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Spacecraft Design for Manual Control

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Introduction

- This presentation is intended to help the attendee gain a framework for thinking about and an overview familiarity with spacecraft manual control and handling qualities.
- NESC intends to soon publish a comprehensive guide to this material as a white paper.
- This presentation complements a previous GN&C Webcast, *Fundamentals of Piloted Spacecraft Handling Qualities*, given by Dr. Karl Bilimoria on January 18, 2012.

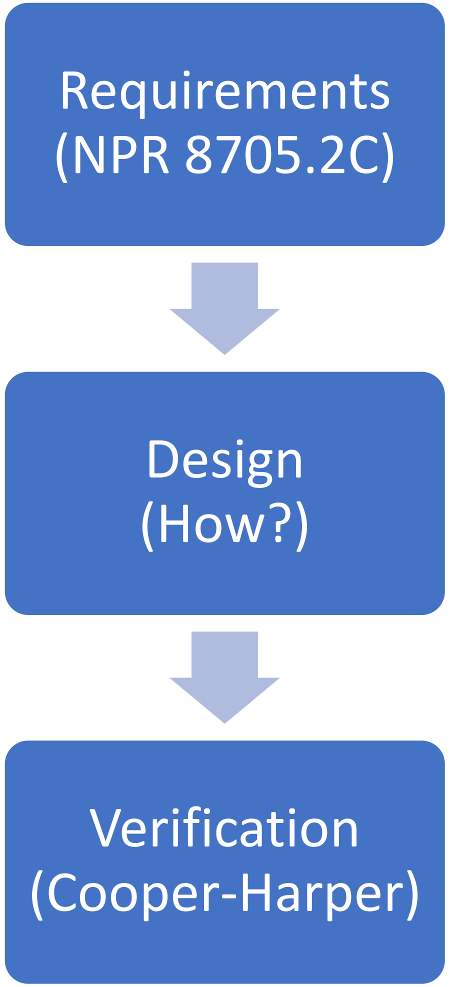
Contents

Part 1:
Manual Control in Context

NASA Human Rating Requirements

- NPR 8705.2C requires (paraphrasing)
  - Manual control of flight path and attitude
  - Satisfactory handling qualities
    - Cooper-Harper ratings of 1,2, or 3 (“Level 1”)
  - Satisfactory pilot workload
    - Not addressed here
- Programs and projects inherit these requirements
  - Orion, SLS
  - Commercial Crew
  - HLS

The Handling Qualities Problem



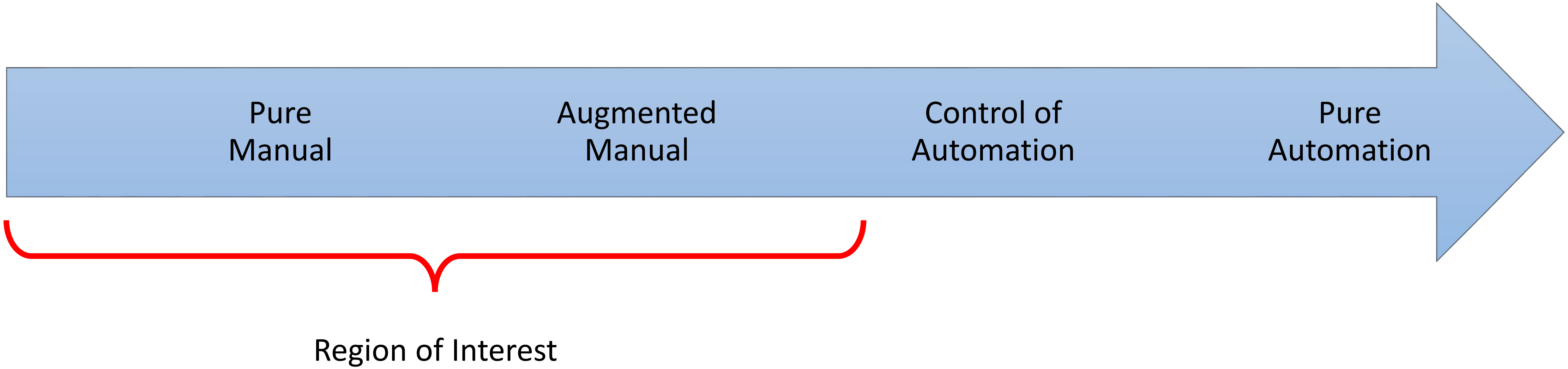
How do we design a spacecraft to have satisfactory handling?

Traditional Answer: Mostly guess.

Starting with Gilruth (1941), aircraft have design requirements for control authority, stability, etc., in order to meet handling requirements.

Goal: Establish conceptually similar design requirements for spacecraft handling qualities.

