Trade Space Exploration for Complex Systems Design*

Timothy W. Simpson

Professor of Mechanical and Industrial Engineering and Engineering Design
The Pennsylvania State University
University Park, PA 16802 USA

phone: (814) 863-7136
email: tws8@psu.edu
http://edog.mne.psu.edu/

* This represents collaborative efforts with David Spencer (AeroE) and Mike Yukish (ARL) at Penn State and researchers at GM, GE, and Aerospace Corporation, and through ONR, and is supported by the National Science Foundation under Grant # DMI-0620948.

Which is the best design?

A	B	C	D	E	F	G	H	I	J	K	Mass	ConVio	Obj1	Obj2	Obj3	Obj4	Obj5
0.624649	0.754049	0.876689	0.343205	0.212124	0.933273	0.57122	3	0.696767	0.520956	0.061564	1.065553	85.3757	1.062015	0.988355	0.975157	0.949053	1.015516
0.060985	0.157698	0.100316	0.147226	0.723355	0.954276	0.18665	5	0.147579	0.594634	0.546073	0.869276	280.5069	0.821385	1.062017	0.984424	1.02363	0.845335
0.79029	0.753857	0.374672	0.23151	0.568749	0.966105	0.926726	5	0.861844	0.206967	0.152046	1.087959	162.1251	1.025622	1.009793	0.935661	0.962082	0.950406
0.386879	0.088587	0.001015	0.89747	0.369036	0.575776	0.907945	1	0.425441	0.129497	0.930208	0.897125	0	1.27605	1.128511	0.925916	1.095028	0.727479
0.00745	0.664116	0.161524	0.613925	0.45661	0.734871	0.954844	6	0.944188	0.415194	0.177407	0.861764	418.1174	0.605767	0.90523	0.961853	0.973201	0.965639
0.995651	0.743935	0.320403	0.090145	0.48886	0.393002	0.876449	4	0.828249	0.673172	0.795096	1.183174	297.2661	0.918957	0.864233	0.994303	1.079725	1.043906
0.328119	0.856472	0.01425	0.842507	0.451588	0.130799	0.974695	1	0.758214	0.163655	0.641987	0.858018	0	1.210881	1.153077	0.930213	1.064094	0.973342
0.435725	0.714144	0.590085	0.488513	0.195516	0.353903	0.095564	6	0.800199	0.121332	0.74331	0.980696	84.54371	0.69339	0.882991	0.924889	1.072899	0.920315
0.140543	0.619531	0.286546	0.547551	0.700957	0.820492	0.122013	3	0.54486	0.027115	0.396837	0.81166	75.67446	0.798757	1.070938	0.913038	1.004613	0.871374
0.053287	0.967234	0.027151	0.285497	0.11165	0.493894	0.312822	2	0.834215	0.607056	0.965347	0.856679	190.3453	0.994475	1.086928	0.985987	1.103027	1.099647
0.016589	0.081024	0.077573	0.970116	0.236366	0.197258	0.299823	4	0.897914	0.996856	0.145421	0.899552	314.8964	0.689412	0.930108	1.035018	0.984929	0.904823
0.339073	0.804103	0.194134	0.595187	0.893329	0.173013	0.599763	3	0.682347	0.211061	0.433533	0.936625	0	0.92971	1.026089	0.936176	1.030417	0.966879
0.807105	0.355682	0.698499	0.347406	0.147357	0.833227	0.239664	5	0.180274	0.339442	0.126236	1.107651	142.5201	1.046443	1.001878	0.952325	0.962201	0.854032
0.461698	0.808808	0.448971	0.555792	0.308602	0.078053	0.713475	1	0.804761	0.911746	0.592818	1.005789	0	1.455601	1.070847	1.024313	1.058098	1.113506
0.893653	0.178552	0.302888	0.772328	0.540938	0.210228	0.633615	2	0.242687	0.707757	0.370249	1.158954	197.4329	1.352289	0.997158	0.998654	1.019435	0.875256
0.593384	0.607663	0.564	0.670026	0.432504	0.034409	0.42949	1	0.765861	0.284269	0.456763	0.990321	25.37839	1.406297	1.099572	0.945385	1.038328	0.920959
0.011539	0.850963	0.099594	0.619666	0.527305	0.132944	0.404533	4	0.163654	5.26E-04	0.410111	0.78425	153.0766	0.593367	0.965405	0.909694	1.028025	0.937833
0.917945	0.354331	0.360415	0.949183	0.654889	0.883763	0.858601	1	0.113017	0.578143	0.005751	1.111352	342.9728	1.58323	1.057398	0.98235	0.941924	0.903065
0.629985	0.367476	0.030701	0.823217	0.751167	0.709767	0.134882	2	0.418778	0.074323	0.700772	1.010063	76.0458	1.163879	1.05292	0.918976	1.055243	0.802774
0.052335	0.607279	0.051817	0.635463	0.083765	0.384859	0.553443	3	0.246573	0.031671	0.894493	0.793414	128.5993	0.786491	1.064864	0.913611	1.095411	0.868508
0.26956	0.542476	0.324995	0.205405	0.925943	0.712346	0.350751	1	0.603615	0.889306	0.925155	0.930262	33.28389	1.350634	1.090706	1.02149	1.090002	1.026037
0.113861	0.023778	0.544848	0.464351	0.032314	0.264167	0.608364	2	0.312497	0.737143	0.487076	0.884893	155.3781	1.022127	1.085544	1.00235	1.0359	0.833215
0.790459	0.561394	0.075355	0.0309	0.604376	0.881564	0.38648	2	0.126824	0.425601	0.840445	1.102166	155.5182	1.286927	1.01118	0.963162	1.071595	0.935852
