Parametric Design

- The Design Process
- Regression Analysis
- Level I Design Example: Project Diana
Akin's Laws of Spacecraft Design - #3

Design is an iterative process. The necessary number of iterations is one more than the number you have currently done. This is true at any point in time.
Overview of the Design Process

Program Objectives $\leadsto$ System Requirements

Vehicle-level Estimation (based on a few parameters from prior art)

System-level Estimation (system parameters based on prior experience)

Increasing complexity
Increasing accuracy
Decreasing ability to comprehend the “big picture”

Basic Axiom:
Relative rankings between competing systems will remain consistent from level to level

System-level Design (based on discipline-oriented analysis)
## Regression Analysis of Existing Vehicles

<table>
<thead>
<tr>
<th>Veh/Stage</th>
<th>prop mass (lbs)</th>
<th>gross mass (lbs)</th>
<th>Type</th>
<th>Propellants</th>
<th>isp vac (sec)</th>
<th>isp sl (sec)</th>
<th>sigma</th>
<th>eps</th>
<th>delta</th>
</tr>
</thead>
<tbody>
<tr>
<td>Delta 6925 Stage 2</td>
<td>13,367</td>
<td>15,394</td>
<td>Storable N2O4-A50</td>
<td>319.4</td>
<td>0.152</td>
<td>0.132</td>
<td>0.070</td>
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<td>Delta 7925 Stage 2</td>
<td>13,367</td>
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<td>0.152</td>
<td>0.132</td>
<td>0.065</td>
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<tr>
<td>Titan II Stage 2</td>
<td>59,000</td>
<td>65,000</td>
<td>Storable N2O4-A50</td>
<td>316.0</td>
<td>0.102</td>
<td>0.092</td>
<td>0.087</td>
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<tr>
<td>Titan III Stage 2</td>
<td>77,200</td>
<td>83,600</td>
<td>Storable N2O4-A50</td>
<td>316.0</td>
<td>0.083</td>
<td>0.077</td>
<td>0.055</td>
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<tr>
<td>Titan IV Stage 2</td>
<td>77,200</td>
<td>87,000</td>
<td>Storable N2O4-A50</td>
<td>316.0</td>
<td>0.127</td>
<td>0.113</td>
<td>0.078</td>
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<tr>
<td>Proton Stage 3</td>
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<td>123,000</td>
<td>Storable N2O4-A50</td>
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<td>0.106</td>
<td>0.078</td>
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<tr>
<td>Titan II Stage 1</td>
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<td>269,000</td>
<td>Storable N2O4-A50</td>
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<td>0.035</td>
<td>0.033</td>
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<tr>
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<td>310,000</td>
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<td>0.052</td>
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<td>0.106</td>
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<td>Proton Stage 1</td>
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<td>1,004,000</td>
<td>Storable N2O4-A50</td>
<td>316.0</td>
<td>0.111</td>
<td>0.100</td>
<td>0.065</td>
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</tbody>
</table>

**average**

<table>
<thead>
<tr>
<th>prop mass (lbs)</th>
<th>gross mass (lbs)</th>
<th>isp vac (sec)</th>
<th>isp sl (sec)</th>
<th>sigma</th>
<th>eps</th>
<th>delta</th>
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</thead>
<tbody>
<tr>
<td>312.2</td>
<td>285.0</td>
<td>0.100</td>
<td>0.089</td>
<td>0.061</td>
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<td></td>
</tr>
</tbody>
</table>

**standard deviation**

<table>
<thead>
<tr>
<th>prop mass (lbs)</th>
<th>gross mass (lbs)</th>
<th>isp vac (sec)</th>
<th>isp sl (sec)</th>
<th>sigma</th>
<th>eps</th>
<th>delta</th>
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</thead>
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<tr>
<td>8.1</td>
<td>0.039</td>
<td>0.033</td>
<td>0.019</td>
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</table>
Regression Analysis of Inert Mass Fraction