Control is a Spectrum

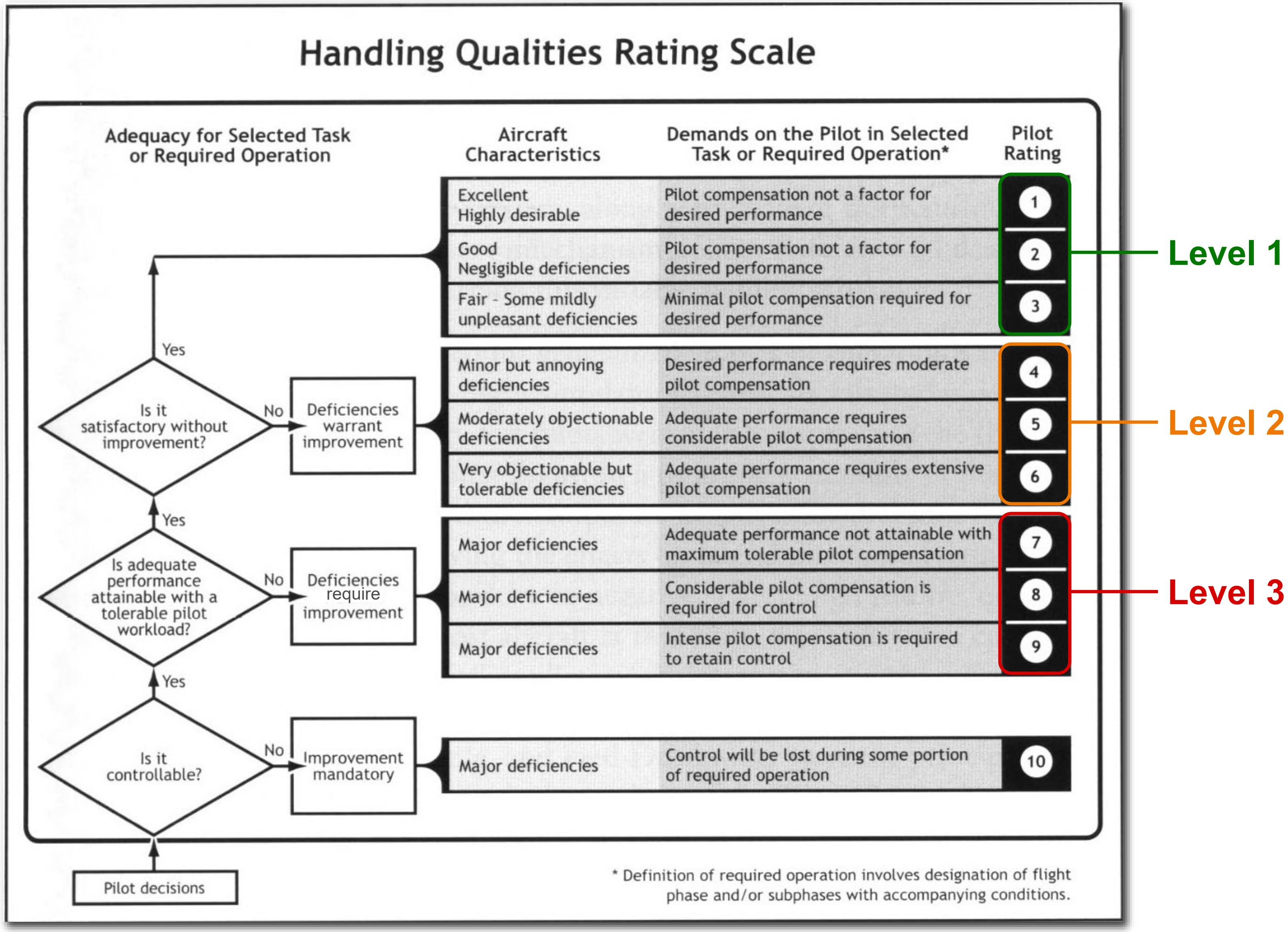


<u>Manual control</u> generally includes augmented control of attitude and translation, but excludes tasks such as management of guidance modes and targets.

<u>Piloting</u> covers all tasks, including monitoring and control of automation, and effort is generally measured with a workload scale such as Bedford or NASA TLX.

Handling Qualities Measurement

- How easily can manual control capability be used?
- Measurement via the Cooper-Harper rating scale (NASA TN D-5153)
  - Pilot evaluation of how difficult it is to perform a task based on the amount of pilot compensation required to perform a task
    - Rating 1: Pilot compensation not a factor for desired performance
    - Rating 3: Minimal pilot compensation required for desired performance
    - Rating 10: Control will be lost during some portion of the required operation
  - Unofficial nomenclature
    - Ratings 1-3: “Level 1” (Satisfactory without improvement)
    - Ratings 4-6: “Level 2” (Deficiencies warrant improvement)
    - Ratings 7-9: “Level 3” (Deficiencies require improvement)
- NASA generally requires “Level 1” (Rating 1-3) handling qualities


