Seminar 11

**Project Management & System Design**

*Spacecraft Guidance*

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FRS 148, From the Earth to the Moon

Princeton University

**Project Management & Spacecraft Design**

*Fundamentals of Space Systems, Ch 1*

NASA-SP-2016-6105

*Spacecraft Guidance:*

*Understanding Space*

*Sec 12.3*

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**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.

- Reduced development time
- Improved satisfaction of requirements
- Reduced total life-cycle costs
- Reduced schedule
- Enhanced system quality, robustness, and reliability
- Reduced risks
- Enhanced ability to maintain and upgrade the system

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

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**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.

*Pisacane, V., Fundamentals of Space System Design, Ch. 1*
Spacecraft Mission Objectives and Requirements

Requirements Definition

- What must the system accomplish?
- Why must it be done?
- How do we achieve the design goal?
- What are the alternatives?
- What sub-systems perform what functions?
- Are all functions technically feasible?
- How can the system be tested to show that it satisfies requirements?
Program Management: Gantt Chart

- Project schedule
- Task breakdown and dependency
- Start, interim, and finish elements
- Time elapsed, time to go

Program Evaluation and Review Technique (PERT) Chart

- Milestones
- Path descriptors
- Activities, precursors, and successors
- Timing and coordination
- Identification of critical path
- Optimization and constraint
Life Cycle Cost Impacts

Spacecraft Subsystems

Space segment

Payload

Structure (5)

Attitude and orbit control (1) and (4)

Power (7)

Mechanisms (5)

Bus

Thermal (1) and (6)

Telemetry (2) and command (3)

Data handling (2)

Propulsion (1) and (4)
Satellite Systems

- **Power and Propulsion**
  - Solar cells
  - “Kick” motor/ payload assist module (PAM)
  - Attitude-control
  - orbit-adjustment
  - station-keeping
  - Batteries, fuel cells
  - Pressure tanks
  - De-orbit 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
  - Radio transmitters and receivers
  - Radar transponders
  - Antennas

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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

- Solar Array: 38%
- Propulsion: 15%
- Battery: 11%
- Antenna: 9%
- Transponder: 6%
- Control Processor: 6%
- Structures: 2%
- Payload Electronics: 13%
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

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
Components of Apollo CSM Primary Navigation Guidance and Control System ("PNGCS")

Landmark Tracking for Apollo Guidance

Mindell, D., Digital Apollo, Ch. 5
**IMU Alignment and State Update**

1. Astronaut enters code into DSKY to identify landmark and star to computer
2. Astronaut uses tracking and space sextant to generate acquisition and tracking signal
3. Inertial measurement unit (IMU) provides spatial direction reference
4. Astronaut enters “mark” when sight is on landmark
5. Computer incorporates sighting and IMU angles
6. Computer determines direction to landmark and star, compares with expected direction, updates state vector and error matrix

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**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)

http://klabs.org/history/build_agc/
Apollo Guidance Computer
Magnetic Core Memory Ropes

1 core = 1 bit

- 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)**

### 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></td>
<td>Heads up-down</td>
<td>+/- 00001</td>
</tr>
<tr>
<td>07</td>
<td>Change of program or major mode</td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>Engine ON enable</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
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
Lunar Descent Guidance

Lunar Module Transfer Ellipse to Powered Descent Initiation

(62 BY 38 N MI) CSM ORBIT

LM DESCENT ORBIT
(60 N MI. BY 50,000 FT)

UNDOCKING

SUN

LANDING

PDI

SEPARATION

EARTH
Lunar Module Powered Descent

**Lunar Module Descent Events**

<table>
<thead>
<tr>
<th>Event</th>
<th>TPI, min</th>
<th>Inertial velocity, fps</th>
<th>Altitude rate, fps</th>
<th>Altitude, ft</th>
<th>ΔV, fps</th>
</tr>
</thead>
<tbody>
<tr>
<td>A Ullage</td>
<td>-00:07</td>
<td>5560</td>
<td>-4</td>
<td>48 014</td>
<td>0</td>
</tr>
<tr>
<td>B Pow-ered descent initiation</td>
<td>00:0</td>
<td>5529</td>
<td>-3</td>
<td>48 725</td>
<td>31</td>
</tr>
<tr>
<td>C Throttle to maximum thrust</td>
<td>00:26</td>
<td>4020</td>
<td>-50</td>
<td>44 934</td>
<td>1572</td>
</tr>
<tr>
<td>D Rotate to windows-up position</td>
<td>02:56</td>
<td>3065</td>
<td>-89</td>
<td>39 201</td>
<td>2536</td>
</tr>
<tr>
<td>E LR altitude update</td>
<td>04:18</td>
<td>1456</td>
<td>-106</td>
<td>24 63%</td>
<td>4239</td>
</tr>
<tr>
<td>F Throttle recovery</td>
<td>06:24</td>
<td>1315</td>
<td>-127</td>
<td>22 644</td>
<td>4359</td>
</tr>
<tr>
<td>G LR velocity update</td>
<td>06:42</td>
<td>506</td>
<td>-145</td>
<td>7 513</td>
<td>5375</td>
</tr>
<tr>
<td>H High gate</td>
<td>08:26</td>
<td>55 (98)</td>
<td>-16</td>
<td>512</td>
<td>6176</td>
</tr>
<tr>
<td>I Low gate</td>
<td>10:06</td>
<td>-15 (0°)</td>
<td>-3</td>
<td>3</td>
<td>6775</td>
</tr>
<tr>
<td>J Touchdown (probe contact)</td>
<td>11:54</td>
<td>-15 (0°)</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

\[
\begin{align*}
\mathbf{r}_i(t) &= \mathbf{r}_i + v_i t + a_i \frac{t^2}{2} + j_i \frac{t^3}{6} + s_i \frac{t^4}{24} \\
\mathbf{r}(t) &= \begin{bmatrix} x(t) \\ y(t) \\ z(t) \end{bmatrix}
\end{align*}
\]