![Graph showing the relationship between Stage Gross Mass (lbs) and Inert Mass Fraction for hypergolic stages. The graph plots data points on a logarithmic scale.]
Regression Analysis

• Given a set of N data points \((x_i, y_i)\)
• Linear curve fit: \(y = Ax + B\)
  - find A and B to minimize sum squared error

\[
error = \sum_{i=1}^{N} (Ax_i + B - y_i)^2
\]

  - Analytical solutions exist, or use Solver in Excel

• Power law fit: \(y = Ax^B\)

\[
error = \sum_{i=1}^{N} \left[A \log(x_i) + B - \log(y_i)\right]^2
\]

• Polynomial, exponential, many other fits possible
Regression Values for Design Parameters

<table>
<thead>
<tr>
<th></th>
<th>Isp (vac) (sec)</th>
<th>delta (m/sec)</th>
<th>Max ΔV (m/sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LOX/LH2</td>
<td>433</td>
<td>0.078</td>
<td>10825</td>
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<tr>
<td>LOX/RP-1</td>
<td>320</td>
<td>0.063</td>
<td>8670</td>
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<tr>
<td>Storables</td>
<td>312</td>
<td>0.061</td>
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<tr>
<td>Solids</td>
<td>283</td>
<td>0.087</td>
<td>6772</td>
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</table>
Additional Issues for Parametric Analysis

- Propulsion system design
- Structural mass estimates
- Propellant performance
- Costing factors
- Scaling factors
- Etc...
Design a system to return humans to the moon before the end of this decade for the minimum achievable cost.
Applicable Requirements

- System must be based on the use of American launch vehicles in operational status as of 2005
- System shall be at least as capable for lunar exploration as the J-mission Apollo system
  - Two landed crew
  - 72 hour stay time, 3 x 6 hour EVAs
  - 300 kg of science payload (each way)
U.S. Heavy-Lift Vehicles (2005)

- Space Shuttle - 27K kg to LEO
- Delta IV Heavy - 23K kg to LEO
## Lunar Mission $\Delta V$ Requirements

<table>
<thead>
<tr>
<th>From:</th>
<th>To:</th>
<th>Low Earth Orbit</th>
<th>Lunar Transfer Orbit</th>
<th>Low Lunar Orbit</th>
<th>Lunar Descent Orbit</th>
<th>Lunar Landing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low Earth Orbit</td>
<td></td>
<td>3.107 km/sec</td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Lunar Transfer Orbit</td>
<td>3.107 km/sec</td>
<td>0.837 km/sec</td>
<td>3.140 km/sec</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Low Lunar Orbit</td>
<td>0.837 km/sec</td>
<td>0.022 km/sec</td>
<td>2.684 km/sec</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lunar Descent Orbit</td>
<td>0.022 km/sec</td>
<td>2.312 km/sec</td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lunar Landing</td>
<td>2.890 km/sec</td>
<td>2.312 km/sec</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Mission Scenario 1

- What can be accomplished with a single shuttle payload (27K kg)?
- Assume $\delta=0.1$, $Isp=320$ sec

- Direct landing
  - LEO-lunar transfer orbit $\Delta V=3.107$ km/sec
  - Lunar transfer orbit-lunar landing $\Delta V=3.140$ km/sec
  - Lunar surface-earth return orbit $\Delta V=2.890$ km/sec
  - Direct atmospheric entry to landing
Scenario 1 Analysis

- Trans-lunar injection
  \[ r_{TLI} = e^{\frac{-\Delta V_{TLI}}{I_{sp}}} = 0.3713 \]
  \[ m_{TLI} = m_o(r_{TLI} - \delta) = 27,000(0.3713 - 0.1) = 7325 \text{ kg} \]

- Lunar landing
  - \( r = 0.3674 \)
  - \( m_{LS} = 1958 \text{ kg} \)

- Earth return
  - \( r = 0.3978 \)
  - \( m_{ER} = 583 \text{ kg} \)

This scenario would work for a moderate robotic sample return mission, but is inadequate for a human program.
Mission Scenario 2