Handling Qualities Rating Scale
Adequacy for Selected Task or Required Operation
Aircraft Characteristics
Demands on the Pilot in Selected Task or Required Operation*
Pilot Rating
Excellent
Highly desirable
Pilot compensation not a factor for desired performance
1
Good
Negligible deficiencies
Pilot compensation not a factor for desired performance
2
Fair - Some mildly unpleasant deficiencies
Minimal pilot compensation required for desired performance
3
Minor but annoying deficiencies
Desired performance requires moderate pilot compensation
4
Moderately objectionable deficiencies
Adequate performance requires considerable pilot compensation
5
Very objectionable but tolerable deficiencies
Adequate performance requires extensive pilot compensation
6
Major deficiencies
Adequate performance not attainable with maximum tolerable pilot compensation
7
Major deficiencies
Considerable pilot compensation is required for control
8
Major deficiencies
Intense pilot compensation is required to retain control
9
Major deficiencies
Control will be lost during some portion of required operation
10
Yes
Is it satisfactory without improvement?
No
Deficiencies warrant improvement
Yes
Is adequate performance attainable with a tolerable pilot workload?
No
Deficiencies require improvement
Yes
Is it controllable?
No
Improvement mandatory
Pilot decisions
* Definition of required operation involves designation of flight phase and/or subphases with accompanying conditions.
Level 1
Level 2
Level 3

Why have manual control?

- Unanticipated or non-required contingency cases
  - Ex: Apollo 13 (LO_2 tank burst)
  - Ex: Skylab 3 (Multiple RCS propulsion failures)
  - “Unknown unknowns” and “Too unlikely to design for”
- Unforeseen missions and tasks
- Reduced cost
  - Crew procedures cost much less than automation software
  - Significant cost and schedule impact to build an automated spacecraft with supplemental manual control capabilities than to build a piloted spacecraft with supplemental automation
- Manual control is a toolkit to handle rare and unforeseen cases

Manual control is…

- Required for NASA human rating of spacecraft
  - "…shall provide the capability for the crew to manually control the flight path and attitude of their spacecraft…" (NPR 8705.2C)
  - Programs inherit this from the NASA Procedural Requirements (NPR)
- On a spectrum from fully manual to fully automated
- Part of the larger task of piloting the spacecraft
- A unique sub-discipline of GNC
  - Specialized body of knowledge
  - Often poorly documented and based on experience
  - Not well suited for reinvention from first principles by every program