Coefficients of the Polynomials

\[
\begin{align*}
\mathbf{r}_i(t) &= \mathbf{r}_i + v_i t + a_i \frac{t^2}{2} + j_i \frac{t^3}{6} + s_i \frac{t^4}{24} \\
\mathbf{r} &= \begin{bmatrix} x \\ y \\ z \end{bmatrix} \\
\mathbf{v} &= \frac{d\mathbf{r}}{dt} = \begin{bmatrix} \dot{x} \\ \dot{y} \\ \dot{z} \end{bmatrix} = \begin{bmatrix} v_x \\ v_y \\ v_z \end{bmatrix} \\
\mathbf{a} &= \frac{d\mathbf{v}}{dt} = \begin{bmatrix} a_x \\ a_y \\ a_z \end{bmatrix} \\
\mathbf{j} &= \frac{d\mathbf{a}}{dt} = \begin{bmatrix} j_x \\ j_y \\ j_z \end{bmatrix} \\
\mathbf{s} &= \frac{d\mathbf{j}}{dt} = \begin{bmatrix} s_x \\ s_y \\ s_z \end{bmatrix}
\end{align*}
\]
Corresponding Reference Velocity and Acceleration Vectors

\[ \mathbf{v}_r(t) = \mathbf{v}_t + \mathbf{a}_r t + \mathbf{j}_t \frac{t^2}{2} + \mathbf{s}_t \frac{t^3}{6} \]

\[ \mathbf{a}_r(t) = \mathbf{a}_t + \mathbf{j}_r t + \mathbf{s}_t \frac{t^2}{2} \]

- \( \mathbf{a}_r(t) \) 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, \( \mathbf{a}_r(t) \) would produce \( \mathbf{r}_r(t) \)

\[ \mathbf{a}_r(t) = \mathbf{a}_t + \mathbf{j}_r t + \mathbf{s}_t \frac{t^2}{2} \Rightarrow \]

\[ \mathbf{r}_r(t) = \mathbf{r}_t + \mathbf{v}_r t + \mathbf{a}_r t^2 + \mathbf{j}_r t^3 + \mathbf{s}_r \frac{t^4}{24} \]

- ... 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)

\[ a_{\text{command}}(t) = a_r(t) + K_v [v_{\text{measured}}(t) - v_r(t)] + K_p [r_{\text{measured}}(t) - r_r(t)] \]

- \( K_v \): velocity error gain
- \( K_p \): 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 paper on Blackboard)

LM Manual Control Response During Simulated Landing
Simulated LM Manual Control Response To Rate Command

Next Time:
The Future of Space Flight
Telemetry, Communications & Tracking
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

Ascent (Launch) Guidance
Gravity-Turn Flight Path

- "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

\[
\tan \theta(t) = \tan \theta_0 \left(1 - \frac{t}{t_{BO}}\right)
\]

- "Open-loop" command, i.e., no feedback of vehicle state
- Accounting for effect of Earth surface curvature on burnout flight path angle

\[
\tan \theta(t) = \tan \theta_0 \left[1 - \frac{t}{t_{BO}} - \tan \beta \left(\frac{t}{t_{BO}}\right)\right]
\]
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 be 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, \( \mathbf{i}_q \)

\[
\mathbf{i}_q = \begin{bmatrix} \sin i_d \sin \Omega_d \\ \sin i_d \cos \Omega_d \\ \cos i_d \end{bmatrix}
\]

\( i_d \): 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**

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

**Velocity**

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

$v_{IMU}$: velocity estimate in IMU frame

**Guidance Program: Velocity and Time to Go**

- Effective gravitational acceleration

\[
g_{eff} = -\frac{\mu}{r^2} + \frac{\lvert r \times v_f \rvert}{r^3}
\]

- Time to go (to burnout)

\[
t_{\text{go, new}} = t_{\text{go, old}} - \Delta t
\]

$\Delta t$: guidance interval

- Velocity to be gained

\[
v_{go} = \begin{bmatrix}
    (\dot{r}_d - \dot{r}) - g_{eff} t_v / 2 \\
    -\dot{y} \\
    -\dot{z} + \dot{z}
\end{bmatrix}
\]

- Time to go prediction (prior to acceleration limiting)

\[
t_{\text{go}} = \frac{m}{\dot{m}} \left( 1 - e^{-v_{go}/c_{eff}} \right)
\]

$c_{eff}$: effective exhaust velocity
Guidance Program Commands

- **Guidance law** produces required radial and cross-range accelerations
  
  \[
  a_{T_r} = a_T [A + B(t - t_o)] - g_{eff} \\
  a_{T_c} = a_T [C + D(t - t_o)]
  \]

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

- **Guidance coefficients,** \(A, B, C,\) and \(D\) are functions of \(r_d, r, \dot{r}, t_{go}\):
  
  \[
  \begin{bmatrix}
  r_d, r, \dot{r}, t_{go}
  
  y, \dot{y}, t_{go}
  \end{bmatrix}
  \]

  plus \(c_{eff}, m/\dot{m},\) acceleration limit

Guidance Program Commands

- **Required thrust direction,** \(i_T\) (i.e., vehicle orientation in \((i_n, i_q, i_z)\) frame
  
  \[
  \mathbf{a}_T = \begin{bmatrix}
  a_{T_r} \\
  a_{T_c}
  \\
  \text{what's left over}
  \end{bmatrix};
  \quad i_T = \frac{\mathbf{a}_T}{|\mathbf{a}_T|}
  \]

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