0.925059	0.529395	0.398783	0.664759	0.711469	0.374232	0.432993	1	0.835886	0.999606	0.914148	1.164511	175.0352	1.718627	1.002366	1.035364	1.098793	1.044821
0.492116	0.483754	0.11385	0.268324	0.139095	0.327651	0.775126	6	0.621833	0.201755	0.208674	1.00229	58.42594	0.706126	0.884241	0.935005	0.990701	0.865333
0.714184	0.664542	0.11446	0.017024	0.642118	0.80771	0.881159	1	0.732738	0.829098	0.932108	1.097304	48.51039	1.606783	1.02979	1.013917	1.088121	1.051521
0.118918	0.017629	0.924812	0.061686	0.046908	0.643381	0.633561	4	0.393291	0.268319	0.75947	0.838012	88.64945	0.640139	0.944516	0.943378	1.066418	0.734174
0.255594	0.214463	0.598632	0.714721	0.033801	0.594344	0.049352	1	0.324555	0.549029	0.104542	0.887475	52.14604	1.250313	1.145112	0.978688	0.966251	0.853539
0.007185	0.837426	0.285541	0.180206	0.001931	0.242974	0.695136	3	0.981152	0.061027	0.13798	0.787168	176.7205	0.771164	1.084224	0.917304	0.982354	0.946158
0.193436	0.59333	0.575079	0.123012	0.805085	0.819283	0.574159	2	0.184029	0.347939	0.975802	0.857098	43.93821	0.990329	1.09325	0.953393	1.094545	0.929693
0.928198	0.389419	0.115175	0.613135	0.762898	0.396141	0.017512	4	0.304104	0.677509	0.91514	1.168977	234.6986	0.909056	0.865166	0.994849	1.098267	0.934562
0.222651	0.467807	0.951467	0.56811	0.520733	0.053605	0.928277	3	0.88145	0.383813	0.740516	0.901219	26.40954	0.90048	1.025809	0.957906	1.08179	0.898092
0.811201	0.133245	0.378015	0.68068	0.872205	0.49669	0.520425	5	0.0733	0.350462	0.452241	1.109873	81.78877	1.053422	0.994934	0.953711	1.023271	0.787145
0.423361	0.642631	0.712732	0.891548	0.734774	0.993534	0.88727	1	0.784954	0.059616	0.47451	0.896664	13.57533	1.260446	1.145038	0.917126	1.011299	0.885291
0.632001	0.461677	0.108156	0.912385	0.016923	0.345369	0.191936	4	0.336829	0.668814	0.53677	1.08797	0	0.83955	0.888839	0.993755	1.041094	0.955231
0.873147	0.508414	0.360317	0.405932	0.222425	0.053973	0.93098	4	0.314139	0.515362	0.294384	1.137171	214.504	0.874249	0.884942	0.974453	1.012508	0.937973
0.885007	0.781797	0.714749	0.35023	0.385047	0.487096	0.690444	4	0.458081	0.539834	0.562325	1.142733	220.8034	0.882082	0.87889	0.977531	1.040661	1.028056
0.036627	0.355758	0.005696	0.757361	0.319842	0.561181	0.406254	2	0.751786	0.880089	0.388129	0.8844	257.4996	1.022278	1.084719	1.020331	1.011313	0.966064
0.621134	0.26736	0.115896	0.698524	0.324068	0.943496	0.557317	2	0.1309	0.522604	0.896984	1.0619	0	1.241092	1.020734	0.975364	1.07845	0.864514
0.493668	0.564122	0.60814	0.117899	0.772721	0.605714	0.547454	4	0.819652	0.090314	0.471688	0.958514	30.04471	0.730484	0.927495	0.920988	1.022904	0.867237
0.273529	0.548112	0.988656	0.882654	0.25439	0.246603	0.397196	5	0.288987	0.436134	0.337391	0.927578	95.88232	0.874011	1.051251	0.964487	1.013204	0.933903
0.149734	0.317481	0.19274	0.388216	0.898963	0.313182	0.953739	5	0.388612	0.048113	0.646596	0.82531	170.1594	0.773724	1.085413	0.915679	1.059146	0.781797
0.653178	0.273579	0.629722	0.666803	0.995326	0.352516	0.104895	4	0.263001	0.49329	0.815411	1.071509	17.21235	0.827531	0.890659	0.971677	1.084137	0.860374
0.472799	0.156696	0.041151	0.345065	0.351738	0.483427	0.93028	6	0.766748	0.388929	0.282111	1.020344	56.32071	0.72098	0.878103	0.958549	0.997266	0.802407
0.907584	0.818911	0.940492	0.757801	0.051914	0.137225	0.701082	5	0.757653	0.958448	0.353178	1.205011	44.55034	1.155917	0.958121	1.030187	1.019052	1.126324
0.861104	0.686593	0.484355	0.998615	0.749554	0.084413	0.891419	1	0.204854	0.612706	0.701557	1.103201	185.3407	1.598347	1.040067	0.986697	1.074784	1.013548
0.160185	0.382135	0.774365	0.092991	0.177952	0.221956	0.016188	3	0.723065	0.144779	0.924658	0.829475	63.8893	0.825459	1.04983	0.927839	1.105154	0.821929
0.031606	0.779571	0.563722	0.351247	0.772206	0.162459	0.396974	4	0.866714	0.130713	0.28886	0.803458	141.0366	0.608358	0.961513	0.926069	1.008282	0.942604
0.04231	0.856992	0.241613	0.63364	0.712683	0.199528	0.611167	1	0.740617	0.473581	0.957145	0.801906	41.5925	1.144678	1.156734	0.969197	1.110894	1.037713

Guiding Questions

How do we visualize and explore system-level trade spaces effectively in support of collaborative decision-making?