Part 2:
Design for Satisfactory Handling

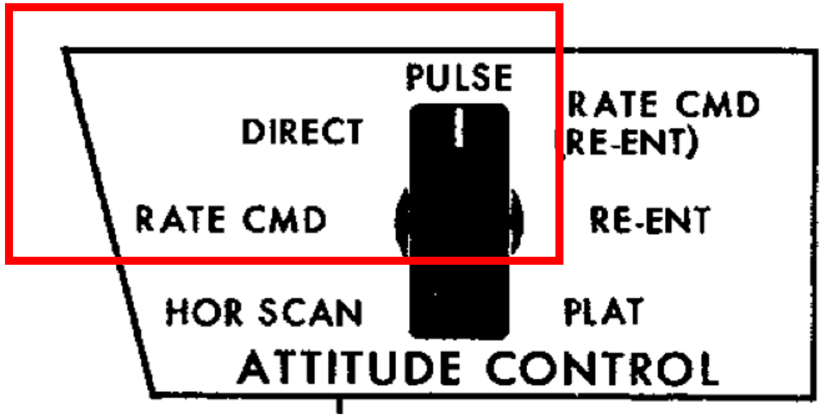
The Design Problem

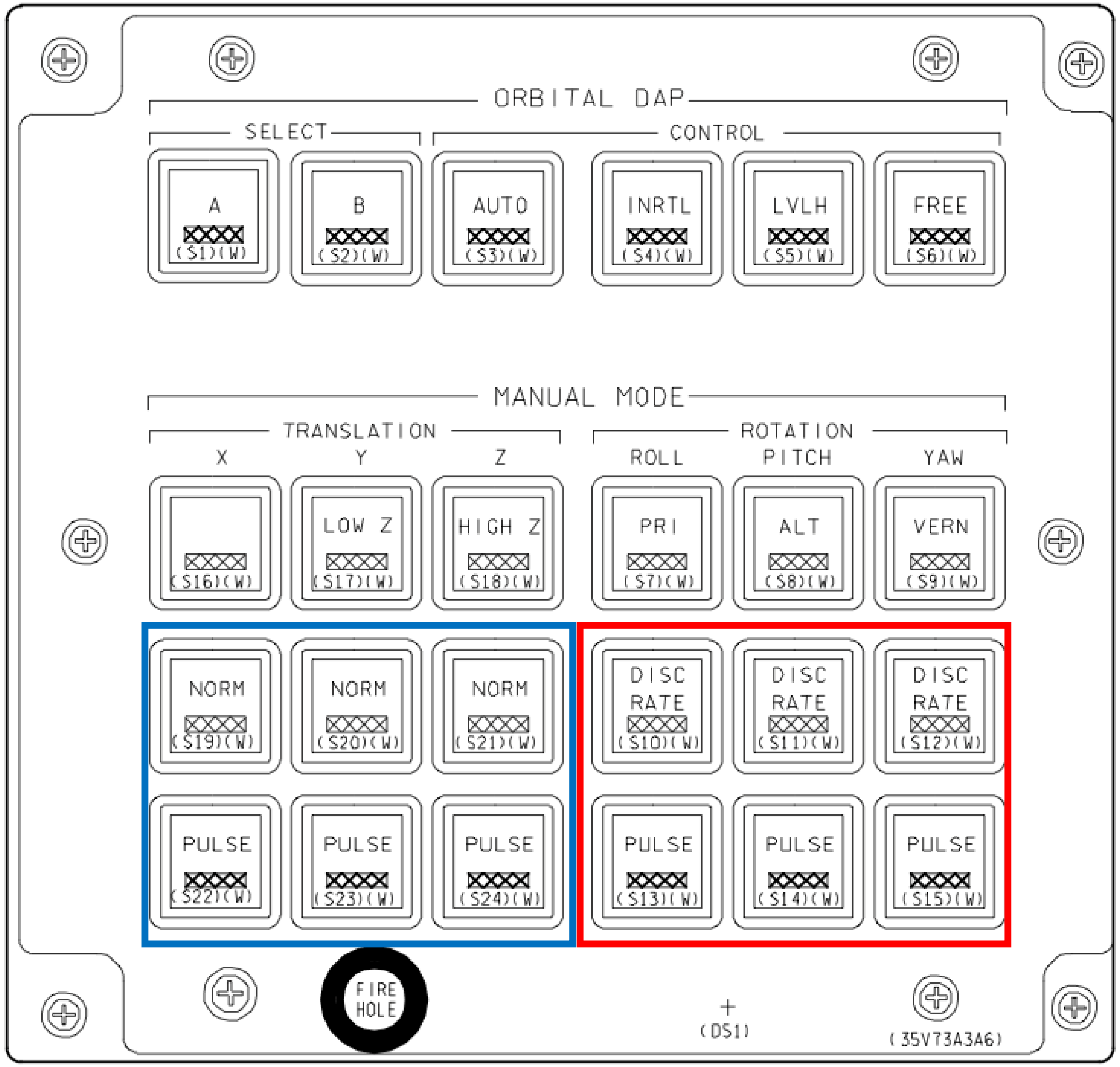
- NASA generally requires Level 1 (“satisfactory”) handling qualities, but how do you design a spacecraft to achieve that?
  - Recall this is the desired result of an evaluation, not a design requirement
  - Relatively little guidance available to spacecraft designers
  - Most historic research evaluates handling of a specific design and task
    - Ex: Can a Gemini spacecraft successfully dock with an Agena target vehicle?
  - Some historic research on specific design requirements
    - Ex: Apollo LM landing control authority requirements are well understood.
- My work has focused on establishing a set of design requirements and guidelines to achieve satisfactory handling qualities.
  - Inspired by *Requirements for Satisfactory Flying Qualities of Airplanes* (R. Gilruth, 1941, NACA R-755)

Control Modes

- Airplanes typically have only a single control mode
  - Aerosurface displacement proportional to stick/yoke/pedal displacement
  - Thrust proportional to throttle displacement
- Spacecraft are more complicated with multiple control modes
  - Rotation
    - Direct/Acceleration, Impulse, Proportional Rate, Discrete Rate
  - Translation
    - Normal/Acceleration, Impulse
  - These are the most common control modes, but many are possible
  - Impulse can be via firing time (historic) or magnitude (modern)

Gemini Control Mode Selector





Shuttle DAP Panel

- Control is per-axis
- Rotation
    - Disc. Rate
    - Impulse
    - Direct (via RHC)
- Translation
    - Impulse
    - Normal

Spaceflight Regimes

- Coasting Flight Attitude Control
- Powered Flight with Reaction Control
- Powered Flight with Thrust Vector Control
- Proximity Operations and Docking
- Atmospheric Entry
- Powered Lift Landing

- Conceptually similar to aircraft phases of flight: Takeoff, Climb, Cruise, Turn, Approach, Landing

Manual Control Context Concept

	Regime A	Regime B	Regime C
Control Mode A			
Control Mode B			Context
Control Mode C			

Manual Control Context	
Design Parameter A (k_A)	Critical Value(s)
Design Parameter B (k_B)	Critical Value(s)
Design Parameter C (k_C)	Critical Value(s)

Handling Contexts

- Discussion of spacecraft handling only makes sense in context, meaning the intersection of
  - Spaceflight regime <u>with</u>
  - Control mode

