Systems Engineering and Management

- Introduction
- Fundamentals of System Engineering
- Concepts in Systems Engineering
- Project Development Process
- Management of the Development of Space Systems
- Organization

*Pisacane, V., Fundamentals of Space System Design, Ch. 1*
Systems Engineering

- To reduce cost at constant risk, the performance must be reduced.
- To reduce cost at constant performance, the risk must be increased.
- To increase performance at constant cost, the risk must be increased.
- To increase performance at constant risk, the cost must be increased.
- To reduce risk at constant cost, the performance must be reduced.
- To reduce risk at constant performance, the cost must be increased.

Product Development

- Formulation results in a plan or concept to achieve a product.
- Evaluation provides an independent assessment of the ability to meet technical and/or programmatic objectives.
- Approval confirms the plan, indicating that a component of the project is ready to proceed to implementation.
- Implementation produces the desired product.
- Evaluation assures that the product is satisfactory and the phase completed.
Requirements Definition

- What must the system do?
- Why must it be done?
- How do we achieve the design goal?
- What are the alternatives?
- What sub-systems perform specified functions?
- Are all functions technically feasible?
- How can the system be tested to show that it satisfies requirements?
Spacecraft Subsystems

Numbers refer to mission functions in Fortesque et al, *Spacecraft Systems Engineering*

Satellite Systems

- **Power and Propulsion**
  - Solar cells
  - “Kick” motor/payload assist module
  - Attitude-control/orbit-adjustment/station-keeping thrusters
  - Batteries, fuel cells
  - Pressurizing bottles
  - De-orbit/“graveyard” systems

- **Structure**
  - Skin, frames, ribs, stringers, bulkheads
  - Propellant tanks
  - Heat/solar/micrometeoroid shields, insulation
  - Articulation/deployment mechanisms
  - Gravity-gradient tether
  - Re-entry system (e.g., sample return)

- **Electronics**
  - Payload
  - Control computers
  - Control sensors and actuators
  - Control flywheels
  - Radio transmitters and receivers
  - Radar transponders
  - Antennas
Functional Requirements of Spacecraft Subsystems

1. Payload must be pointed in the right direction
2. Payload must be operable
3. Data must be communicated to the ground
4. Desired orbit for the mission must be maintained
5. Payload must be held together and mounted on the spacecraft structure
6. Payload must operate reliably over some specified period
7. Adequate power must be provided

Typical Satellite Mass Breakdown

<table>
<thead>
<tr>
<th>Item</th>
<th>Range (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Structure (total)</td>
<td>15–22</td>
</tr>
<tr>
<td>Primary structure</td>
<td>12–15</td>
</tr>
<tr>
<td>Secondary structure</td>
<td>2–5</td>
</tr>
<tr>
<td>Fasteners</td>
<td>1–2</td>
</tr>
<tr>
<td>Power</td>
<td>12–30</td>
</tr>
<tr>
<td>Thermal control</td>
<td>4–8</td>
</tr>
<tr>
<td>Harness</td>
<td>4–10</td>
</tr>
<tr>
<td>Avionics</td>
<td>3–7</td>
</tr>
<tr>
<td>Guidance &amp; control</td>
<td>5–10</td>
</tr>
<tr>
<td>Communication</td>
<td>2–6</td>
</tr>
<tr>
<td>Payload</td>
<td>7–55</td>
</tr>
</tbody>
</table>

- Satellite without on-orbit/de-orbit propulsion
- “Kick” motor/ PAM can add significant mass
Communications Satellite
Mass Breakdown

Recommended Mass Growth Margins

Table 1.3 Mass margin recommendations

<table>
<thead>
<tr>
<th>Maturity</th>
<th>Recommended Growth Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Off the shelf or measured</td>
<td>1.05</td>
</tr>
<tr>
<td>Minor modifications of an existing device</td>
<td>1.07</td>
</tr>
<tr>
<td>Modifications of an existing device</td>
<td>1.10</td>
</tr>
<tr>
<td>New design, mass calculated</td>
<td>1.15</td>
</tr>
<tr>
<td>New design, thoughtful mass estimate</td>
<td>1.20</td>
</tr>
<tr>
<td>New design, uncertainty in mass estimate</td>
<td>1.30</td>
</tr>
</tbody>
</table>