→ What do we mean by trade space exploration?

→ What is our approach to visual decision-making?

→ How does this support and enable collaboration?

Philosophical Underpinnings of Our Work

- The assumption that we can capture a decision-maker's preferences *a priori* is wrong
  - Designers, like people, want to "shop" to gain intuition about trades, what is feasible and what is not, and to learn about their alternatives first

- We deed new paradigm(s) for trade space exploration
  - "Design by Shopping" – coined by Rick Balling in 1998 – enables an *a posteriori* articulation of preferences:
    - Allow decision-makers to view a *variety* of feasible designs
    - Form a preference *after* viewing the trade space
    - Choose an optimal design based on this preference

Trade Space Exploration

Trade space exploration entails:

- A shopping process
  - People form their preferences by exploring the *trade space*, $Z = [X \; Y]^T$
- A negotiation process
  - *"… engineering is as a **socio-technical** decision-making activity, where a team of **stakeholders** with **different expertise** and **mixed motives** engage in **interactive conflict resolutions** to **reach consensus** of some engineering matter" – Prof. S. Lu (USC)*
- A sequential process
  - Exploring the trade space is as much about eliminating the wrong answers as it is about finding the right answer
  - You can tolerate much more uncertainty in eliminating wrong answers
  - More detail → more constraints → further away from the ideal
  - Time and cost vary exponentially with detail
  - *Detail is the enemy of flexibility*

Our Approach to Trade Space Exploration

Build Models

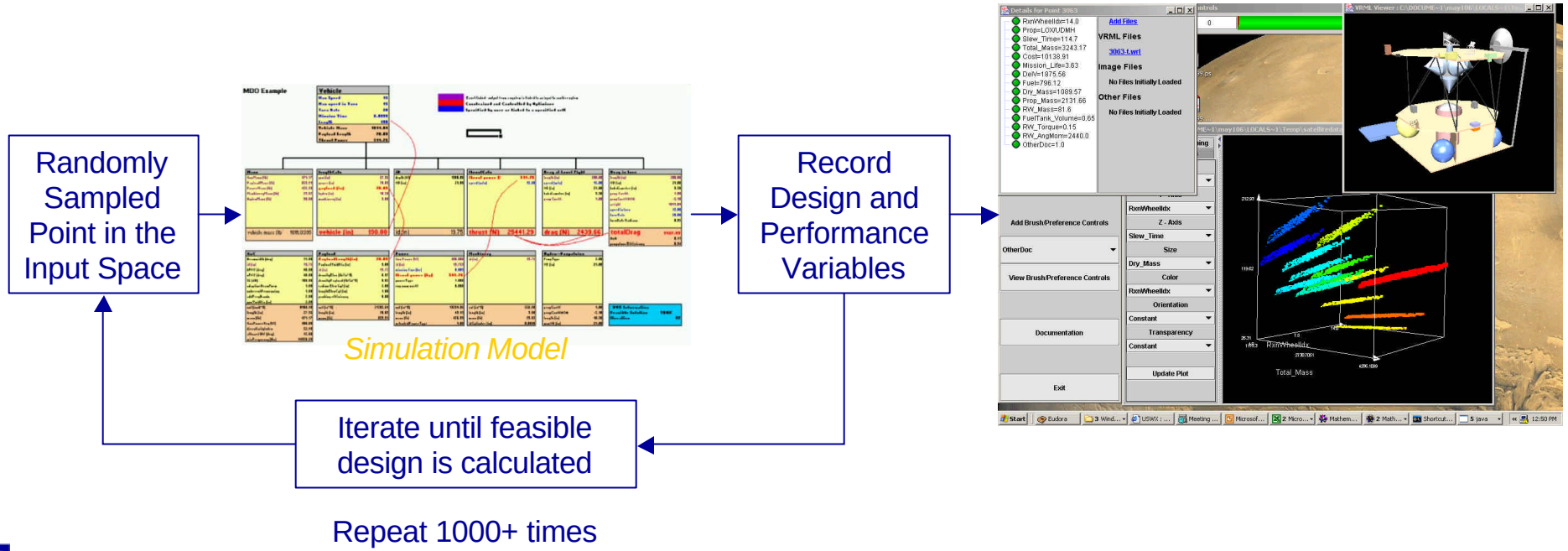
- Assemble models based on design rules and analyses specific to the system being designed
- Model set up to run in batch mode to generate design alternatives

Run Experiments

- Focus on trade study of interest
- 3000-4000 designs
- Augment design with geometry and more

Explore/Visualize

- Look for known trends
- Apply constraints
- Visualize preference structures and Pareto frontiers; optimize
- Identify best design(s)



ARL Trade Space Visualizer (ATSV)