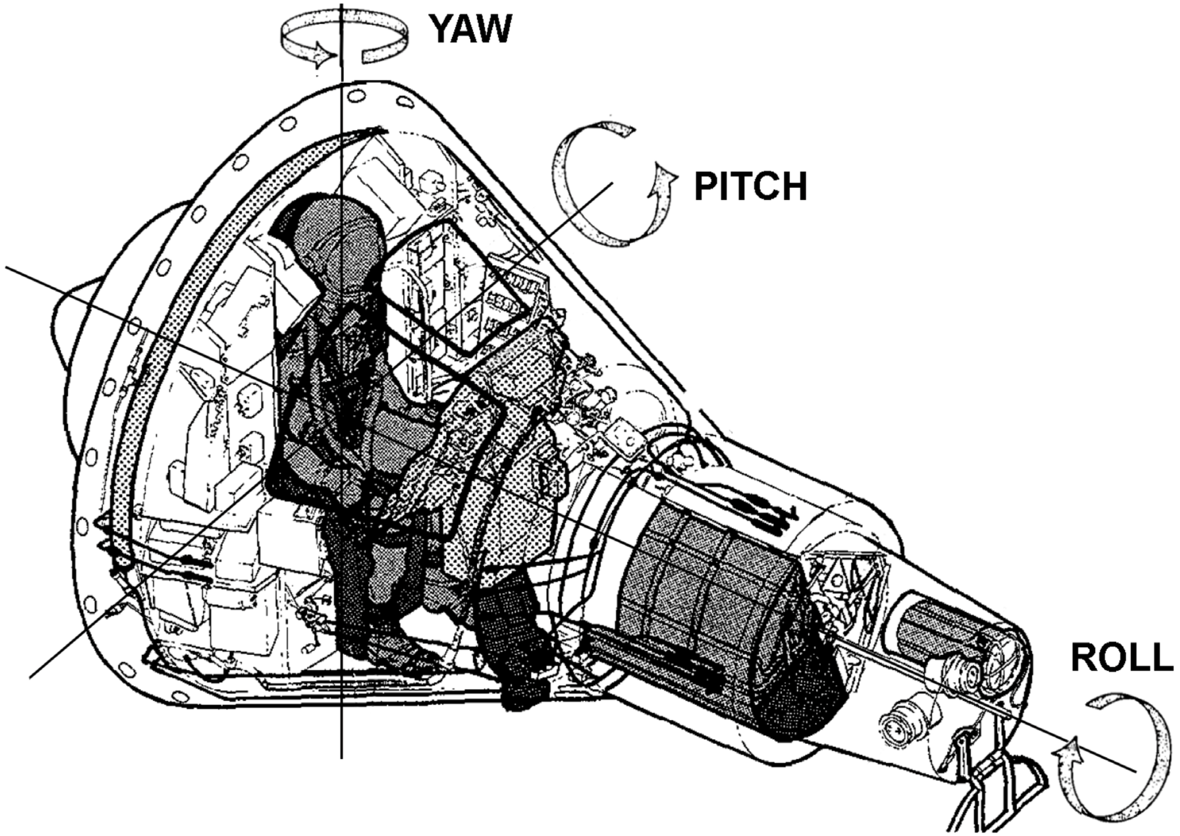
- Examples:
  - Coasting Flight Attitude Control with Rotational Impulse
  - Powered Flight with Thrust Vector Control with Proportional Rate
  - Docking with Impulse Translation and Discrete Rate Attitude Control

- Not all possible intersections are viable or practical

Design Parameters and Critical Values

- Within each handling context we define one or more numerical design parameters that significantly influence handling
  - Ex: Control Authority, Coupling, Response Time
- Design parameters are agnostic (independent of vehicle)
  - Agnostic: Angular Acceleration (deg/s^2)
  - Not Agnostic: Thrust (lb_f)
- We then determine the critical values for each design parameter at which handling transitions between satisfactory and unsatisfactory
  - Ex: Satisfactory handling when 0.1 (deg/s) $< k_{ex}$
  - Ex: Satisfactory handling when $0.5 < k_{ex} < 1.5$ (deg)