Pisacane, V., Fundamentals of Space System Design, Ch. 1
Satellite Buses

- Standardization of common components for a variety of missions

Hine et al
“Braincase on the tip of a firecracker”: Apollo Guidance

Antecedents in Anti-Aircraft Guns and Ballistic Missiles

Mark 14 Gun Sight

Polaris Guidance System

Thor Inertial Measurement Unit

Mindell, D., Digital Apollo, Ch. 5

“Braincase on the tip of a firecracker”: Apollo Guidance

Primary Components of “PNGCS”

Mindell, D., Digital Apollo, Ch. 5
“Braincase on the tip of a firecracker”: Apollo Guidance

Mindell, D., Digital Apollo, Ch. 5

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IMU Alignment and State Update

Mindell, D., Digital Apollo, Ch. 5
“Braincase on the tip of a firecracker”: Apollo Guidance

- Designing the Project
- The LOR Decision
- MIT as a System Integrator
- The Deplorable Optics
- Gimbal Reliability
- Ruled Out as Passengers, Not as Pilots

Mindell, D., Digital Apollo, Ch. 5

Guidance, Navigation, and Control
Guidance, Navigation, and Control

- **Navigation**: Where are we?
- **Guidance**: How do we get to our destination?
- **Control**: What do we tell our vehicle to do?

**First Apollo Program Contract**
*MIT Instrumentation Laboratory*

*August 9, 1961*

*BUT … Lunar landing technique was not decided until July, 1962*
Apollo Guidance Computer

- Parallel processor
- 16-bit word length (hexadecimal)
- Memory
  - 36,864 words (fixed)
  - 2,048 words (variable)
- 1st operational solid-state computer
- Identical computers in CSM and LM
  - Different software (with many identical subroutines)

Apollo Guidance Computer (AGC) vs. iPhone 5S

- 16-bit Processor
  - Storage: 36,864 words (fixed)
  - 2,048 words (variable)
  - Clock speed: 1 million “ticks” per sec
  - Weight: 70 lb
  - 1st operational solid-state computer
  - Separate Inertial Measurement Unit

- 64-bit Processor
  - Storage: 16-64 Gbytes
  - 1 Gbyte RAM
  - Clock speed: 1,300 million “ticks” per sec
  - Weight: 1/4 lb
  - Plus accelerometers angular rate gyros, ...
Apollo Guidance Computer

Magnetic Core Memory Ropes

1 core = 1 bit

1 Kiloword Memory Bank

- No built-in redundancy
- No redundant computers
- No failures
- Mean time between failures = $\infty$

Apollo Lunar Module Radars

- **Landing radar**
  - 3-beam Doppler radar altimeter
  - LM descent stage

- **Rendezvous radar**
  - continuous-wave tracking radar
  - LM ascent stage
Apollo Guidance Computer Commands

- Display/Keyboard (DSKY)
- Sentence
  - Subject and predicate
  - Subject is implied
    - Astronaut, or
    - GNC system
  - Sentence describes action to be taken employing or involving an object
- Predicate
  - Verb = Action
  - Noun = Variable or Program (i.e., the object)

See http://apollo.spaceborn.dk/dsky-sim.html
And http://www.ibiblio.org/apollo/ for simulation