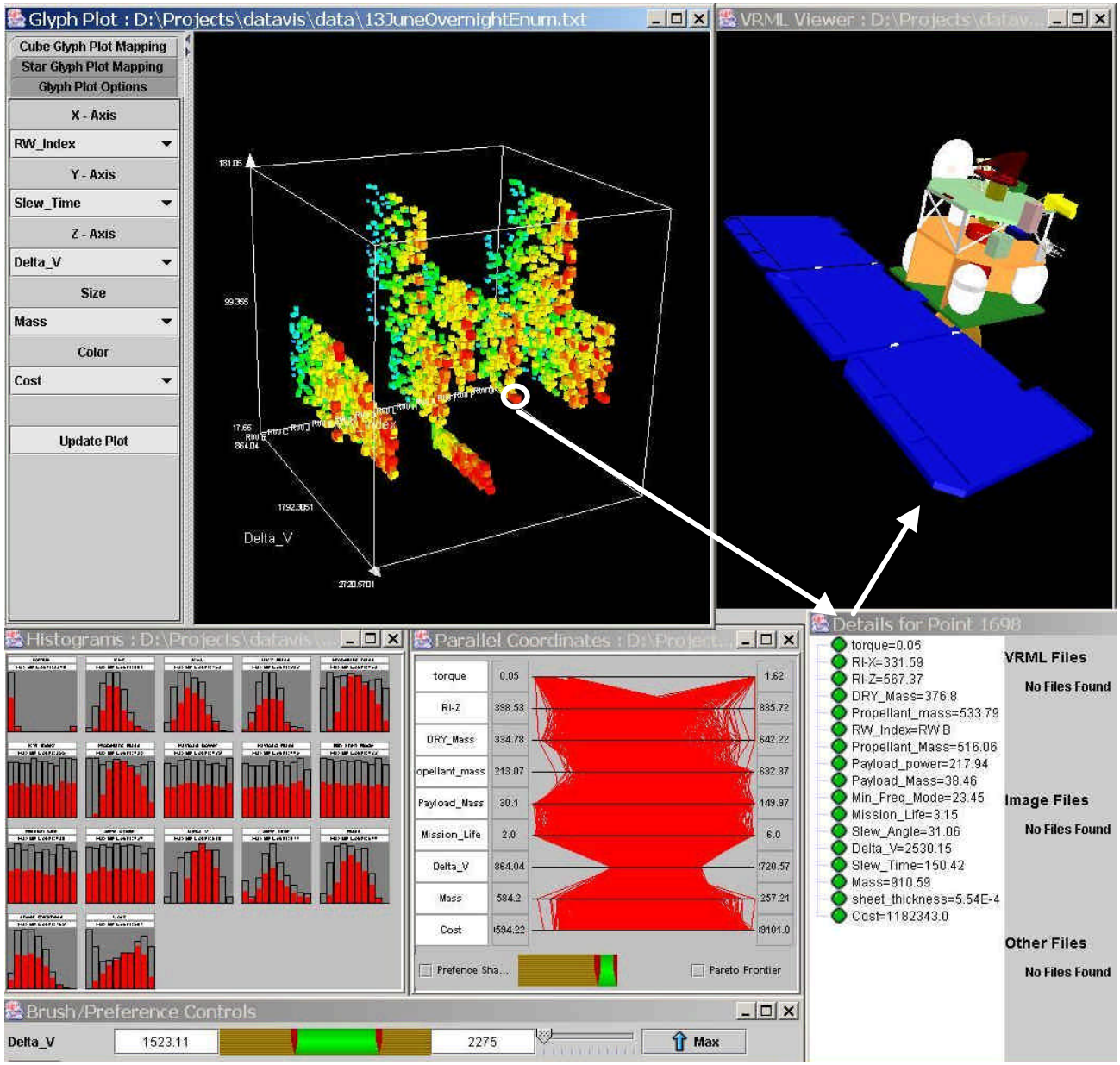
Multi-dimensional data visualization:

- Glyph plots
- Histogram plots
- Parallel coordinates
- Scatter matrices
- Brushing
- Linked views