- Assume a single shuttle payload is used to size the lunar descent and ascent elements
  - Shuttle payload performs landing and return
  - “Something else” performs TLI for shuttle payload
- Assume $\delta=0.1$, $I_{sp}=320$ sec
- Direct landing (unchanged from Scenario 1)
  - LEO-lunar transfer orbit $\Delta V=3.107$ km/sec
  - Lunar transfer orbit-lunar landing $\Delta V=3.140$ km/sec
  - Lunar surface-earth return orbit $\Delta V=2.890$ km/sec
  - Direct atmospheric entry to landing
Scenario 2 Analysis

- Lunar landing (27,000 kg at lunar arrival)
  - $r=0.3674$
  - $m_{LS}=7219$ kg

- Earth return
  - $r=0.3978$
  - $m_{ER}=2150$ kg

- Trans-lunar injection
  - $r=0.3713$

Payload mass still too low for human spacecraft. TLI stage mass of 72,520 kg is too large for any existing launch vehicle.

$$m_{LEO} = \frac{m_{TLI}}{(r_{TLI} - \delta)} = 99,520 \text{ kg}$$
Mission Scenario 3

- Assume three Delta-IV Heavy missions carry identical boost stages which perform TLI and part of descent burn
- Space shuttle payload completes descent and performs ascent and earth return
- All other factors as in previous scenarios
Scenario 3 Standard Boost Stage

- $m_o = 23,000 \text{ kg}$
- $m_i = 2300 \text{ kg}$
- $m_p = 20,700 \text{ kg}$
- LEO departure configuration is three boost stages with 27,000 kg descent/ascent stage as payload
- $m_{LEO} = 96,000 \text{ kg}$
Scenario 3 TLI Performance

- **Boost stage 1**
  \[ \Delta V_1 = -g I_{sp} \ln \left( \frac{m_{LEO} - m_{prop}}{m_{LEO}} \right) = 762 \text{ m/sec} \]
  - \( V_{TLI} \) remaining = 2345 m/sec

- **Boost stage 2**
  - \( r=0.7; \ \Delta V_2=1046 \text{ m/sec} \)
  - \( V_{TLI} \) remaining = 1300 m/sec

- **Boost stage 3**
  - \( r=0.55; \ \Delta V_3=1300 \text{ m/sec} \)
  - Residual \( \Delta V \) after TLI = 376 m/sec

- **Total booster performance** = 3484 m/sec
Alternate Staging Possibilities

- Three identical stages
- Serial staging (previous chart) $\Delta V = 3483$ m/sec
- Parallel staging (all three) $\Delta V = 3264$ m/sec
- Parallel/serial staging (2/1) $\Delta V = 3446$ m/sec

Pure serial staging is preferred
Ascent/Descent Performance

- 376 m/sec of lunar descent maneuver performed by boost stage 4
- Remaining descent requires 2764 m/sec
  - $r=0.4143$
  - $m_i=2700$ kg
  - $m_{LS}=8485$ kg
- Earth return
  - $r=0.3978$
  - $m_i=849$ kg
  - $m_{ER}=2528$ kg

Return vehicle mass is still significantly below that of the Gemini spacecraft - need to examine other numbers of boost vehicles.
Effect of Number of Boost Stages

![Bar chart showing the effect of number of boost stages on Earth return payload. The number of boost stages increases from 0 to 4, resulting in an increase in payload from 583 kg to 3229 kg.](chart.png)
Creating a Baseline

- Need to modify Scenario 3 to provide more than 3000 kg of Earth return mass (Gemini-class spacecraft)
- Select 4 boost modules based on trade study performed
- Repeat calculations
- Establish as an early baseline: something to use as standard, vary parameters to identify promising modifications
- Often termed “strawman” design
- It won’t last!!! Design iteration will continue
Baseline System Schematic

Boost Stage 1: 23,000 kg
Boost Stage 2: 23,000 kg
Boost Stage 3: 23,000 kg
Boost Stage 4: 23,000 kg
Descent/Landing Stage: 16,160 kg
Ascent Stage: 7611 kg
Crew Cabin: 3299 kg
Initial Configuration Sketch