Numerical Codes for Verbs and Nouns in Apollo Guidance Computer Programs

<table>
<thead>
<tr>
<th>Verb Code</th>
<th>Description</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>01</td>
<td>Display 1st component of</td>
<td>Octal display of data on REGISTER 1</td>
</tr>
<tr>
<td>02</td>
<td>Display 2nd component of</td>
<td>Octal display of data on REGISTER 1</td>
</tr>
<tr>
<td>03</td>
<td>Display 3rd component of</td>
<td>Octal display of data on REGISTER 1</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Noun Code</th>
<th>Description</th>
<th>Scale/Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>01</td>
<td>Specify machine address</td>
<td>XXXXX</td>
</tr>
<tr>
<td>02</td>
<td>Specify machine address</td>
<td>XXXXX</td>
</tr>
<tr>
<td>03</td>
<td>(Spare)</td>
<td></td>
</tr>
<tr>
<td>04</td>
<td>(Spare)</td>
<td></td>
</tr>
<tr>
<td>05</td>
<td>Angular error</td>
<td>XXX.XX degrees</td>
</tr>
<tr>
<td>06</td>
<td>Pitch angle</td>
<td>XXX.XX degrees</td>
</tr>
<tr>
<td>07</td>
<td>Heads up-down</td>
<td>+/- 00001</td>
</tr>
<tr>
<td>11</td>
<td>Change of program or major mode</td>
<td></td>
</tr>
</tbody>
</table>
Verbs and Nouns in Apollo Guidance Computer Programs

- **Verbs (Actions)**
  - Display
  - Enter
  - Monitor
  - Write
  - Terminate
  - Start
  - Change
  - Align
  - Lock
  - Set
  - Return
  - Test
  - Calculate
  - Update

- **Selected Nouns (Variables)**
  - Checklist
  - Self-test ON/OFF
  - Star number
  - Failure register code
  - Event time
  - Inertial velocity
  - Altitude
  - Latitude
  - Miss distance
  - Delta time of burn
  - Velocity to be gained

- **Selected Programs (CM)**
  - AGC Idling
  - Gyro Compassing
  - LET Abort
  - Landmark Tracking
  - Ground Track Determination
  - Return to Earth
  - SPS Minimum Impulse
  - CSM/IMU Align
  - Final Phase
  - First Abort Burn

A Little AGC Digital Autopilot Code

[Source Code Listing]

[Website Link]
Apollo GNC Software
Testing and Verification

- Major areas of testing
  - Computational accuracy
  - Proper logical sequences

- Testing program
  - Comprehensive test plans
  - Specific initial conditions and operating sequences
  - Performance of tests
  - Comparison with prior simulations, evaluation, and re-testing

- Levels of testing
  - 1: Specifications coded in higher-order language for non-flight hardware (e.g., mainframe then, PCs now)
  - 2: Digital simulation of flight code
  - 3: Verification of complete programs or routines on laboratory flight hardware
  - 4: Verification of program compatibility in mission scenarios
  - 5: Repeat 3 and 4 with flight hardware to be used for actual mission
  - 6: Prediction of mission performance using non-flight computers and laboratory flight hardware

Lunar Module Navigation, Guidance, and Control Configuration
Ascent (Launch) Guidance

• “Oberth’s Synergy Curve”
• Gravity-turn flight path is function of 3 variables
  – Initial pitchover angle (from vertical launch)
  – Velocity at pitchover
  – Acceleration profile, \( T(t)/m(t) \)
• Gravity-turn program closely approximated by tangent steering laws
Tangent Steering Laws
Approximate Gravity Turn

- Neglecting surface curvature

\[ \tan \theta(t) = \tan \theta_o \left( 1 - \frac{t}{t_{BO}} \right) \]

- “Open-loop” command, i.e., no feedback of vehicle state

- Accounting for effect of Earth surface curvature on burnout flight path angle

\[ \tan \theta(t) = \tan \theta_o \left[ 1 - \frac{t}{t_{BO}} - \tan \beta \left( \frac{t}{t_{BO}} \right) \right] \]