Display multiple plots simultaneously

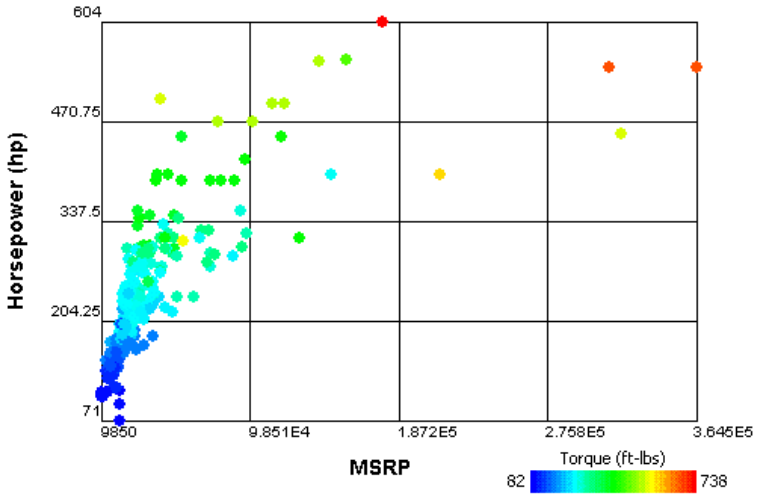
Interrogate specific design points

Interactively apply preferences and constraints

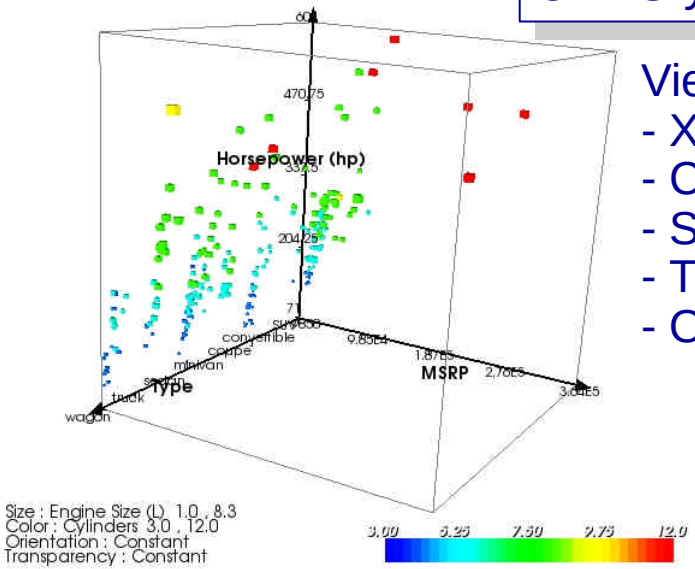


Examples of Multi-Dimensional Visualization

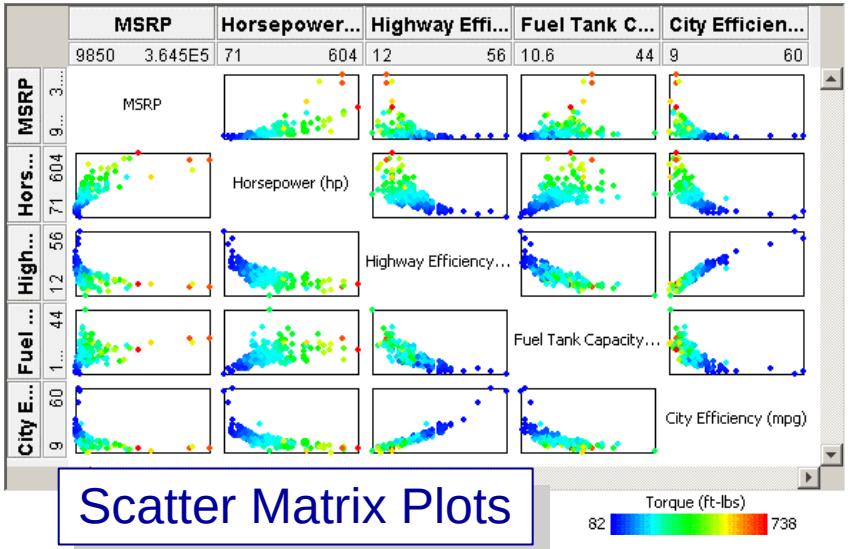
2-D Scatter Plots



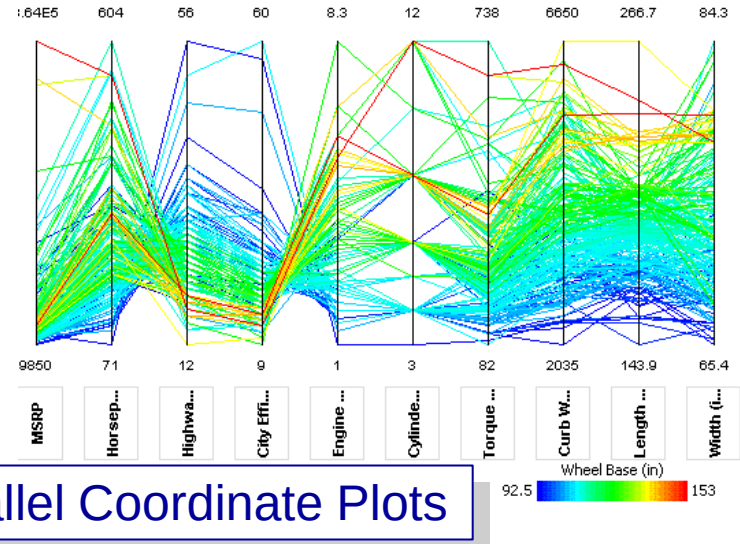
3-D Glyph Plots



View up to 7D:
- X, Y, Z axes
- Color
- Size
- Transparency
- Orientation



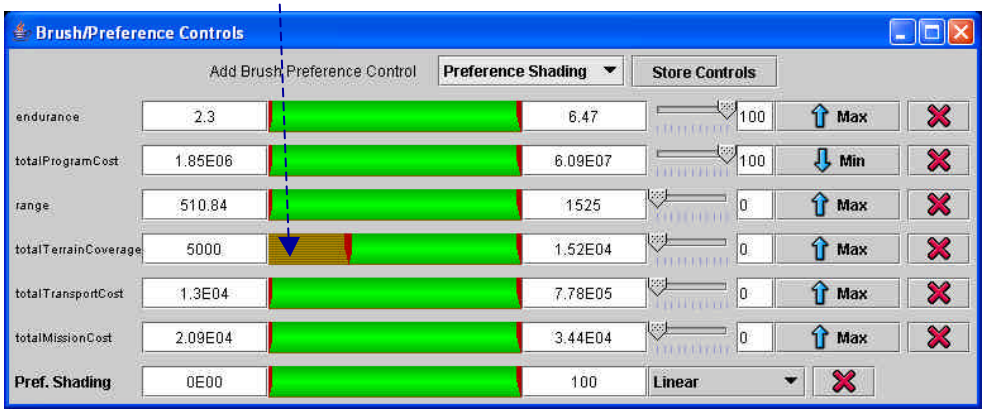
Scatter Matrix Plots