Boost Module
Boost Module
Boost Module
Boost Module
Descent Stage
Ascent/TEI Stage
Crew Cabin
(von Tiesenhausen's Law of Engineering Design) If you want to have a maximum effect on the design of a new engineering system, learn to draw. Engineers always wind up designing the vehicle to look like the initial artist's concept.
Transport Architecture Options

• Transportation node at intermediate point (low lunar orbit, Earth-Moon L1)
• Leave systems at node if not needed on the lunar surface, e.g.:
  – TransEarth injection stage
  – Orbital life support module
  – Entry, descent, and landing systems
• Will increase payload capacities at the expense of additional operational complexity, potential for additional safety critical failures
Variation 1: Lunar Orbit Staging

- Assume same process as baseline, but use lunar parking orbit before/after landing
- Additional ΔV’s required for LLO stops
  - Lunar landing additional ΔV=+31 m/sec
  - Lunar take-off additional ΔV=+53 m/sec
- Low lunar orbit waypoint changes baseline payload to 3118 kg (-3.5%)
- Not useful without taking advantage of node to limit lunar landing mass
Variation 2: Lunar Orbit Rendezvous

- Use specialized vehicle for descent/ascent
- Use four boost stages as per baseline
- Boost stage 4 residual propellants
  - 10,680 kg following trans lunar insertion
  - 1315 kg following lunar orbit insertion
  - Use remaining stage 4 capacity to aid descent stage
- Leave TEI stage in lunar orbit during ascent/descent
  - Descent $\Delta V=2334$ m/sec
  - Ascent $\Delta V=2084$ m/sec
  - TEI $\Delta V=837$ m/sec
Variation 2 Sketch

Boost Module
Boost Module
Boost Module
Boost Module
Descent Stage
Ascent Stage
Crew Cabin
TEI Stage
Variation 3: Maximal LOR

• Retain all features of Variation 2:
  – Use specialized vehicle for descent/ascent
  – Use four boost stages as per baseline
  – Boost stage 4 residual propellants
    • 10,680 kg following trans lunar insertion
    • 1315 kg following lunar orbit insertion
    • Use remaining stage 4 capacity to aid descent stage
  – Leave TEI stage in lunar orbit during ascent/descent

• Also leave equipment for earth return and entry in lunar orbit
  – Heat shield
  – Parachutes
  – Total assumed mass = 1000 kg
Akin's Laws of Spacecraft Design - #9

Not having all the information you need is never a satisfactory excuse for not starting the analysis.
Variation 3 System Schematic

Boost Stage 1: 23,000 kg
Boost Stage 2: 23,000 kg
Boost Stage 3: 23,000 kg
Boost Stage 4: 23,000 kg
Descent/Landing Stage: 14,174 kg
TEI Stage: 2453 kg
Landing Equip.: 1000 kg
Ascent Stage: 5488 kg
Crew Cabin: 3885 kg
Variation 3 Sketch

- Boost Module
- Boost Module
- Boost Module
- Boost Module
- Descent Stage
- Ascent Stage
- Crew Cabin
- Entry/Landing Equipment
- TEI Stage

Space Systems Laboratory – University of Maryland
Akin's Laws of Spacecraft Design - #10

When in doubt, estimate. In an emergency, guess. But be sure to go back and clean up the mess when the real numbers come along.
Sensitivity to Orbital Payload

- One kg on surface = 4.4 kg in orbit
- Mass left in orbit increases total payload by 30%
The Next Steps From Here

- Perform parametric sensitivity analyses
  - Inert mass fractions
  - Specific impulse
- Investigate reduction from 4 to 3 boost stages for minimal system
- Trade studies, e.g.
  - 2 crew cabins vs. 1
  - Cryo first stage for TLI
- Reach decision(s) on revision of baseline design
- Configuration design
Overview of the Design Process

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Vehicle-level Estimation

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