Feedback Guidance Law

Errors due to disturbances and modeling errors corrected by feedback control with damping

\[ \text{Thrust Angle}(t) = c_\theta \left[ \theta_c(t) - \theta(t) \right] - c_q q(t) \]

\[ q = \frac{d\theta}{dt} = \text{pitch rate} \]
Phases of Ascent Guidance

- Vertical liftoff
- Roll to launch azimuth
- Pitch program to atmospheric “exit”
  - Jet stream penetration
  - Booster cutoff and staging
- Explicit guidance to desired orbit
  - Booster separation
  - Acceleration limiting
  - Orbital insertion

Jet Stream Profiles

- Launch vehicle must able to fly through strong wind profiles
- Design profiles assume 95th-99th-percentile worst winds and wind shear
Thrust Vector Control During Launch

- Attitude control
  - Attitude and rate feedback
- Drift-minimum control
  - Attitude and accelerometer feedback
  - Increased loads
- Load relief control
  - Rate and accelerometer feedback
  - Increased drift

Explicit Guidance Law
~Lunar Module Ascent, Space Shuttle Launch
(Brand, Brown, Higgins, and Pu, CSDL, 1972)

- Initial conditions
  - End of pitch program, outside atmosphere
- Final condition
  - Insertion in desired orbit
- Initial inputs
  - Desired radius
  - Desired velocity magnitude
  - Desired flight path angle
  - Desired inclination angle
  - Desired longitude of the ascending/descending node
- Continuing outputs
  - Unit vector describing desired thrust direction
  - Throttle setting
Guidance Program Initialization

- Thrust acceleration estimate
- Mass/mass flow rate
- Acceleration limit (~ 3g)
- Effective exhaust velocity
- Various coefficients
- Unit vector normal to desired orbital plane, \( i_q \)

\[
i_q = \begin{bmatrix}
\sin i_d \sin \Omega_d \\
\sin i_d \cos \Omega_d \\
\cos i_d
\end{bmatrix}
\]

\( i_d \): desired inclination angle
\( \Omega_d \): desired longitude of descending node

Guidance Program Operation: Position and Velocity

- Thrust acceleration estimate, \( a_T \), from guidance system
- Compute corresponding mass/flow rate and throttle setting, \( \delta T \)

**Position**

\[
\begin{bmatrix}
r \\
y \\
z
\end{bmatrix} = r \sin^{-1}(i_r \cdot i_q)
\]

**Velocity**

\[
\begin{bmatrix}
r \\
y \\
z
\end{bmatrix} = v_{IMU} \cdot i_r \\
v_{IMU} \cdot i_q \\
v_{IMU} \cdot i_z
\]

\( v_{IMU} \): velocity estimate in IMU frame
Guidance Program: Velocity and Time to Go

- Effective gravitational acceleration
  \[ g_{\text{eff}} = -\frac{\mu}{r^2} + \frac{|\mathbf{r} \times \dot{\mathbf{v}}|^2}{r^3} \]

- Time to go (to burnout)
  \[ t_{g_{\text{new}}} = t_{g_{\text{old}}} - \Delta t \]
  \( \Delta t \): guidance interval

- Velocity to be gained
  \[ \mathbf{v}_{g_{\text{old}}} = \left[ \begin{array}{c} (\dot{r} - \ddot{r}) - g_{\text{eff}} t_{g_{\text{old}}}/2 \\ -\dot{y} \\ \ddot{z} - \dot{z} \end{array} \right] \]

- Time to go prediction (prior to acceleration limiting)
  \[ t_{g_{\text{old}}} = \frac{m}{\dot{m}} \left( 1 - e^{-v_{g_{\text{old}}}/c_{\text{eff}}} \right) \]
  \( c_{\text{eff}} \): effective exhaust velocity

Guidance Program Commands

- Guidance law produces required radial and cross-range accelerations
  \[ a_{r_1} = a_T \left[ A + B(t - t_0) \right] - g_{\text{eff}} \]
  \[ a_{r_2} = a_T \left[ C + D(t - t_0) \right] \]