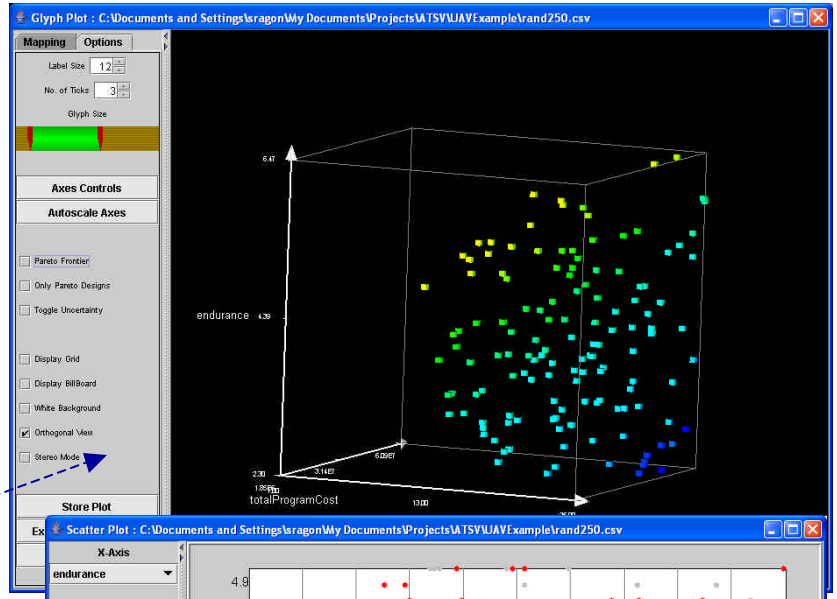


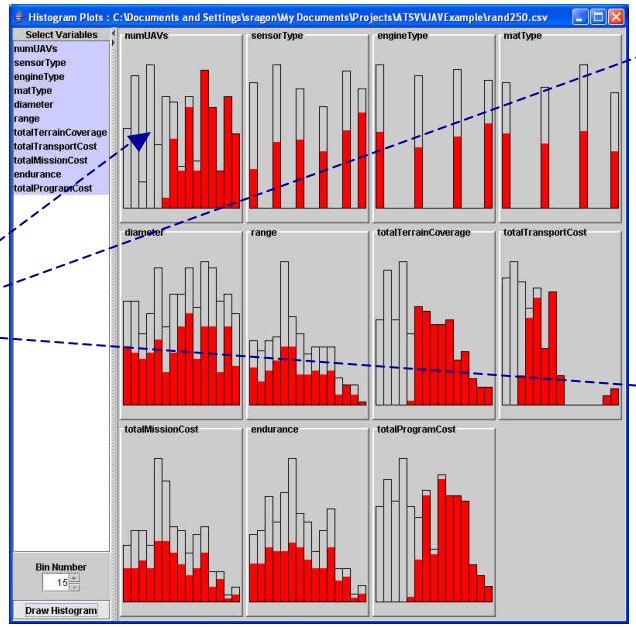
Parallel Coordinate Plots

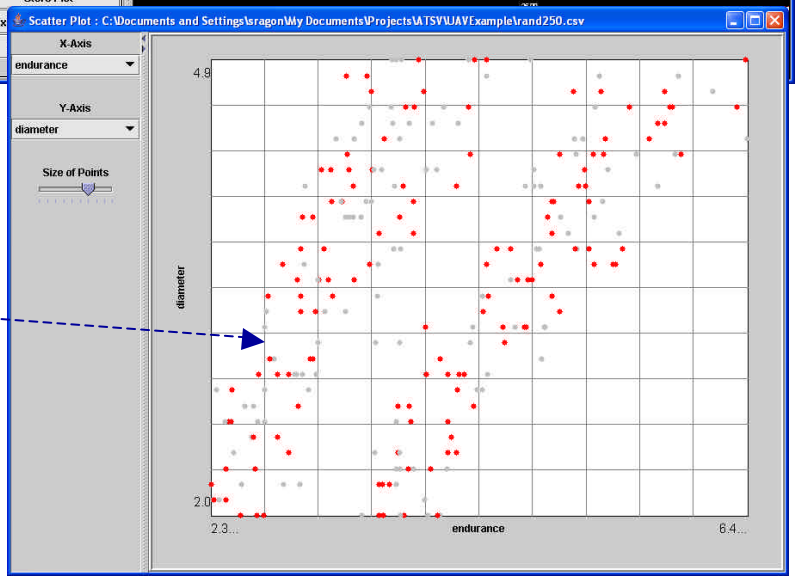
Interactive Brushing and Linking

- For example, interactively apply constraints with brushing







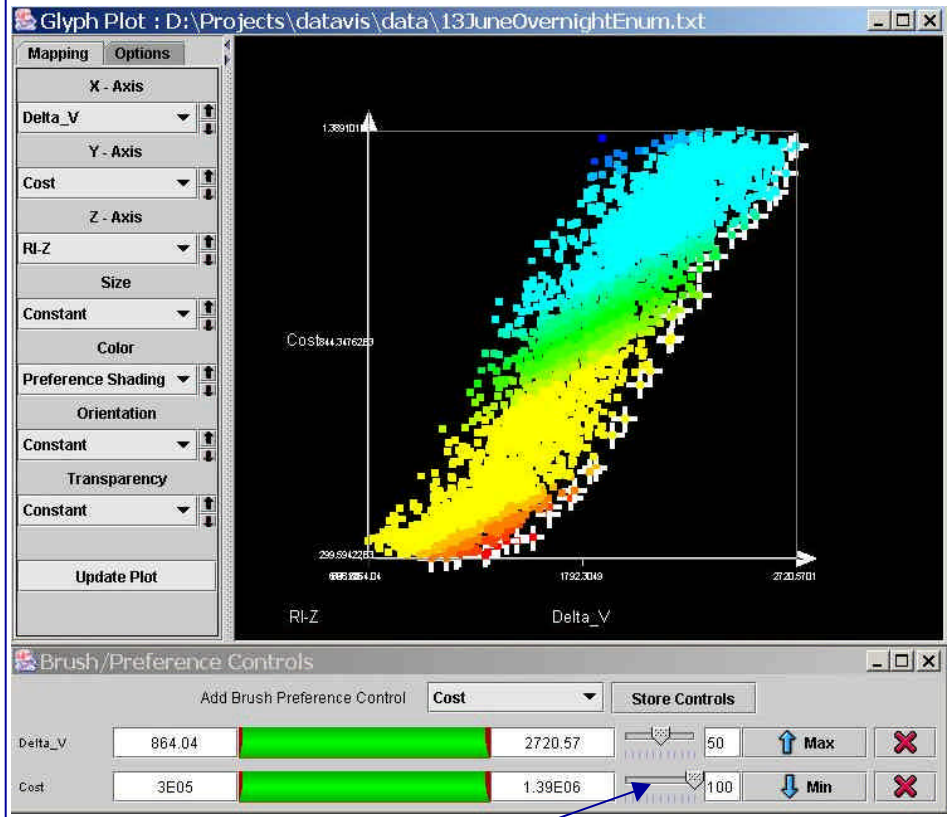


Infeasible designs are grayed out/disappear

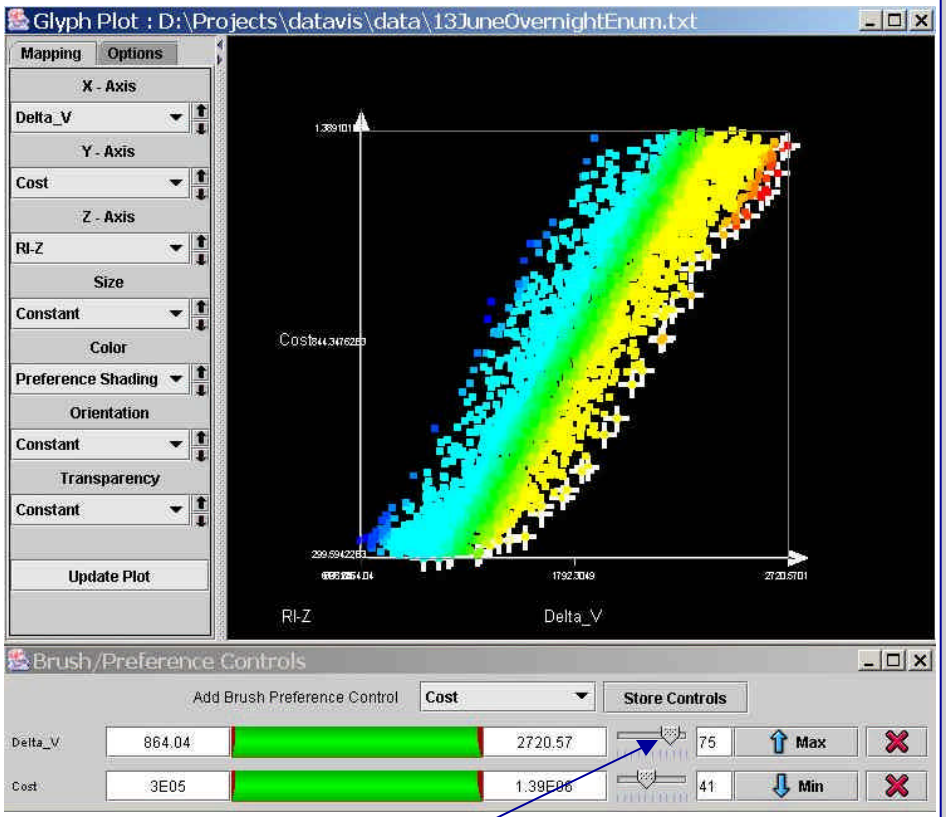
All displays are linked and interactively updated in real-time

Preference Structures and Pareto Frontiers

