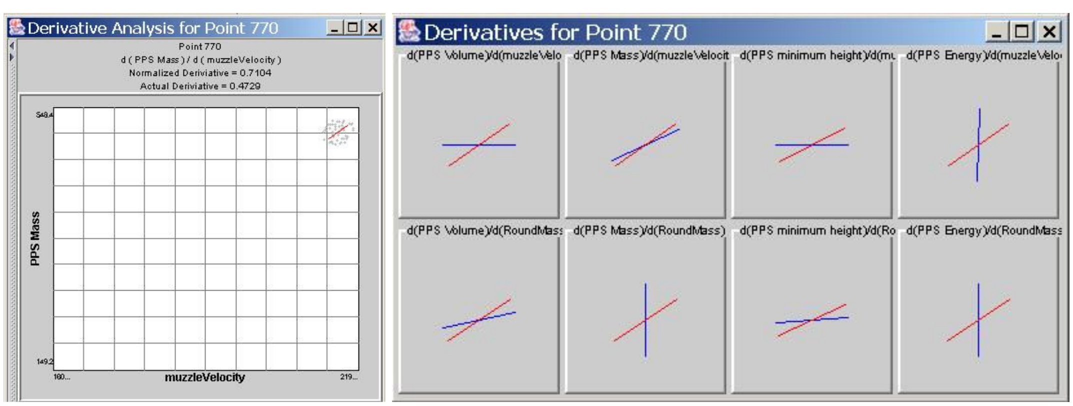

Figure 14. ATSV Derivative Display.

Figure 15 illustrates a glyph plot and two derivative plots for selected designs in the trade space. The glyph plot displays muzzle velocity on the x-axis and PPS Mass on the y-axis. Each of the derivative plots display $\frac{\Delta PPSMass}{\Delta muzzleVelocity}$, which corresponds to $\frac{\Delta y}{\Delta x}$ on the glyph plot. Notice the first derivative plot has a slope less than the second derivative plot, which corresponds to the convex shape of the isosurface in the glyph plot.

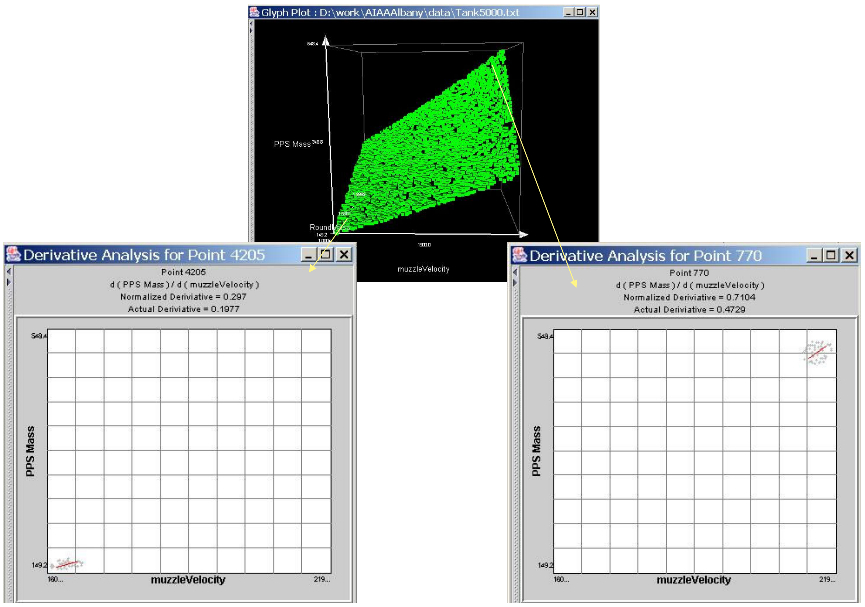

Figure 15. Local Derivatives at Two Selected Points in the Trade Space.

IV. Conclusions and Future Work

We have extended our data visualization interface, the ARL Trade Space Visualizer (ATSV), to include uncertainty visualization, the feature finder tool, and derivative analysis display. These extensions have been incorporated in a manner that can use existing ATSV capabilities. Our future work will focus on additional algorithms and methods to calculate and display uncertainty and derivative information. Alternative approximation methods such as kriging models can be used to calculate derivative and uncertainty information. Also, the ATSV could implement projection pursuit algorithms to aid the decision-maker in searching for interesting projections in the trade space, thereby reducing the time needed by a decision-maker to find interesting features. Additional research will focus on group decision-making and implementing algorithms to combine several preference structures into one metric.

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