Coasting Flight Attitude Control

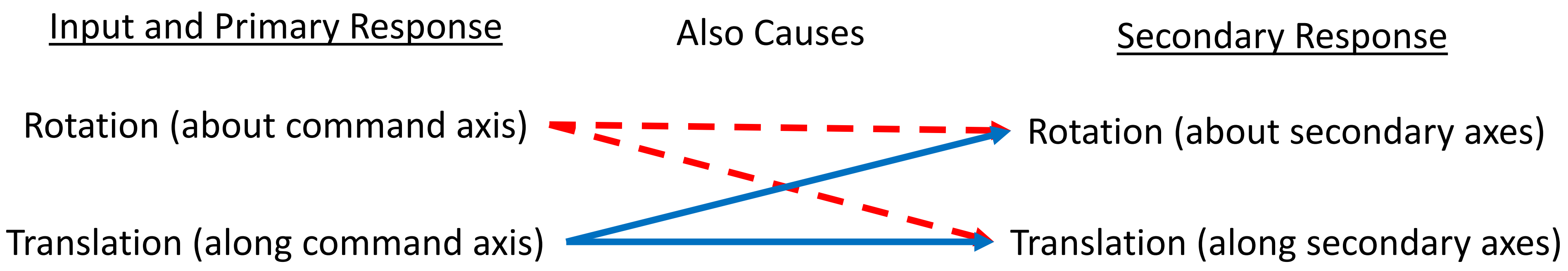


Coasting Flight Attitude Control

Control Mode	Control Authority Parameter	Coupling Parameter
Direct	k_{acd} (deg/s^2)	
Impulse	k_{aci} (deg/s)	
Proportional Rate		
Discrete Rate		

What about coupling?
(What IS coupling?!)

Coupling Overview



Rotation can couple into rotation and/or translation.
Translation can couple into rotation and/or translation.

Rotational coupling (rotation to rotation) can be quantified as the angle between the desired and actual response axes (coupling angle).

Coasting Flight Attitude Control

Control Mode	Control Authority Parameter	Coupling Parameter
Direct	k_{acd} (deg/s^2)	k_{ard} (deg)
Impulse	k_{aci} (deg/s)	k_{ari} (deg)
Proportional Rate		
Discrete Rate		

It's not immediately obvious how to describe the control authority of a rate command system.

(Spoiler: See next slide.)

Rate Command Control Authority

- Observation:
  There seems to be a relationship between attitude maneuvering rate, angular acceleration, and handling. Insufficient angular acceleration tends to cause overshoot. (A fast car needs strong brakes.)
- Assume relationship is linear.

$$k_{acpr}\left({}^{1}/_{s}\right) = \frac{Angular\ Accel\ \left({}^{deg}/_{s^2}\right)}{Max\ Mnvr\ Rate\ \left({}^{deg}/_{s}\right)}$$

Notes: Value increases numerically with increasing control authority. (Intuitive)
Discrete rate control authority (k_{acdr}) is defined similarly.

Coasting Flight Attitude Control (Revised)

Control Mode	Control Authority Parameter	Coupling Parameter
Direct	$0.3 < k_{acd} < 12.7$ (deg/s^2)	$k_{ard} < 14.3$ (deg)
Impulse	$0.01 < k_{aci} < 0.19$ (deg/s)	$k_{ari} < 15.5$ (deg)
Proportional Rate	0.1 (1/s) $< k_{acpr}$	n/a
Discrete Rate	0.1 (1/s) $< k_{acdr}$	n/a

Rotation to rotation coupling is generally not a factor with rate command control systems because rates are automatically damped in secondary axes.

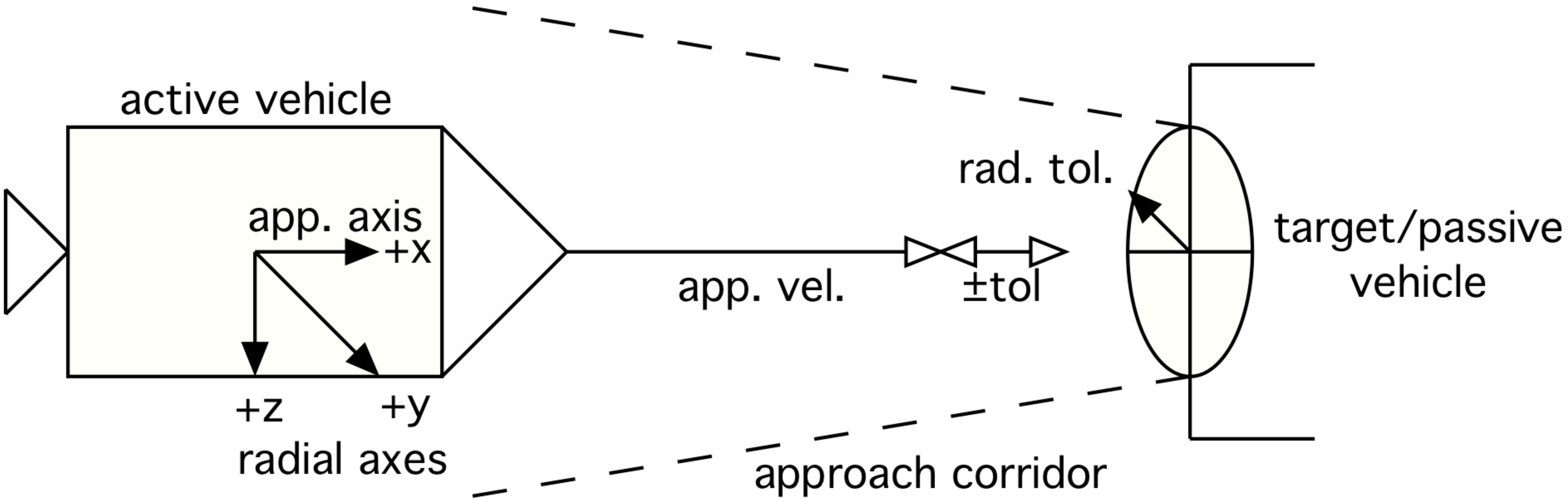
Rotation to translation coupling assumed to be unimportant in this regime.