- Interactively visualize preference structures and Pareto frontiers with preference shading and a fast Pareto sorting algorithm



Greater importance on minimizing cost

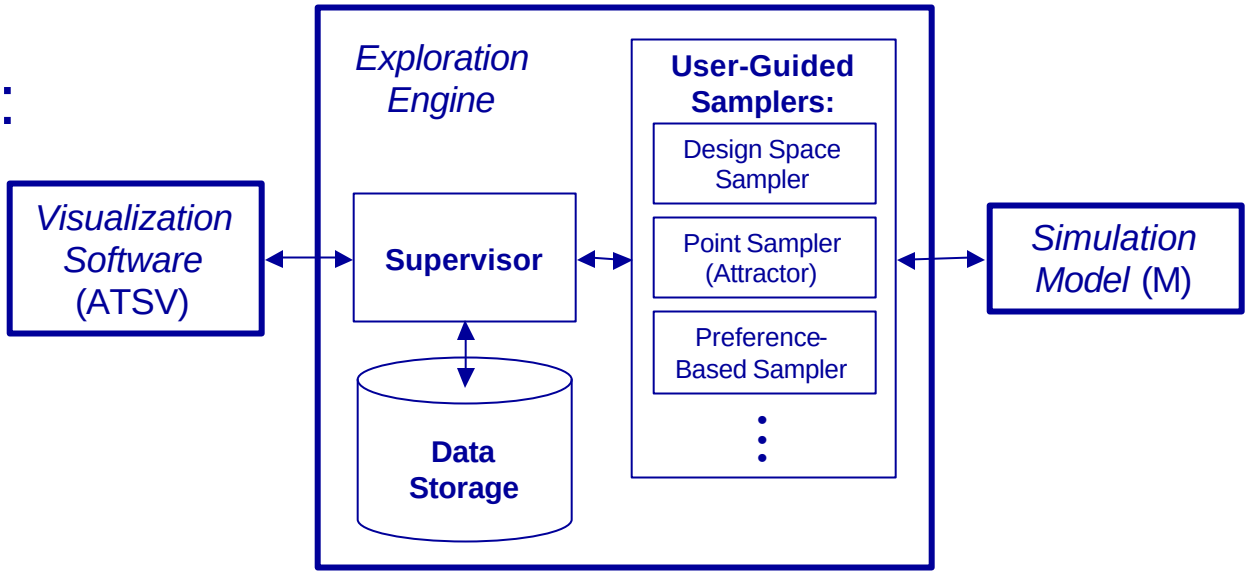


Greater importance on maximizing ?V

Visual Design Steering

- ATSV can now “drive” simulation models based on one of three visual steering commands issued by a user:
  - ***Design Space Samplers:*** sample randomly on inputs
  - ***Attractors*:** sample near a point of interest in trade space
  - ***Preference-Based Samplers:*** sample in preferred regions