  \( a_T \): net available acceleration, accounting for limit

- Guidance coefficients, \( A, B, C, \) and \( D \) are functions of
  \[ \begin{pmatrix} r_d, r, \dot{r}, t_{g_{\text{old}}} \\ y, \dot{y}, t_{g_{\text{old}}} \end{pmatrix} \]
  plus \( c_{\text{eff}}, m/\dot{m} \), acceleration limit
Guidance Program Commands

- Required thrust direction, $i_T$ (i.e., vehicle orientation in $(i_r, i_q, i_z)$ frame)

\[
a_T = \begin{bmatrix}
a_{T_r} \\
a_{T_q} \\
\text{what's left over}
\end{bmatrix}; \quad i_T = \frac{a_T}{|a_T|}
\]

- Guidance philosophy
  - Force spacecraft into desired orbital plane
  - Climb toward desired 2-D orbit
  - Achieve orbital velocity

Lunar Descent Guidance
Lunar Module Transfer Ellipse to Powered Descent Initiation

Lunar Module Powered Descent

<table>
<thead>
<tr>
<th>PHASE</th>
<th>INITIAL EVENT</th>
<th>DESIGN CRITERIA</th>
</tr>
</thead>
<tbody>
<tr>
<td>BRAKING</td>
<td>PDI</td>
<td>MINIMIZE PROPELLANT USAGE</td>
</tr>
<tr>
<td>APPROACH</td>
<td>HIGH GATE</td>
<td>CREW VISIBILITY</td>
</tr>
<tr>
<td>LANDING</td>
<td>LOW GATE</td>
<td>MANUAL CONTROL</td>
</tr>
</tbody>
</table>
### Lunar Module Descent Events

<table>
<thead>
<tr>
<th>Event</th>
<th>TFI, min:sec</th>
<th>Inertial velocity, fps</th>
<th>Altitude, ft</th>
<th>Altitude, fps</th>
<th>ΔV, fps</th>
</tr>
</thead>
<tbody>
<tr>
<td>A Ullage</td>
<td>-00:07</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>B Pow-red descent initiation</td>
<td>00:13</td>
<td>5560</td>
<td>-4</td>
<td>48 814</td>
<td>0</td>
</tr>
<tr>
<td>C Throttle to maximum thrust</td>
<td>00:26</td>
<td>5529</td>
<td>-3</td>
<td>48 725</td>
<td>31</td>
</tr>
<tr>
<td>D Rotate to windows up position</td>
<td>02:56</td>
<td>4000</td>
<td>-50</td>
<td>44 934</td>
<td>1572</td>
</tr>
<tr>
<td>E LR altitude update</td>
<td>04:18</td>
<td>3065</td>
<td>-69</td>
<td>39 201</td>
<td>2536</td>
</tr>
<tr>
<td>F Throttle recovery</td>
<td>06:24</td>
<td>1456</td>
<td>-106</td>
<td>24 635</td>
<td>4239</td>
</tr>
<tr>
<td>G LR velocity update</td>
<td>06:42</td>
<td>1315</td>
<td>-127</td>
<td>22 644</td>
<td>4399b</td>
</tr>
<tr>
<td>H High gate</td>
<td>08:26</td>
<td>506</td>
<td>-145</td>
<td>7 515</td>
<td>5375</td>
</tr>
<tr>
<td>I Low gate</td>
<td>10:06</td>
<td>55 (b) 68</td>
<td>-16</td>
<td>512</td>
<td>6176</td>
</tr>
<tr>
<td>J Touchdown (probe contact)</td>
<td>11:54</td>
<td>-15 (b) 60</td>
<td>-3</td>
<td>12</td>
<td>6775</td>
</tr>
</tbody>
</table>

*Time from ignition of the DPS.

Horizontal velocity relative to surface.