Critical values shown are estimates.

Powered Flight

- with Reaction Control
  - Translation engine typically creates a <u>perturbing moment</u>
  - Requirement is to have sufficient attitude control authority when working <u>against</u> the perturbing moment
- with Thrust Vector Control
  - Assume proportional rate command
  - Behaves similarly to control with RCS assuming TVC actuators are fast enough
  - Angular acceleration is taken at maximum actuator displacement

Docking Geometry



Proximity Operations and Docking

- Observation:
  The primary task is to make contact within radial position and approach velocity tolerances, tighter tolerances are harder to achieve, so there is a relationship between those tolerances, impulse magnitude, and handling.
- Assumptions
  - 3-DOF task (attitude is held automatically)
  - Relationship is linear
  - Translation control is Impulse or Normal (but with human impulsive input)
  - Docking is more constraining to design than proximity operations
  - Coupling is of second order importance compared to control authority

Docking Control Authority

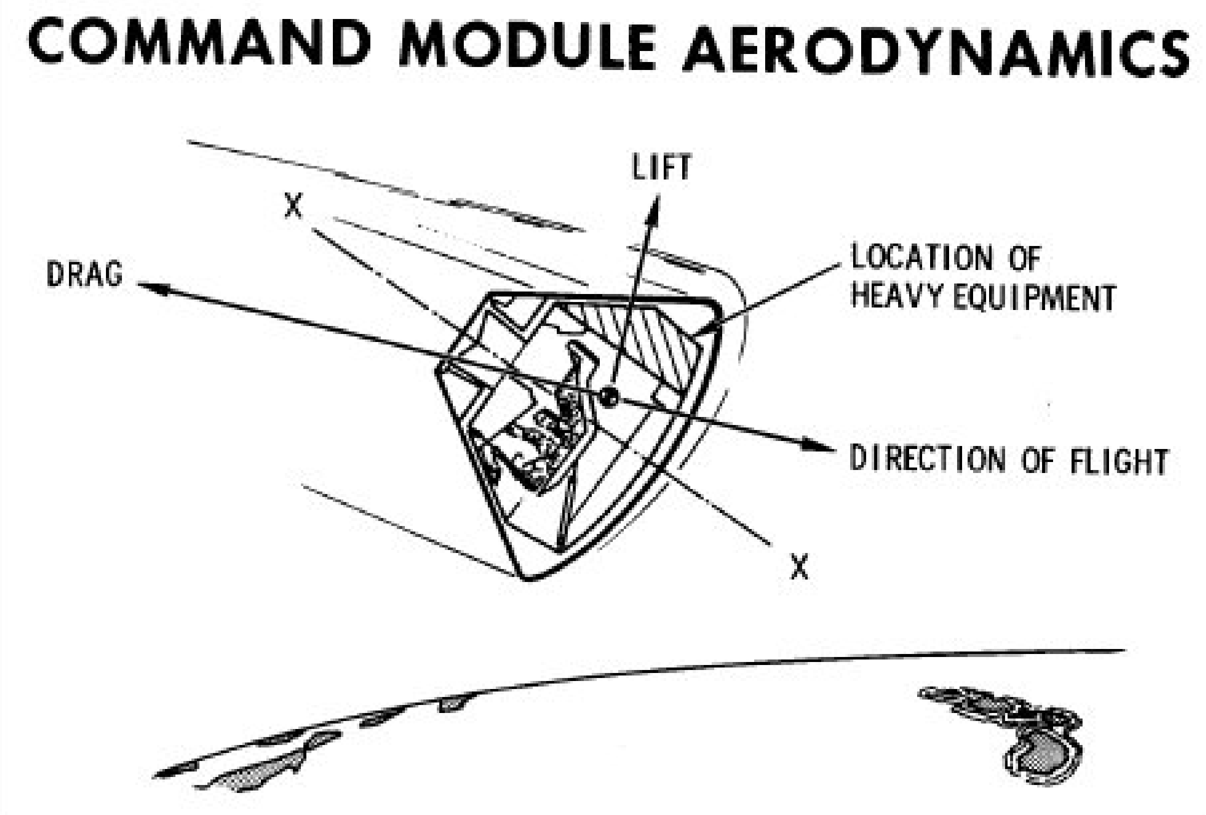
$$k_{dai}(-) = \frac{Min\ Approach\ Impulse\ \left({}^{ft}/_{s}\right)}{Approach\ Velocity\ Tolerance\ \left({}^{ft}/_{s}\right)}$$

$$k_{dri}\left({}^{1}/_{s}\right) = \frac{Min\ Radial\ Impulse\ \left({}^{ft}/_{s}\right)}{Radial\ Position\ Tolerance\ (ft)}$$

Design Parameter	Critical Values
Approach Control Authority (k_{dai})	$0.02 < k_{dai} < 1.0$
Radial Control Authority (k_{dri})	$0.01 < k_{dri} < 0.05$ (1/s)

Critical values are estimates.