- Implementation:



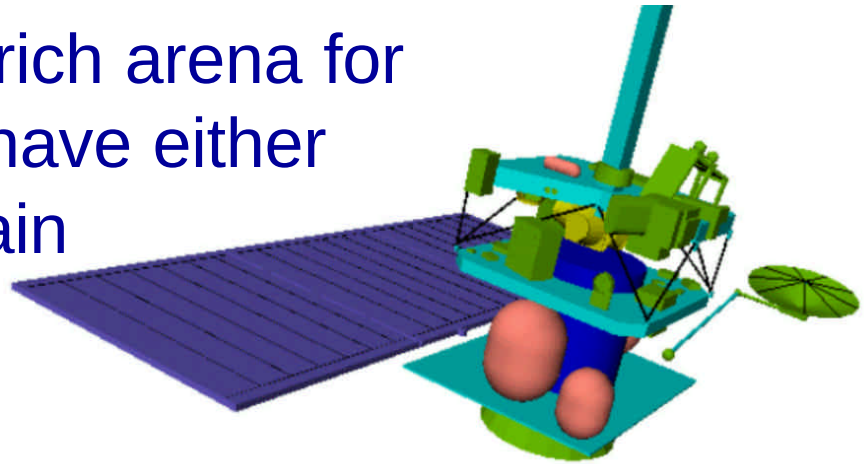
ATSV DEMO

Useful Roles for Visualization

- Explaining
  - a.k.a. “Story telling”
  - Already know the data
  - Use the visualization to explain data to others
- Verifying
  - Expect a certain answer, verify the anticipated result
  - Debugging, fact checking
- Exploring
  - Not sure *a priori* hypothesis of what lies in the data
  - Looking for structure and relationships
- *Deciding*
  - *A mixture of the other three*

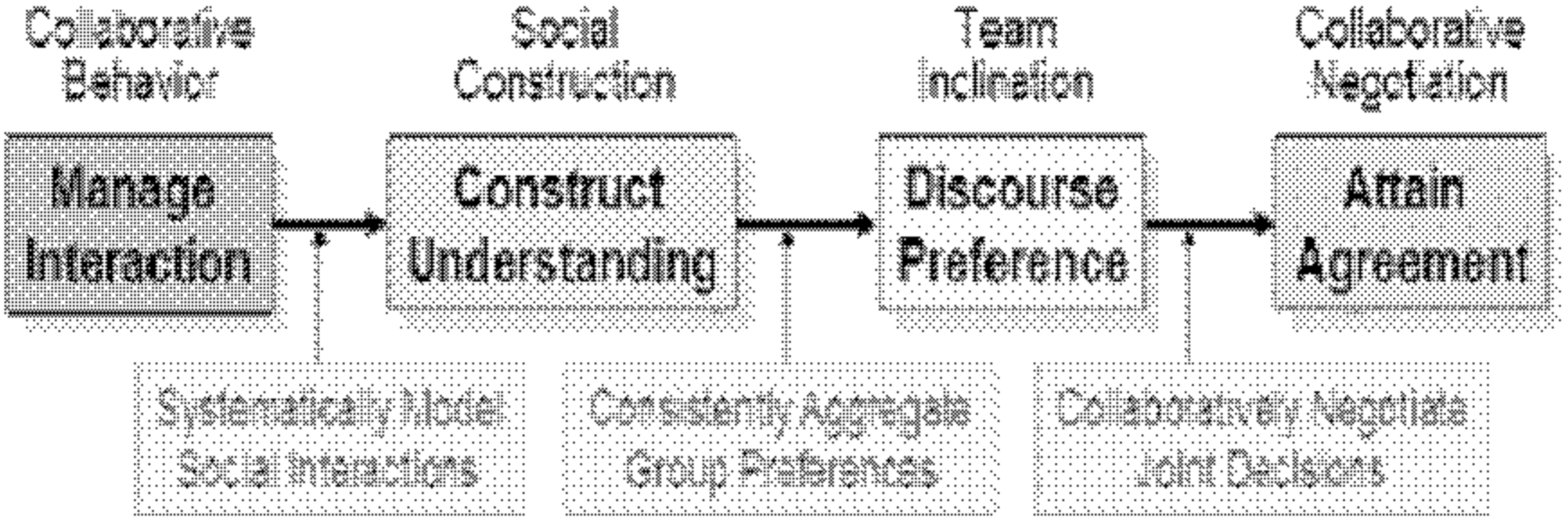
Closing Remarks

- ATSV offers a variety of multi-dimensional visualization capabilities to support a Design by Shopping paradigm
  - 1D and 2D histograms; 2D scatter, scatter matrix, and parallel coordinate plots; linked views and brushing
  - Data reduction and zooming capabilities
  - Preference shading and Pareto filtering
- We have implemented three visual steering commands to "drive" simulation models from within ATSV
- Trade space exploration is a rich arena for research in many areas that have either not been examined or have lain dormant for many years



Engineering as Collaborative Negotiation

- Prof. Stephen Lu (USC) advocates a four-step process to support engineering via collaborative negotiation:
  - Manage Interactions
  - Construct Understanding
  - Discourse Preferences
  - Attain Agreement



Parallels to Visualization Approach

Manage interactions	Build modular system models with care given to sequencing them
Construct understanding	Run models to populate the trade space to understand the impact of each other's domains; identify where conflicts lie = "sources of tension"
Discourse preference	Run models to populate the trade space to identify the consensus region to carry forward
Attain agreement	Agree on region of interest; add level of detail to models for more depth REPEAT

Our Proving Ground: JPL's Team-X

- Used by JPL's Product Design Center
  - JPL does 50+ concept designs per year
  - Team-X does rapid conceptual design
  - Using ATSV to explore trade space