### Lunar Module Descent Targeting Sequence

- **Braking Phase (P63)**
- **Approach Phase (P64)**
- **Terminal Descent Phase (P66)**
Characterize Braking Phase
By Five Points

Lunar Module Descent Guidance Logic
(Klumpp, Automatica, 1974)

- Reference (nominal) trajectory, $r(t)$, from target position back to starting point (Braking Phase example)
  - Calculated before mission
  - Three 4th-degree polynomials in time
  - 5 points needed to specify each polynomial

$$r_r(t) = r_i + v_i t + \frac{a_i t^2}{2} + \frac{j_i t^3}{6} + \frac{s_i t^4}{24}$$

$r(t) = \begin{bmatrix} x(t) \\ y(t) \\ z(t) \end{bmatrix}$
Coefficients of the Polynomials

\[ \mathbf{r}_r(t) = \mathbf{r}_i + \mathbf{v}_t t + a_t t^2 + j_t t^3 + s_t t^4 \]

- \( \mathbf{r} \) = position vector
- \( \mathbf{v} \) = velocity vector
- \( \mathbf{a} \) = acceleration vector
- \( \mathbf{j} \) = jerk vector (time derivative of acceleration)
- \( \mathbf{s} \) = snap vector (time derivative of jerk)

Corresponding Reference Velocity and Acceleration Vectors

\[ \mathbf{v}_r(t) = \mathbf{v}_t + \mathbf{a}_t t + j_t t^2 + s_t t^3 \]

\[ \mathbf{a}_r(t) = \mathbf{a}_t + j_t t + s_t t^2 \]

- \( \mathbf{a}_r(t) \) is the reference control vector
  - Descent engine thrust / mass = total acceleration
  - Vector components controlled by orienting yaw and pitch angles of the Lunar Module
Guidance Logic Defines Desired Acceleration Vector

- If initial conditions, dynamic model, and thrust control were perfect, $a_r(t)$ would produce $r_r(t)$

$$a_r(t) = a_t + j_t t + s_t \frac{t^2}{2} \Rightarrow$$

$$r_r(t) = r_t + v_r t + a_t \frac{t^2}{2} + j_t \frac{t^3}{6} + s_t \frac{t^4}{24}$$

- ... but they are not
- Therefore, feedback control is required to follow the reference trajectory

Guidance Law for the Lunar Module Descent

Linear feedback guidance law (real time)

$$a_{command}(t) = a_r(t) + K_V [v_{measured}(t) - v_r(t)] + K_R [r_{measured}(t) - r_r(t)]$$

$K_V$ : velocity error gain
$K_R$ : position error gain

- Nominal acceleration profile is corrected for measured differences between actual and reference flight paths
- Considerable modifications made in actual LM implementation (see Klumpp’s original paper on Blackboard)
LM Manual Control Response During Simulated Landing

Simulated LM Manual Control Response To Rate Command
Next Time:

Telemetry, Communications & Tracking
[Understanding Space] Sec 13.1, 15.1

Commercial Space Flight
[Understanding Space] Sec 13.1;
[Augustine’s Laws] Ch 1, 8, 26, 36, 37, 40 (ER)

Supplemental Material
Apollo GNC Software Specification Control

- **Guidance System Operations Plan (GSOP)**
  - NASA-approved specifications document for mission software
  - Changes must be approved by NASA Software Control Board
- **Change control procedures**
  - Program Change Request (NASA) or Notice (MIT)
  - Anomaly reports
  - Program and operational notes
- **Software control meetings**
  - Biweekly internal meetings
  - Joint development plan meetings
  - First Article Configuration Inspection
  - Customer Acceptance Readiness Review
  - Flight Software Readiness Review

Apollo GNC Software Documentation and Mission Support

- **Documentation generation and review**
  - Functional description document: H/W-S/W interfaces, flowcharts of procedures
  - Computer listing of flight code
  - Independently generated program flowchart
  - Users’ Guide to AGC
- **Mission support**
  - Pre-flight briefings to the crew
  - Personnel in Mission Control and at MIT during mission