Atmospheric Entry



Other Spaceflight Regimes

- Atmospheric Entry
  - Assume capsule
  - Direct or Proportional Rate attitude control
  - Essentially a single-axis attitude control problem
  - Control authority definitions similar to Coasting Flight Attitude Control
  - Additional factor: Maximum maneuver rate needs to be large enough
- Powered Lift Landing
  - Apollo LM landing is the only flown example, but it is well documented
    - See also: Lunar Landing Research Vehicle (LLRV)
  - Too complicated to address here

Design Parameter Critical Values

- Critical values for most design parameters have been estimated using a combination of techniques
  - Analysis of historic spacecraft
    - Parameter values determined from historic design data and 6-DOF sim
    - Contemporary accounts (test reports, pilot debriefings) used to determine if handling is satisfactory or unsatisfactory, allowing for a critical value to be estimated
  - Informal handling evaluations using existing simulators
    - Shuttle Mission Simulator
    - Shuttle Desktop Simulator
  - Estimated values and rationale to be published by NESC
- More comprehensive studies are needed

Part 3:
Additional Factors

Biomechanical Interface: Hand Controllers

- Rotational Hand Controller (RHC)
  - Pivot Points
  - Breakout and Feedback Torque Curves
  - Range of Motion
  - Rate Shaping
    - Mapping between angular displacement and commanded rate
    - Can be linear (usually) or non-linear (special cases)
  - Sampling Rate
- Translational Hand Controller (THC)
  - Breakout and Force Curves
  - Sampling Rate
    - Caused problems on Shuttle
- Bi-modal hand controllers tend to cause problems
  - Combination RHC/THC with mode switch
  - Hand controllers with selectable direction sense

Biomechanical Interface: Flight Instruments and Displays

- Attitude Direction Indicator (ADI)
  - Sign Convention
    - Shuttle changed this mid-program due to pilot error tendency
  - Euler Sequence
    - Where do you want your singularity?
  - Attitude Error and Attitude Rate Indicators
    - Scaling should vary depending upon usage
  - Reference Frames
    - Inertial, LVLH, User Selectable
- Incremental Velocity Indicator (IVI)
  - Sign Convention

Control System Lag

- “How much lag is too much?”
- Probably most critical for docking and powered lift landing
- Potential exists for PIO if delay and control authority are large
  - Ex: Shuttle ALT-5 Landing PIO Incident
- Hugely important issue for satisfactory handling but very little data exists to guide vehicle designers
- Strong need for additional research

Part 4:
Closing Thoughts

Takeaways and Conclusions

- Manual Control
  - Important GNC sub-discipline with unique skills
  - Poorly suited for reinvention from first principles by every program
  - Continues to be important for safety and mission success
- Satisfactory Handling
  - Needs to be designed into the vehicle from conception
  - CDR is a terrible time to discover you have a problem
  - Useful framework exists, along with estimated critical values
  - Institutional support is needed to do additional research

References

- Gilruth, Robert R., *Requirements for Satisfactory Flying Qualities of Airplanes*, NACA Report 755, 1941.
  - Highly influential first compilation of comprehensive design requirements for satisfactory handling qualities of airplanes.
- Cooper, George E. and Robert P. Harper, Jr., *The Use of Pilot Rating in the Evaluation of Aircraft Handling Qualities*, NASA TN D-5153, April 1969.
  - Defines the rating scale used to evaluate vehicle handling qualities.
- Bilimoria, Karl, *Fundamentals of Piloted Spacecraft Handling Qualities*, NESC GN&C Webcast, January 2012.
  - Overview of several handling qualities studies.

References (cont.)

- Anonymous, *Human-Rating Requirements for Space Systems*, NASA Procedural Requirements (NPR) 8705.2C, July 2022.
  - Defines agency requirements for manual control and satisfactory handling qualities that are inherited by individual programs.
- Osborn, John H., *Requirements for Satisfactory Handling Qualities of Manned Spacecraft*, Ph.D. Dissertation, University of Texas at Austin, May 2018.
  - Essentially the long form version of this presentation. Currently under publication hold pending release as NESC white paper.

Questions?

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YOUR FEEDBACK IS WELCOME